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Title: Influence of spatial differentiation in impact assessment for LCA-based decision support: implementation of biochar technology in Indonesia

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Abstract: Spatial differentiation in evaluation of environmental impacts in life cycle assessment (LCA) may give more accurate and realistic results, especially in cases where impacts occur at a local or regional scale and where sensitivity of receiving ecosystems differs from generic conditions. However, from a decision maker's perspective it is of interest to investigate whether the use of spatially differentiated impact assessment methods in addition leads to better decisions. Biochar production and agricultural utilization in Indonesia is an example of a micro-level decision-support case where spatial differentiation could be relevant.

To study the influence of spatial differentiation on implementation of biochar as a waste management strategy and the choice of best performing biochar production techniques, agricultural utilization systems and geographic locations, comparisons were made between four communities living on different Indonesian islands, three biochar production techniques and two types of fertilizer.

Results showed that the differences in impact scores between generic and spatially differentiated impact scores were an order of magnitude different for some of the considered impact categories. These differences influenced the identification of which system performed best when considering total damage to human health, which was mainly due to differences in accounting for impacts arising from water use. By contrast, trade-offs between impact categories combined with relatively small contribution of some spatially differentiated impacts rendered spatial differentiation less relevant with regard to total damage to ecosystems. Total impact scores were influenced to a greater extent by variations in inventories determining environmental burden and benefits, than by differences between generic and spatially differentiated characterization factors. Hence, irrespective of the scenario and type of damage considered, both generic and spatially differentiated assessments showed that implementing biochar technology in Indonesia is expected to bring environmental benefits.

It was shown that spatial differentiation in impact assessment did not necessary lead to better decisions in this case study. This may suggest that depending on the goal of the LCA, practitioners should consider potential benefits of implementing spatially differentiated life cycle impact assessment methods as opposed to potential benefits from collecting site-specific inventories.

DTU Management Engineering

Cover letter

25 July 2018

Dear Dr. Kannan Govindan,

Enclosed please find the revised manuscript, entitled **“Influence of spatial differentiation in impact assessment for LCA-based decision support: implementation of biochar technology in Indonesia”.** We are thankful for the valuable comments given that helped us make the paper clearer and highlight its novelty better. As explained in our response letter and in the revised manuscript, the novelty of this paper is two-fold:

1. This is the first regionalized comparative LCA study where influence of spatial differentiation on decision-support has been investigated. It shows that even in biodiversity-rich country like Indonesia, where conditions are far from average conditions, spatial differentiation in impact assessment did not necessary lead to better decision support, which was unexpected.
2. This is the first regionalized LCA study where spatially differentiated LCIA methods were consistently applied to all relevant impact categories at damage level. This broad application complex and has not been systemized in this way before.

We hope that the revised version of our paper highlighting these aspects is now acceptable for publication in Journal of Cleaner Production.

Yours sincerely,
Mikolaj Owsianiak

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Response to comments from Reviewers'

Ms. Ref. No.: JCLEPRO-D-18-01416R1
Title: Influence of spatial differentiation in impact assessment for LCA-based decision support: implementation of biochar technology in Indonesia
Authors: Mikołaj Owsianiak, Gerard Cornelissen, Sarah E. Hale, Henrik Lindhjem and Magnus Sparrevik

Reviewer #1:

1. The abstract should be brief and up to the point. Still the abstract should be able to state briefly the purpose of the research, the principal results and major conclusions.

Response: We agree on the importance of this point. The abstract contains the three items mentioned by the reviewer as explained below, although we admit that presentation of the purpose of research could be made clearer.
i) purpose of research: "To study the influence of spatial differentiation on these aspects" (that is, aspects which were presented in the first paragraph of the abstract)
ii) the principal result: "Results showed that that the differences in impact scores between generic and spatially differentiated impact scores were an order of magnitude different for some of the considered impact categories. (...) Irrespective of the scenario and type of damage considered, both generic and spatially differentiated assessments showed that implementing biochar technology in Indonesia is expected to bring environmental benefits"
iii) major conclusions: "Thus, spatial differentiation in impact assessment did not necessary lead to better decisions in this case study. This may suggest that depending on the goal of the LCA, practitioners should consider potential benefits of implementing spatially differentiated life cycle impact assessment methods as opposed to potential benefits from collecting site-specific inventories".
Change in the manuscript: To make presentation of the purpose clearer, the abstract is rewritten:

"Spatial differentiation in evaluation of environmental impacts in life cycle assessment (LCA) may give more accurate and realistic results, especially in cases where impacts occur at a local or regional scale and where sensitivity of receiving ecosystems differs from generic conditions. However, from a decision maker's perspective it is of interest to investigate whether the use of spatially differentiated impact assessment methods in addition leads to better decisions. Biochar production and agricultural utilization in Indonesia is an example of a micro-level decision-support case where spatial differentiation could be relevant.

To study the influence of spatial differentiation on implementation of biochar as a waste management strategy and the choice of best performing biochar production techniques, agricultural utilization systems and geographic locations, comparisons were made between four communities living on different Indonesian islands, three biochar production techniques and two types of fertilizer.

Results showed that the differences in impact scores between generic and spatially differentiated impact scores were an order of magnitude different for some of the considered impact categories. These differences influenced the identification of which system performed best when considering total damage to human health, which was mainly due to differences in accounting for impacts arising from water use. By contrast, trade-offs between impact categories combined with relatively small contribution of some spatially differentiated impacts rendered spatial differentiation less relevant with regard to total damage to ecosystems. Total impact scores were influenced to a greater extent by variations in inventories determining environmental burden and benefits, than by differences between generic and spatially differentiated characterization factors. Hence, irrespective of the scenario and type of damage considered, both generic and spatially differentiated assessments showed that implementing biochar technology in Indonesia is expected to bring environmental benefits.

It was shown that spatial differentiation in life cycle impact assessment did not necessary lead to better decisions in this case study. This may suggest that depending on the goal of the LCA, practitioners should *consider potential benefits of implementing spatially differentiated life cycle impact assessment methods as opposed to potential benefits from collecting site-specific inventories."*

2. Highlights are a short collection of bullet points that convey the core findings of the article. The given highlights are not up to the mark.

Response: We agree that core findings should be presented in the bullet points.
Change in the manuscript. As suggested, the bullet points are rewritten:

"-Spatial differentiation was found important for total damage to human health
- Spatial differentiation was less relevant for total damage to ecosystems
- Tradeoffs between impact categories influenced total scores
- Geographical variations in inventory flows influenced comparisons
- Spatial differentiation did not necessarily lead to better decisions"

3. The authors have not still presented the research questions in the introduction section. The current version is just stating what is present in the earlier literature.

Response: We realize that formulation of our research question in the introduction was not very clear, which may have led to it being unnoticed.
Change in the manuscript: To make research question clearer, it is rephrased:

"It is therefore of interest to investigate whether the use of spatially differentiated LCIA methods leads to better decisions, in addition to more accurate and realistic LCIA results. Our research question is therefore: does spatial differentiation in life cycle impact assessment lead to better decisions?"

4. The literature review is very weak. There is no critical addressing of existing literature. This will be affecting the novelty and contribution aspect of the research.

Response: This comment is in conflict with the last round of comments from the reviewer, who wrote that "the authors satisfactorily review the earlier literature". We note that although several papers present spatially differentiated LCIA methods, only few regionalized LCA studies were published to date (Anton et al., 2014; Heidari et al., 2017; Henderson et 48 al., 2017a; Mutel et al., 2011). We referred to both the papers presenting spatially differentiated LCIA methods (17 papers in total) and the papers on regionalized LCA studies (4 papers in total) in our study.

Based on the comments presented above we consider that we have done a systematic review of existing literature. Unfortunately the literature in this field is limited, but we hope that this paper will add on to the topic.
Change in the manuscript: No change is deemed necessary.

5. Still authors have no concrete reason to answer why LCIA ? or why this type of research is carried out ?

Response: We realize that we still have not formulated the aim of our study precisely enough, which might have led to the misunderstanding of the reviewer. It seems that the reviewer got the impression that we want to address the relevance of carrying out life cycle impact assessments (LCIA). This was never the aim, as LCIA is a part of LCA, according to the ISO 14040 standard. We only studied the influence of the choice of spatially differentiated LCIA methods (that is, methods which offer spatially differentiated characterization factors as indicators of potential environmental impacts) on LCA results and ultimately on decision which can be supported by the LCA.
Change in the manuscript: We have now added definition of LCIA and clearly stated the aim of the study. We hope this will prevent any future misunderstandings:

"Life cycle impact assessment (LCIA) the part of life cycle assessment (LCA) in which the life cycle inventory of a system's material flows is translated into their potential contributions to the environmental impacts. LCIA supports the interpretation phase of the LCA, where questions posed in the goal definitions are answered (Hauschild and Huijbregts 2015). Spatially differentiated life cycle impact assessment (LCIA) methods enable execution or regionalized life cycle assessment (LCA) studies as they take into consideration local conditions and sensitivities of receiving ecosystems. In contrast to generic methods, which should be valid on a global scale (at the expense of higher spatial uncertainty), spatially-differentiated LCIA methods are more accurate as they operate at either regional or local scales, corresponding to site-dependent and site-specific assessments, respectively (Potting and Hauschild, 2006). In this paper, we studied the influence of the choice of spatially differentiated LCIA methods on the interpretation phase of a comparative LCA."

6. Discussion should be improved in compliance with the research findings and it applicability.

Response: We agree that discussion should relate to research findings and their applicability. This is why we included paragraphs on the relevance of spatial differentiation for decision support and a paragraph on practical implications. Several studies presenting development of spatially differentiated LCIA methods, and all four regionalized LCA studies, are referred to in the discussion. Since the reviewer is not specifically addresses where there is need for improvements, we hope that this clarification is satisfactory for a positive conclusion on this point.
Change in the manuscript: As most important aspects which relate to research findings and their applicability were already discussed in our study, no change is deemed necessary.

7. List out some future scope for expansion for your research or suggest some future direction which your research has opened up.

Response: We agree that it is relevant to suggest future direction for research and have therefore clarified this point in the text.
Change in the manuscript: As suggested, we list future direction for research in expanded conclusions section:

"The findings presented in this study raise several additional questions. First, it is unknown whether environmental benefits from implementation of biochar systems are larger than environmental burdens in other regions of the World. Second, it is unknown whether the findings generally apply to other comparative LCA case studies. Third, an intelligent approach needs to be developed to determine which of the flows in the foreground system are relevant to consider for spatially differentiated impact assessments, and which can be omitted. Forth, in this study, spatial differentiation was considered for all flows in the foreground system, but this can be challenging if more complex systems are modelled. Finally, the use of spatially differentiated LCIA methods depends on the ability of LCA modelling software to consider them, and solutions are needed to enable easy and consistent use of spatially differentiated LCIA methods in LCA of products and systems in the future."

Thought the authors satisfactorily review the earlier literature this paper lacks in novelty and I could not see any scientific value added to the existing literature. Hence, I recommend for a Minor revision.

Response: As explained in our previous response during the first revision round, the novelty of this paper is two-fold:

1. This is the first regionalized comparative LCA study where influence of spatial differentiation on decision-support has been investigated. It was shown that even in biodiversity-rich country like Indonesia, where conditions are far from average conditions , spatial differentiation did not necessary lead to better decision support, which was unexpected.

2. This is the first regionalized LCA study where spatially differentiated LCIA methods were consistently applied to all relevant impact categories at damage level. This broad application complex and has not been systemized in this way before.

We therefore disagree that the paper lacks novelty, although we admit that it could be presented better in the text. We are thankful for the valuable comments given that helped us highlight the aspects of novelty better.
Change in the manuscript: Novelty of the paper is now highlighted in the discussion and conclusions sections:

"This is the first regionalized comparative LCA study where influence of spatial differentiation on decision support was investigated. While this study corroborates earlier regionalized LCA studies in terms of influence of spatial differentiation on impact scores, it demonstrates that the benefits of spatial differentiation for decision-support are not obvious, and are closely connected to the goal of the LCA. The discussion below therefore relates to various aspects in a decision support context, using the application of biochar technology as the example."

"This first regionalized LCA study where spatially differentiated LCIA methods were consistently applied to all relevant impact categories at damage level showed that although spatial differentiation improved accuracy and realism of environmental impacts, it did not necessarily lead to better decisions."

Reviewer #2:
The author has addresses all the reviewer comments.

Response: We appreciate the reviewer for her/his feedback.

Wordcount: 8826

Influence of spatial differentiation in impact assessment for LCA-based decision support: implementation of biochar technology in Indonesia

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Highlights (for review)

- Spatial differentiation was found important for total damage to human health
- Spatial differentiation was less relevant for total damage to ecosystems
- Tradeoffs between impact categories influenced total scores
- Geographical variations in inventory flows influenced comparisons
- Spatial differentiation did not necessarily lead to better decisions

Abstract

Spatial differentiation in evaluation of environmental impacts in life cycle assessment (LCA) may give more accurate and realistic results, especially in cases where impacts occur at a local or regional scale and where sensitivity of receiving ecosystems differs from generic conditions. However, from a decision maker's perspective it is of interest to investigate whether the use of spatially differentiated impact assessment methods in addition leads to better decisions. Biochar production and agricultural utilization in Indonesia is an example of a micro-level decision-support case where spatial differentiation could be relevant.

To study the influence of spatial differentiation on implementation of biochar as a waste management strategy and the choice of best performing biochar production techniques, agricultural utilization systems and geographic locations, comparisons were made between four communities living on different Indonesian islands, three biochar production techniques and two types of fertilizer.

Results showed that the differences in impact scores between generic and spatially differentiated impact scores were an order of magnitude different for some of the considered impact categories. These differences influenced the identification of which system performed best when considering total damage to human health, which was mainly due to differences in accounting for impacts arising from water use. By contrast, trade-offs between impact categories combined with relatively small contribution of some spatially differentiated impacts rendered spatial differentiation less relevant with regard to total damage to ecosystems. Total impact scores were influenced to a greater extent by variations in inventories determining environmental burden and benefits, than by differences between generic and spatially differentiated characterization factors. Hence, irrespective of the scenario and type of damage considered, both generic and spatially differentiated assessments showed that implementing biochar technology in Indonesia is expected to bring environmental benefits.

It was shown that spatial differentiation in impact assessment did not necessary lead to better decisions in this case study. This may suggest that depending on the goal of the LCA, practitioners should consider potential benefits of implementing spatially differentiated life cycle impact assessment methods as opposed to potential benefits from collecting site-specific inventories.

Keywords

decision-making, decision-support, LCA, LCIA, regionalization, spatialization

1. Introduction

Life cycle impact assessment (LCIA) the part of life cycle assessment (LCA) in which the life cycle inventory of a system's material flows is translated into their potential contributions to the environmental impacts. LCIA supports the interpretation phase of the LCA, where questions posed in the goal definitions are answered (Hauschild and Huijbregts, 2015). Spatially differentiated life cycle impact assessment (LCIA) methods enable execution or regionalized life cycle assessment (LCA) studies as they take into consideration local conditions and sensitivities of receiving ecosystems. In contrast to generic methods, which should be valid on a global scale (at the expense of higher spatial uncertainty), spatially-differentiated LCIA methods are more accurate as they operate at either regional or local scales, corresponding to site-dependent and site-specific assessments, respectively (Potting and Hauschild, 2006). In this paper, we studied the influence of the choice of spatially differentiated LCIA methods on the interpretation phase of an LCA.

The development of spatially differentiated LCIA methods has intensified in the past few years (Patouillard et al., 2018; Rosenbaum et al., 2018; Verones et al., 2017). A review of characterization models included in spatially differentiated LCIA methods, like IMPACT World+ (Bulle et al., 2012) or LC-Impact (Verones et al., 2016), is given in Rosenbaum (2018). Examinations of these models shows, that depending on the impact category, geographic variability in characterization factors (CF) can be higher than differences in characterization factors between substances covered by the method. Applications of such methods in LCA studies results in more accurate and realistic evaluations of environmental impacts, as was demonstrated for the few regionalized LCA studies published to date (Anton et al., 2014; Heidari et al., 2017; Henderson et al., 2017a; Mutel et al., 2011).

LCA is a decision support tool. Two (out of three) commonly used archetype goal situations (namely, situation A for micro-level decision support and situation B for meso/macro-level decision support) involve a decision context (Bjørn et al., 2018a; European Commission, 2010). It is therefore of interest to investigate whether the use of spatially differentiated LCIA methods leads to better decisions, in addition to more accurate and realistic LCIA results. Our research question is therefore: does spatial differentiation in life cycle impact assessment lead to better decisions? The answer to this research question is not obvious. Even large differences in impact scores for individual impact categories might become less influential for decision support. This could be due to potential trade-offs between impact categories (Heidari et al., 2017), due to a larger influence of spatial variability in inventory flows compared to spatial differences in characterization factors (Henderson et al., 2017b), or due to a smaller contribution of spatially-differentiated impact categories to total damage. The influence of spatial differentiation in impact assessment on LCA-based decision support has not previously been investigated.

Spatial differentiation may be particularly important for application of biochar systems in tropical rural areas like Indonesia, where conditions with regard to biodiversity or water availability can vary significantly from generic characterization factors used in traditional LCA (Boulay et al., 2011; Chaudhary et al., 2015). Biochar is typically used as soil conditioner, increasing crop productivity while contributing to climate change mitigation through carbon sequestration and storage (Lehmann, 2007; Woolf et al., 2010). Biochar is produced from biomass residues, and in developing and middle-income countries often small-scale, low-cost pyrolysis technologies traditionally based on earth-mound kilns are used (Nsamba et al., 2015). Alternatively, more innovative and cleaner flame curtain (“Kon-Tiki”) kilns or retort kilns made out of bricks and steel, can be used (Cornelissen et al., 2016; Sparrevik et al., 2015). Experimental studies have shown that biochar production leads to emission of toxic organic compounds and greenhouse gases (Cornelissen et al., 2016; Sparrevik et al., 2015). Environmental impacts from biochar systems have previously been assessed using LCA (e.g. Galgani and Delft, 2012; Gwenzi et al., 2015; Sparrevik et al., 2014). However, the relative immaturity of spatially differentiated LCIA approaches and their limited implementation into LCA modelling software, have restricted the use of spatially differentiated methods in these studies.

The objective of this study was therefore to assess implications of spatial differentiation in LCIA on decision support related to implementation of a biochar systems in Indonesia. For this purpose, generic and spatially differentiated impact scores were calculated and compared using a suite of relatively recent LCIA methods, which offer spatially differentiated characterization factors at the damage level. Firstly, the influence on an *absolute scale,* i.e. whether the conversion of biomass residues to biochar and its subsequent use in agriculture provides has a net positive effect compared to the current situation (no treatment of biomass residues), was investigated. Secondly, when selecting management strategies, decision makers must know in which geographic locations biochar systems are expected to perform optimally, and furthermore which biochar production technique and biochar application conditions (inorganic vs. organic fertilizer based agriculture) perform best from an environmental point of view. Thus, the effect of spatial differentiation on the *relative importance* for ranking of subsystems and technologies was assessed. Finally, decision makers may be interested in identifying potential improvements for biochar systems, and a process contribution analysis, i.e. identifying the processes with the largest environmental burden, can be used for this purpose. Thus, the impact of spatial influence on *process contribution* was examined.

2. Methods

2.1. Goal and scope

The goals of the LCA were three fold: The first goal was to assess and compare life cycle impacts of biochar systems in Indonesia in order to support decision making related to the implementation of biochar as a waste management strategy in four Indonesian island communities. The second goal was to identify the best biochar production technique and agriculture practice in these communities. The third goal was to identify improvement potentials for the biochar systems. The results of this LCA are used to discuss the effect on spatial differentiation for LCA-based decision support in the Indonesian context.

The LCA was carried out following the requirements of the ISO standards and the guidelines of the International Reference Life Cycle Data System (ILCD) handbook (European Commission, 2010; European Committee for Standardization, 2006a, 2006b) According to the ILCD guidelines, the current study is a micro-level decision support (type-A) situation, and the assessment carried out applies an attributional approach in accordance with the recommendations of the ILCD guidelines for this decision support type. A system expansion (through crediting) using average processes in this attributional approach, consistent with both ILCD and the ISO hierarchy for solving multifunctionality, was therefore applied (Bjørn et al., 2018b).

2.1.1. Functional unit and system boundaries

The primary function of the biochar systems in this context is to utilize biomass waste to produce biochar and use of this biochar as a soil conditioner. Thus, the functional unit was defined as the “treatment of 1 kg of biogenic carbon from biomass residues in rural areas in Indonesia”. This definition allows for a fair comparison between residues treated using different techniques. A secondary function of biochar when used as soil conditioner is its ability to support crop growth. In this case, the benefits from increasing yields are modelled as avoided production of crops (mainly fertilizer use). In addition, system boundaries included the complete underlying biochar production life cycle, including the construction of the biochar kilns and production of biochar from biowaste (Fig. 1). Avoided impacts from current waste management system are also relevant to considered, but in this case there is no treatment of biomass residues, which are allowed to decompose in aerobic conditions. Thus, following Sparrevik et al., (2014) no net emissions of carbon dioxide and no emission of methane during decomposition of biomass residues were assumed.

Fig. 1.

2.1.2. Biochar systems investigated

The influence of spatial differentiation was studied by using site specific inventory data from four distinct geographic locations of Indonesia (Ngata Toro on the island of Sulawesi, Napu on Sumba, Lampung on Sumatra, and Lamongan on Java) (see SI, Section S1 for details). On the basis of previous work in Nepal and Zambia, the most promising method for the production of biochar in the four villages was considered to be the flame curtain technique (Table 1, scenarios 1-4) (Cornelissen et al., 2016; Schmidt et al., 2014). This novel production technology was compared to biochar systems based on other available alternative production technologies, such as retort kilns (the Adam retort) (Adam, 2009) and simple non-retort earth-mound kilns (Table 1, scenarios 5-12). Inorganic fertilizers (N, P, K, and urea) are used in all villages, except for Napu where compost is used. Thus, comparisons were made with compost as the sole source of nutrient input in Ngata

Toro, Lampung, and Lamongan, and with inorganic fertilizers as the source of nutrient input in Napu (Table 1, scenarios 13-24).

Table 1. Overview of the compared biochar systems.

# Scenario	Sensitivity parameter	Geographic location (production and use) [a]	Biochar production technique [b]	Fertilizer type and amount [c]
1	Baseline	NT	“Kon-Tiki" flame curtain kiln	NPK and urea fertilizers
3-4	Geographic location of biochar production and use	N, LS, LJ	“Kon-Tiki" flame curtain kiln (all locations)	NPK and urea fertilizers (NT, LS, LJ); compost (N)
5-12	Biochar production technique	NT, N, LS, LJ	retort kiln (all locations); earth mound kiln (all locations)	NPK and urea fertilizers (NT, LS, LJ); compost (N)
13-24	Fertilizer type and amount	NT, N, LS, LJ	“Kon-Tiki" flame curtain kiln, retort kiln; earth mound kiln (all locations)	compost (NT, LS, LJ); NPK and urea fertilizers (N)

[a] NT: Ngata Toro; N: Napu; LS; Lampung, Sumatra; LJ: Lamongan, Java

[b] retort kiln made from bricks and steel (Adam retort) and earth-mound kiln were alternatives to steel-made “Kon-Tiki” flame curtain kiln

[c] in Lampung and Lamongan NPK and urea fertilizers were applied in higher amounts compared to Ngata Toro (see SI, Section S2 for details)

2.2. Life cycle inventory analysis

Data for background processes, like construction of kilns or (avoided) production of inorganic fertilizers are based on generic processes available in Ecoinvent, version 3.3 (Weidema et al., 2013). Ecoinvent is currently one of the most comprehensive databases of life cycle inventories. Consideration of spatial differentiation in LCIA for these generic processes was not possible, as it is not known where emissions occur in the background system. Data for foreground processes in the biochar system, such as biochar production or soil application, should be represented as accurately as possible and were thus based on primary data measured in Indonesia and reported previously (Sparrevik et al., 2014), or collected specifically in surveys carried out for this work. Spatial differentiation was used in the LCIA in all relevant processes in the foreground system. All inventory data were site-specific representative field data aggregated from seven years of biochar research activities. This data, which included biochar properties, biochar application rate, irrigation and agricultural yields, varied between sites. Outdoor emissions resulting from the production of biochar, concentrations of CO_2, CO, CH_4, NMVOC, and PM_{10} and nitrous oxides, measured in Cornelissen et al., (2016) and Sparrevik et al., (2015) were used. Emissions of nitrate, phosphate, phosphorus and metals (co-contaminants) to soils, and emissions of GHG to air from organic and inorganic fertilizers were taken from generic Ecoinvent process for production of maize. Differences in fertilizer amounts between the Ecoinvent process and amounts in these case studies were corrected for, assuming that composition of fertilizers with regard to metal content was the same. Site-specific data related to the mineralization kinetics of biochar in soil were not available for this study and as such were assumed to follow bi-exponential decay kinetics and average (geometric mean) kinetic parameters measured for six biochars representing a wide range of mineralization rate constants were therefore used (Zimmerman and Gao, 2013). Based on Woolf and Lehmann, (2012) a negative priming equal to 45% increase in soil organic carbon stock in the long-term (100 years) was used. Model parameters and underlying data are presented in the SI, Section S2. Unit processes for the foreground system are given in the SI, Section S3.

2.3. Life cycle impact assessment

To answer the research question (does spatial differentiation lead to better decisions?), spatially differentiated LCIA methods must be applied to all relevant categories of environmental impacts and must express impacts in common units. Hence, the following set of criteria was applied to choose LCIA methods: (i) a method must be published in peer-reviewed literature; (ii) it must offer modelling at damage level; (iii) it must allow a calculation of spatially-explicit impact score at sufficient resolution to be made (e.g. country- or Southeast-Asia level for regional impact categories like photochemical ozone formation, and island- or biome-level for local impact categories like land use); and (iv) it can be further adapted to specific geographic situation based on available details of the case study (e.g. adapting the particulate matter (PM) model to local exposure parameters). A comparison of impact assessment methods based on their environmental relevance or scientific robustness was not carried out here and no preference was given to one method over another for this study. Damage scores were computed allowing for weighting of impact categories contributing to total damage in two important areas of protection in LCIA: (i) human health, where impacts are expressed in disability adjusted life years, DALY; and (ii) ecosystem quality considering terrestrial, freshwater, and marine ecosystems, where impacts are expressed as loss of biodiversity (in species-years) (Hauschild and Huijbregts, 2015). The full list of LCIA methods with details of the spatial scales considered is given in Table 2. A detailed description of each method is presented in the SI, Section S5.

Table 2. Generic and site-explicit LCIA methods for the impact categories considered in this study.

Impact category	Area of protection	Impact score unit	Geographical and temporal reference unit	Reference
Climate change	Human health	DALY	Indonesia; 1-yr time steps	Levasseur et al., 2010); ReCiPe2016 (Huijbregts et al., 2016); IPCC (2013); Cherubini et al., (2016)
Climate change	Ecosystems (freshwater)	species×year	Indonesia; 1-yr time steps	
Climate change	Ecosystems (terrestrial)	species×year	Indonesia; 1-yr time steps	
Ozone depletion	Human health	DALY	Global	ReCiPe2016 (Huijbregts et al., 2016)
Ionizing radiation	Human health	DALY	Global	ReCiPe2016 (Huijbregts et al., 2016)
Particulate matter formation	Human health	DALY	Outdoor rural: Southeast Asia Indoor: air exchange rate for open building and no attenuation, measured village-specific exposure parameters (see Table S1)	(Fantke et al., 2017b)
Land use	Ecosystems (terrestrial)	species×year	Village-specific	Chaudhary et al., (2015)
Water use (distribution)	Human health	DALY	Watershed/Indonesia [a]	Boulay et al., (2011)
Water use	Ecosystems (terrestrial)	species×year	Watershed	ReCiPe2016 (Huijbregts et al., 2016), based on Pfister et al., (2009)
Water use	Ecosystems (freshwater)	species×year	Indonesia [b]	ReCiPe2016 (Huijbregts et al., 2016), based on Hanafiah et al., (2011)
Toxicity (cancer and	Human health	DALY	Outdoor: Southeast Asia Indoor: household indoor exposure settings based	USEtox 2.02 (Fantke et al., 2017a)

Impact category	Area of protection	Impact score unit	Geographical and temporal reference unit	Reference
non-cancer effects)			on non-OECD archetype combined with village-specific exposure parameters (see Table S2)	
Freshwater ecotoxicity	Ecosystems (freshwater)	species×year (converted from PDF×m3×d)	Southeast Asia	USEtox 2.02 (Fantke et al., 2017a)
Terrestrial ecotoxicity	Ecosystems (terrestrial)	species×year (converted from PDF×m3×d)	Village-specific for metallic elements; Global for organic chemicals	ReCiPe2016 (Huijbregts et al., 2016); (Owsianiak et al., 2017; Owsianiak et al., 2013) for metallic elements
Marine ecotoxicity	Ecosystems (marine)	species×year (converted from PDF×m3×d)	Indonesian Sea marine ecosystem for metallic elements; Global for organic chemicals	ReCiPe2016 (Huijbregts et al., 2016) for organics; Dong et al., (2016) for metallic elements
Freshwater eutrophication	Ecosystems (freshwater)	species×year	Indonesia	ReCiPe2016 (Huijbregts et al., 2016)
Marine eutrophication	Ecosystems (marine)	species×year	Village-specific	Cosme et al., (2017; Cosme and Hauschild, 2017); Roy et al., (2014)
Terrestrial acidification	Ecosystems (terrestrial)	species×year	Village-specific	ReCiPe2016 (Huijbregts et al., 2016)
Photochemical ozone	Human health	DALY	Region comprising Indonesia, Papua New Guinea, and East Timor	ReCiPe2016 (Huijbregts et al.,

Impact category	Area of protection	Impact score unit	Geographical and temporal reference unit	Reference
formation				2016)
Photochemical ozone Formation	Ecosystems (terrestrial)	species×year	Region comprising Indonesia, Papua New Guinea, and East Timor	ReCiPe2016 (Huijbregts et al., 2016)
Mineral resource scarcity	Resources	USD2013	Global	ReCiPe2016 (Huijbregts et al., 2016)
Fossil resource scarcity	Resources	USD2013	Global	ReCiPe2016 (Huijbregts et al., 2016)

[a] although watershed-specific characterization factors were calculated by Boulay et al., (2011) for main watersheds (ca. 600 in total), all four villages are located outside main watersheds and thus assigned the same characterization factor

[b] although watershed-specific characterization factors were calculated by Hanafiah et al., (2011) for well-known river basins above 42° latitude (214 in total), none of the four villages could be mapped on the watershed.

2.4. Sensitivity and uncertainty analyses

A sensitivity analysis of the results of the discrete parameters as determined by scenarios presented in Table 1 (Section 2.1) was conducted by comparing impact scores without any internal normalization. For continuous parameters, sensitivity of impact scores was quantified by computing normalized sensitivity coefficients (eq 1), based on Ryberg et al., (2015):

$$X_{IS,k} = \frac{\Delta IS / IS}{\Delta a_k / a_k} \qquad \text{(eq 1)}$$

where $X_{IS,k}$ is the dimensionless normalized sensitivity coefficient of impact score (IS) for perturbance of continuous parameter k, a_k is the kth parameter value, Δa_k is the perturbation of parameter a_k, IS is the calculated impact score, and ΔIS is the change of the impact score that resulted from the perturbation of parameter a_k. Baseline parameter values were used as default in all scenarios listed in Table 1. They originate from measurements and are described in Section 2.2. Perturbed parameter values representing lower and higher ranges of parameters were defined based on variations reported earlier in other experimental studies on biochar in developing and middle-income countries (Table 3). A parameter is considered important if $X_{IS,k} \geq 0.3$, corresponding to a medium sensitivity (Cohen et al., 2013). Uncertainties in those parameters which were found important in the perturbation analysis (see SI, Section S6.5 for results of the sensitivity analysis) were assigned either normal, or triangular, or uniform distributions based on the distribution of measured values (SI, Section S4).

In addition to parameter uncertainties, uncertainties in the life cycle inventories were also considered. For the foreground processes (e.g. in material inputs or emissions) they were estimated using the Pedigree matrix approach, as illustrated in Ciroth et al., (2013) assuming that the data was log-normally distributed (Huijbregts et al., 2003). Uncertainties in the background processes were based on geometric standard deviations already assigned to flows in the ecoinvent processes used. Uncertainties in characterization factors are not provided for the majority of the methods, and were therefore not considered. Monte Carlo simulations (1000 iterations) were carried out for pairwise comparison between scenarios listed in Table 1 while keeping track of the correlations between pairs of systems. Comparisons were considered statistically significant if at least 95% of all 1000 Monte Carlo runs were favourable for one scenario.

Table 3. Uncertain, continuous model parameters for processes associated with biochar systems. Values referred to as default apply to all relevant scenarios listed in Table 1. Perturbation analysis was carried out to test the influence of a parameter value on the results for selected scenarios.

Parameter	Parameter values		Unit	Source
	Default	Perturbation		

		s (min-max)		
Biochar yield (flame curtain and earth-mound kilns)	22	17-27	%	Measured in Cornelissen et al., (2016) Error of 5.0% as measured by Sparrevik et al., (2015)
Biochar yield (Adam retort)	32	27.4-36.6	%	Measured in Sparrevik et al., (2015) Error of 4.6% as measured by Sparrevik et al., (2015)
Biochar application rate (per village) [a]	NT: 1200	1140-1260	kg/ha	Measured in Sparrevik et al., (2014) Error of 5% assumed, expected to be in realistic range of values
	N: 4000	3800-4200		
	LS: 5000	4750-5250		
	LJ: 4000	3800-4200		
Crop yield without biochar addition (per village) [a]	NT: 6500	5655-7345	%	Measured in Sparrevik et al., (2014) (NT) and in this study (for the other locations). Error of 13% based on values reported in Zambia by Sparrevik et al., (2013)
	N: 2000	1740-2260		
	LS: 6000	5220-6780		
	LJ: 8000	6960-9040		
Crop yield change when biochar is used (per village)	NT: 10	7.1-11.6	%	Measured in Sparrevik et al., (2014) (NT), in this study (N and LS) or assumed (LJ) equal to 10%, which is a conservative estimate (Jeffery et al., 2017, 2011). Perturbation ranges based on measurements in Napu (N) were scaled to other villages assuming equal variance
	N: 248	176-287		
	LS: 100	71-116		
	LJ: 10	7.1-11.6		
Mineralization rate constant for the recalcitrant pool	8.58E-04	9.2E-06 - 6.1E-03	yr^{-1}	Measured in Zimmerman and Gao, (2013) for six different biochars. Default (geometric mean), minimum, and maximum values were used
Priming effect	45	30-60	%	Modelled in Woolf and Lehmann, (2012) Increase in soil organic carbon stock in the long-term (100 years) was used. Perturbation

				values are ranges reported (Woolf and Lehmann, 2012)
Water use for irrigation (per village) [a]	NT: 0.155	0.11-0.20	m^3/kg output	Measured in this study. Perturbation values assumed 30% increased and decrease, which is in realistic range of values
	N: 0	0-0		
	LS: 0.155	0.11-0.20		
	LJ: 0.155	0.11-0.20		
Fraction of PM smaller than 2.5 µm	0.92	0.73-0.95	kg/kg	Measured for residential wood combustion as reported in Humbert et al., (2011) Value of 0.73 is for low-stack emissions, value of 0.95 is in higher range of measured values for various sources (Humbert et al., 2011)

[a] NT: Ngata Toro; N: Napu; LS; Lampung, Sumatra; LJ: Lamongan, Java

3. Results

3.1. Comparison between generic and spatially differentiated impacts

Figure 2 shows the comparison between generic and spatially differentiated impacts from biochar produced using a flame curtain kiln and used in agriculture, as influenced by geographic location of the field and fertilizer type (scenarios 1-4 and 13-15 in Table 1). Impact scores for individual impact categories either increased or decreased compared with generic scores, depending on the impact category (see also SI, Section S6.1). The largest consistent increase (by ca. 2 orders of magnitude) was observed at all locations for the *human health impacts from water use* (except Napu). Spatially differentiated characterization factors for human health impacts in the watersheds are equal to 0 DALY/m^3 for all sites except Napu where the characterization factor is higher and reflects water scarcity problems on Sumba. However, current agricultural practice does not rely on irrigation in this village. This explains why there are no apparent benefits in terms of water used impacts when the system is credited for increasing crop yields in Napu for both spatially differentiated and generic assessments. The comparison between spatially differentiated and generic impacts also shows that there is some reduction in human health impacts stemming from emissions of PM2.5 (difference up to factor of 2), mainly because the site-specific intake of PM2.5 resulting from emissions are smaller at the site-specific level at these rural sites, than the default value used in global-generic assessment.

The largest consistent decrease when spatial differentiation was used (by ca. 1 order of magnitude) was observed at all locations for *land use impacts on birds and mammals*. Indonesian ecoregions are among the most biodiverse globally, and characterization factors are generally one order of magnitude higher in all villages when compared to global-generic values (Chaudhary et al., 2015). Changes in impact scores for other impact categories ranged from small (below 10%) to large (up to a factor of 5) when spatial differentiation was considered, but these differences were largely non-conspicuous as the contribution of these impacts categories to total damage was often very small (less than 1% of total damage). Statistically significant differences between regionalized and generic impacts were found in nearly all impact categories, except for freshwater eutrophication. Similar trends were observed for other kilns (see SI, Section S6.2). The major differences between spatially differentiated and generic impacts were, again, due to significantly smaller (but not equal to zero) contributions from water use impacts on the terrestrial ecosystem (Fig. 2b). Here, the very high resolution of watersheds used in the method of Pfister et al., (2009) which includes relevant minor watersheds, allowed each village and its corresponding watershed to be mapped. In addition, there was an increase in impact scores for terrestrial acidification due to a small alkaline buffering capacity of the soils, making them more vulnerable to acidic emissions. Figure 2b also shows that there is some reduction in ecotoxicological impacts stemming from using soil-specific characterization factors for metallic elements (like Cd or Zn) emitted together with fertilizer as co-contaminants. Terrestrial ecotoxicity characterization factors for these elements are generally higher (approximately twice as high) compared to generic values because acidic soils have a higher bioavailable metal concentration and thus a higher toxicity potentials in soils (Owsianiak et al., 2017; Owsianiak et al., 2015).

When aggregating impacts at the human health and ecosystem level, the impact of spatial differentiation was less pronounced. The spatially differentiated damage to human health was approximately 3 to 5 times higher when compared to generic scores, except for Napu where total damage was comparable between approaches (Fig. 2a). For aggregated potential impacts on ecosystems, the effect of spatial differentiation was not significant (Fig. 2b), although impact scores varied by up to one order of magnitude for the individual impact categories. This is mainly caused by the small absolute numbers for the impact categories mostly influenced by spatial differentiation (such as marine eutrophication or ozone formation) (see SI, Section S6.1), as well as trade-offs between categories, where an increase in impact scores for some categories was compensated by a decrease in others. For example, the increase in impact from water use and acidification in the regionalized assessment was compensated by increased benefits from land use impacts on plants. These benefits roughly doubled when compared with the global-generic assessment.

Fig. 2.

4. Discussion

4.1 Relevance of spatial differentiation for decision support

Results presented in Fig. 2 and in Section S6.1 of the SI show that spatially differentiated impact assessments resulted in more accurate and realistic results than generic assessments. This finding is consistent with earlier regionalized LCA studies demonstrating the use of spatially differentiated LCIA methods. Mutel et al., (2011) already showed that spatially differentiated ecosystem damage and human health scores of coal-based power generation in America were 30% higher and 38% lower, respectively, compared to generic scores. Anton et al., (2014) reported that regionalized human toxicity impacts of tomato agriculture in Spain were one order of magnitude higher than those determined from generic assessment. More recently, Henderson et al., (2017) demonstrated that spatial differentiation resulted in a nearly double water stress for American food production when compared to a generic assessment.

This is the first regionalized comparative LCA study where influence of spatial differentiation on decision support was investigated. While this study corroborates earlier regionalized LCA studies in terms of influence of spatial differentiation on impact scores, it demonstrates that the benefits of spatial differentiation for decision-support are closely connected to the goal of the LCA. The discussion below therefore relates to various aspects in a decision support context, using the application of biochar technology as the example.

4.1.1 Evaluation at an absolute scale

In order to make decisions about the implementation of a new biowaste management strategy, information about overall environmental performance of the technology is needed. In this study, impact scores were negative in most (but not all) of the individual impact categories, and the total damages were all negative (Fig. 2). Thus, environmental benefits from increased crop productivity outweighed the environmental burden of biochar production, which can include human health impacts from particulate matter and emission of toxic carcinogenic compounds. This holds true for all of the geographic locations, biochar production techniques, and fertilizers compared, suggesting that spatial differentiation does not influence decisions about implementing biochar systems in Indonesia. This study showed that a crop productivity increase as low as 10%, such as in Lampung and Ngata Toro (and lower than 25% as reported in a recent meta-analysis for tropical soils (Jeffery et al., 2017), is sufficient to make spatial differentiation irrelevant with regards to making decisions about the implementation of biochar-based management strategy for biowaste in Indonesia. Burden and benefits can also be determined by the current waste management practice that is replaced by the new biowaste management strategy (Owsianiak et al., 2016). In the biochar context, spatial differentiation is therefore expected to be less relevant in cases where the replaced waste management system is based on the polluting methods composting or landfilling, which emit the potent greenhouse gas methane (Laurent et al., 2014).

The increase in crop productivity of 10% may, however, be sufficient to make spatial differentiation relevant for certain chars where production and/or transportation to the field are important contributors to total impacts, as has been shown to be the case for hydrochars (Owsianiak et al., 2017). This may also hold true for biochars made on an industrial scale (and thus off-site). It is therefore important to see spatial differentiation in connection to the quality of the inventory, which for most relevant processes in this study used site-specific data.

4.1.2 Relative ranking

One plausible management decision from the LCA would be a relative feasibility ranking of villages to assess the benefit of implementing biochar technology in that specific region. For human health damage, both generic and spatially differentiated assessments identified Lampung as the village performing best, while Napu and Ngata Toro/Lamongan were identified as least optimal in both the generic and site-specific assessments (Fig. 3 and SI, Section 6.3). This difference is due to different quantities of water used for irrigation. Further, different villages were identified as best in scenarios with alternative fertilization strategies. This makes spatial differentiation relevant to consider in cases where detailed rank information is desirable. For total ecosystem damage however, Lampung and Lamongan performed best in both generic and spatially differentiated assessments, with no statistically significant difference between them. This was mainly due relatively large geographic differences in life cycle inventories between villages, which were larger than geographic differences in characterization factors. Indeed, the good performance of Napu (relative to the other villages) is explained by the very high productivity increase when biochar is amended to soils (250% increase compared to the control; Table 2). The relatively good performance of Lampung is explained by the high productivity increase (100% increase compared to the control; Table 2) which in turn reduces the need for inorganic fertilizers, combined with the fact that the absolute yield was relatively high for agricultural practices without biochar.

To isolate the effects of variability in life cycle inventories from spatial differences in characterization factors, inventory flows in all villages were set to be the same, and equal to that of Ngata Toro. Spatially differentiated LCA carried out showed that a different village performed best when considering total damage to human health (Lamongan, against Lampung for site-specific inventories) (Table S36). This further emphasizes that differences in ranking between villages were mainly caused by variability in life cycle inventories between villages. Henderson et al., (2017) also showed that in addition to spatial differences in characterization factors, variability in inventories of water used for irrigation explained a large part of the differences in water deprivation impacts from corn production and from milk production between different geographic locations within the U.S.

4.1.3. Process contribution

Finally, decision makers are interested in identifying improvement options in the biochar life cycle. At the total damage level, spatial differentiation was generally not important in determining which processes contributed most to overall benefits (here, agricultural benefits from increasing yields or sequestration and storage of carbon). Only in one case (scenario 1) were the largest benefits attributed to increases in crop productivity in the generic assessment, while both the productivity increase and biochar production (specifically, sequestration of carbon) contributed nearly equally to human health benefits in regionalized assessment (SI, Section 6.4). However, spatial differentiation did influence the identification of processes with the largest environmental burdens in some individual impact categories. For example, it identified biochar use as a major driver of freshwater eutrophication (due to direct emissions of phosphorus together with the biochar added to soil) in the generic assessment, while in the spatially differentiated assessment the contribution of this process was smaller and comparable to that of biochar production. Thus, spatial differentiation could still be relevant to support decision about improving environmental performance of a given biochar system by suggesting changes in processes which decision-makers have influence on (foreground processes). In this particular case, the decision-maker could focus on reducing P emissions by using biochar with smaller content of P, but more accurate and realistic assessment of environmental impacts as offered by spatially differentiated impact assessment is needed to determine whether such improvement is valuable.

Fig. 3.

4.2. Practical implications

This study corroborates earlier studies showing that spatial differentiation is particularly relevant in cases where geographic variability in characterization factors is large (e.g., land or water use), and where total impact is dominated by one or few flows contributing to that impact category (e.g. irrigation or land occupation) (Chaudhary et al., 2016; Henderson et al., 2017b). As product life cycles are global, emissions in the life cycles can occur anywhere, making spatially differentiated LCA the preferred option if accuracy and realism of impacts are important for the goal of the LCA. This includes cases where the intended application is identification of weak points in the product system as a basis for environmental optimization. In this case, different conclusions were drawn related to potential improvement options in the biochar system to address eutrophication impacts on freshwater ecosystems.

Due to trade-offs between burden and benefits spatial differentiation had no relevance for decisions related to whether a new biochar-based waste management strategy should be implemented. Thus, in this aspect of the goal definition, spatial differentiation in LCIA did not lead to better decision support. This conclusion is expected to hold for systems where environmental benefits largely outweigh burdens, including the use of other chars in agriculture (Owsianiak et al., 2017) or technologies which replace inefficient waste management systems or allow reducing food losses (Fabbri et al., 2018).

Large geographic variability in life cycle inventories, combined with trade-offs between impact categories, resulted in spatial differentiation having a limited relevance for decisions about identification of best biochar production techniques and agricultural use conditions for ecosystem damage. Heidari et al., (2017) also showed that for pasta production in Iran the impact of ozone formation was up to a factor two larger than the generic determined impact, while impacts for land use and acidification were up to a factor of three smaller. Trade-offs between impact categories like those presented in this study and earlier in Heidari et al., (2017) are expected to occur for other product systems if they are located in dry and not very biodiverse regions (e.g. Iran), or in water-rich and biodiverse areas (like the majority of the Indonesian islands). However, in less extreme conditions with regard to water availability and biodiversity status (e.g. in Europe), similar trade-offs may not occur, and other impact categories may become dominant contributors (e.g. marine eutrophication impacts in Baltic Sea are expected to be higher compared with the Indonesian Sea marine ecosystems) (Cosme et al., 2017). Further, tradeoffs between impact categories were less relevant for total damage to human health. In addition, species can be weighted differently in LCIA, influencing trade-offs between impact categories (Verones et al., 2015). Thus, spatial differentiation is recommended to be considered as a default approach in comparative LCA studies.

4.3. Limitations of the study

Execution of this case study required implementation of regionalized characterization factors for most impact categories into the modelling software employed (SimaPro) and a subsequent matching of them with regionalized input and output flows. This practice, although perhaps the most straightforward from the LCA practitioner's perspective, has some limitations.

Uncertainties in characterization factors were not considered due to incomplete knowledge related to them and the limited ability of the modelling software to consider them. If these uncertainties had been considered, the number of pairwise comparisons with statistically significant differences between regionalized and generic assessments is expected to be smaller. It is a challenge for LCA practitioners to determine whether uncertainties in characterization factors combined with inventory and parameter uncertainties are larger than geographic variability in life cycle inventories. Henderson et al., (2017) showed that for water use impacts, spatial variability may be larger than uncertainty.

The second limitation is that the selection of the spatial scale for the impact assessment was based on a simple method of matching regionalized inventories with available respective characterization factors at the smallest scale possible. This limitation is not expected to influence conclusions because geographic locations of each village are accurate and because locations of respective ecoregions, watersheds and agricultural fields corresponding to each village were known. This allowed for both accurate and precise quantification of impacts for relevant impact categories, including water use, land use, and ecotoxicity emissions. Thus, aggregating grid-specific characterization factors in these categories, as proposed by Mutel et al., (2011) is not expected to reduce uncertainty in this case study. Selection of appropriate spatial scale of impact assessment could be relevant however, for some regional impact categories such as freshwater eutrophication. In this case eutrophication relied on the use of country-specific characterization factors, but this impact category was not important contributor to total damage.

5. Conclusions

This first regionalized LCA study where spatially differentiated LCIA methods were consistently applied to all relevant impact categories at damage level level showed that although spatial differentiation improved accuracy and realism of environmental impacts, it did not necessarily lead to better decisions. This finding was unexpected considering that conditions in Indonesia with regard to biodiversity are very different compared to generic conditions. Geographic variability in life cycle inventories, combined with small contribution of some impact categories to total damage and tradeoffs between impact categories influenced the role of spatial differentiation for decision-support in this case study.

Although extrapolation of these findings to other cases is not straightforward, this study may suggest that depending on the goal of the LCA, practitioners should consider potential benefits of implementing spatially differentiated LCIA methods as opposed to potential benefits from collecting site-specific inventories. This study indicates that the former should be the priority in studies where accuracy and realism are required (e.g. in weak point analyses and eco-design LCA studies), but also in comparative LCA studies, while the latter should be the priority in studies where environmental performance of a system is expected to be mainly determined by trade-offs between burden and benefits.

The findings presented in this study raise several additional questions. First, it is unknown whether environmental benefits from implementation of biochar systems are larger than environmental burdens in other regions of the World. Second, it is unknown whether the findings generally apply to other comparative LCA case studies. Third, an intelligent approach needs to be developed to determine which of the flows in the foreground system are relevant to consider for spatially differentiated impact assessments, and which can be omitted. Forth, in this study, spatial differentiation was considered for all flows in the foreground system, but this can be challenging if more complex systems are modelled. Finally, the use of spatially differentiated LCIA methods depends on the ability of LCA modelling software to consider them, and solutions are needed to enable easy and consistent use of spatially differentiated LCIA methods in LCA of products and systems in the future.

Supplementary material

Details of case studies, model parameters, unit processes, details of uncertainty analysis, details of LCIA methods, and additional results.

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Figure captions

Fig. 1. System boundaries for treatment of biogenic carbon with use of biochar as soil conditioner to support crop productivity. The functional unit was defined as “treatment of 1 kg of biogenic carbon from biomass residues in rural areas in Indonesia”. Dashed lines indicate avoided processes.

Fig. 2. Generic and spatially differentiated damage to human health **(a)** and ecosystems **(b)** from biochar production using flame curtain kiln and its use for improving agriculture in Indonesia, as influenced by geographic location and fertilizer type (scenarios 1-4 and 13-16 in Table 1). Absolute uncertainties are too large to be shown, but comparison taking into account correlations revealed statistically significant differences between generic and regionalized damage (see the SI, Section S6.2). Scores for biochar production using Adam retort and earth-mound kilns are presented in the SI, Section S6.1.

Fig. 3. Ranking of biochar systems (all scenarios) in terms of total damage to human health **(a)** and ecosystems **(b)** as influenced by switching from generic to regionalized LCA. Values presented in each cell represent to median impact score from 1000 iterations, in DALY/functional unit **(a)** and species.yr/functional unit **(b)**. A colour scaling system was applied, where colours are determined by values in each cell, where increasing shades of green correspond to biochar systems performing better, respectively. Details of the comparison between systems taking into account uncertainties are presented in SI, Section S6.3.

Figure 1

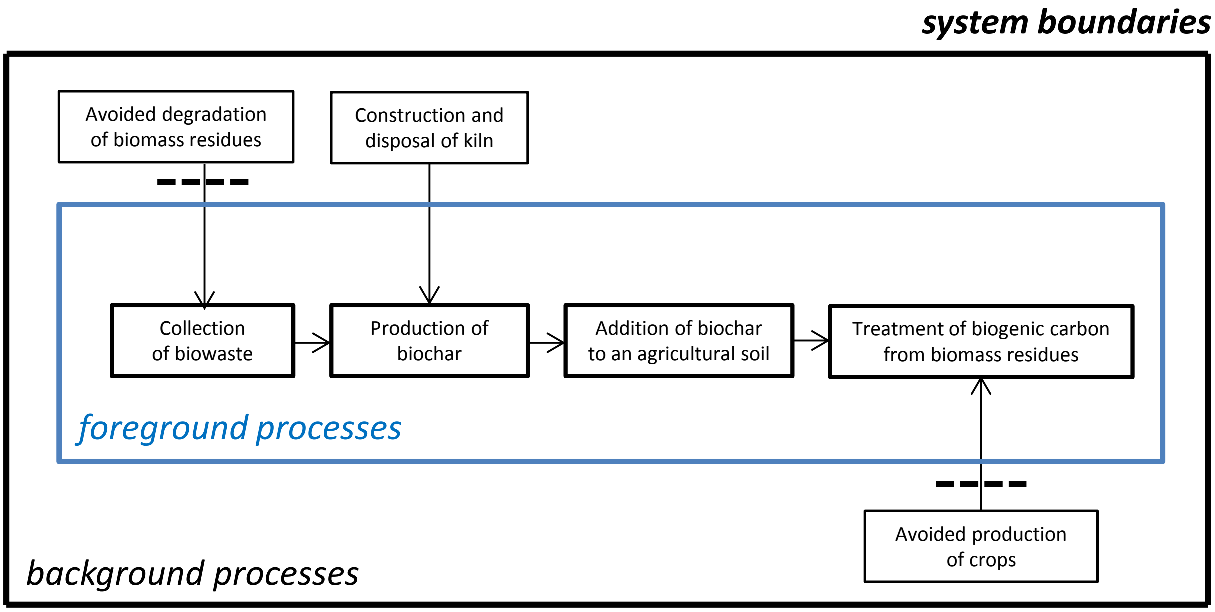


Fig. 1 (in color)

Figure 2

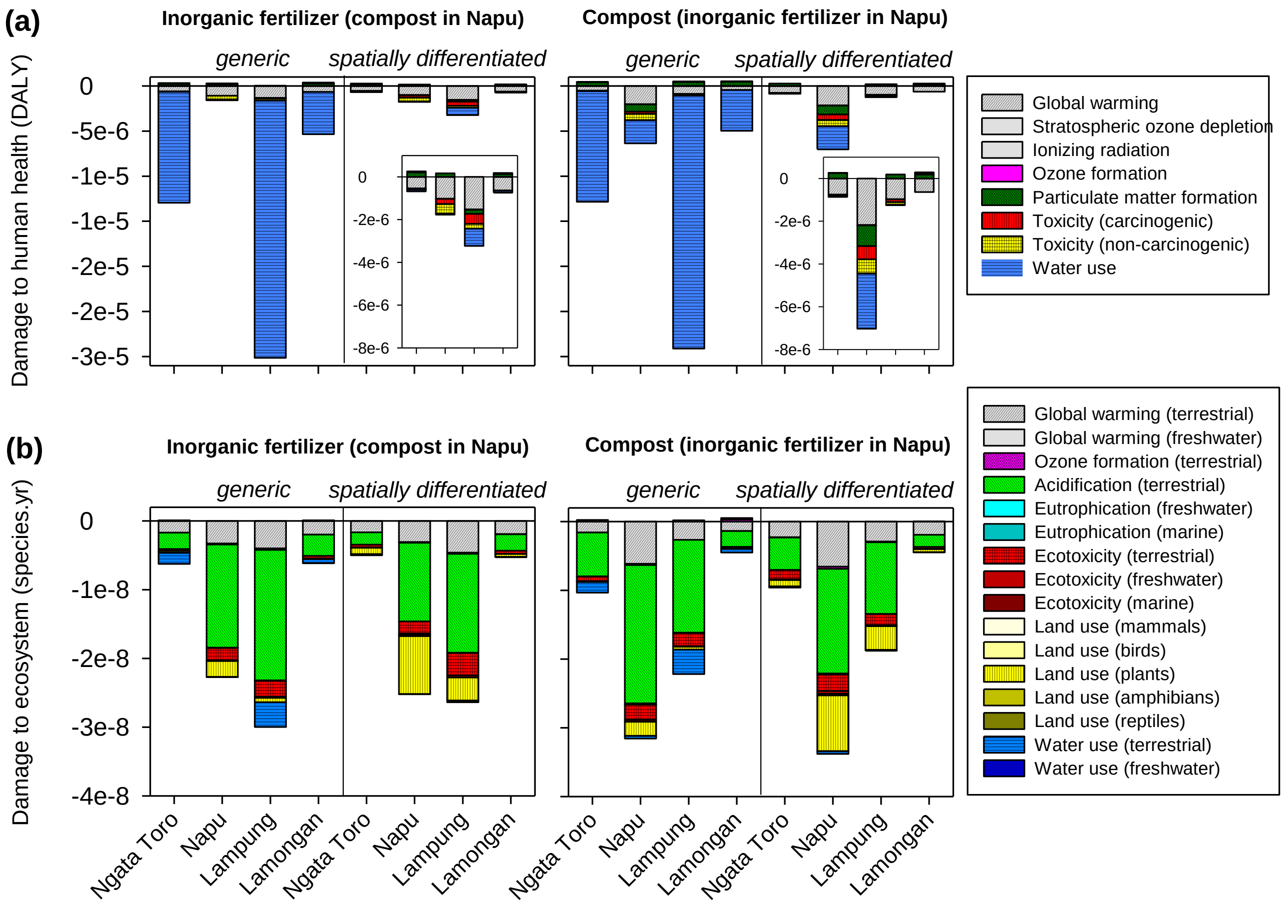
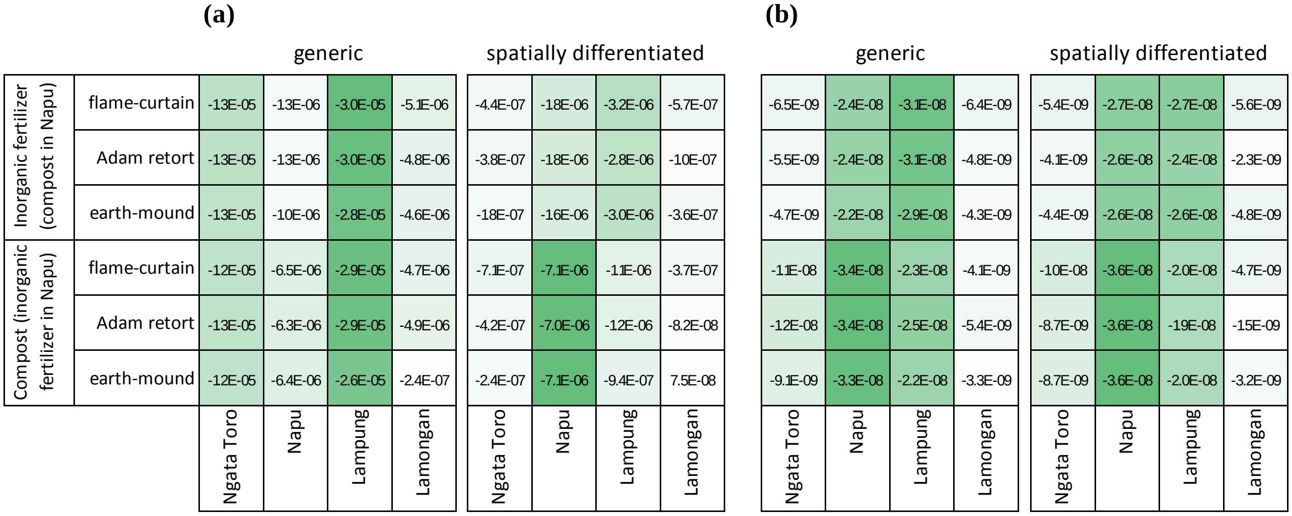


Fig.2 (in color)

Figure 3



(a)

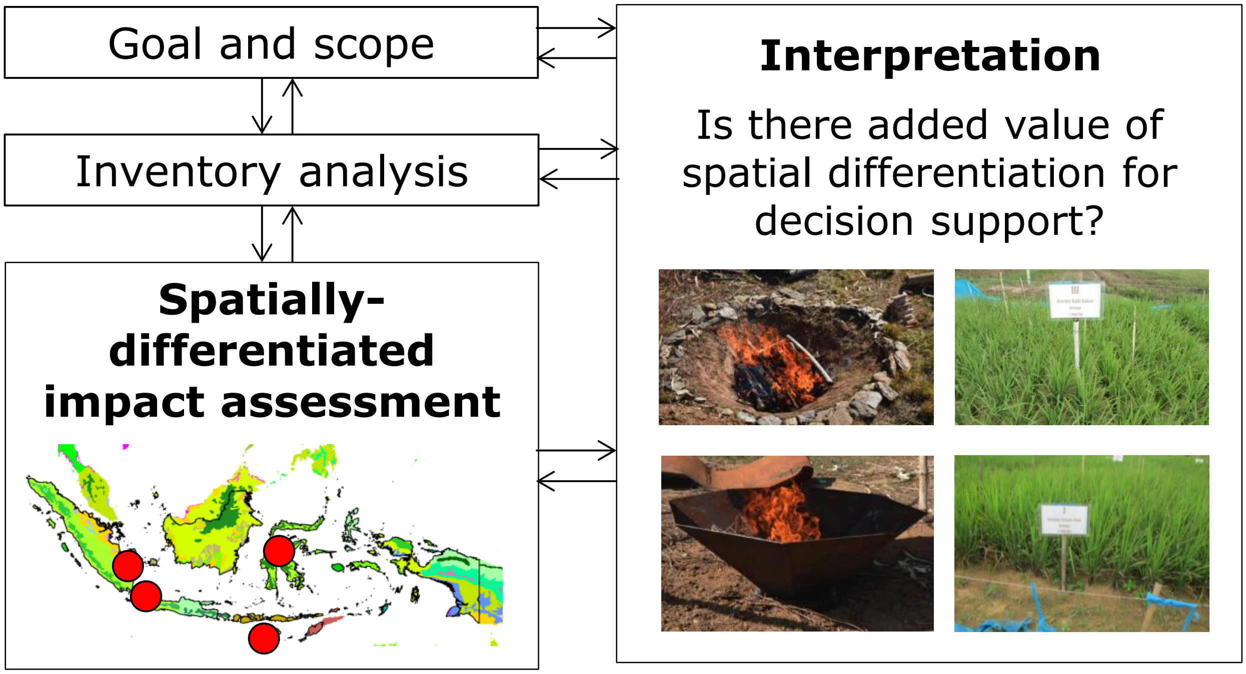
		generic				spatially differentiated			
		Ngata Toro	Napu	Lampung	Lamongan	Ngata Toro	Napu	Lampung	Lamongan
Inorganic fertilizer (compost in Napu)	flame-curtain	-13E-05	-13E-06	-3.0E-05	-5.1E-06	-4.4E-07	-18E-06	-3.2E-06	-5.7E-07
	Adam retort	-13E-05	-13E-06	-3.0E-05	-4.8E-06	-3.8E-07	-18E-06	-2.8E-06	-10E-07
	earth-mound	-13E-05	-10E-06	-2.8E-05	-4.6E-06	-18E-07	-16E-06	-3.0E-06	-3.6E-07
Compost (inorganic fertilizer in Napu)	flame-curtain	-12E-05	-6.5E-06	-2.9E-05	-4.7E-06	-7.1E-07	-7.1E-06	-1.1E-06	-3.7E-07
	Adam retort	-13E-05	-6.3E-06	-2.9E-05	-4.9E-06	-4.2E-07	-7.0E-06	-12E-06	-8.2E-08
	earth-mound	-12E-05	-6.4E-06	-2.6E-05	-2.4E-07	-2.4E-07	-7.1E-06	-9.4E-07	7.5E-08

(b)

generic				spatially differentiated			
Ngata Toro	Napu	Lampung	Lamongan	Ngata Toro	Napu	Lampung	Lamongan
-6.5E-09	-2.4E-08	-3.1E-08	-6.4E-09	-5.4E-09	-2.7E-08	-2.7E-08	-5.6E-09
-5.5E-09	-2.4E-08	-3.1E-08	-4.8E-09	-4.1E-09	-2.6E-08	-2.4E-08	-2.3E-09
-4.7E-09	-2.2E-08	-2.9E-08	-4.3E-09	-4.4E-09	-2.6E-08	-2.6E-08	-4.8E-09
-1.1E-08	-3.4E-08	-2.3E-08	-4.1E-09	-10E-08	-3.6E-08	-2.0E-08	-4.7E-09
-12E-08	-3.4E-08	-2.5E-08	-5.4E-09	-8.7E-09	-3.6E-08	-19E-08	-15E-09
-9.1E-09	-3.3E-08	-2.2E-08	-3.3E-09	-8.7E-09	-3.6E-08	-2.0E-08	-3.2E-09

Fig. 3 (in color)

Graphical Abstract



Graphical abstract

Supplementary material for

Influence of spatial differentiation in impact assessment for LCA-based decision support: implementation of biochar technology in Indonesia

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Contents

S1. Details of case studies

Table S1. Description of the four case study sites in Indonesia.

Parameter/Site name	Ngata Toro	Napu	Lampung	Lamongan
Location	Ngata Toro village, Central Sulawesi	Sumba	KP. Taman Bogo, Kec. Probolinggo, Kab. Lampung Timur	Banyubang village; Solokuro sub-District, Lamongan District, East Java Province
Geographic position coordinates (GPS)	120°01'25.6"E 1°30'42.6"S -1.511833, 120.023778	9°23'37.3"S 119°55'36.5"E -9.393700, 119.926808	05°00.406'S 105°29.405'E -5.006767, 105.490083	6°55’25.9”S 112°25’3.7”E -6.923861, 112.417694
Closest city	Kendari	Kupang	Bandar Lampung	Surabaja
Terrestrial Ecoregion	Sulawesi Montane Rain Forests, AA0124	Sumba Deciduous Forests, AA0203	Sumatran Lowland Rain Forests, IM0158	Eastern Java-Bali Rain Forests, IM0113
Soil type and properties	weathered oxisols, pH 4.6; 11 gC/kg soil	unknown soil type and properties	Typic Kanhapludults; Sandy loam; pH 4.1; 7.4 gC/kg soil	Typic Haplustepts; pH 5.4; 10.6 gC/kg soil
Watershed-ID	54221	57349	55811	56392

S2. Model parameters

Table S2. Model parameters and data sources for four case study sites.

Parameter	Village				Source
	Ngata Toro	Napu	Lampung	Lamongan	
Biomass residues					
Biomass residues carbon content, $kgC/kg_{biomass}$	0.5	0.5	0.5	0.5	assumed the same as wood
Biomass residues moisture, kgwater/kgbiomass	0.35	0.25	0.45	0.45	assumed, realistic value
Biomass residues availability (kg/village/yr)	5000	2000	10000	10000	Sparrevik et al.[1]
Pyrolysis and biochar					
“Kon Tiki” steel kiln life time (yr)	1	1	1	1	Smebye et al.[2]; assuming 100 runs per year
“Kon Tiki” steel kiln capacity (kg/yr)	10000	10000	10000	10000	Smebye et al.[2]; assuming 100 runs per year

Retort kiln life time (yr)	4	4	4	4	Smebye et al.[2]
Retort kiln capacity (kg/yr)	10000	10000	10000	10000	Smebye et al.[2]
Biochar yield, "Kon Tiki" steel kiln (%, per feedstock) and earth-mound kiln	22	22	22	22	Cornelissen et al.[3]
Biochar yield, retort kiln (%, per feedstock)	32	32	32	32	Sparrevik et al.[4]
Biochar carbon content, kgC/kg$_{biochar}$	0.7	0.7	0.7	0.7	Sparrevik et al.
Biochar ash content (kg/kg)	0.01	0.01	0.01	0.01	assumed; in lower range of values measured by Enders et al.[5]
Agriculture					
Biochar application rate (kg/ha)	1200	4000	5000	4000	Sparrevik et al.[1]
Seeds application rate (kg/ha)	20	20	20	20	Sparrevik et al.[1]
Crop yield without biochar addition (kg/ha)	6500	2000	6000	8000	Sparrevik et al.[1]
Crop yield change when biochar is used (%)	10	250	100	10	measured or assumed (Lamongan)
Duration of period from sowing to crop harvest (yr)	0.25	0.29	0.25	0.25	measured (Napu) or assumed
N fertilizer application rate, NH_4NO_3 (kg/ha, as N)	7.5	not used	30	30	Sparrevik et al.[1]
P fertilizer application rate, superphosphate (kg/ha, as P_2O_5)	15	not used	30	30	Sparrevik et al.[1]
K fertilizer application rate, K_2O (kg/ha, as K)	7.5	not used	30	30	Sparrevik et al.[1]
Urea application rate (kg/ha, as N)	34.5	not used	140	140	Sparrevik et al.[1]
Compost application rate (t/ha)	not used	20	not used	not used	measured
Water use for irrigation (m3/kg$_{maize}$)	0.155	0	0.155	0.155	assumed equal to Maize grain {AR}| maize grain production | Alloc Rec, U
Scaling factor for emissions of metals, nutrients and GHG (except CO_2) from NPK or compost fertilizers (-)	0.58	1.60	2.07	2.07	calculated based on fertilizer inputs and emissions from Maize grain {AR}| maize grain production | Alloc Rec, U
Scaling factor for emissions of CO_2 from urea (-)	1.25	-	5.49	4.11	calculated based on fertilizer inputs and emissions from Maize grain {AR}| maize grain production | Alloc Rec, U
Mineralization rate constant for labile carbon pool (k_1, yr^{-1})	2.62	2.62	2.62	2.62	geomean across 6 values measured during microbial incubations (Zimmerman and Gao[6])
Mineralization rate constant for recalcitrant carbon pool (k_2, yr^{-1})	8.57E-04	8.57E-04	8.57E-04	8.57E-04	geomean across 6 values measured during microbial incubations (Zimmerman and Gao[6])
Fraction of labile carbon pool (kg/kg)	8.68E-03	8.68E-03	8.68E-03	8.68E-03	geomean across 6 values measured during microbial incubations (Zimmerman and Gao[6])
Transportation					
Transportation distance to the village (km)	100	250	20	20	measured

S2.1. Emissions

For outdoor emissions from the production of biochar, measured values of CO_2, CO, CH_4, NMVOC, and PM10 and Nitrogen oxides were used, from Cornelissen et al.[3] and Sparrevik et al.[4] for "Kon Tiki" flame curtain and retort kilns, respectively. Although measured data for individual NMVOC are available for earth-mound kilns, total NMVOC were used because the comparison between sum of NMVOC values measured and sum of NMVOC calculated for earth-mound kilns showed that the latter are 20-30 times large. Thus, although there is some uncertainty about which compounds are present in the NMVOC category, total NMVOC was used as a basis for calculating human health impact scores. Aggregation of NVMOC is not an issue for the photochemical oxidant formation impact category, where impact scores were found to be insensitive to NMVOC composition.[7] Emissions of nitrate, phosphate phosphorus and metals to soils, and emissions of GHG to air from organic and inorganic fertilizers were taken from generic ecoinvent process for production of maize while correcting for differences in fertilizer amounts between the ecoinvent process and amounts in our case studies, assuming that composition of fertilizers was the same.

Table S3. Airborne emissions from kilns during pyrolysis, in kg per kg of biochar output.

Parameter	"Kon Tiki" flame curtain all-steel deep-cone kiln	retort kiln	earth-mound kiln	Source
Carbon dioxide, biogenic	1.626	1.626	1.626	Values from Agaki et al.[8]
Carbon monoxide, biogenic	0.054	0.15	0.35	Emission data from measured values in Cornelissen et al.[4] and from Sparrevik et al.[4]
Methane, biogenic	3.00E-02	3.50E-02	4.90E-02	
NMVOC	5.70E-03	6.87E-03	5.30E-02	
Nitrogen oxides	3.80E-05	1.70E-03	2.20E-03	
Particulates, < 10 um	7.40E-03	7.69E-03	1.30E-02	

Table S4. Biochar total nutrient concentration, in kg/kg. Based on Ippolito et al.[9] for biochar made from rice straw/husk assumed representative to feedstocks used in our study.

Element	Concentration
Potassium	0.0007
Sulfur	0.0039
Phosphorus	0.0012

Table S5. Emissions from organic and inorganic fertilizers (in kg/kg grain) in the ecoinvent process Maize grain {AR}| maize grain production | Alloc Rec, U, which were used to estimate emissions in this case study.

Compound	Emission
Carbon dioxide, fossil	0.00899
Ammonia	0.01267
Nitrogen oxides	0.0006126
Dinitrogen monoxide	0.0004417
Lead	2.54E-08
Mercury	1.41E-09
Nickel	2.33E-10
Zinc	3.43E-06
Phosphorus	3.93E-05
Phosphate	1.11E-06
Cadmium	9.86E-09
Chromium	1.11E-06
Copper	9.66E-07
Nitrate	0.0146762
Mercury	3.42E-09
Nickel	8.83E-07
Phosphate	2.94E-05
Zinc	1.92E-06
Chromium	2.62E-06
Lead	3.07E-07
Copper	4.66E-07
Cadmium	3.75E-07
Chromium	1.21E-06
Copper	3.15E-06
Lead	5.58E-07
Mercury	8.41E-08
Nickel	5.01E-07
Zinc	1.64E-05

Table S6. Wood ash element concentration, in kg/kg. Based on Doka.[10]

Element	Concentration
Potassium	0.0545
Sulfur	0.0092
Phosphorus	0.0098
Arsenic	0.0000067
Molybdenum	0.0000037
Lead	0.000065
Aluminium	0.0208
Copper	0.000163
Manganese	0.02
Calcium	0.284
Chromium	0.000195
Magnesium	0.0321
Titanium	0.00138
Zinc	0.00166
Nickel	0.0000552
Vanadium	0.0000395
Silicon	0.0826

Mercury	0.0000001
Cadmium	0.0000142
Carbon	0.012
Chloride	0.0032
Cobalt	0.000018
Iron	0.0228

S2.2. Biochar stability and priming

Biochar stability varies between biochar type, with residence times in soils ranging from 6 to 5000 years, although a mathematical description of biochar mineralization is not so straightforward and various models of different complexity and environmental relevance have been proposed (Zimmerman and Gao[6]). Site-specific data and mineralization kinetics were not available in this study, and it was assumed that mineralization of biochar in soils followed bi-exponential decay kinetics and average (geometric mean) kinetic parameters measured for six biochars representing a wide range of mineralization rate constants were used (Zimmerman and Gao[6]). Similarly, no data were available about the potential influence of biochar on priming of mineralization of native soil organic carbon. Thus, assuming that 50% of above-ground crop residues would be converted to biochar annually, a conservative assumption of negative priming equal to a 45% increase in soil organic carbon stock in the long-term (100 years) was used and which is within the range of values estimated by Woolf and Lehmann.[11]

S3. Unit processes

The information given here include all input and outputs flows from each process throughout the biochar life cycles constructed using model parameters given in Section S2. The unit processes are representative to the systems in Indonesia, however practitioners can readily adapt them to other geographic locations (e.g. by adjusting fertilizer inputs). Pedigree criteria and resulting geometric standard deviations squared (σ_g^2) underlying uncertainty analysis are described in detail in Section S6.

Table S7. Inventory for the unit process "Management of 1 kg of biogenic carbon from biowaste with carbon reuse, {ID}, miow". Flows in *italics* refer to different scenarios or sensitivity checks.

Activity	Amount				Unit	Type	Pedigree	σ_g^2	Source
	Ngata Toro	Napu	Lampung	Lamongan					
Management of biogenic carbon	1	1	1	1	kg	output			
Decomposition of biowaste {ID}, miow	2.198	1.905	2.597	2.597	kg	avoided products	(1, 1, 1, 1, 1, 1.05)	1.05	calculated using data in Table S2
Maize agriculture {ID}, miow	0.774	1.786	1.714	0.286	kg	avoided products	(1, 1, 1, 1, 1, 1.05)	1.05	calculated using data in Table S2
Biochar, "Kon Tiki" flame curtain kiln, {ID}, miow	0.484	0.419	0.571	0.571	kg	input (materials)	(1, 1, 1, 1, 1, 1.05)	1.05	calculated using data in Table S2
Biochar, retort kiln, {ID}, miow	*0.703*	*0.610*	*0.831*	*0.831*	*kg*	*input (materials)*	*(1, 1, 1, 1, 1, 1.05)*	*1.05*	*calculated using data in Table S2*
Biochar, earth-mound kiln, {ID}, miow	*0.484*	*0.419*	*0.571*	*0.571*	*kg*	*input (materials)*	*(1, 1, 1, 1, 1, 1.05)*	*1.05*	*calculated using data in Table S2*
Carbon dioxide, biogenic	*inventory temporarily disaggregated, site-generic*				*kg*	*output (air)*	*(1, 1.2, 1.1, 1.1, 1.05, 1.05)*	*1.2674*	*calculated offline as explained in Section S2.2, depends on biochar mineralization kinetics*
Carbon dioxide, to soil or biomass stock	1.241	1.076	1.467	1.467	kg	output (soil)	(1, 1.2, 1.1, 1.1, 1.2, 1.05)	1.3431	calculated using data in Table S2
Potassium	3.4E-04	2.9E-04	4.0E-04	4.0E-04	kg	output (soil)	(1, 1.2, 1.03, 1.1, 1.2, 1.5)	1.6336	calculated using data in Table S2 and Table S5
Sulfur	1.9E-03	1.6E-03	2.2E-03	2.2E-03	kg	output (soil)	(1, 1.2, 1.03, 1.1, 1.2, 1.5)	1.6336	calculated using data in Table S2 and Table S5
Phosphorus	5.8E-04	5.0E-04	6.9E-04	6.9E-04	kg	output (soil)	(1, 1.2, 1.03, 1.1, 1.2, 1.5)	1.6336	calculated using data in Table S2 and Table S5
Carbon dioxide (in air)	*0.03918*	*0.25824*	*0.06326*	*0.01133*	*kg*	*input (resources)*	*(1, 1.2, 1.03, 1.1, 1.2, 1.05)*	*1.3241*	*calculated as explained in Section S2.2, slow mineralization kinetics*
Carbon dioxide (in air)	0.05877	0.38736	0.09489	0.01699	kg	input (resources)	(1, 1.2, 1.03, 1.1, 1.2, 1.05)	1.3241	calculated as explained in Section S2.2, default mineralization kinetics
Carbon dioxide (in air)	*0.07836*	*0.51648*	*0.12652*	*0.02265*	*kg*	*input (resources)*	*(1, 1.2, 1.03, 1.1, 1.2, 1.05)*	*1.3241*	*calculated as explained in Section S2.2, fast mineralization kinetics*

Table S8. Inventory for the unit process “Maize agriculture {ID}, miow”.

Activity	Amount				Unit	Type	Pedigree	σ_g^2	Source
	Ngata Toro	Napu	Lampung	Lamongan					
Maize	1	1	1	1	kg	output			
Occupation, annual crop, non-irrigated, extensive	0.385	1.438	0.417	0.313	m2a	input (resources)	(1, 1, 1, 1, 1, 1.5)	1.5	calculated using data in Table S2
Transformation, to annual crop, non-irrigated, extensive	1.538	5.000	1.667	1.250	m2	input (resources)	(1, 1, 1, 1, 1, 1.5)	1.5	calculated using data in Table S2
Transformation, from annual crop, non-irrigated, extensive	1.538	5.000	1.667	1.250	m2	input (resources)	(1, 1, 1, 1, 1, 1.5)	1.5	calculated using data in Table S2
Water, river, ID	0.155	0.155	0.155	0.155	m3	input (resources)	(1.1, 1.2, 1, 1, 1, 1.5)	1.5757	calculated using data in Table S2
Maize seed, organic, for sowing {RoW}| production | Alloc Rec, U	3.08E-03	1.00E-02	3.33E-03	2.50E-03	kg	input (materials)	(1, 1, 1, 1, 1, 1.05)	1.05	calculated using data in Table S2
Nitrogen fertiliser, as N {GLO}| market for | Alloc Rec, U	1.15E-03	0	5.00E-03	3.75E-03	kg	input (materials)	(1, 1, 1, 1, 1, 1.05)	1.05	calculated using data in Table S2
Phosphate fertiliser, as P2O5 {GLO}| market for | Alloc Rec, U	2.31E-03	0	5.00E-03	3.75E-03	kg	input (materials)	(1, 1, 1, 1, 1, 1.05)	1.05	calculated using data in Table S2
Potassium fertiliser, as K2O {GLO}| market for | Alloc Rec, U	1.15E-03	0	5.00E-03	3.75E-03	kg	input (materials)	(1, 1, 1, 1, 1, 1.05)	1.05	calculated using data in Table S2
Urea, as N {GLO}| market for | Alloc Rec, U	5.31E-03	0	2.33E-02	1.75E-02	kg	input (materials)	(1, 1, 1, 1, 1, 1.05)	1.05	calculated using data in Table S2
Carbon dioxide, fossil	1.12E-02	0	4.93E-02	3.70E-02	kg	output (air)	(1.05, 1.2, 1, 1.05, 1.2, 1.05)	1.3117	calculated using data in Table S2 and Table S5
Ammonia	7.36E-03	2.03E-02	2.63E-02	2.63E-02	kg	output (air)	(1.05, 1.2, 1, 1.05, 1.2, 1.5)	1.6249	calculated using data in Table S2 and Table S5
Nitrogen oxides	3.56E-04	9.80E-04	1.27E-03	1.27E-03	kg	output (air)	(1.05, 1.2, 1, 1.05, 1.2, 1.5)	1.6249	calculated using data in Table S2 and Table S5
Dinitrogen monoxide	2.57E-04	7.07E-04	9.15E-04	9.15E-04	kg	output (air)	(1.05, 1.2, 1, 1.05, 1.2, 1.5)	1.6249	calculated using data in Table S2 and Table S5
Lead	1.48E-08	4.06E-08	5.26E-08	5.26E-08	kg	output (groundwater)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Mercury	8.22E-10	2.26E-09	2.93E-09	2.93E-09	kg	output (groundwater)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Nickel	1.35E-10	3.73E-10	4.83E-10	4.83E-10	kg	output (groundwater)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Zinc	1.99E-06	5.48E-06	7.10E-06	7.10E-06	kg	output (groundwater)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Phosphorus	2.28E-05	6.29E-05	8.15E-05	8.15E-05	kg	output	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2

						(river)			and Table S5
Phosphate	6.45E-07	1.78E-06	2.30E-06	2.30E-06	kg	output (river)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Cadmium	5.73E-09	1.58E-08	2.04E-08	2.04E-08	kg	output (river)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Chromium	6.45E-07	1.78E-06	2.30E-06	2.30E-06	kg	output (river)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Copper	5.61E-07	1.55E-06	2.00E-06	2.00E-06	kg	output (river)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Nitrate	8.53E-03	2.35E-02	3.04E-02	3.04E-02	kg	output (groundwater)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Mercury	1.99E-09	5.47E-09	7.08E-09	7.08E-09	kg	output (river)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Nickel	5.13E-07	1.41E-06	1.83E-06	1.83E-06	kg	output (river)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Phosphate	1.71E-05	4.71E-05	6.10E-05	6.10E-05	kg	output (groundwater)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Zinc	1.12E-06	3.07E-06	3.98E-06	3.98E-06	kg	output (river)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Chromium	1.52E-06	4.20E-06	5.44E-06	5.44E-06	kg	output (groundwater)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Lead	1.78E-07	4.91E-07	6.36E-07	6.36E-07	kg	output (river)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Copper	2.71E-07	7.45E-07	9.65E-07	9.65E-07	kg	output (groundwater)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Cadmium	2.18E-07	6.01E-07	7.78E-07	7.78E-07	kg	output (soil, agr.)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Chromium	7.01E-07	1.93E-06	2.50E-06	2.50E-06	kg	output (soil, agr.)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Copper	1.83E-06	5.03E-06	6.52E-06	6.52E-06	kg	output (soil, agr.)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Lead	3.24E-07	8.93E-07	1.16E-06	1.16E-06	kg	output (soil, agr.)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Mercury	4.89E-08	1.35E-07	1.74E-07	1.74E-07	kg	output (soil, agr.)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Nickel	2.91E-07	8.01E-07	1.04E-06	1.04E-06	kg	output (soil, agr.)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Zinc	9.51E-06	2.62E-05	3.39E-05	3.39E-05	kg	output (soil, agr.)	(1.05, 1.2, 1, 1.05, 1.2, 5)	5.1111	calculated using data in Table S2 and Table S5
Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RoW}| transport, freight, lorry 3.5-7.5 metric ton, EURO4 | Alloc Rec, U	0.01300	0.02500	0.00833	0.00625	tkm	input (materials)	(1, 1, 1, 1, 1, 2)	2	calculated using data in Tables S2

Table S9. Inventory for the unit process “Decomposition of wet biowaste {ID}, miow”.

Activity	Amount				Unit	Type	Pedigree	σ_g^2	Source
	Ngata Toro	Napu	Lampung	Lamongan					
Biowaste, decomposition	1	1	1	1	kg	output			
empty process; biowaste is assumed to be degraded to biogenic CO_2 (Smebye et al.[2])									

Table S10. Inventory for the unit process “Biochar, “Kon Tiki” flame curtain kiln, {ID}, miow”.

Activity	Amount				Unit	Type	Pedigree	σ_g^2	Source
	Ngata Toro	Napu	Lampung	Lamongan					
Biochar	1	1	1	1	kg	output			
Carbon dioxide, in air	4.19	4.19	4.19	4.19	kg	input (resources)	(1.2, 1.2, 1.5, 1.1, 2, 1.05)	2.3401	calculated
“Kon Tiki” flame kiln, {ID}, miow	1.0E-04	1.0E-04	1.0E-04	1.0E-04	p	input (materials)	(1, 1, 1, 1, 1, 1.05)	1.05	calculated using data in Table S2
Carbon dioxide, biogenic	1.626	1.626	1.626	1.626	kg	output (air)	(1, 1, 1, 1, 1, 1.05)	1.05	see Table S3
Carbon monoxide, biogenic	0.054	0.054	0.054	0.054	kg	output (air)	(1, 1, 1, 1, 1, 5)	5	see Table S3
Methane, biogenic	0.03	0.03	0.03	0.03	kg	output (air)	(1, 1, 1, 1, 1, 1.5)	1.5	see Table S3
NMVOC	0.0057	0.0057	0.0057	0.0057	kg	output (air)	(1, 1, 1, 1, 1, 1.5)	1.5	see Table S3
Nitrogen oxides	0.000038	0.000038	0.000038	0.000038	kg	output (air)	(1, 1, 1, 1, 1, 1.5)	1.5	see Table S3
Particulates, < 2.5 um	0.0074	0.0074	0.0074	0.0074	kg	output (air)	(1, 1, 1, 1, 1, 2)	2	see Table S3
“Kon Tiki” flame curtain all-steel deep-cone kiln, disposal, {ID}, miow	1.0E-04	1.0E-04	1.0E-04	1.0E-04	kg	output (waste)	(1, 1, 1, 1, 1, 1.05)	1.05	calculated using data in Table S2

Table S11. Inventory for the unit process “Biochar, retort kiln, {ID}, miow”.

Activity	Amount				Unit	Type	Pedigree	σ_g^2	Source
	Ngata Toro	Napu	Lampung	Lamongan					
Biochar	1	1	1	1	kg	output			
Carbon dioxide, in air	4.19	4.19	4.19	4.19	kg	input (resources)	(1.2, 1.2, 1.5, 1.1, 2, 1.05)	2.3401	calculated
Wood, wet mass {ID}, miow	0.410	0.410	0.410	0.410	kg	input (materials)	(1, 1, 1, 1, 1, 1)	1	calculated using data in Table S2
Retort kiln, {ID}, miow	2.5E-05	2.5E-05	2.5E-05	2.5E-05	p	input (materials)	(1, 1, 1, 1, 1, 1)	1	calculated using data in Table S2
Carbon dioxide, biogenic	1.626	1.626	1.626	1.626	kg	output (air)	(1, 1, 1, 1, 1, 1.05)	1.05	see Table S3
Carbon monoxide, biogenic	0.15	0.15	0.15	0.15	kg	output (air)	(1, 1, 1, 1, 1, 1.05)	1.05	see Table S3
Methane, biogenic	0.035	0.035	0.035	0.035	kg	output (air)	(1, 1, 1, 1, 1, 5)	5	see Table S3
NMVOC	0.00687	0.00687	0.00687	0.00687	kg	output (air)	(1, 1, 1, 1, 1, 1.5)	1.5	see Table S3
Nitrogen oxides	0.0017	0.0017	0.0017	0.0017	kg	output (air)	(1, 1, 1, 1, 1, 1.5)	1.5	see Table S3
Particulates, < 2.5 um	7.69E-03	0.00769	0.00769	0.00769	kg	output (air)	(1, 1, 1, 1, 1, 1.5)	1.5	see Table S3
Retort kiln, disposal, {ID}, miow	2.5E-05	2.5E-05	2.5E-05	2.5E-05	kg	output (waste)	(1, 1, 1, 1, 1, 2)	2	see Table S3

Table S12. Inventory for the unit process “Biochar, earth-mound kiln, {ID}, miow”.

Activity	Amount				Unit	Type	Pedigree	σ_g^2	Source
	Ngata Toro	Napu	Lampung	Lamongan					
Biochar	1	1	1	1	kg	output			
Carbon dioxide, in air	4.19	4.19	4.19	4.19	kg	input (resources)	(1.2, 1.2, 1.5, 1.1, 2, 1.05)	2.3401	calculated
Carbon dioxide, biogenic	1.626	1.626	1.626	1.626	kg	output (air)	(1, 1, 1, 1, 1, 1.05)	1.05	see Table S3
Carbon monoxide, biogenic	0.35	0.35	0.35	0.35	kg	output (air)	(1, 1, 1, 1, 1, 5)	5	see Table S3
Methane, biogenic	4.90E-02	4.90E-02	4.90E-02	4.90E-02	kg	output (air)	(1, 1, 1, 1, 1, 1.5)	1.5	see Table S3
NMVOC	5.30E-02	5.30E-02	5.30E-02	5.30E-02	kg	output (air)	(1, 1, 1, 1, 1, 1.5)	1.5	see Table S3
Nitrogen oxides	2.20E-03	2.20E-03	2.20E-03	2.20E-03	kg	output (air)	(1, 1, 1, 1, 1, 1.5)	1.5	see Table S3
Particulates, < 2.5 um	1.20E-02	1.20E-02	1.20E-02	1.20E-02	kg	output (air)	(1, 1, 1, 1, 1, 2)	2	see Table S3

Table S13. Inventory for the unit process “”Kon Tiki” flame curtain kiln, {ID}, miow”.

Activity	Amount				Unit	Type	Pedigree	σ_g^2	Source
	Ngata Toro	Napu	Lampung	Lamongan					
“Kon Tiki” flame curtain kiln	1	1	1	1	p	output			
Steel, low-alloyed, hot rolled {RoW}| production | Alloc Rec, U	100	100	100	100	kg	input (resources)	(1, 1, 1, 1, 1, 1.05)	1.05	Sparrevik et al.[1]
Clay brick {RoW}| production | Alloc Rec, U	4000	4000	4000	4000	kg	input (resources)	(1, 1, 1, 1, 1, 1.05)	1.05	Sparrevik et al.[1]
Cement, Portland {RoW}| production | Alloc Rec, U	100	100	100	100	kg	input (resources)	(1, 1, 1, 1, 1, 1.05)	1.05	Sparrevik et al.[1]
Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RoW}| transport, freight, lorry 3.5-7.5 metric ton, EURO4 | Alloc Rec, U	420	1050	84	84	tkm	input (materials)	(1, 1, 1, 1, 1, 2)	2	Sparrevik et al.[1]

Table S14. Inventory for the unit process “Retort kiln {ID}, miow”.

Activity	Amount				Unit	Type	Pedigree	σ_g^2	Source
	Ngata Toro	Napu	Lampung	Lamongan					
Retort kiln	1	1	1	1	p	output			
Steel, low-alloyed, hot rolled {RoW}| production | Alloc Rec, U	100	100	100	100	kg	input (resources)	(1, 1, 1, 1, 1, 1.05)	1.05	Smebye et al.[2]
Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RoW}| transport, freight, lorry 3.5-7.5 metric ton, EURO4 | Alloc Rec, U	10	25	2	2	tkm	input (materials)	(1, 1, 1, 1, 1, 2)	2	Sparrevik et al.[1]

Table S15. Inventory for the unit process “Wood, wet mass {ID}, miow”.

Activity	Amount				Unit	Type	Pedigree	σ_g^2	Source
	Ngata Toro	Napu	Lampung	Lamongan					
Wood	1	1	1	1	kg	output			wet mass
Carbon dioxide, in air	1.467	1.650	1.375	1.375	kg	input (resources)	(1.2, 1.2, 1, 1.1, 1.2, 1.05)	1.3958	calculated using data in Table S2
Occupation, forest, extensive	1.656	1.863	1.552	1.552	m2a	input (resources)	(1.05, 1.2, 1, 1.1, 1.2, 1.5)	1.6361	assumed [a]
Wood, soft, standing	0.0013	0.0013	0.0013	0.0013	m3	input (resources)	(1.2, 1.2, 1, 1.1, 1.2, 1.05)	1.3958	calculated using data in Table S2

[a] as in Cleft timber, measured as dry mass {CH}| softwood forestry, mixed species, sustainable forest management | Alloc Rec, U; corrected for moisture

Table S16. Inventory for the unit process “Biochar ash, landfarming, {ID}, miow”.

Activity	Amount				Unit	Type	Pedigree	σ_g^2	Source
	Ngata Toro	Napu	Lampung	Lamongan					
Biochar ash, landfarming	1	1	1	1	kg	output			
Potassium	7.0E-04	7.0E-04	7.0E-04	7.0E-04	kg	output (soil)	(1, 1.2, 1.03, 1.05, 1.2, 1.5)	1.6224	calculated using data in Table S2
Sulfur	3.9E-03	3.9E-03	3.9E-03	3.9E-03	kg	output (soil)	(1, 1.2, 1.03, 1.05, 1.2, 1.5)	1.6224	calculated using data in Table S2
Phosphorus	1.2E-03	1.2E-03	1.2E-03	1.2E-03	kg	output (soil)	(1, 1.2, 1.03, 1.05, 1.2, 1.5)	1.6224	calculated using data in Table S2

Table S17. Inventory for the unit process “Wood ash, landfarming, {ID}, miow”.

Activity	Amount				Unit	Type	Pedigree	σ_g^2	Source
	Ngata Toro	Napu	Lampung	Lamongan					
Wood ash, landfarming	1	1	1	1	kg	output			
Potassium	5.5E-04	5.5E-04	5.5E-04	5.5E-04	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 1.5)	1.5839	calculated using data in Table S2 and Table S6
Sulfur	9.2E-05	9.2E-05	9.2E-05	9.2E-05	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 1.5)	1.5839	calculated using data in Table S2 and Table S6
Phosphorus	9.8E-05	9.8E-05	9.8E-05	9.8E-05	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 1.5)	1.5839	calculated using data in Table S2 and Table S6
Arsenic	6.7E-08	6.7E-08	6.7E-08	6.7E-08	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 5)	5.0733	calculated using data in Table S2 and Table S6
Molybdenum	3.7E-08	3.7E-08	3.7E-08	3.7E-08	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 5)	5.0733	calculated using data in Table S2 and Table S6
Lead	6.5E-07	6.5E-07	6.5E-07	6.5E-07	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 5)	5.0733	calculated using data in Table S2 and Table S6
Aluminium	2.1E-04	2.1E-04	2.1E-04	2.1E-04	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 5)	5.0733	calculated using data in Table S2 and Table S6
Copper	1.6E-06	1.6E-06	1.6E-06	1.6E-06	kg	output	(1, 1.05, 1.1, 1.05, 1.2, 5)	5.0733	calculated using data in Table S2 and

						(soil)				Table S6
Manganese	2.0E-04	2.0E-04	2.0E-04	2.0E-04	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 5)	5.0733	calculated using data in Table S2 and Table S6
Calcium	2.8E-03	2.8E-03	2.8E-03	2.8E-03	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 1.5)	1.5839	calculated using data in Table S2 and Table S6
Chromium	2.0E-06	2.0E-06	2.0E-06	2.0E-06	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 5)	5.0733	calculated using data in Table S2 and Table S6
Magnesium	3.2E-04	3.2E-04	3.2E-04	3.2E-04	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 1.5)	1.5839	calculated using data in Table S2 and Table S6
Titanium	1.4E-05	1.4E-05	1.4E-05	1.4E-05	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 5)	5.0733	calculated using data in Table S2 and Table S6
Zinc	1.7E-05	1.7E-05	1.7E-05	1.7E-05	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 5)	5.0733	calculated using data in Table S2 and Table S6
Nickel	5.5E-07	5.5E-07	5.5E-07	5.5E-07	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 5)	5.0733	calculated using data in Table S2 and Table S6
Vanadium	4.0E-07	4.0E-07	4.0E-07	4.0E-07	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 5)	5.0733	calculated using data in Table S2 and Table S6
Silicon	8.3E-04	8.3E-04	8.3E-04	8.3E-04	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 1.5)	1.5839	calculated using data in Table S2 and Table S6
Mercury	1.0E-09	1.0E-09	1.0E-09	1.0E-09	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 5)	5.0733	calculated using data in Table S2 and Table S6
Cadmium	1.4E-07	1.4E-07	1.4E-07	1.4E-07	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 5)	5.0733	calculated using data in Table S2 and Table S6
Carbon	1.2E-04	1.2E-04	1.2E-04	1.2E-04	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 5)	5.0733	calculated using data in Table S2 and Table S6
Chloride	3.2E-05	3.2E-05	3.2E-05	3.2E-05	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 1.5)	1.5839	calculated using data in Table S2 and Table S6
Cobalt	1.8E-07	1.8E-07	1.8E-07	1.8E-07	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 5)	5.0733	calculated using data in Table S2 and Table S6
Iron	2.3E-04	2.3E-04	2.3E-04	2.3E-04	kg	output (soil)	(1, 1.05, 1.1, 1.05, 1.2, 5)	5.0733	calculated using data in Table S2 and Table S6

S4. Details of uncertainty analysis

To acknowledge uncertainties in emission inventories for foreground processes, uncertainty factors were estimated from characteristics of the flows, emissions and the respective processes using a Pedigree matrix approach that takes into account quality.[41] Details of the approach are presented in Owsianiak et al.[42] Briefly, each uncertain data point was assessed using five criteria and combined with the basic uncertainty factor based on the type of data. Next, these criteria were used to calculate squared geometric standard deviations assuming lognormal distribution (eq S1) Uncertainties in emission inventories for background processes were used as reported in the ecoinvent database version 3.3, as presented in the manual to SimaPro, version 8.3.0.0. The criteria, the basic uncertainty factors, and resulting geometric standard deviations are reported in Tables S7-S17 in Section S3.

$$\sigma_g^2 = \exp\left(\sqrt{[\ln(U_1)]^2 + [\ln(U_2)]^2 + [\ln(U_3)]^2 + [\ln(U_4)]^2 + [\ln(U_5)]^2 + [\ln(U_b)]^2}\right) \qquad \text{eq S1}$$

where σ_g^2 is the squared geometric standard deviation (variance, 95% interval); U_1-U_5 are the uncertainty factors of reliability, completeness, temporal correlation, geographic correlation, and future technological correlation; and U_b is the basic uncertainty factor.

Parameters which were found important in the perturbation analysis presented in Section S5 (namely, biochar yield, biochar application rate, crop yield in conventional agriculture, and fraction of PM smaller than 2.5 μm) were considered in the uncertainty analysis, assuming either normal, triangular, or uniform distributions (Table S18).

Table S18. Uncertainty distribution of the important model parameters.

Parameter	Distribution	Source
Biochar yield (%)	~n(a,b) [a]	Mean and standard deviation were set to reflect ranges of values presented in Table 2
Biochar application rate (kg/ha)	~T(a,b,c) [b]	Median, minimum, and maximum values were assumed equal to default and perturbed parameter values reported in Table 2
Crop yield in conventional agriculture (kg/ha)	~T(a,b,c) [b]	Median, minimum, and maximum values were assumed equal to default and perturbed parameter values reported in Table 2
Fraction of PM smaller than 2.5 μm (kg/kg)	~U(a,b) [c]	Interval corresponds to perturbed parameter values as reported in Table 2

[a] the term ~n(a,b) denotes a normal distribution with a mean and standard deviation equal to (a) and (b), respectively.

[b] the term ~T(a,b,c) denotes the triangular distribution based on minimum (a), median (b), and maximum (c) values

[c] the term ~U(a,b) denotes a uniform distribution with interval [a, b], respectively.

S5. Details of life cycle impact assessment

Ozone depletion. Impact scores for this global impact category were calculated using updated ozone depletion potentials (ODP) from the World Meteorological Organization,[12] as implemented in ReCiPe2016.[13]

Ionizing radiation. Global-generic characterization factors based on Frischknecht et al.[14] were used. Damage to human health was based on De Schryver et al.[15], as implemented in ReCiPe2016.[13]

Mineral and fossil resource scarcity. Mineral and fossil resource scarcity indicators were those of Vieira et al.[16–18] and Ponsioen et al.,[19] respectively, where endpoint scores are based on surplus cost potential. Their method is also implemented in ReCiPe2016.[13]

Climate change. The method of Levasseur et al.[20] combined with temporarily disaggregated inventory for CO_2 emissions were used to quantify impacts stemming from time-dependent mineralization of biochar carbon dynamic global warming potentials (GWP). Emissions of CO_2 from other activities in the biochar life cycles, including biogenic CO_2 emission from combustion of wood, were assigned a GWP equal to 1 kg CO_2 eq. Owing to the fact that biomass residues originate from annual cropping systems, CO_2 released from biochar mineralization is assumed to be re-captured quickly due to fast CO_2 uptake by crop re-growth. Thus, CO_2 sequestered from air into crop biomass was assigned a GWP equal to -1 kg CO_2 eq., consistently with recommendations of IPCC.[21] Trees, however, take a longer time to grow before they sequester CO_2. Thus, CO_2 sequestered from air into wood biomass was assigned a GWP equal to Indonesia-specific value of -0.54 kg CO_2 eq (Cherubini et al.[22]). A value of -0.51 kg CO_2 eq was used in site-generic assessment. Damages to human health and ecosystems (terrestrial and aquatic) were calculated using midpoint to endpoint characterization factors based on De Schryver et al.,[15] as implemented in ReCiPe2016.[13]

Particulate matter formation. The model by Fantke et al.[23] was used as a basis for further adaptation to local case study conditions. The model calculates characterization factors for primarily PM2.5 emissions for outdoor in both urban (including 77 Indonesian cities) and rural compartments (parameterized for Southeast Asia), and in the indoor compartment. While the outdoor compartment is deemed sufficiently representative of this case study, indoor exposure is also relevant for outdoor emissions from biochar making, and is expected to vary between the case studies. Thus, the model was further adapted by incorporating actual local data for residential indoor environments and occupancy levels in order to increase accuracy of quantification of impacts. Details of the adaptations made are presented in the SI, Section S3. Note, that Fantke et al.[23] developed a model for predicting intake fractions only. To quantify damages to human health resulting from PM2.5 intake, unpublished human health effect factors from Fantke were used, which considered mortality from stroke, ischemic heart disease, acute lower respiratory infections, chronic obstructive pulmonary disease, and lung cancer. These effect factors were developed using linear dose-response function.

Table S19. Parameters of the indoor compartment and human health effect parameters of the PM model used to quantify damages to human health from outdoor emissions of PM2.5.

Parameter	Global-generic	Village-specific			
		Ngata Toro	Napu	Lampung	Lamongan
Indoor environment parameters					
Individual breathing rate in indoor environments (m3/d/person)	16	16	16	16	16
Fraction of daily time spend in indoor environments (d/d)	0.9	0.9	0.58 a	0.9	0.9
Height of indoor environments (m)	3	3	3.14 b	3	3
Air exchange rate of indoor air to outdoor air in rural areas (d^{-1})	366	366	14.88 c	366	366
Recirculation rate of indoor air in urban areas (d^{-1})	0	0	0	0	0
Filter efficiency in indoor environments of urban areas (-)	0	0	0	0	0
Occupancy: air volume of indoor air per person in rural areas (m^3)	67	67	89.3 d	67	67
Human health effect parameters					
Background concentration indoor rural air (µg/m^3)	250	100e	100e	150e	150e
Background concentration outdoor rural air (µg/m^3)	31.8	70e	70	70	70

[a] the majority of inhabitants spends above 6 h per day indoor; value calculated assuming 8 h of sleep, so 14h/24h=0.58

[b] average across 59 housings in the village

[c] as housings in the village have windows and door, they can be considered as housings with low exchange rate (as compared to open houses with high exchange rate in model-default settings for Southeast Asia and Indochina sub-continental regions)

[d] average across 59 housings in the village, calculated using housing-specific dimensions and number of inhabitants

[e] measured or estimated

Table S20. Intake fractions, effect factors, and resulting characterization factors for PM2.5 emissions calculated using the PM model of Fantke et al.[23]

Emission compartment	Generic	Village-specific			
		Ngata Toro	Napu	Lampung	Lamongan
Intake fractions					
Outdoor urban	3.3e-5	1.6e-5	3.1e-6	6.3e-5	2.4e-5
Outdoor rural	2.2e-6	1.1e-6	9.5e-7	1.1e-6	1.1e-6
Effect factor (slope to threshold)					
Outdoor urban	137.16	102	152.70	184.45	183.25
Outdoor rural	128.56	95.52	95.09	93.54	93.57
Characterization factors					
Outdoor urban	4.8e-3	1.5e-3	4.0e-4	1.2e-2	4.3e-3
Outdoor rural	8.8e-5	8.3e-5	6.6e-5	5.1e-5	5.2e-5

Land use. The method of Chaudhary et al.[24] who calculated characterization factors for land occupation and transformation considering 6 land use types, 5 taxa, and 804 terrestrial ecoregions, was used. As Indonesia contains ecoregions of relatively high species richness their characterization factors are relatively high compared to many other parts of the world.[24] Further, there is considerable variability in characterization factors between the 38 ecoregions of Indonesia (approximately 1 order of magnitude). Vulnerability of ecoregions to loss of endemic species was not considered, and species within each taxon were considered to be equally important.

Water use. To quantify human health impacts from water consumption, the method of Boulay et al.[25] who calculated watershed-specific characterization factors for 619 main watersheds, was used. Characterization factors are derived for a total of 17 flows, considering on the water source (surface water, groundwater, rain) and water quality (from excellent to unusable). In this case study, all four villages are located outside main watersheds and are thus assigned characterization factors corresponding to "outside of main watershed". In all villages except Napu water is relatively abundant, so an Indonesia-specific characterization factor equal to 0 DALY/m^3 was used. In Napu, where water is scarce, the characterization factor is equal to 2.93E-7 DALY/m^3. However as irrigation does not takes place this factor was not used in regionalized assessment.

Damage to terrestrial ecosystems was quantified using watershed-specific characterization factors computed by Pfister et al.,[26] who computed them for about 10000 global, major and minor, watersheds.

Damage from water consumption to freshwater fish species was quantified using Indonesia-specific values because none of our villages could be mapped to one of well-known 214 river basins covered in the method of Hanafiah et al.[27]

Toxicity. USEtox, version 2.02 was employed to quantify damage to human health arising from emissions of organic and inorganic substances (considering both cancer and non-cancer effects).[28] The predefined Southeast Asia archetype was employed for outdoor emissions. Indoor exposure settings for toxic chemicals were based on non-OECD household archetype combined with village-specific exposure parameters, as done for the PM model.

Ecotoxicity. Again, USEtox, version 2.02 was employed to quantify damage to freshwater ecosystems from emissions of organic and inorganic substances outdoors (Southeast Asia) or indoors (adjusted non-OECD).[28] As USEtox currently does not include a terrestrial compartment, ReCiPe2016 factors were used for terrestrial ecotoxicity for organic substances, except for metallic elements, where the method of Owsianiak et al.[29,30] was used to calculate soil-specific CF. Similarly, marine ecotoxicity characterization factors were those of ReCiPe2016, except for metallic elements which were taken from Dong et al.[31] and calculated specifically for the Indonesian Sea marine ecosystem. These methods were preferred as they consider site-dependent metal speciation in environmental fate, exposure, and effects. Although environmental parameters in the underlying multimedia fate models used to calculate fate factors are not always same as those in the fate model used in ReCiPe2016, the approach of combining Recipe2006 factors for organics with the proposed methods for metals is still an improvement as metals are dominant contributor to life cycle impacts in general,[32,33] and in this case study in particular.

Eutrophication. Damage to freshwater ecosystems from emissions of phosphorus (P) were characterized using Indonesia-specific characterization factors based on the work of Azevedo et al.[34,35], as implemented in ReCiPe2016.[13] Although maps of grid-specific factors were presented, the actual grid-specific CFs were not available at the time of the study. Variability in the characterization factors in Indonesia is within 1 order of magnitude, and country-specifc characterization factors of P for direct emission to soil in Indonesia (7.65×10^{-9} species.yr) is in lower range of values in the world (6.1×10^{-8} species.yr).

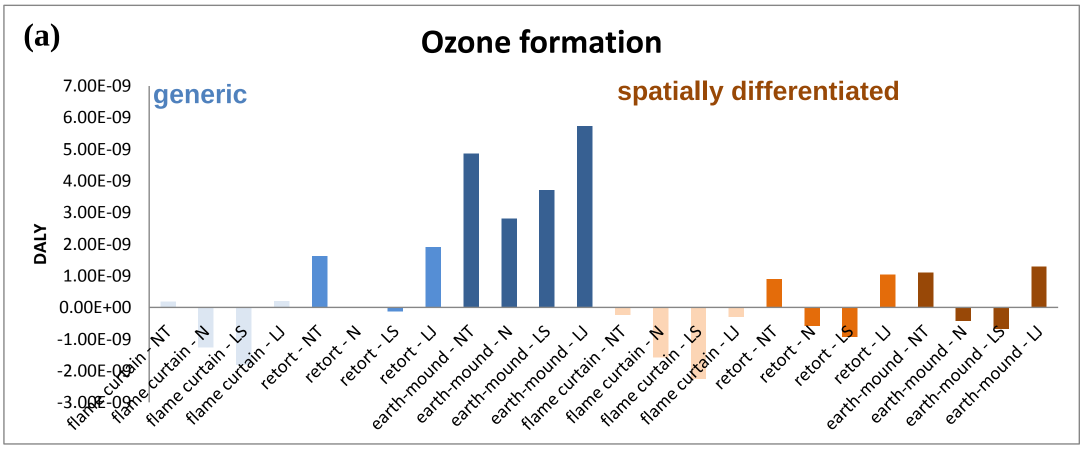
Marine eutrophication for airborne emissions of NO_x is based on the model of Cosme et al.[36,37] who calculate marine fate, exposure and effect factors the Indonesian Sea marine ecosystems. The fraction of NO_x emissions deposited in the sea village-specific, as provided by Roy et al.[38] who developed spatially-differentiated atmospheric source-receptor relationships for NO_x emissions. A continental-level source-receptor relationships was used for emissions occurring in Asia and deposition in seas/oceans. For generic values, mean deposited fraction, fate factors, and damage indicators, were used.

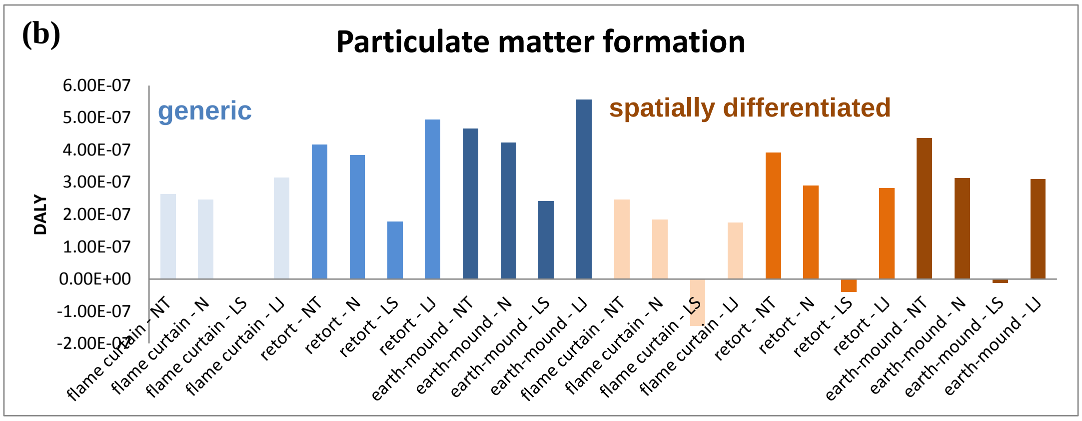
Acidification. Village-specific characterization factors provided by Roy et al.[39], using the method implemented in both IMPACT World+ and ReCiPe2016, were used to quantify damage to terrestrial ecosystems from emission of acidifying gases.

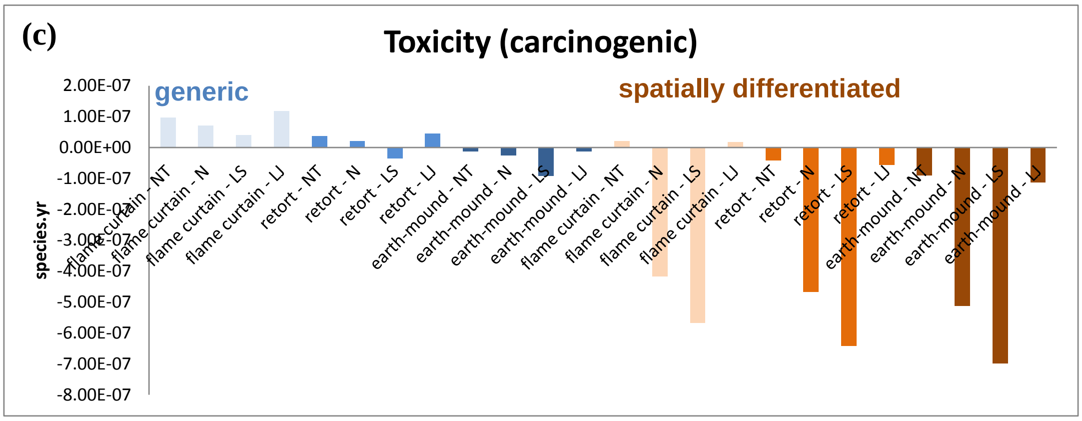
Photochemical ozone formation. The method of Van Zelm et al.[40] as implemented in ReCiPe2016[13] was used to quantify damage to human health and terrestrial ecosystems from emission of ozone-forming pollutants using region specific characterization factors for the region comprising Indonesia, Papua New Guinea, and East Timor. Both human health and ecosystem damage characterization factors for this region are within the range (NO_x) or ca. 1 order of magnitude lower (NMVOC) compared to global-generic characterization factors. As no region-specific characterization factors for individual NMVOCs reported in inventories were available, global-generic values were used for individual NMVOCs reported in inventories for emissions from biochar production.

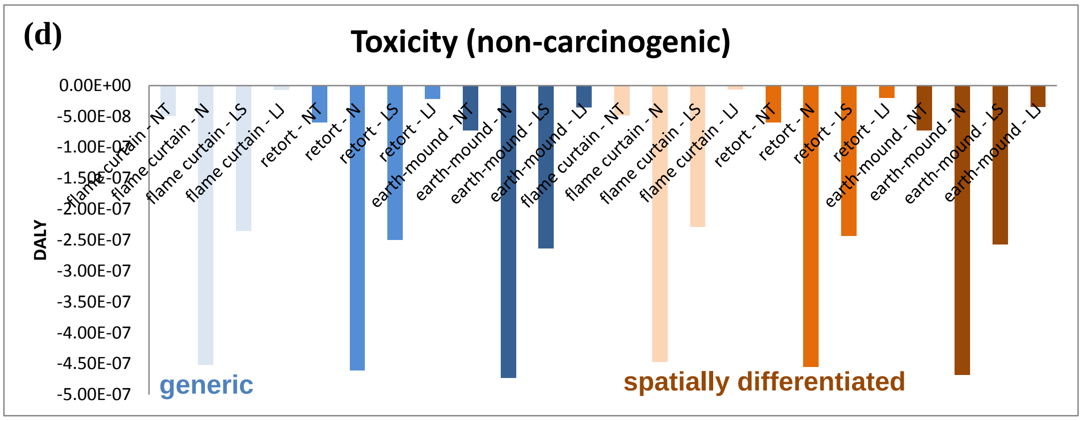
S6. Additional life cycle impact assessment results

S6.1. Comparison between generic and spatially differentiated impacts

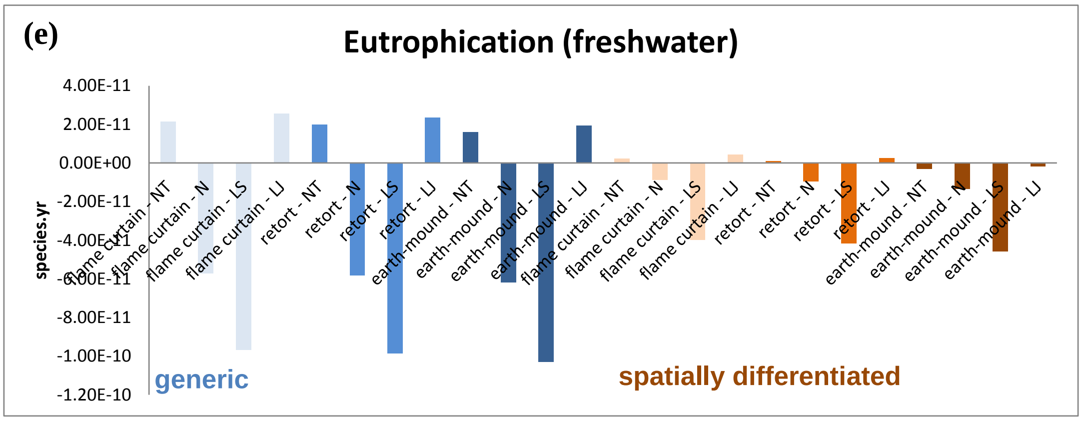




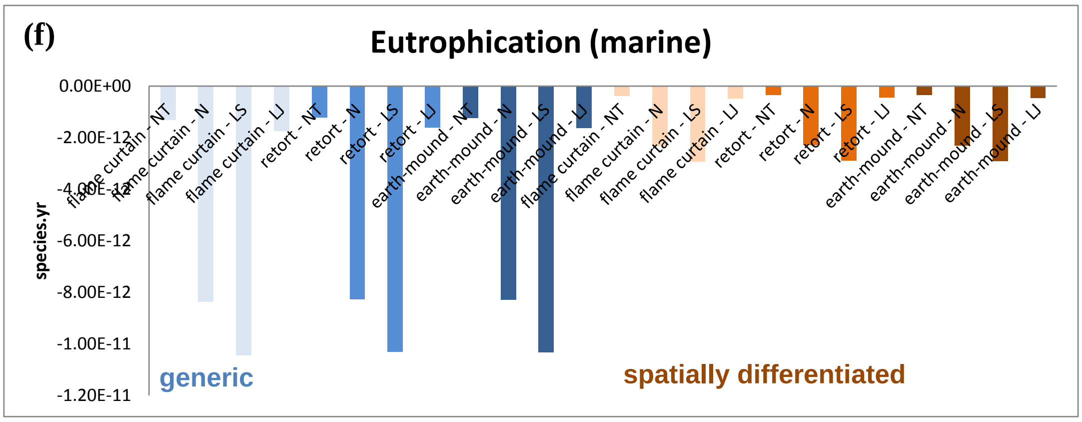




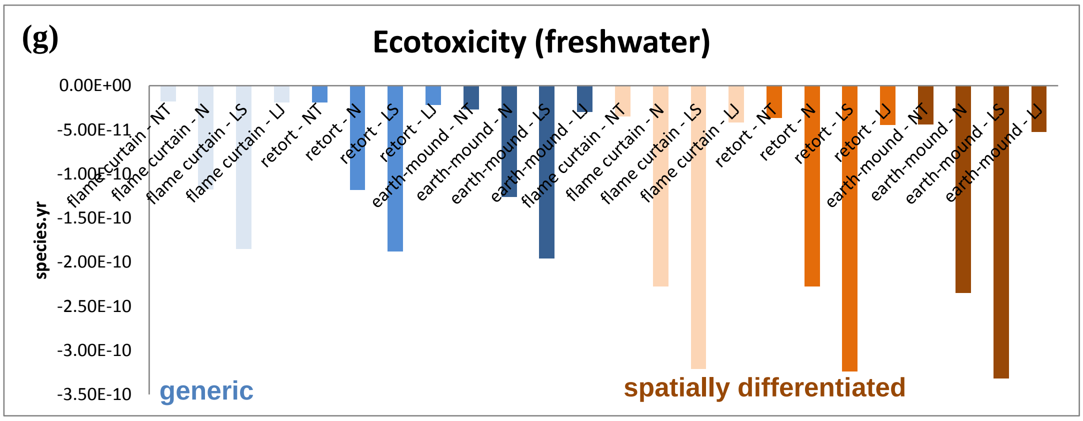
(d) Toxicity (non-carcinogenic)



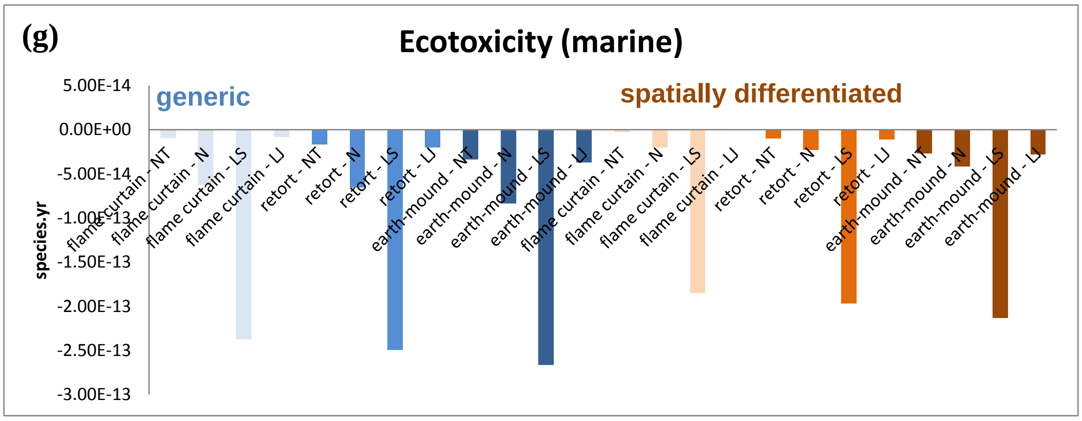
(e) Eutrophication (freshwater)



(f) Eutrophication (marine)



(g) Ecotoxicity (freshwater)


(g)
Ecotoxicity (marine)
species.yr
5.00E-14
0.00E+00
-5.00E-14
-1.00E-13
-1.50E-13
-2.00E-13
-2.50E-13
-3.00E-13
generic
spatially differentiated
flame curtain - NT
flame curtain - N
flame curtain - LS
flame curtain - LJ
retort - NT
retort - N
retort - LS
retort - LJ
earth-mound - NT
earth-mound - N
earth-mound - LS
earth-mound - LJ
flame curtain - NT
flame curtain - N
flame curtain - LS
flame curtain - LJ
retort - NT
retort - N
retort - LS
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earth-mound - NT
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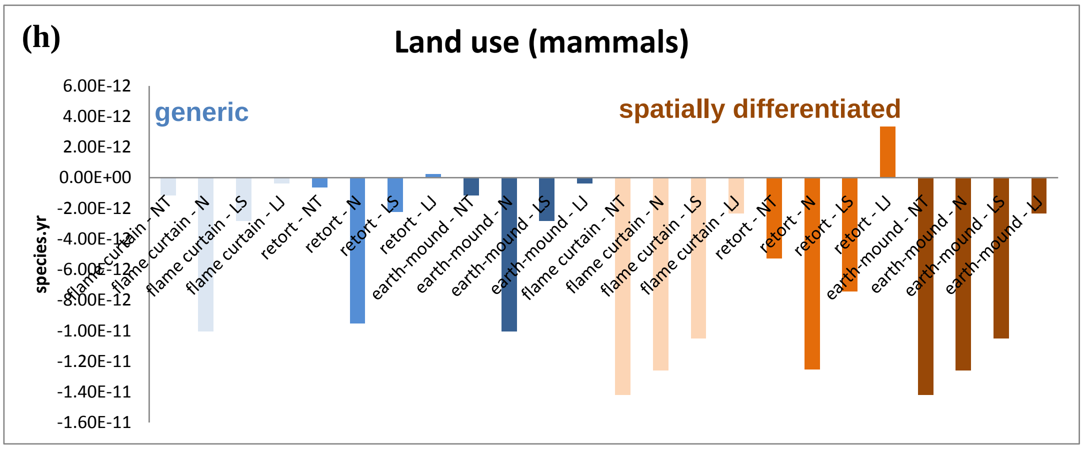
earth-mound - LS
earth-mound - LJ


(h)
Land use (mammals)
species.yr
6.00E-12
4.00E-12
2.00E-12
0.00E+00
-2.00E-12
-4.00E-12
-6.00E-12
-8.00E-12
-1.00E-11
-1.20E-11
-1.40E-11
-1.60E-11
generic
spatially differentiated
flame curtain - NT
flame curtain - N
flame curtain - LS
flame curtain - LJ
retort - NT
retort - N
retort - LS
retort - LJ
earth-mound - NT
earth-mound - N
earth-mound - LS
earth-mound - LJ
flame curtain - NT
flame curtain - N
flame curtain - LS
flame curtain - LJ
retort - NT
retort - N
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retort - LJ
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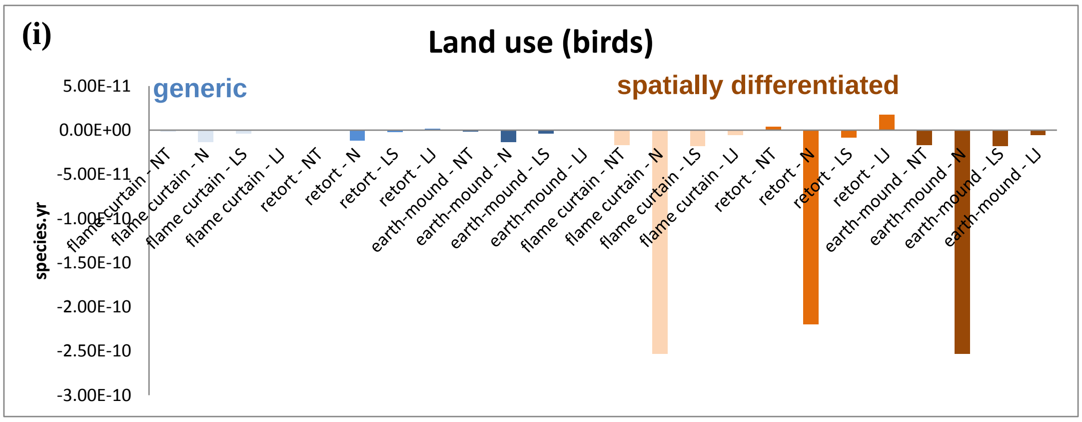
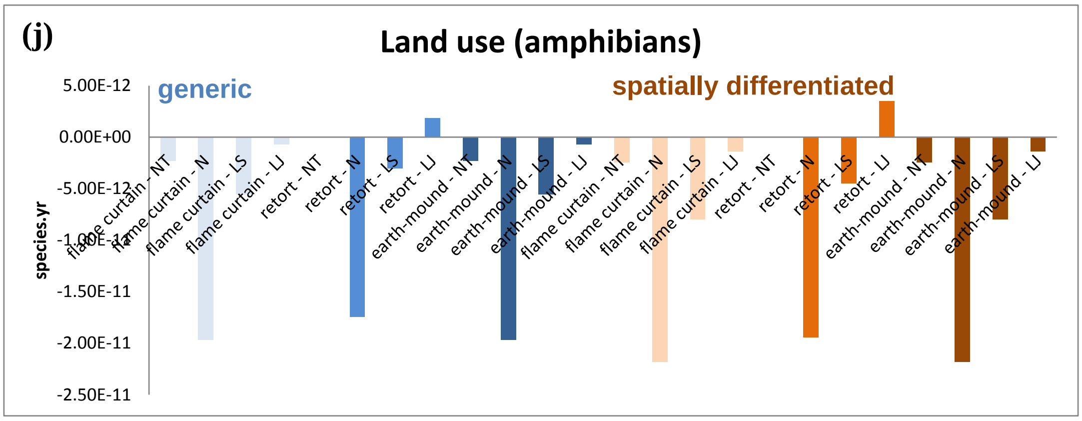
earth-mound - N
earth-mound - LS
earth-mound - LJ


(i)
Land use (birds)
species.yr
5.00E-11
0.00E+00
-5.00E-11
-1.00E-10
-1.50E-10
-2.00E-10
-2.50E-10
-3.00E-10
generic
spatially differentiated
flame curtain - NT
flame curtain - N
flame curtain - LS
flame curtain - LJ
retort - NT
retort - N
retort - LS
retort - LJ
earth-mound - NT
earth-mound - N
earth-mound - LS
earth-mound - LJ
flame curtain - NT
flame curtain - N
flame curtain - LS
flame curtain - LJ
retort - NT
retort - N
retort - LS
retort - LJ
earth-mound - NT
earth-mound - N
earth-mound - LS
earth-mound - LJ


(j)
Land use (amphibians)
species.yr
5.00E-12
0.00E+00
-5.00E-12
-1.00E-11
-1.50E-11
-2.00E-11
-2.50E-11
generic
spatially differentiated
flame curtain - NT
flame curtain - N
flame curtain - LS
flame curtain - LJ
retort - NT
retort - N
retort - LS
retort - LJ
earth-mound - NT
earth-mound - N
earth-mound - LS
earth-mound - LJ
flame curtain - NT
flame curtain - N
flame curtain - LS
flame curtain - LJ
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earth-mound - LS
earth-mound - LJ

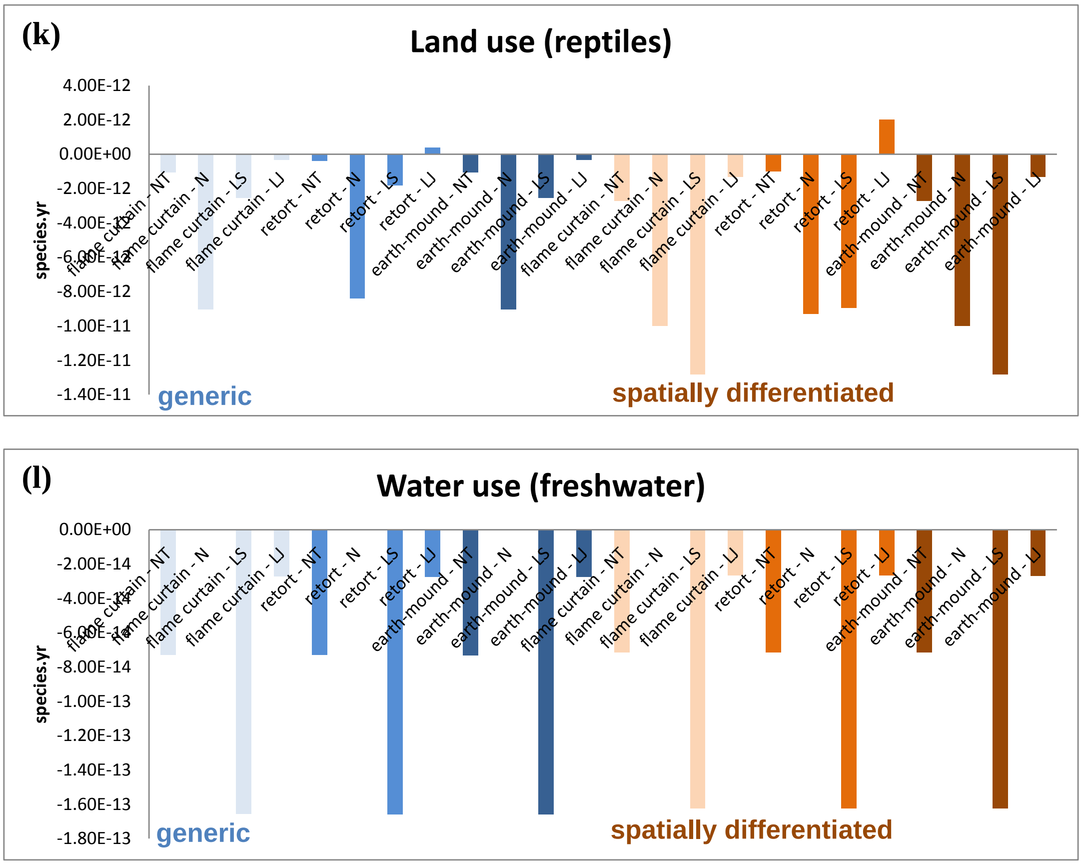


Fig. S1. Comparison between generic and spatially differentiated impacts (scenarios 1-12) for selected impact categories contributing to damage to human health (**a-d**) and to damage to ecosystems (**e-l**). NT: Ngata Toro, N-Napu, LS-Lampung, LJ-Lamongan.

S6.2. Results for other scenarios

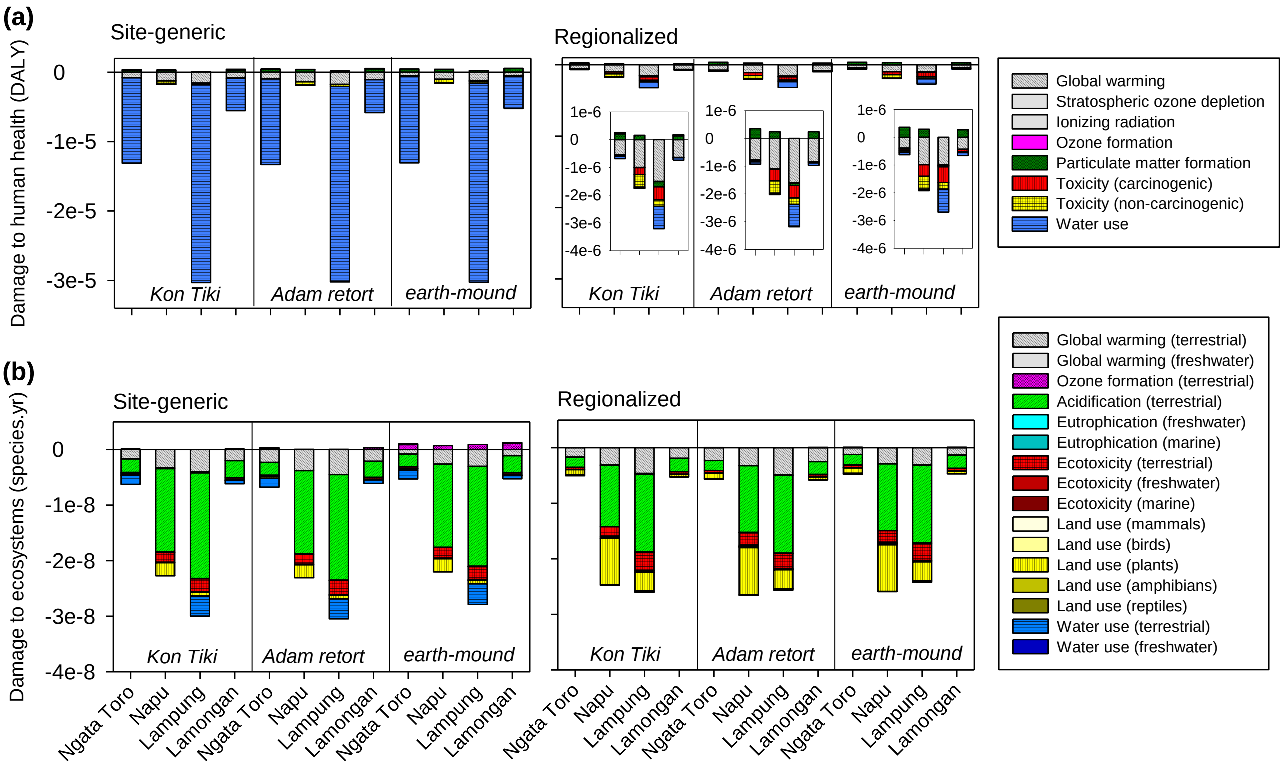


Fig. S2. Site-generic and regionalized damage to human health (a) and ecosystems (b) from biochar production using "Kon Tiki" kiln and its use for improving agriculture in Indonesia, as influenced by geographic location and type of kiln (scenarios 5-12 in Table 1). Absolute uncertainties are too large to be shown, but comparison taking into account correlations revealed statistically significant differences between site-generic and site-specific damage. It also revealed statistically significant differences in total damages scores between regionalized and site-generic assessments.

Table S21. Characterized spatially differentiated impacts and total damage at endpoint and accompanying 95% probability ranges from Monte Carlo simulations, for biochar production using “Kon Tiki” flame curtain kiln and used in maize agriculture in four different Indonesian villages (Scenarios 1-4 in Table 1). The probability ranges represent both parameter and inventory uncertainties. Statistical comparison between impact scores taking into account correlations is presented in Table S33.

			Impact score (95% probability range)							
			1		2		3		4	
Impact category	Unit	Spatial scale	flame curtain, NT		flame curtain, N		flame curtain, LS		flame curtain, LJ	
Global warming	DALY	Indonesia	-5.465E-07	(-2.2E-06 – 3.2E-07)	-1.021E-06	(-4.1E-06 – -1.3E-07)	-1.530E-06	(-3.8E-06 – -1.3E-07)	-6.396E-07	(-3.8E-06 – 5.1E-07)
Stratospheric ozone depletion	DALY	Global	-1.255E-09	(-1.8E-09 – -8.3E-10)	-7.385E-09	(-1.3E-08 – -4.5E-09)	-1.005E-08	(-1.6E-08 – -6.3E-09)	-1.629E-09	(-2.6E-09 – -1.1E-09)
Ionizing radiation	DALY	Global	-4.059E-12	(-5.0E-12 – -3.2E-12)	-6.216E-12	(-7.3E-12 – -5.3E-12)	-4.670E-11	(-5.3E-11 – -4.2E-11)	-2.691E-12	(-3.4E-12 – -1.8E-12)
Ozone formation	DALY	Region	-2.031E-10	(-3.4E-10 – -1.1E-10)	-1.514E-09	(-2.6E-09 – -9.2E-10)	-2.188E-09	(-3.4E-09 – -1.4E-09)	-2.568E-10	(-4.6E-10 – -1.4E-10)
Particulate matter formation	DALY	Southeast Asia / village	2.111E-07	(1.0E-07 – 5.1E-07)	1.623E-07	(8.7E-08 – 3.2E-07)	-1.880E-07	(-2.7E-07 – -4.6E-08)	1.381E-07	(3.8E-08 – 3.5E-07)
Toxicity (carcinogenic)	DALY	Southeast Asia / village	4.906E-08	(-2.1E-07 – 9.6E-08)	-2.462E-07	(-2.2E-06 – 6.4E-09)	-4.682E-07	(-3.1E-06 – -4.1E-08)	3.988E-08	(-5.7E-07 – 1.2E-07)
Toxicity (non-carcinogenic)	DALY	Southeast Asia / village	-4.641E-08	(-6.8E-08 – -3.7E-08)	-4.473E-07	(-6.1E-07 – -4.0E-07)	-2.262E-07	(-4.4E-07 – -1.8E-07)	-4.919E-09	(-5.3E-08 – 6.2E-09)
Water use	DALY	Village / Indonesia	-8.626E-08	(-9.6E-08 – -7.7E-08)	-5.037E-08	(-5.5E-08 – -4.5E-08)	-8.055E-07	(-9.2E-07 – -7.3E-07)	-9.360E-08	(-1.0E-07 – -8.5E-08)
Global warming (terrestrial)	species.yr	Indonesia	-1.651E-09	(-6.8E-09 – 9.8E-10)	-3.079E-09	(-1.2E-08 – -4.0E-10)	-4.616E-09	(-1.2E-08 – -3.8E-10)	-1.932E-09	(-1.1E-08 – 1.5E-09)
Global warming (freshwater)	species.yr	Indonesia	-4.512E-14	(-1.9E-13 – 2.7E-14)	-8.415E-14	(-3.4E-13 – -1.1E-14)	-1.262E-13	(-3.2E-13 – -1.1E-14)	-5.280E-14	(-3.1E-13 – 4.2E-14)
Ozone formation (terrestrial)	species.yr	Region	-1.194E-11	(-2.2E-11 – -4.3E-12)	-1.010E-10	(-1.7E-10 – -6.2E-11)	-1.696E-10	(-2.5E-10 – -1.2E-10)	-1.376E-11	(-2.7E-11 – -6.6E-12)
Acidification (terrestrial)	species.yr	Village	-1.806E-09	(-2.7E-09 – -1.1E-09)	-1.145E-08	(-2.0E-08 – -6.9E-09)	-1.440E-08	(-2.4E-08 – -8.4E-09)	-2.394E-09	(-3.9E-09 – -1.6E-09)
Eutrophication (freshwater)	species.yr	Indonesia	2.535E-12	(-3.3E-12 – 5.4E-12)	-4.907E-12	(-4.7E-11 – 1.6E-12)	-3.924E-11	(-9.6E-11 – -2.6E-11)	4.731E-12	(-9.3E-12 – 8.4E-12)
Ecotoxicity (terrestrial)	species.yr	Southeas Asia / village	-3.968E-10	(-2.5E-09 – -9.7E-11)	-1.721E-09	(-1.2E-08 – -3.4E-10)	-3.254E-09	(-2.1E-08 – -6.3E-10)	-4.398E-10	(-4.0E-09 – -8.5E-11)
Ecotoxicity (freshwater)	species.yr	Southeast Asia	-2.210E-11	(-1.3E-10 – -6.7E-12)	-1.544E-10	(-9.8E-10 – -4.3E-11)	-2.750E-10	(-1.4E-09 – -1.0E-10)	-3.143E-11	(-3.0E-10 – -3.1E-12)
Ecotoxicity (marine)	species.yr	Indonesia	-1.613E-15	(-1.7E-14 – 6.7E-15)	-9.235E-15	(-1.2E-13 – 7.8E-15)	-1.822E-13	(-3.4E-13 – -1.5E-13)	6.202E-16	(-3.3E-14 – 1.1E-14)
Land use (mammals)	species.yr	Village	-1.369E-11	(-2.1E-11 – -8.7E-12)	-1.232E-11	(-1.8E-11 – -8.8E-12)	-1.002E-11	(-1.4E-11 – -6.7E-12)	-2.187E-12	(-3.5E-12 – -1.6E-12)
Land use (birds)	species.yr	Village	-1.609E-11	(-2.5E-11 – -1.0E-11)	-2.468E-10	(-3.7E-10 – -1.7E-10)	-1.678E-11	(-2.3E-11 – -1.1E-11)	-4.989E-12	(-7.9E-12 – -3.6E-12)
Land use (plants)	species.yr	Village	-9.185E-10	(-1.4E-09 – -5.8E-10)	-8.421E-09	(-1.3E-08 – -6.0E-09)	-3.359E-09	(-4.6E-09 – -2.2E-09)	-4.244E-10	(-6.7E-10 – -3.0E-10)
Land use (amphibians)	species.yr	Village	-2.381E-12	(-3.6E-12 – -1.5E-12)	-2.132E-11	(-3.2E-11 – -1.5E-11)	-7.638E-12	(-1.0E-11 – -5.2E-12)	-1.287E-12	(-2.0E-12 – -9.2E-13)
Land use (reptiles)	species.yr	Village	-2.623E-12	(-4.0E-12 – -1.7E-12)	-9.803E-12	(-1.5E-11 – -7.0E-12)	-1.226E-11	(-1.7E-11 – -8.2E-12)	-1.252E-12	(-2.0E-12 – -8.9E-13)
Water use (terrestrial)	species.yr	Village	-1.632E-10	(-2.4E-10 – -1.0E-10)	-4.535E-12	(-5.1E-12 – -4.0E-12)	-2.187E-10	(-2.9E-10 – -1.8E-10)	-3.624E-11	(-5.3E-11 – -2.8E-11)
Water use (freshwater)	species.yr	Indonesia	-6.968E-14	(-1.1E-13 – -4.2E-14)	-2.029E-16	(-2.3E-16 – -1.8E-16)	-1.585E-13	(-2.6E-13 – -1.0E-13)	-2.481E-14	(-4.3E-14 – -1.6E-14)
Eutrophication (marine)	species.yr	Indonesia	-3.598E-13	(-5.4E-13 – -2.3E-13)	-2.255E-12	(-3.9E-12 – -1.4E-12)	-2.843E-12	(-4.6E-12 – -1.7E-12)	-4.681E-13	(-7.5E-13 – -3.1E-13)
Mineral resource scarcity	USD2013	Global	6.245E-05	(3.9E-05 – 9.7E-05)	8.247E-05	(5.7E-05 – 1.2E-04)	-1.623E-04	(-1.9E-04 – -1.2E-04)	8.985E-05	(6.4E-05 – 1.3E-04)
Fossil resource scarcity	USD2013	Global	-2.486E-03	(-2.8E-03 – -2.2E-03)	-1.058E-03	(-1.3E-03 – -8.5E-04)	-2.485E-02	(-2.8E-02 – -2.3E-02)	-2.660E-03	(-3.0E-03 – -2.4E-03)
Human health	species.yr	Various	-4.427E-07	(-2.2E-06 – 4.7E-07)	-1.816E-06	(-5.1E-06 – -6.6E-07)	-3.213E-06	(-7.9E-06 – -1.9E-06)	-5.683E-07	(-3.7E-06 – 6.4E-07)
Ecosystems	DALY	Various	-5.449E-09	(-1.1E-08 – -2.0E-09)	-2.685E-08	(-4.1E-08 – -1.8E-08)	-2.738E-08	(-5.0E-08 – -1.8E-08)	-5.643E-09	(-1.4E-08 – -1.9E-09)
Resources	USD2013	Global	-2.411E-03	(-2.8E-03 – -2.1E-03)	-9.757E-04	(-1.2E-03 – -7.5E-04)	-2.501E-02	(-2.8E-02 – -2.3E-02)	-2.568E-03	(-2.9E-03 – -2.3E-03)

NT=Ngata Toro; N=Napu, LS=Lampung, LJ=Lamongan

Table S22. Characterized spatially differentiated impacts and total damage at endpoint and accompanying 95% probability ranges from Monte Carlo simulations, for biochar production using retort kiln and used in maize agriculture in four different Indonesian villages (Scenarios 5-8 in Table 1). The probability ranges represent both parameter and inventory uncertainties.

			Impact score (95% probability range)							
			5		6		7		8	
Impact category	Unit	Spatial scale	Retort, NT		Retort, N		Retort, LS		Retort, LJ	
Global warming	DALY	Indonesia	-5.032E-07	(-4.3E-06 – 1.1E-06)	-9.799E-07	(-3.3E-06 – 2.9E-07)	-1.140E-06	(-5.5E-06 – 6.8E-07)	-2.067E-07	(-3.8E-06 – 1.7E-06)
Stratospheric ozone depletion	DALY	Global	-1.217E-09	(-2.1E-09 – -8.3E-10)	-7.533E-09	(-1.1E-08 – -5.0E-09)	-1.002E-08	(-1.6E-08 – -6.7E-09)	-1.697E-09	(-2.3E-09 – -9.6E-10)
Ionizing radiation	DALY	Global	-3.148E-12	(-4.0E-12 – -2.1E-12)	-4.680E-12	(-6.1E-12 – -3.7E-12)	-4.631E-11	(-5.3E-11 – -4.1E-11)	-1.065E-12	(-7.0E-12 – 3.2E-13)
Ozone formation	DALY	Region	8.734E-10	(4.3E-10 – 1.6E-09)	-5.885E-10	(-1.4E-09 – 6.7E-11)	-8.835E-10	(-2.2E-09 – 5.1E-11)	9.899E-10	(4.6E-10 – 1.8E-09)
Particulate matter formation	DALY	Southeast Asia / vill	3.370E-07	(1.4E-07 – 7.6E-07)	2.458E-07	(1.4E-07 – 4.7E-07)	-9.185E-08	(-2.3E-07 – 2.2E-07)	2.258E-07	(1.0E-07 – 5.6E-07)
Toxicity (carcinogenic)	DALY	Southeast Asia / vill	-9.980E-09	(-2.1E-07 – 2.6E-08)	-3.359E-07	(-2.0E-06 – -5.4E-08)	-4.607E-07	(-2.0E-06 – -1.3E-07)	-2.255E-08	(-2.2E-07 – 7.7E-08)
Toxicity (non-carcinogenic)	DALY	Southeast Asia / vill	-5.712E-08	(-7.2E-08 – -5.0E-08)	-4.467E-07	(-5.8E-07 – -4.0E-07)	-2.312E-07	(-3.7E-07 – -1.9E-07)	-1.798E-08	(-3.9E-08 – 1.3E-08)
Water use	DALY	Village / Indonesia	-8.850E-08	(-9.7E-08 – -8.1E-08)	-4.932E-08	(-5.6E-08 – -4.5E-08)	-8.112E-07	(-9.2E-07 – -7.2E-07)	-4.116E-08	(-1.1E-06 – 1.1E-06)
Global warming (terrestrial)	species.yr	Indonesia	-1.523E-09	(-1.3E-08 – 3.3E-09)	-2.957E-09	(-1.0E-08 – 8.8E-10)	-3.440E-09	(-1.7E-08 – 2.1E-09)	-6.273E-10	(-1.1E-08 – 5.1E-09)
Global warming (freshwater)	species.yr	Indonesia	-4.167E-14	(-3.6E-13 – 9.0E-14)	-8.085E-14	(-2.8E-13 – 2.4E-14)	-9.405E-14	(-4.5E-13 – 5.6E-14)	-1.720E-14	(-3.1E-13 – 1.4E-13)
Ozone formation (terrestrial)	species.yr	Region	6.388E-11	(3.2E-11 – 1.2E-10)	-3.501E-11	(-9.1E-11 – 9.6E-12)	-7.639E-11	(-1.7E-10 – -1.3E-11)	7.462E-11	(3.6E-11 – 1.3E-10)
Acidification (terrestrial)	species.yr	Village	-1.679E-09	(-3.1E-09 – -1.1E-09)	-1.163E-08	(-1.8E-08 – -7.6E-09)	-1.416E-08	(-2.4E-08 – -9.0E-09)	-2.376E-09	(-3.5E-09 – -1.3E-09)
Eutrophication (freshwater)	species.yr	Indonesia	1.199E-12	(-3.2E-12 – 4.2E-12)	-6.806E-12	(-4.2E-11 – 2.8E-13)	-3.847E-11	(-7.4E-11 – -2.9E-11)	2.970E-12	(-2.0E-12 – 8.3E-12)
Ecotoxicity (terrestrial)	species.yr	Southeas Asia / villa	-3.970E-10	(-2.1E-09 – -9.3E-11)	-1.927E-09	(-1.1E-08 – -4.4E-10)	-2.745E-09	(-1.3E-08 – -6.6E-10)	-3.733E-10	(-1.5E-09 – -9.0E-11)
Ecotoxicity (freshwater)	species.yr	Southeast Asia	-2.299E-11	(-1.1E-10 – -8.0E-12)	-1.718E-10	(-8.7E-10 – -5.0E-11)	-2.443E-10	(-9.1E-10 – -1.0E-10)	-2.844E-11	(-1.1E-10 – -6.0E-12)
Ecotoxicity (marine)	species.yr	Indonesia	-8.589E-15	(-1.9E-14 – -4.2E-15)	-1.605E-14	(-1.1E-13 – 2.4E-15)	-1.884E-13	(-2.9E-13 – -1.6E-13)	-8.788E-15	(-2.9E-14 – 1.9E-14)
Land use (mammals)	species.yr	Village	-4.391E-12	(-1.5E-11 – 2.6E-12)	-1.252E-11	(-1.8E-11 – -8.6E-12)	-7.533E-12	(-1.2E-11 – -3.0E-12)	2.741E-12	(-7.0E-14 – 7.6E-12)
Land use (birds)	species.yr	Village	3.983E-12	(-1.2E-11 – 1.8E-11)	-2.153E-10	(-3.4E-10 – -1.3E-10)	-8.654E-12	(-1.7E-11 – 7.3E-13)	1.465E-11	(5.2E-12 – 3.5E-11)
Land use (plants)	species.yr	Village	1.583E-10	(-7.2E-10 – 9.1E-10)	-8.159E-09	(-1.2E-08 – -5.5E-09)	-1.704E-09	(-3.5E-09 – 2.0E-10)	1.268E-09	(4.6E-10 – 3.0E-09)
Land use (amphibians)	species.yr	Village	-9.861E-15	(-2.1E-12 – 1.7E-12)	-1.903E-11	(-2.9E-11 – -1.2E-11)	-4.556E-12	(-8.3E-12 – -7.8E-13)	2.921E-12	(8.3E-13 – 7.2E-12)
Land use (reptiles)	species.yr	Village	-8.366E-13	(-2.8E-12 – 4.8E-13)	-9.136E-12	(-1.4E-11 – -6.0E-12)	-9.110E-12	(-1.5E-11 – -3.5E-12)	1.657E-12	(2.8E-14 – 4.5E-12)
Water use (terrestrial)	species.yr	Village	-1.630E-10	(-2.6E-10 – -1.0E-10)	-4.395E-12	(-5.1E-12 – -3.9E-12)	-2.187E-10	(-2.8E-10 – -1.8E-10)	-3.152E-11	(-1.8E-10 – 1.1E-10)
Water use (freshwater)	species.yr	Indonesia	-6.949E-14	(-1.1E-13 – -4.3E-14)	-1.967E-16	(-2.3E-16 – -1.7E-16)	-1.597E-13	(-2.5E-13 – -1.1E-13)	-2.520E-14	(-4.3E-14 – -1.5E-14)
Eutrophication (marine)	species.yr	Indonesia	-3.142E-13	(-5.9E-13 – -2.0E-13)	-2.275E-12	(-3.5E-12 – -1.5E-12)	-2.776E-12	(-4.6E-12 – -1.8E-12)	-4.435E-13	(-6.5E-13 – -2.3E-13)
Mineral resource scarcity	USD2013	Global	2.362E-04	(1.9E-04 – 2.9E-04)	2.305E-04	(1.9E-04 – 2.8E-04)	3.545E-05	(-1.3E-05 – 1.0E-04)	2.597E-04	(1.1E-04 – 6.1E-04)
Fossil resource scarcity	USD2013	Global	-9.604E-04	(-1.4E-03 – -2.7E-04)	8.933E-04	(3.5E-04 – 1.7E-03)	-2.363E-02	(-2.7E-02 – -2.1E-02)	-1.333E-03	(-2.6E-03 – -1.0E-04)
Human health	species.yr	Various	-3.816E-07	(-4.2E-06 – 1.5E-06)	-1.783E-06	(-4.3E-06 – -2.7E-07)	-2.817E-06	(-6.9E-06 – -7.8E-07)	-1.035E-07	(-4.4E-06 – 1.8E-06)
Ecosystems	DALY	Various	-4.064E-09	(-1.6E-08 – 6.8E-10)	-2.590E-08	(-3.7E-08 – -1.8E-08)	-2.381E-08	(-4.2E-08 – -1.4E-08)	-2.289E-09	(-1.3E-08 – 4.0E-09)
Resources	USD2013	Global	-7.322E-04	(-1.1E-03 – -9.9E-06)	1.126E-03	(5.5E-04 – 1.9E-03)	-2.357E-02	(-2.7E-02 – -2.1E-02)	-1.049E-03	(-2.3E-03 – 3.7E-04)

NT=Ngata Toro; N=Napu, LS=Lampung, LJ=Lamongan

Table S23. Characterized spatially differentiated impacts and total damage at endpoint and accompanying 95% probability ranges from Monte Carlo simulations, for biochar production using earth-mound kiln and used in maize agriculture in four different Indonesian villages (Scenarios 9-12 in Table 1). The probability ranges represent both parameter and inventory uncertainties.

			Impact score (95% probability range)							
			9		10		11		12	
Impact category	Unit	Spatial scale	earth-mound, NT		earth-mound, N		earth-mound, LS		earth-mound, LJ	
Global warming	DALY	Indonesia	-2.207E-07	(-2.9E-06 – 7.4E-07)	-9.759E-07	(-2.1E-06 – -1.8E-08)	-1.031E-06	(-3.1E-06 – 4.4E-07)	-4.311E-07	(-3.0E-06 – 8.9E-07)
Stratospheric ozone depletion	DALY	Global	-1.336E-09	(-2.0E-09 – -7.6E-10)	-7.444E-09	(-1.2E-08 – -4.0E-09)	-9.914E-09	(-1.5E-08 – -6.6E-09)	-1.677E-09	(-2.6E-09 – -1.1E-09)
Ionizing radiation	DALY	Global	-7.228E-12	(-8.0E-12 – -6.5E-12)	-9.016E-12	(-1.0E-11 – -8.2E-12)	-5.121E-11	(-5.7E-11 – -4.5E-11)	-6.375E-12	(-7.1E-12 – -5.7E-12)
Ozone formation	DALY	Region	1.035E-09	(5.5E-10 – 1.9E-09)	-3.932E-10	(-1.5E-09 – 5.2E-10)	-5.899E-10	(-1.8E-09 – 4.4E-10)	1.220E-09	(5.9E-10 – 2.4E-09)
Particulate matter formation	DALY	Southeast Asia / village	3.695E-07	(1.5E-07 – 7.6E-07)	2.934E-07	(1.2E-07 – 6.4E-07)	-5.675E-08	(-2.4E-07 – 2.8E-07)	2.651E-07	(8.9E-08 – 6.3E-07)
Toxicity (carcinogenic)	DALY	Southeast Asia / village	-7.079E-08	(-2.7E-07 – -2.2E-08)	-4.215E-07	(-1.9E-06 – -1.5E-07)	-5.591E-07	(-2.9E-06 – -1.9E-07)	-8.878E-08	(-3.6E-07 – -2.6E-08)
Toxicity (non-carcinogenic)	DALY	Southeast Asia / village	-7.135E-08	(-9.0E-08 – -6.0E-08)	-4.626E-07	(-6.1E-07 – -4.0E-07)	-2.449E-07	(-4.3E-07 – -2.0E-07)	-3.260E-08	(-5.5E-08 – -2.6E-08)
Water use	DALY	Village / Indonesia	-9.461E-08	(-1.0E-07 – -8.4E-08)	-5.675E-08	(-6.3E-08 – -5.1E-08)	-8.290E-07	(-9.3E-07 – -7.3E-07)	-1.032E-07	(-1.1E-07 – -9.2E-08)
Global warming (terrestrial)	species.yr	Indonesia	-6.682E-10	(-8.7E-09 – 2.2E-09)	-2.945E-09	(-6.3E-09 – -5.6E-11)	-3.112E-09	(-9.3E-09 – 1.3E-09)	-1.304E-09	(-9.2E-09 – 2.7E-09)
Global warming (freshwater)	species.yr	Indonesia	-1.828E-14	(-2.4E-13 – 6.1E-14)	-8.050E-14	(-1.7E-13 – -1.6E-15)	-8.506E-14	(-2.6E-13 – 3.6E-14)	-3.566E-14	(-2.5E-13 – 7.3E-14)
Ozone formation (terrestrial)	species.yr	Region	1.024E-10	(5.5E-11 – 1.8E-10)	-1.008E-12	(-8.3E-11 – 7.8E-11)	-2.726E-11	(-1.3E-10 – 5.1E-11)	1.199E-10	(6.3E-11 – 2.3E-10)
Acidification (terrestrial)	species.yr	Village	-1.903E-09	(-2.9E-09 – -1.0E-09)	-1.153E-08	(-1.8E-08 – -6.2E-09)	-1.415E-08	(-2.2E-08 – -8.9E-09)	-2.420E-09	(-3.8E-09 – -1.5E-09)
Eutrophication (freshwater)	species.yr	Indonesia	-2.891E-12	(-8.1E-12 – 1.5E-13)	-1.169E-11	(-4.5E-11 – -4.9E-12)	-4.248E-11	(-9.3E-11 – -3.3E-11)	-1.547E-12	(-8.0E-12 – 1.6E-12)
Ecotoxicity (terrestrial)	species.yr	Southeas Asia / village	-4.832E-10	(-2.1E-09 – -8.9E-11)	-2.146E-09	(-1.0E-08 – -6.8E-10)	-3.081E-09	(-1.8E-08 – -6.7E-10)	-4.518E-10	(-2.0E-09 – -8.9E-11)
Ecotoxicity (freshwater)	species.yr	Southeast Asia	-3.623E-11	(-1.2E-10 – -1.5E-11)	-1.960E-10	(-8.5E-10 – -7.6E-11)	-2.716E-10	(-1.3E-09 – -1.1E-10)	-4.205E-11	(-1.6E-10 – -1.5E-11)
Ecotoxicity (marine)	species.yr	Indonesia	-2.566E-14	(-3.9E-14 – -2.1E-14)	-3.632E-14	(-1.3E-13 – -1.9E-14)	-2.051E-13	(-3.4E-13 – -1.7E-13)	-2.696E-14	(-4.3E-14 – -2.2E-14)
Land use (mammals)	species.yr	Village	-1.373E-11	(-2.0E-11 – -8.9E-12)	-1.231E-11	(-2.0E-11 – -8.0E-12)	-1.004E-11	(-1.4E-11 – -6.6E-12)	-2.335E-12	(-3.6E-12 – -1.4E-12)
Land use (birds)	species.yr	Village	-1.614E-11	(-2.3E-11 – -1.0E-11)	-2.469E-10	(-4.0E-10 – -1.6E-10)	-1.680E-11	(-2.4E-11 – -1.1E-11)	-5.326E-12	(-8.3E-12 – -3.3E-12)
Land use (plants)	species.yr	Village	-9.210E-10	(-1.3E-09 – -6.0E-10)	-8.419E-09	(-1.4E-08 – -5.4E-09)	-3.363E-09	(-4.9E-09 – -2.2E-09)	-4.531E-10	(-7.0E-10 – -2.8E-10)
Land use (amphibians)	species.yr	Village	-2.387E-12	(-3.4E-12 – -1.6E-12)	-2.129E-11	(-3.4E-11 – -1.4E-11)	-7.654E-12	(-1.1E-11 – -5.1E-12)	-1.375E-12	(-2.1E-12 – -8.6E-13)
Land use (reptiles)	species.yr	Village	-2.630E-12	(-3.8E-12 – -1.7E-12)	-9.788E-12	(-1.6E-11 – -6.4E-12)	-1.228E-11	(-1.8E-11 – -8.1E-12)	-1.336E-12	(-2.1E-12 – -8.3E-13)
Water use (terrestrial)	species.yr	Village	-1.622E-10	(-2.6E-10 – -1.1E-10)	-5.732E-12	(-6.4E-12 – -5.2E-12)	-2.195E-10	(-2.9E-10 – -1.8E-10)	-3.940E-11	(-5.5E-11 – -2.9E-11)
Water use (freshwater)	species.yr	Indonesia	-6.847E-14	(-1.1E-13 – -4.3E-14)	-2.564E-16	(-2.9E-16 – -2.3E-16)	-1.591E-13	(-2.6E-13 – -9.9E-14)	-2.660E-14	(-4.2E-14 – -1.6E-14)
Eutrophication (marine)	species.yr	Indonesia	-3.622E-13	(-5.6E-13 – -1.9E-13)	-2.261E-12	(-3.5E-12 – -1.2E-12)	-2.773E-12	(-4.4E-12 – -1.8E-12)	-4.596E-13	(-7.3E-13 – -2.8E-13)
Mineral resource scarcity	USD2013	Global	-4.462E-05	(-4.9E-05 – -4.0E-05)	-1.729E-05	(-2.0E-05 – -1.6E-05)	-2.920E-04	(-3.3E-04 – -2.6E-04)	-3.635E-05	(-4.0E-05 – -3.3E-05)
Fossil resource scarcity	USD2013	Global	-2.992E-03	(-3.3E-03 – -2.7E-03)	-1.559E-03	(-1.9E-03 – -1.4E-03)	-2.584E-02	(-2.9E-02 – -2.3E-02)	-3.216E-03	(-3.6E-03 – -2.9E-03)
Human health	species.yr	Various	-1.815E-07	(-2.6E-06 – 9.3E-07)	-1.621E-06	(-3.6E-06 – -4.2E-07)	-3.007E-06	(-5.3E-06 – -1.1E-06)	-3.632E-07	(-3.1E-06 – 1.0E-06)
Ecosystems	DALY	Various	-4.420E-09	(-1.3E-08 – -1.3E-09)	-2.646E-08	(-3.8E-08 – -1.7E-08)	-2.615E-08	(-4.0E-08 – -1.5E-08)	-4.833E-09	(-1.3E-08 – -6.1E-10)
Resources	USD2013	Global	-3.036E-03	(-3.3E-03 – -2.7E-03)	-1.576E-03	(-1.9E-03 – -1.4E-03)	-2.613E-02	(-2.9E-02 – -2.3E-02)	-3.252E-03	(-3.6E-03 – -2.9E-03)

NT=Ngata Toro; N=Napu, LS=Lampung, LJ=Lamongan

Table S24. Characterized spatially differentiated impacts and total damage at endpoint and accompanying 95% probability ranges from Monte Carlo simulations, for biochar production using “Kon Tiki” flame curtain kiln and used in maize agriculture in four different Indonesian villages (Scenarios 13-16 in Table 1) with compost as sole fertilizer. The probability ranges represent both parameter and inventory uncertainties.

			Impact score (95% probability range)							
			13		14		15		16	
Impact category	Unit	Spatial scale	flame curtain, NT		flame curtain, N		flame curtain, LS		flame curtain, LJ	
Global warming	DALY	Indonesia	-7.583E-07	(-3.8E-06 – 4.2E-07)	-2.178E-06	(-3.9E-06 – -1.3E-06)	-9.696E-07	(-3.3E-06 – 2.8E-07)	-6.343E-07	(-3.1E-06 – 5.9E-07)
Stratospheric ozone depletion	DALY	Global	-3.016E-09	(-5.1E-09 – -1.8E-09)	-1.271E-08	(-1.8E-08 – -9.2E-09)	-6.651E-09	(-1.1E-08 – -4.1E-09)	-1.140E-09	(-2.0E-09 – -7.2E-10)
Ionizing radiation	DALY	Global	2.033E-12	(1.3E-12 – 2.8E-12)	-1.618E-10	(-1.8E-10 – -1.5E-10)	9.636E-13	(2.3E-13 – 2.0E-12)	3.412E-12	(2.4E-12 – 4.4E-12)
Ozone formation	DALY	Region	-5.654E-10	(-1.0E-09 – -3.1E-10)	-3.238E-09	(-4.3E-09 – -2.5E-09)	-1.322E-09	(-2.3E-09 – -7.9E-10)	-1.514E-10	(-3.4E-10 – -6.0E-11)
Particulate matter formation	DALY	Southeast Asia / village	2.606E-07	(1.4E-07 – 6.1E-07)	-9.718E-07	(-1.1E-06 – -7.3E-07)	1.907E-07	(9.0E-08 – 3.5E-07)	1.891E-07	(9.2E-08 – 3.7E-07)
Toxicity (carcinogenic)	DALY	Southeast Asia / village	-5.923E-08	(-4.1E-07 – 7.5E-08)	-6.148E-07	(-2.5E-06 – -3.0E-07)	-1.328E-07	(-1.0E-06 – 7.2E-08)	7.394E-08	(-2.5E-07 – 1.4E-07)
Toxicity (non-carcinogenic)	DALY	Southeast Asia / village	-4.591E-08	(-7.8E-08 – -3.4E-08)	-6.734E-07	(-8.4E-07 – -6.0E-07)	-1.309E-07	(-2.0E-07 – -1.1E-07)	6.249E-09	(-2.2E-08 – 1.6E-08)
Water use	DALY	Village / Indonesia	4.609E-10	(-1.3E-09 – 2.4E-09)	-2.573E-06	(-2.8E-06 – -2.3E-06)	-8.579E-09	(-1.1E-08 – -6.0E-09)	7.243E-09	(4.7E-09 – 9.5E-09)
Global warming (terrestrial)	species.yr	Indonesia	-2.289E-09	(-1.2E-08 – 1.3E-09)	-6.569E-09	(-1.2E-08 – -3.9E-09)	-2.926E-09	(-1.0E-08 – 8.6E-10)	-1.916E-09	(-9.2E-09 – 1.8E-09)
Global warming (freshwater)	species.yr	Indonesia	-6.255E-14	(-3.2E-13 – 3.5E-14)	-1.795E-13	(-3.2E-13 – -1.1E-13)	-7.997E-14	(-2.7E-13 – 2.3E-14)	-5.236E-14	(-2.5E-13 – 4.8E-14)
Ozone formation (terrestrial)	species.yr	Region	-3.173E-11	(-6.0E-11 – -1.5E-11)	-3.183E-10	(-3.9E-10 – -2.7E-10)	-8.162E-11	(-1.5E-10 – -4.3E-11)	-2.754E-12	(-1.6E-11 – 4.5E-12)
Acidification (terrestrial)	species.yr	Village	-4.732E-09	(-8.1E-09 – -2.8E-09)	-1.524E-08	(-2.4E-08 – -9.9E-09)	-1.044E-08	(-1.8E-08 – -6.5E-09)	-1.786E-09	(-3.1E-09 – -1.1E-09)
Eutrophication (freshwater)	species.yr	Indonesia	5.384E-12	(-3.6E-12 – 9.2E-12)	-1.215E-10	(-1.6E-10 – -1.1E-10)	2.954E-12	(-1.5E-11 – 8.9E-12)	9.400E-12	(3.2E-12 – 1.4E-11)
Ecotoxicity (terrestrial)	species.yr	Southeas Asia / village	-1.371E-09	(-4.3E-09 – -2.7E-10)	-2.411E-09	(-1.2E-08 – -6.5E-10)	-1.627E-09	(-7.2E-09 – -4.0E-10)	-2.910E-10	(-2.2E-09 – -6.7E-11)
Ecotoxicity (freshwater)	species.yr	Southeast Asia	-6.518E-11	(-2.2E-10 – -8.0E-12)	-3.887E-10	(-1.2E-09 – -2.5E-10)	-1.073E-10	(-4.8E-10 – -2.4E-11)	-1.219E-11	(-1.5E-10 – 5.5E-12)
Ecotoxicity (marine)	species.yr	Indonesia	1.302E-14	(-7.8E-15 – 2.4E-14)	-5.844E-13	(-7.0E-13 – -5.2E-13)	9.153E-15	(-4.3E-14 – 2.5E-14)	2.418E-14	(3.7E-15 – 3.3E-14)
Land use (mammals)	species.yr	Village	-1.379E-11	(-2.1E-11 – -9.0E-12)	-1.189E-11	(-1.9E-11 – -8.0E-12)	-1.037E-11	(-1.7E-11 – -7.0E-12)	-2.336E-12	(-3.4E-12 – -1.6E-12)
Land use (birds)	species.yr	Village	-1.621E-11	(-2.4E-11 – -1.1E-11)	-2.370E-10	(-3.8E-10 – -1.6E-10)	-1.735E-11	(-2.8E-11 – -1.2E-11)	-5.329E-12	(-7.6E-12 – -3.6E-12)
Land use (plants)	species.yr	Village	-9.248E-10	(-1.4E-09 – -6.0E-10)	-8.092E-09	(-1.3E-08 – -5.4E-09)	-3.479E-09	(-5.6E-09 – -2.3E-09)	-4.530E-10	(-6.5E-10 – -3.0E-10)
Land use (amphibians)	species.yr	Village	-2.390E-12	(-3.6E-12 – -1.6E-12)	-2.064E-11	(-3.3E-11 – -1.4E-11)	-7.854E-12	(-1.2E-11 – -5.3E-12)	-1.364E-12	(-2.0E-12 – -9.2E-13)
Land use (reptiles)	species.yr	Village	-2.640E-12	(-4.0E-12 – -1.7E-12)	-9.465E-12	(-1.5E-11 – -6.4E-12)	-1.270E-11	(-2.0E-11 – -8.6E-12)	-1.334E-12	(-1.9E-12 – -8.9E-13)
Water use (terrestrial)	species.yr	Village	-1.483E-10	(-2.6E-10 – -9.6E-11)	-3.793E-10	(-4.1E-10 – -3.4E-10)	-9.643E-11	(-1.6E-10 – -6.0E-11)	-2.211E-11	(-3.8E-11 – -1.3E-11)
Water use (freshwater)	species.yr	Indonesia	-6.819E-14	(-1.2E-13 – -4.4E-14)	-1.697E-14	(-1.8E-14 – -1.5E-14)	-1.496E-13	(-2.5E-13 – -9.2E-14)	-2.494E-14	(-4.2E-14 – -1.5E-14)
Eutrophication (marine)	species.yr	Indonesia	-9.165E-13	(-1.6E-12 – -5.4E-13)	-3.187E-12	(-4.8E-12 – -2.1E-12)	-2.023E-12	(-3.4E-12 – -1.3E-12)	-3.448E-13	(-6.0E-13 – -2.2E-13)
Mineral resource scarcity	USD2013	Global	1.087E-04	(8.2E-05 – 1.3E-04)	-8.293E-04	(-9.1E-04 – -7.5E-04)	1.242E-04	(9.6E-05 – 1.6E-04)	1.288E-04	(9.3E-05 – 1.6E-04)
Fossil resource scarcity	USD2013	Global	3.237E-04	(2.2E-04 – 4.4E-04)	-8.350E-02	(-9.2E-02 – -7.6E-02)	1.578E-04	(4.8E-05 – 3.2E-04)	5.130E-04	(3.6E-04 – 6.6E-04)
Human health	species.yr	Various	-7.118E-07	(-3.7E-06 – 6.2E-07)	-7.098E-06	(-9.5E-06 – -5.9E-06)	-1.134E-06	(-3.6E-06 – 1.5E-07)	-3.744E-07	(-2.7E-06 – 8.6E-07)
Ecosystems	DALY	Various	-9.993E-09	(-2.0E-08 – -4.8E-09)	-3.568E-08	(-4.8E-08 – -2.6E-08)	-1.978E-08	(-3.3E-08 – -1.2E-08)	-4.732E-09	(-1.2E-08 – -8.2E-10)
Resources	USD2013	Global	4.316E-04	(3.0E-04 – 5.7E-04)	-8.432E-02	(-9.2E-02 – -7.6E-02)	2.841E-04	(1.5E-04 – 4.8E-04)	6.420E-04	(4.6E-04 – 8.2E-04)

NT=Ngata Toro; N=Napu, LS=Lampung, LJ=Lamongan

Table S25. Characterized spatially differentiated impacts and total damage at endpoint and accompanying 95% probability ranges from Monte Carlo simulations, for biochar production using Adam retort kiln and used in maize agriculture in four different Indonesian villages (Scenarios 17-20 in Table 1) with compost as sole fertilizer. The probability ranges represent both parameter and inventory uncertainties.

			Impact score (95% probability range)							
			17		18		19		20	
Impact category	Unit	Spatial scale	retort, NT		retort, N		retort, LS		retort, LJ	
Global warming	DALY	Indonesia	-4.457E-07	(-4.5E-06 – 8.5E-07)	-2.016E-06	(-6.2E-06 – -7.3E-07)	-1.064E-06	(-5.3E-06 – 9.2E-07)	-4.528E-07	(-3.5E-06 – 1.5E-06)
Stratospheric ozone depletion	DALY	Global	-3.154E-09	(-5.0E-09 – -2.0E-09)	-1.304E-08	(-1.9E-08 – -9.0E-09)	-6.963E-09	(-1.1E-08 – -4.6E-09)	-1.134E-09	(-1.9E-09 – -7.3E-10)
Ionizing radiation	DALY	Global	2.945E-12	(2.2E-12 – 3.8E-12)	-1.591E-10	(-1.8E-10 – -1.4E-10)	1.473E-12	(9.7E-13 – 2.3E-12)	3.966E-12	(3.2E-12 – 5.1E-12)
Ozone formation	DALY	Region	5.066E-10	(2.2E-11 – 1.1E-09)	-2.276E-09	(-3.6E-09 – -1.4E-09)	-1.441E-10	(-1.0E-09 – 8.5E-10)	1.174E-09	(5.9E-10 – 2.0E-09)
Particulate matter formation	DALY	Southeast Asia / village	3.555E-07	(2.0E-07 – 7.4E-07)	-8.676E-07	(-1.1E-06 – -7.1E-07)	2.493E-07	(1.4E-07 – 5.2E-07)	3.011E-07	(1.5E-07 – 6.7E-07)
Toxicity (carcinogenic)	DALY	Southeast Asia / village	-1.230E-07	(-6.4E-07 – 6.3E-09)	-6.841E-07	(-2.7E-06 – -2.7E-07)	-2.951E-07	(-1.2E-06 – -2.5E-08)	1.758E-09	(-1.8E-07 – 4.8E-08)
Toxicity (non-carcinogenic)	DALY	Southeast Asia / village	-5.763E-08	(-1.0E-07 – -4.6E-08)	-6.791E-07	(-8.5E-07 – -5.9E-07)	-1.506E-07	(-2.3E-07 – -1.2E-07)	-7.531E-09	(-2.1E-08 – -3.0E-09)
Water use	DALY	Village / Indonesia	-5.174E-10	(-1.5E-09 – 7.3E-10)	-2.559E-06	(-2.8E-06 – -2.3E-06)	-1.092E-08	(-1.2E-08 – -9.2E-09)	5.145E-09	(3.9E-09 – 7.0E-09)
Global warming (terrestrial)	species.yr	Indonesia	-1.346E-09	(-1.4E-08 – 2.5E-09)	-6.082E-09	(-1.9E-08 – -2.2E-09)	-3.212E-09	(-1.6E-08 – 2.8E-09)	-1.370E-09	(-1.0E-08 – 4.5E-09)
Global warming (freshwater)	species.yr	Indonesia	-3.682E-14	(-3.7E-13 – 7.0E-14)	-1.662E-13	(-5.1E-13 – -6.0E-14)	-8.782E-14	(-4.4E-13 – 7.6E-14)	-3.748E-14	(-2.9E-13 – 1.2E-13)
Ozone formation (terrestrial)	species.yr	Region	4.396E-11	(1.0E-11 – 9.0E-11)	-2.464E-10	(-3.3E-10 – -1.8E-10)	8.619E-13	(-5.7E-11 – 7.0E-11)	8.989E-11	(4.8E-11 – 1.5E-10)
Acidification (terrestrial)	species.yr	Village	-4.887E-09	(-7.8E-09 – -3.1E-09)	-1.592E-08	(-2.5E-08 – -9.7E-09)	-1.088E-08	(-1.7E-08 – -7.0E-09)	-1.694E-09	(-3.0E-09 – -1.1E-09)
Eutrophication (freshwater)	species.yr	Indonesia	4.190E-12	(-7.1E-12 – 7.2E-12)	-1.211E-10	(-1.7E-10 – -1.1E-10)	2.025E-13	(-2.0E-11 – 6.8E-12)	7.655E-12	(4.7E-12 – 1.2E-11)
Ecotoxicity (terrestrial)	species.yr	Southeas Asia / village	-1.390E-09	(-5.7E-09 – -3.1E-10)	-2.502E-09	(-1.3E-08 – -3.0E-10)	-2.178E-09	(-8.0E-09 – -4.6E-10)	-3.041E-10	(-1.3E-09 – -4.7E-11)
Ecotoxicity (freshwater)	species.yr	Southeast Asia	-6.775E-11	(-2.9E-10 – -1.2E-11)	-4.073E-10	(-1.3E-09 – -2.3E-10)	-1.469E-10	(-5.4E-10 – -3.1E-11)	-1.648E-11	(-9.2E-11 – 3.4E-12)
Ecotoxicity (marine)	species.yr	Indonesia	5.483E-15	(-2.6E-14 – 1.4E-14)	-5.841E-13	(-7.0E-13 – -5.1E-13)	-5.709E-15	(-6.2E-14 – 1.0E-14)	1.344E-14	(1.6E-15 – 1.9E-14)
Land use (mammals)	species.yr	Village	-5.595E-12	(-1.4E-11 – 6.6E-12)	-1.264E-11	(-1.9E-11 – -8.4E-12)	-7.123E-12	(-1.4E-11 – -2.4E-12)	2.581E-12	(4.6E-13 – 6.9E-12)
Land use (birds)	species.yr	Village	2.647E-12	(-1.1E-11 – 2.9E-11)	-2.160E-10	(-3.5E-10 – -1.3E-10)	-8.497E-12	(-1.9E-11 – 4.4E-12)	1.444E-11	(5.6E-12 – 3.2E-11)
Land use (plants)	species.yr	Village	8.959E-11	(-6.5E-10 – 1.5E-09)	-8.256E-09	(-1.3E-08 – -5.3E-09)	-1.680E-09	(-3.8E-09 – 9.4E-10)	1.250E-09	(4.9E-10 – 2.7E-09)
Land use (amphibians)	species.yr	Village	-1.181E-13	(-1.9E-12 – 3.0E-12)	-1.935E-11	(-3.1E-11 – -1.2E-11)	-4.398E-12	(-9.1E-12 – 5.9E-13)	2.856E-12	(1.0E-12 – 6.5E-12)
Land use (reptiles)	species.yr	Village	-1.071E-12	(-2.7E-12 – 1.3E-12)	-9.269E-12	(-1.4E-11 – -5.9E-12)	-8.596E-12	(-1.6E-11 – -2.7E-12)	1.571E-12	(3.2E-13 – 4.1E-12)
Water use (terrestrial)	species.yr	Village	-1.463E-10	(-2.5E-10 – -9.0E-11)	-3.768E-10	(-4.2E-10 – -3.4E-10)	-1.025E-10	(-1.6E-10 – -6.3E-11)	-2.349E-11	(-3.9E-11 – -1.5E-11)
Water use (freshwater)	species.yr	Indonesia	-6.721E-14	(-1.2E-13 – -4.1E-14)	-1.686E-14	(-1.9E-14 – -1.5E-14)	-1.583E-13	(-2.5E-13 – -9.8E-14)	-2.617E-14	(-4.3E-14 – -1.7E-14)
Eutrophication (marine)	species.yr	Indonesia	-9.270E-13	(-1.5E-12 – -5.8E-13)	-3.283E-12	(-5.0E-12 – -2.1E-12)	-2.090E-12	(-3.2E-12 – -1.3E-12)	-3.071E-13	(-5.5E-13 – -1.8E-13)
Mineral resource scarcity	USD2013	Global	2.815E-04	(2.3E-04 – 3.3E-04)	-6.759E-04	(-7.6E-04 – -6.1E-04)	3.233E-04	(2.7E-04 – 4.0E-04)	3.284E-04	(2.7E-04 – 4.2E-04)
Fossil resource scarcity	USD2013	Global	1.878E-03	(1.4E-03 – 2.5E-03)	-8.087E-02	(-8.9E-02 – -7.2E-02)	1.516E-03	(1.2E-03 – 1.9E-03)	1.899E-03	(1.5E-03 – 2.4E-03)
Human health	species.yr	Various	-4.244E-07	(-4.3E-06 – 9.4E-07)	-6.994E-06	(-1.1E-05 – -5.5E-06)	-1.170E-06	(-6.3E-06 – 8.3E-07)	-8.226E-08	(-3.1E-06 – 1.8E-06)
Ecosystems	DALY	Various	-8.716E-09	(-1.9E-08 – -3.3E-09)	-3.578E-08	(-5.2E-08 – -2.6E-08)	-1.905E-08	(-3.6E-08 – -1.0E-08)	-1.464E-09	(-1.1E-08 – 3.8E-09)
Resources	USD2013	Global	2.173E-03	(1.6E-03 – 2.8E-03)	-8.154E-02	(-9.0E-02 – -7.3E-02)	1.839E-03	(1.5E-03 – 2.3E-03)	2.224E-03	(1.8E-03 – 2.8E-03)

NT=Ngata Toro; N=Napu, LS=Lampung, LJ=Lamongan

Table S26. Characterized spatially differentiated impacts and total damage at endpoint and accompanying 95% probability ranges from Monte Carlo simulations, for biochar production using earth-mound kiln and used in maize agriculture in four different Indonesian villages (Scenarios 21-24 in Table 1) with compost as sole fertilizer. The probability ranges represent both parameter and inventory uncertainties.

			Impact score (95% probability range)							
			21		22		23		24	
Impact category	Unit	Spatial scale	earth-mound, NT		earth-mound, N		earth-mound, LS		earth-mound, LJ	
Global warming	DALY	Indonesia	-2.813E-07	(-2.9E-06 – 6.9E-07)	-2.005E-06	(-4.2E-06 – -1.1E-06)	-6.007E-07	(-3.2E-06 – 6.6E-07)	-1.707E-07	(-2.7E-06 – 9.5E-07)
Stratospheric ozone depletion	DALY	Global	-3.056E-09	(-4.9E-09 – -1.8E-09)	-1.270E-08	(-1.8E-08 – -8.3E-09)	-6.680E-09	(-1.3E-08 – -4.3E-09)	-1.104E-09	(-1.9E-09 – -6.1E-10)
Ionizing radiation	DALY	Global	-1.168E-12	(-1.3E-12 – -1.1E-12)	-1.627E-10	(-1.9E-10 – -1.4E-10)	-2.779E-12	(-3.1E-12 – -2.5E-12)	-3.483E-13	(-4.0E-13 – -3.1E-13)
Ozone formation	DALY	Region	6.950E-10	(-3.2E-11 – 1.5E-09)	-2.138E-09	(-3.3E-09 – -8.2E-10)	2.210E-10	(-9.7E-10 – 1.2E-09)	1.447E-09	(7.4E-10 – 2.5E-09)
Particulate matter formation	DALY	Southeast Asia / village	3.785E-07	(1.9E-07 – 8.8E-07)	-8.697E-07	(-1.1E-06 – -5.9E-07)	2.754E-07	(1.4E-07 – 6.0E-07)	3.012E-07	(1.4E-07 – 5.9E-07)
Toxicity (carcinogenic)	DALY	Southeast Asia / village	-1.604E-07	(-7.7E-07 – -3.0E-08)	-7.732E-07	(-3.2E-06 – -3.4E-07)	-3.318E-07	(-1.6E-06 – -4.9E-08)	-6.824E-08	(-3.7E-07 – -6.8E-09)
Toxicity (non-carcinogenic)	DALY	Southeast Asia / village	-7.009E-08	(-1.2E-07 – -5.7E-08)	-6.924E-07	(-8.9E-07 – -5.9E-07)	-1.614E-07	(-2.7E-07 – -1.4E-07)	-2.288E-08	(-4.7E-08 – -1.7E-08)
Water use	DALY	Village / Indonesia	-7.526E-09	(-8.5E-09 – -6.9E-09)	-2.541E-06	(-2.9E-06 – -2.2E-06)	-1.824E-08	(-2.0E-08 – -1.7E-08)	-2.287E-09	(-2.6E-09 – -2.0E-09)
Global warming (terrestrial)	species.yr	Indonesia	-8.508E-10	(-8.8E-09 – 2.1E-09)	-6.050E-09	(-1.3E-08 – -3.3E-09)	-1.813E-09	(-9.8E-09 – 2.0E-09)	-5.181E-10	(-8.1E-09 – 2.9E-09)
Global warming (freshwater)	species.yr	Indonesia	-2.328E-14	(-2.4E-13 – 5.6E-14)	-1.653E-13	(-3.4E-13 – -8.9E-14)	-4.958E-14	(-2.7E-13 – 5.4E-14)	-1.418E-14	(-2.2E-13 – 7.8E-14)
Ozone formation (terrestrial)	species.yr	Region	8.153E-11	(2.2E-11 – 1.5E-10)	-2.139E-10	(-3.0E-10 – -1.1E-10)	5.686E-11	(-3.0E-11 – 1.4E-10)	1.409E-10	(7.5E-11 – 2.4E-10)
Acidification (terrestrial)	species.yr	Village	-4.763E-09	(-7.7E-09 – -2.8E-09)	-1.548E-08	(-2.4E-08 – -8.8E-09)	-1.044E-08	(-2.0E-08 – -6.7E-09)	-1.699E-09	(-3.0E-09 – -9.1E-10)
Eutrophication (freshwater)	species.yr	Indonesia	5.670E-13	(-1.3E-11 – 4.5E-12)	-1.265E-10	(-1.8E-10 – -1.0E-10)	-4.358E-12	(-3.2E-11 – 3.4E-12)	3.250E-12	(-3.1E-12 – 7.5E-12)
Ecotoxicity (terrestrial)	species.yr	Southeas Asia / village	-1.314E-09	(-6.3E-09 – -2.3E-10)	-2.722E-09	(-1.5E-08 – -4.6E-10)	-2.078E-09	(-1.0E-08 – -2.7E-10)	-3.855E-10	(-2.1E-09 – -3.4E-11)
Ecotoxicity (freshwater)	species.yr	Southeast Asia	-7.107E-11	(-3.3E-10 – -1.5E-11)	-4.298E-10	(-1.5E-09 – -2.4E-10)	-1.477E-10	(-7.1E-10 – -2.6E-11)	-2.997E-11	(-1.6E-10 – -3.5E-12)
Ecotoxicity (marine)	species.yr	Indonesia	-1.082E-14	(-4.7E-14 – -3.1E-15)	-5.998E-13	(-7.4E-13 – -5.1E-13)	-2.268E-14	(-9.9E-14 – -6.0E-15)	-4.410E-15	(-2.2E-14 – -7.8E-16)
Land use (mammals)	species.yr	Village	-1.383E-11	(-2.1E-11 – -8.3E-12)	-1.219E-11	(-1.8E-11 – -8.1E-12)	-1.051E-11	(-1.5E-11 – -7.0E-12)	-2.298E-12	(-3.4E-12 – -1.4E-12)
Land use (birds)	species.yr	Village	-1.626E-11	(-2.4E-11 – -9.8E-12)	-2.431E-10	(-3.7E-10 – -1.6E-10)	-1.757E-11	(-2.5E-11 – -1.2E-11)	-5.243E-12	(-7.8E-12 – -3.3E-12)
Land use (plants)	species.yr	Village	-9.276E-10	(-1.4E-09 – -5.6E-10)	-8.303E-09	(-1.3E-08 – -5.4E-09)	-3.523E-09	(-4.9E-09 – -2.4E-09)	-4.458E-10	(-6.6E-10 – -2.8E-10)
Land use (amphibians)	species.yr	Village	-2.399E-12	(-3.5E-12 – -1.5E-12)	-2.115E-11	(-3.2E-11 – -1.4E-11)	-7.966E-12	(-1.1E-11 – -5.4E-12)	-1.347E-12	(-2.0E-12 – -8.5E-13)
Land use (reptiles)	species.yr	Village	-2.648E-12	(-3.9E-12 – -1.6E-12)	-9.700E-12	(-1.5E-11 – -6.4E-12)	-1.286E-11	(-1.8E-11 – -8.6E-12)	-1.314E-12	(-1.9E-12 – -8.2E-13)
Water use (terrestrial)	species.yr	Village	-1.536E-10	(-2.6E-10 – -7.8E-11)	-3.744E-10	(-4.3E-10 – -3.3E-10)	-1.066E-10	(-1.7E-10 – -6.1E-11)	-2.483E-11	(-4.1E-11 – -1.5E-11)
Water use (freshwater)	species.yr	Indonesia	-7.006E-14	(-1.2E-13 – -3.5E-14)	-1.675E-14	(-1.9E-14 – -1.5E-14)	-1.626E-13	(-2.7E-13 – -9.2E-14)	-2.617E-14	(-4.3E-14 – -1.6E-14)
Eutrophication (marine)	species.yr	Indonesia	-9.074E-13	(-1.5E-12 – -5.3E-13)	-3.196E-12	(-4.8E-12 – -1.9E-12)	-2.001E-12	(-3.8E-12 – -1.3E-12)	-3.119E-13	(-5.5E-13 – -1.6E-13)
Mineral resource scarcity	USD2013	Global	-2.170E-06	(-2.4E-06 – -2.0E-06)	-9.133E-04	(-1.0E-03 – -7.9E-04)	-5.095E-06	(-5.6E-06 – -4.6E-06)	-6.391E-07	(-7.3E-07 – -5.6E-07)
Fossil resource scarcity	USD2013	Global	-1.793E-04	(-2.0E-04 – -1.6E-04)	-8.317E-02	(-9.5E-02 – -7.2E-02)	-4.019E-04	(-4.4E-04 – -3.6E-04)	-5.054E-05	(-5.8E-05 – -4.4E-05)
Human health	species.yr	Various	-2.389E-07	(-2.7E-06 – 1.1E-06)	-7.075E-06	(-9.0E-06 – -5.8E-06)	-9.368E-07	(-3.8E-06 – 5.0E-07)	7.469E-08	(-2.7E-06 – 1.1E-06)
Ecosystems	DALY	Various	-8.746E-09	(-1.8E-08 – -3.0E-09)	-3.553E-08	(-5.0E-08 – -2.7E-08)	-1.981E-08	(-3.2E-08 – -1.2E-08)	-3.210E-09	(-1.1E-08 – 9.7E-11)
Resources	USD2013	Global	-1.815E-04	(-2.1E-04 – -1.6E-04)	-8.407E-02	(-9.6E-02 – -7.3E-02)	-4.070E-04	(-4.5E-04 – -3.7E-04)	-5.118E-05	(-5.9E-05 – -4.5E-05)

NT=Ngata Toro; N=Napu, LS=Lampung, LJ=Lamongan

Table S27. Percentage of Monte Carlo iterations where characterized spatially differentiated impact scores are larger for one village compared to the other for the system with “Kon Tiki” flame curtain kiln. Values below 5% (in green) indicate impact scores significantly smaller for first village compared to the other. Values above 95% (in yellow) indicate impact scores significantly larger for first village compared to the other.

Impact category	Unit	Spatial scale	Percentage of Monte Carlo iterations					
			NT≥N	NT≥LS	NT≥LJ	N≥LS	N≥LJ	LS≥LJ
Global warming	DALY	Indonesia	99	100	75	92	8	0
Stratospheric ozone depletion	DALY	Global	100	100	100	100	0	0
Ionizing radiation	DALY	Global	100	100	0	100	0	0
Ozone formation	DALY	Region	100	100	99	100	0	0
Particulate matter formation	DALY	Southeast Asia / village	99	100	100	100	95	0
Toxicity (carcinogenic)	DALY	Southeast Asia / village	100	100	39	100	0	0
Toxicity (non-carcinogenic)	DALY	Southeast Asia / village	100	100	0	0	0	0
Water use	DALY	Village / Indonesia	0	100	100	100	100	0
Global warming (terrestrial)	species.yr	Indonesia	99	100	75	92	8	0
Global warming (freshwater)	species.yr	Indonesia	99	100	75	92	8	0
Ozone formation (terrestrial)	species.yr	Region	100	100	93	100	0	0
Acidification (terrestrial)	species.yr	Village	100	100	100	99	0	0
Eutrophication (freshwater)	species.yr	Indonesia	100	100	2	100	0	0
Ecotoxicity (terrestrial)	species.yr	Southeas Asia / village	100	100	18	100	0	0
Ecotoxicity (freshwater)	species.yr	Southeast Asia	100	100	72	100	0	0
Ecotoxicity (marine)	species.yr	Indonesia	88	100	9	100	3	0
Land use (mammals)	species.yr	Village	0	0	0	0	0	0
Land use (birds)	species.yr	Village	100	97	0	0	0	0
Land use (plants)	species.yr	Village	100	100	0	0	0	0
Land use (amphibians)	species.yr	Village	100	100	0	0	0	0
Land use (reptiles)	species.yr	Village	100	100	0	100	0	0
Water use (terrestrial)	species.yr	Village	0	100	0	100	100	0
Water use (freshwater)	species.yr	Indonesia	0	100	0	100	100	0
Eutrophication (marine)	species.yr	Indonesia	100	100	100	100	0	0
Mineral resource scarcity	USD2013	Global	0	100	0	100	0	0
Fossil resource scarcity	USD2013	Global	0	100	99	100	100	0
Human health	DALY	Various	100	100	86	100	0	0
Ecosystems	species.yr	Various	100	100	68	50	0	0
Resources	USD2013	Global	0	100	98	100	100	0

NT=Ngata Toro; N=Napu, LS=Lampung, LJ=Lamongan

Table S28. Percentage of Monte Carlo iterations where characterized spatially differentiated impact scores are larger for one village compared to the other for the system with Adam retort kiln. Values below 5% (in green) indicate impact scores significantly smaller for first village compared to the other. Values above 95% (in yellow) indicate impact scores significantly larger for first village compared to the other.

Impact category	Unit	Spatial scale	Percentage of Monte Carlo iterations					
			NT≥N	NT≥LS	NT≥LJ	N≥LS	N≥LJ	LS≥LJ
Global warming	DALY	Indonesia	100	100	56	71	6	0
Stratospheric ozone depletion	DALY	Global	100	100	100	100	0	0
Ionizing radiation	DALY	Global	100	100	0	100	0	0
Ozone formation	DALY	Region	100	100	0	100	0	0
Particulate matter formation	DALY	Southeast Asia / village	100	100	100	100	94	0
Toxicity (carcinogenic)	DALY	Southeast Asia / village	100	100	76	100	0	0
Toxicity (non-carcinogenic)	DALY	Southeast Asia / village	100	100	0	0	0	0
Water use	DALY	Village / Indonesia	0	100	100	100	100	0
Global warming (terrestrial)	species.yr	Indonesia	100	100	56	71	6	0
Global warming (freshwater)	species.yr	Indonesia	100	100	56	71	6	0
Ozone formation (terrestrial)	species.yr	Region	100	100	0	100	0	0
Acidification (terrestrial)	species.yr	Village	100	100	100	100	0	0
Eutrophication (freshwater)	species.yr	Indonesia	100	100	0	100	0	0
Ecotoxicity (terrestrial)	species.yr	Southeast Asia / village	100	100	7	100	0	0
Ecotoxicity (freshwater)	species.yr	Southeast Asia	100	100	89	100	0	0
Ecotoxicity (marine)	species.yr	Indonesia	69	100	73	100	33	0
Land use (mammals)	species.yr	Village	100	85	0	0	0	0
Land use (birds)	species.yr	Village	100	100	0	0	0	0
Land use (plants)	species.yr	Village	100	100	0	0	0	0
Land use (amphibians)	species.yr	Village	100	100	0	0	0	0
Land use (reptiles)	species.yr	Village	100	100	0	43	0	0
Water use (terrestrial)	species.yr	Village	0	100	0	100	100	0
Water use (freshwater)	species.yr	Indonesia	0	100	0	100	100	0
Eutrophication (marine)	species.yr	Indonesia	100	100	100	100	0	0
Mineral resource scarcity	USD2013	Global	99	100	0	100	0	0
Fossil resource scarcity	USD2013	Global	0	100	100	100	100	0
Human health	DALY	Various	100	100	74	100	1	0
Ecosystems	species.yr	Various	100	100	17	32	0	0
Resources	USD2013	Global	0	100	99	100	100	0

NT=Ngata Toro; N=Napu, LS=Lampung, LJ=Lamongan

Table S29. Percentage of Monte Carlo iterations where characterized spatially differentiated impact scores are larger for one village compared to the other for the system with earth-mound kiln. Values below 5% (in green) indicate impact scores significantly smaller for first village compared to the other. Values above 95% (in yellow) indicate impact scores significantly larger for first village compared to the other.

Impact category	Unit	Spatial scale	Percentage of Monte Carlo iterations					
			NT≥N	NT≥LS	NT≥LJ	N≥LS	N≥LJ	LS≥LJ
Global warming	DALY	Indonesia	100	100	51	82	8	0
Stratospheric ozone depletion	DALY	Global	100	100	100	100	0	0
Ionizing radiation	DALY	Global	100	100	0	100	0	0
Ozone formation	DALY	Region	100	100	0	94	0	0
Particulate matter formation	DALY	Southeast Asia / village	100	100	100	100	69	0
Toxicity (carcinogenic)	DALY	Southeast Asia / village	100	100	100	100	0	0
Toxicity (non-carcinogenic)	DALY	Southeast Asia / village	100	100	0	0	0	0
Water use	DALY	Village / Indonesia	0	100	100	100	100	0
Global warming (terrestrial)	species.yr	Indonesia	100	100	52	82	8	0
Global warming (freshwater)	species.yr	Indonesia	100	100	52	82	8	0
Ozone formation (terrestrial)	species.yr	Region	100	100	0	98	0	0
Acidification (terrestrial)	species.yr	Village	100	100	100	99	0	0
Eutrophication (freshwater)	species.yr	Indonesia	100	100	2	100	0	0
Ecotoxicity (terrestrial)	species.yr	Southeast Asia / village	100	100	12	100	0	0
Ecotoxicity (freshwater)	species.yr	Southeast Asia	100	100	92	100	0	0
Ecotoxicity (marine)	species.yr	Indonesia	78	100	87	100	28	0
Land use (mammals)	species.yr	Village	0	0	0	0	0	0
Land use (birds)	species.yr	Village	100	96	0	0	0	0
Land use (plants)	species.yr	Village	100	100	0	0	0	0
Land use (amphibians)	species.yr	Village	100	100	0	0	0	0
Land use (reptiles)	species.yr	Village	100	100	0	100	0	0
Water use (terrestrial)	species.yr	Village	0	99	0	100	100	0
Water use (freshwater)	species.yr	Indonesia	0	100	0	100	100	0
Eutrophication (marine)	species.yr	Indonesia	100	100	99	99	0	0
Mineral resource scarcity	USD2013	Global	0	100	0	100	100	0
Fossil resource scarcity	USD2013	Global	0	100	99	100	100	0
Human health	DALY	Various	100	100	86	100	1	0
Ecosystems	species.yr	Various	100	100	37	43	0	0
Resources	USD2013	Global	0	100	99	100	100	0

NT=Ngata Toro; N=Napu, LS=Lampung, LJ=Lamongan

Table S30. Percentage of Monte Carlo iterations where characterized spatially differentiated impact scores are larger for one village compared to the other for the system with “Kon Tiki” flame curtain kiln with compost as sole fertilizer. Values below 5% (in green) indicate impact scores significantly smaller for first village compared to the other. Values above 95% (in yellow) indicate impact scores significantly larger for first village compared to the other.

Impact category	Unit	Spatial scale	Percentage of Monte Carlo iterations					
			NT≥N	NT≥LS	NT≥LJ	N≥LS	N≥LJ	LS≥LJ
Global warming	DALY	Indonesia	99	100	37	27	8	0
Stratospheric ozone depletion	DALY	Global	100	100	0	22	0	0
Ionizing radiation	DALY	Global	100	100	0	0	0	0
Ozone formation	DALY	Region	100	100	0	9	0	0
Particulate matter formation	DALY	Southeast Asia / village	100	100	100	0	0	0
Toxicity (carcinogenic)	DALY	Southeast Asia / village	100	100	0	4	0	0
Toxicity (non-carcinogenic)	DALY	Southeast Asia / village	100	100	0	0	0	0
Water use	DALY	Village / Indonesia	100	100	0	0	0	0
Global warming (terrestrial)	species.yr	Indonesia	99	100	37	27	8	0
Global warming (freshwater)	species.yr	Indonesia	99	100	37	27	8	0
Ozone formation (terrestrial)	species.yr	Region	100	100	0	1	0	0
Acidification (terrestrial)	species.yr	Village	100	100	0	27	0	0
Eutrophication (freshwater)	species.yr	Indonesia	100	99	0	0	0	0
Ecotoxicity (terrestrial)	species.yr	Southeast Asia / village	100	100	0	94	0	0
Ecotoxicity (freshwater)	species.yr	Southeast Asia	100	100	0	5	0	0
Ecotoxicity (marine)	species.yr	Indonesia	100	96	0	0	0	0
Land use (mammals)	species.yr	Village	0	0	0	0	0	0
Land use (birds)	species.yr	Village	100	95	0	0	0	0
Land use (plants)	species.yr	Village	100	100	0	0	0	0
Land use (amphibians)	species.yr	Village	100	100	0	0	0	0
Land use (reptiles)	species.yr	Village	100	100	0	100	0	0
Water use (terrestrial)	species.yr	Village	0	0	0	100	100	0
Water use (freshwater)	species.yr	Indonesia	0	100	0	100	100	0
Eutrophication (marine)	species.yr	Indonesia	100	100	0	21	0	0
Mineral resource scarcity	USD2013	Global	100	0	0	0	0	0
Fossil resource scarcity	USD2013	Global	100	100	0	0	0	0
Human health	DALY	Various	100	100	17	6	0	0
Ecosystems	species.yr	Various	100	100	0	0	0	0
Resources	USD2013	Global	100	100	0	0	0	0

NT=Ngata Toro; N=Napu, LS=Lampung, LJ=Lamongan

Table S31. Percentage of Monte Carlo iterations where characterized spatially differentiated impact scores are larger for one village compared to the other for the system with Adam retort kiln with compost as sole fertilizer. Values below 5% (in green) indicate impact scores significantly smaller for first village compared to the other. Values above 95% (in yellow) indicate impact scores significantly larger for first village compared to the other.

Impact category	Unit	Spatial scale	Percentage of Monte Carlo iterations					
			NT≥N	NT≥LS	NT≥LJ	N≥LS	N≥LJ	LS≥LJ
Global warming	DALY	Indonesia	100	97	30	1	1	0
Stratospheric ozone depletion	DALY	Global	100	100	0	0	0	0
Ionizing radiation	DALY	Global	100	100	0	0	0	0
Ozone formation	DALY	Region	100	100	0	0	0	0
Particulate matter formation	DALY	Southeast Asia / village	100	100	100	0	0	0
Toxicity (carcinogenic)	DALY	Southeast Asia / village	100	100	0	0	0	0
Toxicity (non-carcinogenic)	DALY	Southeast Asia / village	100	100	0	0	0	0
Water use	DALY	Village / Indonesia	100	100	0	0	0	0
Global warming (terrestrial)	species.yr	Indonesia	100	97	30	1	1	0
Global warming (freshwater)	species.yr	Indonesia	100	97	30	1	1	0
Ozone formation (terrestrial)	species.yr	Region	100	100	0	0	0	0
Acidification (terrestrial)	species.yr	Village	100	100	0	0	0	0
Eutrophication (freshwater)	species.yr	Indonesia	100	100	0	0	0	0
Ecotoxicity (terrestrial)	species.yr	Southeas Asia / village	100	100	0	2	0	0
Ecotoxicity (freshwater)	species.yr	Southeast Asia	100	100	0	0	0	0
Ecotoxicity (marine)	species.yr	Indonesia	100	100	0	0	0	0
Land use (mammals)	species.yr	Village	100	89	0	0	0	0
Land use (birds)	species.yr	Village	100	100	0	0	0	0
Land use (plants)	species.yr	Village	100	100	0	0	0	0
Land use (amphibians)	species.yr	Village	100	100	0	0	0	0
Land use (reptiles)	species.yr	Village	100	100	0	36	0	0
Water use (terrestrial)	species.yr	Village	100	0	0	0	0	0
Water use (freshwater)	species.yr	Indonesia	0	100	0	100	94	0
Eutrophication (marine)	species.yr	Indonesia	100	100	0	0	0	0
Mineral resource scarcity	USD2013	Global	100	0	0	0	0	0
Fossil resource scarcity	USD2013	Global	100	100	39	0	0	0
Human health	DALY	Various	100	100	16	0	0	0
Ecosystems	species.yr	Various	100	100	0	0	0	0
Resources	USD2013	Global	100	100	27	0	0	0

NT=Ngata Toro; N=Napu, LS=Lampung, LJ=Lamongan

Table S32. Percentage of Monte Carlo iterations where characterized spatially differentiated impact scores are larger for one village compared to the other for the system with earth-mound kiln with compost as sole fertilizer. Values below 5% (in green) indicate impact scores significantly smaller for first village compared to the other. Values above 95% (in yellow) indicate impact scores significantly larger for first village compared to the other.

Impact category	Unit	Spatial scale of impact	Percentage of Monte Carlo iterations					
			NT≥N	NT≥LS	NT≥LJ	N≥LS	N≥LJ	LS≥LJ
Global warming	DALY	Indonesia	100	99	28	0	0	0
Stratospheric ozone depletion	DALY	Global	100	100	0	0	0	0
Ionizing radiation	DALY	Global	100	100	0	0	0	0
Ozone formation	DALY	Region	100	100	0	0	0	0
Particulate matter formation	DALY	Southeast Asia / village	100	100	100	0	0	0
Toxicity (carcinogenic)	DALY	Southeast Asia / village	100	100	0	0	0	0
Toxicity (non-carcinogenic)	DALY	Southeast Asia / village	100	100	0	0	0	0
Water use	DALY	Village / Indonesia	100	100	0	0	0	0
Global warming (terrestrial)	species.yr	Indonesia	100	99	28	0	0	0
Global warming (freshwater)	species.yr	Indonesia	100	99	28	0	0	0
Ozone formation (terrestrial)	species.yr	Region	100	100	0	0	0	0
Acidification (terrestrial)	species.yr	Village	100	100	0	0	0	0
Eutrophication (freshwater)	species.yr	Indonesia	100	100	0	0	0	0
Ecotoxicity (terrestrial)	species.yr	Southeast Asia / village	100	100	0	2	0	0
Ecotoxicity (freshwater)	species.yr	Southeast Asia	100	100	0	0	0	0
Ecotoxicity (marine)	species.yr	Indonesia	100	100	0	0	0	0
Land use (mammals)	species.yr	Village	0	0	0	0	0	0
Land use (birds)	species.yr	Village	100	96	0	0	0	0
Land use (plants)	species.yr	Village	100	100	0	0	0	0
Land use (amphibians)	species.yr	Village	100	100	0	0	0	0
Land use (reptiles)	species.yr	Village	100	100	0	100	0	0
Water use (terrestrial)	species.yr	Village	100	0	0	0	0	0
Water use (freshwater)	species.yr	Indonesia	0	100	0	100	95	0
Eutrophication (marine)	species.yr	Indonesia	100	100	0	0	0	0
Mineral resource scarcity	USD2013	Global	100	100	0	0	0	0
Fossil resource scarcity	USD2013	Global	100	100	0	0	0	0
Human health	DALY	Various	100	100	22	0	0	0
Ecosystems	species.yr	Various	100	100	0	0	0	0
Resources	USD2013	Global	100	100	0	0	0	0

NT=Ngata Toro; N=Napu, LS=Lampung, LJ=Lamongan

Table S33. Percentage of Monte Carlo iterations where characterized spatially differentiated impact scores are larger for one kiln compared to the other. Values below 5% (in green) indicate impact scores significantly smaller for first kiln compared to the other. Values above 95% (in yellow) indicate impact scores significantly larger for first kiln compared to the other.

Impact category	Unit	Spatial scale	Percentage of Monte Carlo iterations											
			Ngata Toro			Napu			Lampung			Lamongan		
			KT≥AR	KT≥EM	AR≥EM	KT≥AR	KT≥EM	AR≥EM	KT≥AR	KT≥EM	AR≥EM	KT≥AR	KT≥EM	AR≥EM
Global warming	DALY	Indonesia	37	8	23	37	6	28	34	7	27	32	7	27
Stratospheric ozone depletion	DALY	Global	0	100	100	0	100	100	0	100	100	0	100	100
Ionizing radiation	DALY	Global	2	100	100	0	100	100	10	100	100	24	100	100
Ozone formation	DALY	Region	0	0	15	0	0	15	0	0	14	0	0	7
Particulate matter formation	DALY	Southeast Asia / village	0	0	29	0	0	33	0	1	28	1	0	27
Toxicity (carcinogenic)	DALY	Southeast Asia / village	100	100	100	100	100	100	100	100	100	100	100	100
Toxicity (non-carcinogenic)	DALY	Southeast Asia / village	100	100	100	100	100	100	100	100	100	100	100	100
Water use	DALY	Village / Indonesia	90	100	100	52	100	100	93	100	100	94	100	100
Global warming (terrestrial)	species.yr	Indonesia	37	8	23	37	6	28	34	7	27	32	7	27
Global warming (freshwater)	species.yr	Indonesia	37	8	23	37	6	28	34	7	27	32	7	27
Ozone formation (terrestrial)	species.yr	Region	0	0	1	0	0	2	0	0	0	0	0	0
Acidification (terrestrial)	species.yr	Village	0	0	100	0	0	100	0	0	100	0	0	100
Eutrophication (freshwater)	species.yr	Indonesia	99	100	100	95	100	100	100	100	100	99	100	100
Ecotoxicity (terrestrial)	species.yr	Southeas Asia / village	6	100	100	0	100	100	81	100	100	87	100	100
Ecotoxicity (freshwater)	species.yr	Southeast Asia	94	100	100	63	100	100	98	100	100	96	100	100
Ecotoxicity (marine)	species.yr	Indonesia	99	100	100	80	100	100	100	100	100	100	100	100
Land use (mammals)	species.yr	Village	0	100	100	0	100	100	0	100	100	0	100	100
Land use (birds)	species.yr	Village	0	100	100	0	100	100	0	100	100	0	100	100
Land use (plants)	species.yr	Village	0	100	100	0	100	100	0	100	100	0	100	100
Land use (amphibians)	species.yr	Village	0	100	100	0	100	100	0	100	100	0	100	100
Land use (reptiles)	species.yr	Village	0	100	100	0	100	100	0	100	100	0	100	100
Water use (terrestrial)	species.yr	Village	78	100	100	34	100	100	82	100	100	89	100	100
Water use (freshwater)	species.yr	Indonesia	78	100	100	34	100	100	82	100	100	89	100	100
Eutrophication (marine)	species.yr	Indonesia	0	0	97	0	0	100	0	0	100	0	0	99
Mineral resource scarcity	USD2013	Global	0	100	100	0	100	100	0	100	100	0	100	100
Fossil resource scarcity	USD2013	Global	0	100	100	0	100	100	0	100	100	0	100	100
Human health	DALY	Various	35	7	23	34	8	0	34	11	32	32	9	33
Ecosystems	species.yr	Various	10	5	65	18	5	3	14	5	82	7	5	78
Resources	USD2013	Global	0	100	100	0	100	100	0	100	100	0	100	100

KT: "Kon Tiki" flame curtain; AR: Adam retort; EM: earth-mound

Table S34. Percentage of Monte Carlo iterations where characterized spatially differentiated impact scores are larger for one kiln compared to the other with compost as sole fertilizer. Values below 5% (in green) indicate impact scores significantly smaller for first kiln compared to the other. Values above 95% (in yellow) indicate impact scores significantly larger for first kiln compared to the other.

Impact category	Unit	Spatial scale	Percentage of Monte Carlo iterations											
			Ngata Toro			Napu			Lampung			Lamongan		
			KT≥AR	KT≥EM	AR≥EM	KT≥AR	KT≥EM	AR≥EM	KT≥AR	KT≥EM	AR≥EM	KT≥AR	KT≥EM	AR≥EM
Global warming	DALY	Indonesia	32	9	23	40	7	31	37	7	27	38	11	29
Stratospheric ozone depletion	DALY	Global	0	100	100	0	100	100	0	100	100	0	100	100
Ionizing radiation	DALY	Global	5	100	100	1	100	100	11	100	100	11	100	100
Ozone formation	DALY	Region	0	0	13	0	0	11	0	0	12	0	0	16
Particulate matter formation	DALY	Southeast Asia / village	0	0	28	0	0	30	0	0	31	0	0	34
Toxicity (carcinogenic)	DALY	Southeast Asia / village	100	100	100	100	100	100	100	100	100	100	100	100
Toxicity (non-carcinogenic)	DALY	Southeast Asia / village	100	100	100	100	100	100	100	100	100	100	100	100
Water use	DALY	Village / Indonesia	89	100	100	47	100	100	96	100	100	93	100	100
Global warming (terrestrial)	species.yr	Indonesia	32	9	23	40	7	31	37	7	27	38	11	29
Global warming (freshwater)	species.yr	Indonesia	32	9	23	40	7	31	37	7	27	38	11	29
Ozone formation (terrestrial)	species.yr	Region	0	0	0	0	0	1	0	0	2	0	0	0
Acidification (terrestrial)	species.yr	Village	0	0	100	0	0	100	0	0	100	0	0	100
Eutrophication (freshwater)	species.yr	Indonesia	100	100	100	97	100	100	99	100	100	100	100	100
Ecotoxicity (terrestrial)	species.yr	Southeast Asia / village	10	100	100	0	100	100	90	100	100	84	100	100
Ecotoxicity (freshwater)	species.yr	Southeast Asia	95	100	100	66	100	100	98	100	100	97	100	100
Ecotoxicity (marine)	species.yr	Indonesia	100	100	100	89	100	100	100	100	100	100	100	100
Land use (mammals)	species.yr	Village	0	100	100	0	100	100	0	100	100	0	100	100
Land use (birds)	species.yr	Village	0	100	100	0	100	100	0	100	100	0	100	100
Land use (plants)	species.yr	Village	0	100	100	0	100	100	0	100	100	0	100	100
Land use (amphibians)	species.yr	Village	0	100	100	0	100	100	0	100	100	0	100	100
Land use (reptiles)	species.yr	Village	0	100	100	0	100	100	0	100	100	0	100	100
Water use (terrestrial)	species.yr	Village	72	100	100	30	100	100	93	100	100	85	100	100
Water use (freshwater)	species.yr	Indonesia	72	100	100	30	100	100	93	100	100	85	100	100
Eutrophication (marine)	species.yr	Indonesia	0	0	98	0	0	100	0	0	100	0	0	100
Mineral resource scarcity	USD2013	Global	0	100	100	0	100	100	0	100	100	0	100	100
Fossil resource scarcity	USD2013	Global	0	100	100	0	100	100	0	100	100	0	100	100
Human health	DALY	Various	29	8	26	37	5	35	38	8	33	36	11	33
Ecosystems	species.yr	Various	6	6	65	26	6	50	5	3	78	10	7	75
Resources	USD2013	Global	0	100	100	0	100	100	0	100	100	0	100	100

KT: “Kon Tiki” flame curtain; AR: Adam retort; EM: earth-mound

Table S35. Percentage of Monte Carlo iterations where characterized spatially differentiated impact scores are larger for one fertilizer type compared to the other. Values below 5% (in green) indicate impact scores significantly smaller for first fertilizer type compared to the other. Values above 95% (in yellow) indicate impact scores significantly larger for first kiln compared to the other.

Impact category	Unit	Spatial scale	Percentage of Monte Carlo iterations											
			flame curtain				retort				earth-mound			
			NT	N	LS	LJ	NT	N	LS	LJ	NT	N	LS	LJ
			fi≥fc	**fc≥fi**	fi≥fc	fi≥fc	fi≥fc	**fc≥fi**	fi≥fc	fi≥fc	fi≥fc	**fc≥fi**	fi≥fc	fi≥fc
Global warming	DALY	Indonesia	100	100	0	0	100	100	0	0	100	100	0	0
Stratospheric ozone depletion	DALY	Global	100	100	0	0	100	100	0	0	100	100	0	0
Ionizing radiation	DALY	Global	0	100	0	0	0	100	0	0	0	100	0	0
Ozone formation	DALY	Region	100	100	0	0	100	100	0	0	100	100	0	0
Particulate matter formation	DALY	Southeast Asia / village	0	100	0	0	0	100	0	0	0	100	0	0
Toxicity (carcinogenic)	DALY	Southeast Asia / village	99	100	0	0	98	100	0	0	100	100	0	0
Toxicity (non-carcinogenic)	DALY	Southeast Asia / village	45	100	0	0	44	100	0	0	51	100	0	0
Water use	DALY	Village / Indonesia	0	100	0	0	0	100	0	0	0	100	0	0
Global warming (terrestrial)	species.yr	Indonesia	100	100	0	0	100	100	0	0	100	100	0	0
Global warming (freshwater)	species.yr	Indonesia	100	100	0	0	100	100	0	0	100	100	0	0
Ozone formation (terrestrial)	species.yr	Region	100	100	0	0	100	100	0	0	100	100	0	0
Acidification (terrestrial)	species.yr	Village	100	100	0	0	100	100	0	0	100	100	0	0
Eutrophication (freshwater)	species.yr	Indonesia	14	100	0	0	14	100	0	0	15	100	0	0
Ecotoxicity (terrestrial)	species.yr	Southeast Asia / village	100	100	0	0	100	100	0	0	100	100	0	0
Ecotoxicity (freshwater)	species.yr	Southeast Asia	98	100	0	0	97	100	0	0	99	100	0	0
Ecotoxicity (marine)	species.yr	Indonesia	2	100	0	0	7	100	0	0	5	100	0	0
Land use (mammals)	species.yr	Village	0	100	0	0	0	100	0	0	0	100	0	0
Land use (birds)	species.yr	Village	0	100	0	0	0	100	0	0	0	100	0	0
Land use (plants)	species.yr	Village	0	100	0	0	0	100	0	0	0	100	0	0
Land use (amphibians)	species.yr	Village	0	100	0	0	0	100	0	0	0	100	0	0
Land use (reptiles)	species.yr	Village	0	100	0	0	0	100	0	0	0	100	0	0
Water use (terrestrial)	species.yr	Village	0	100	0	0	0	100	0	0	0	100	0	0
Water use (freshwater)	species.yr	Indonesia	0	100	0	0	0	100	0	0	0	100	0	0
Eutrophication (marine)	species.yr	Indonesia	100	100	0	0	100	100	0	0	100	100	0	0
Mineral resource scarcity	USD2013	Global	0	100	0	0	0	100	0	0	0	100	0	0
Fossil resource scarcity	USD2013	Global	0	100	0	0	0	100	0	0	0	100	0	0
Human health	DALY	Various	62	100	0	0	71	100	0	0	64	100	0	0
Ecosystems	species.yr	Various	100	100	0	0	100	100	0	0	100	100	0	0
Resources	USD2013	Global	0	100	0	0	0	100	0	0	0	100	0	0

NT=Ngata Toro; N=Napu, LS=Lampung, LJ=Lamongan

fi=inorganic fertilizers and urea; fc=compost

Table S36. Percentage of Monte Carlo iterations where characterized spatially differentiated impact scores are larger for one village compared to the other, assuming that life cycle inventories are the same and equal to those of Ngata Toro. Values below 5% (in green) indicate impact scores significantly smaller for one village compared to the other. Values above 95% (in yellow) indicate impact scores significantly larger for one village compared to the other.

Impact category	Unit	Spatial scale	Percentage of Monte Carlo iterations					
			NT≥N	NT≥LS	NT≥LJ	N≥LS	N≥LJ	LS≥LJ
Global warming	DALY	Indonesia	100	100	100	100	100	100
Stratospheric ozone depletion	DALY	Global	100	100	100	100	100	100
Ionizing radiation	DALY	Global	100	100	100	100	100	100
Ozone formation	DALY	Region	100	100	100	100	100	100
Particulate matter formation	DALY	Southeast Asia / village	100	100	100	100	100	100
Toxicity (carcinogenic)	DALY	Southeast Asia / village	100	100	100	100	100	100
Toxicity (non-carcinogenic)	DALY	Southeast Asia / village	100	100	100	100	100	100
Water use	DALY	Village / Indonesia	100	100	100	0	0	100
Global warming (terrestrial)	species.yr	Indonesia	100	100	100	100	100	100
Global warming (freshwater)	species.yr	Indonesia	100	100	100	100	100	100
Ozone formation (terrestrial)	species.yr	Region	100	100	100	100	100	100
Acidification (terrestrial)	species.yr	Village	100	100	100	100	100	100
Eutrophication (freshwater)	species.yr	Indonesia	100	100	100	100	100	100
Ecotoxicity (terrestrial)	species.yr	Southeas Asiat / village	0	0	0	100	100	0
Ecotoxicity (freshwater)	species.yr	Southeast Asia	100	100	100	100	100	100
Ecotoxicity (marine)	species.yr	Indonesia	100	100	100	100	100	100
Land use (mammals)	species.yr	Village	0	0	0	100	100	0
Land use (birds)	species.yr	Village	100	0	100	0	0	100
Land use (plants)	species.yr	Village	100	100	100	100	100	100
Land use (amphibians)	species.yr	Village	100	100	100	100	100	100
Land use (reptiles)	species.yr	Village	0	100	100	100	100	0
Water use (terrestrial)	species.yr	Village	100	0	0	0	0	100
Water use (freshwater)	species.yr	Indonesia	100	100	100	100	100	100
Eutrophication (marine)	species.yr	Indonesia	100	100	100	100	100	100
Mineral resource scarcity	USD2013	Global	100	100	100	100	100	100
Fossil resource scarcity	USD2013	Global	100	100	100	100	100	100
Human health	DALY	Various	100	100	100	0	0	100
Ecosystems	species.yr	Various	20	93	94	100	100	21
Resources	USD2013	Global	100	100	100	100	100	100

NT=Ngata Toro; N=Napu, LS=Lampung, LJ=Lamongan

S6.3. Details of relative ranking

Table S37. Summary of changes introduced by switching from generic to regionalized impact assessment on identifications of biochar systems performing best or worst in terms of total damage while taking into account parameter and inventory uncertainties. No statistically significant differences between systems are indicated with “≈”.

Biochar production technique (scenarios 1-12; inorganic fertilizer, compost in Napu) [a]									
Village		**Ngata Toro**		**Napu**		**Lampung**		**Lamongan**	
Assessment		**Generic**	**Regionalized**	**Generic**	**Regionalized**	**Generic**	**Regionalized**	**Generic**	**Regionalized**
Human health	best	k1≈k2	k1≈k2≈k3	k1≈k2	k1≈k2	k1≈k2	k1≈k2≈k3	k1≈k2	k1≈k2≈k3
	worst	k2≈k3	k1≈k2≈k3	k2≈k3	k3	k2≈k3	k1≈k2≈k3	k2≈k3	k1≈k2≈k3
Ecosystems	best	k1≈k2	k1≈k2	k1≈k2	k1≈k2	k1≈k2	k1≈k2	k1≈k2	k1≈k2
	worst	k2≈k3	k2≈k3	k2≈k3	k3	k2≈k3	k2≈k3	k2≈k3	k2≈k3
Biochar production technique (scenarios 13-24; compost, inorganic fertilizer in Napu) [a]									
Human health	best	k1≈k2≈k3	k1≈k2≈k3	k1≈k2≈k3	k1≈k2≈k3	k1≈k2	k1≈k2≈k3	k1≈k2	k1≈k2≈k3
	worst	k1≈k2≈k3	k1≈k2≈k3	k1≈k2≈k3	k1≈k2≈k3	k2≈k3	k1≈k2≈k3	k2≈k3	k1≈k2≈k3
Ecosystems	best	k1≈k2	k1≈k2≈k3	k1≈k2≈k3	k1≈k2≈k3	k1≈k2	k1	k1≈k2	k1≈k2≈k3
	worst	k2≈k3	k1≈k2≈k3	k1≈k2≈k3	k1≈k2≈k3	k2≈k3	k2≈k3	k2≈k3	k1≈k2≈k3
Fertilizer type (scenarios 1-4; “Kon Tiki”) [b]									
Village		**Ngata Toro**		**Napu**		**Lampung**		**Lamongan**	
Assessment		**Generic**	**Regionalized**	**Generic**	**Regionalized**	**Generic**	**Regionalized**	**Generic**	**Regionalized**
Human health	best	f1	f1≈f2	f1	f1	f1	f1	f1	f1
	worst	f2	f1≈f2	f2	f2	f2	f2	f2	f2
Ecosystems	best	f2	f2	f1	f1	f1	f1	f1	f1
	worst	f1	f1	f2	f2	f2	f2	f2	f2
Fertilizer type (scenarios 5-8; Adam retort) [b]									
Human health	best	f1	f1≈f2	f1	f1	f1	f1	f1	f1
	worst	f2	f1≈f2	f2	f2	f2	f2	f2	f2
Ecosystems	best	f2	f2	f1	f1	f1	f1	f1	f1
	worst	f1	f1	f2	f2	f2	f2	f2	f2
Fertilizer type (scenarios 9-12; earth-mound) [b]									
Human health	best	f1	f1≈f2	f1	f1	f1	f1	f1	f1
	worst	f2	f1≈f2	f2	f2	f2	f2	f2	f2
Ecosystems	best	f2	f2	f1	f1	f1	f1	f1	f1
	worst	f1	f1	f2	f2	f2	f2	f2	f2

Village (scenarios 1-12; inorganic fertilizer, compost in Napu) [c]							
Kiln		**“Kon Tiki”**		**Adam retort**		**earth-mound**	
Assessment		**Generic**	**Regionalized**	**Generic**	**Regionalized**	**Generic**	**Regionalized**
Human health	best	v3	v3	v3	v3	v3	v3
	worst	v2	v1≈v4	v2	v1≈v4	v2	v1≈v4
Ecosystems	best	v3	v2≈v3	v3	v2≈v3	v3	v2
	worst	v1	v1≈v4	v1≈v4	v1≈v4	v1≈v4	v1≈v4
Village (scenarios 13-24; compost, inorganic fertilizer in Napu) [c]							
Human health	best	v3	v2	v3	v2	v3	v2
	worst	v2	v1≈v4	v2≈v4	v4	v4	v4
Ecosystems	best	v2	v2	v2	v2	v2	v2
	worst	v4	v4	v4	v4	v4	v4

[a] k1=“Kon Tiki” flame curtain kiln; k2=Adam retort kiln; k3=earth-mound kiln

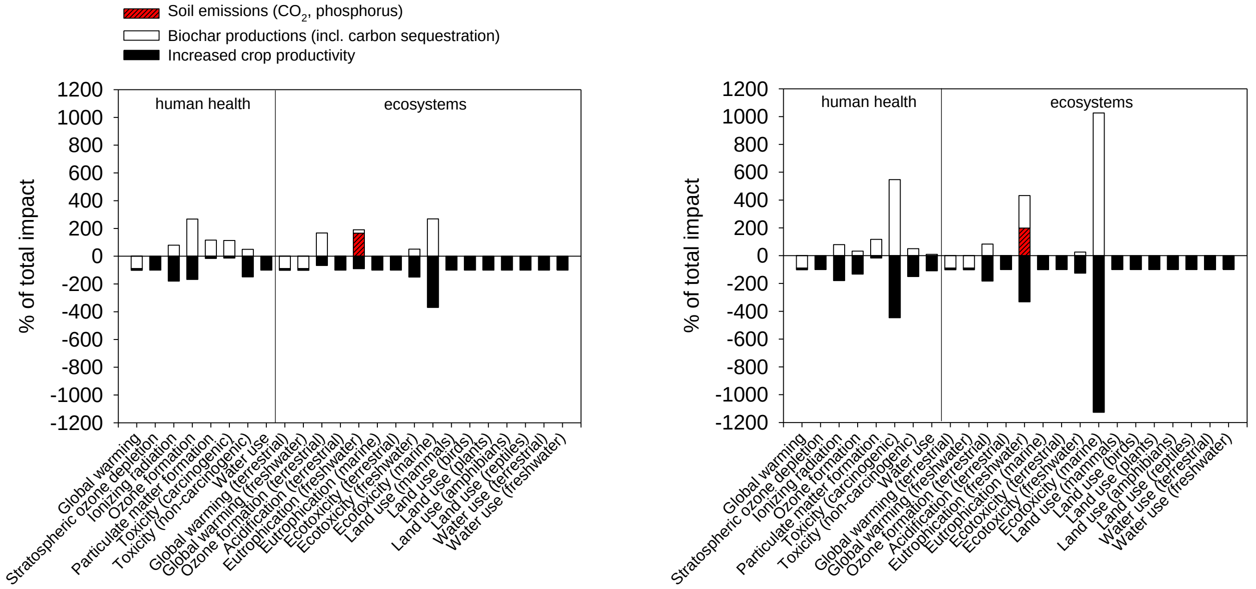
[b] f1=inorganic fertilizer ; f2=compost

[c] v1=Ngata Toro; v2=Napu, v3=Lampung, v4=Lamongan

S6.4. Details of process contribution

(a) generic **(b) spatially-differentiated**

per impact category



at total damage level

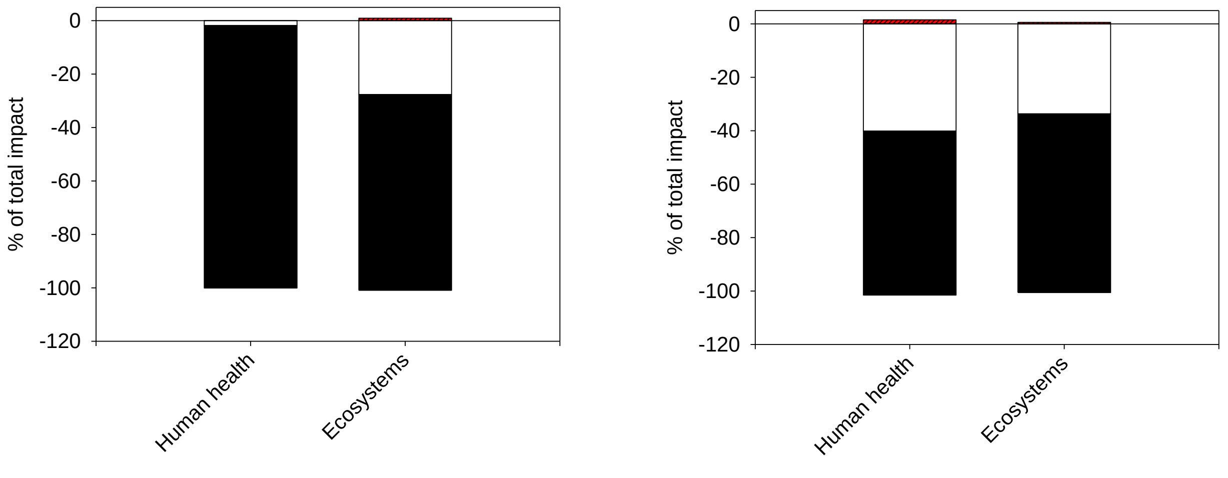


Fig. S3. Contribution of life cycle processes to total impacts from biochar production using “Kon Tiki” flame curtain kiln and use in inorganic fertilizer based agriculture in Ngata Toro (Scenario 1 in Table 1) calculated using generic **(a)** and spatially differentiated **(b)** impact assessment methods. The contribution is show per impact category and at the level of total damage.

S6.5. Details of sensitivity analysis

Table S38. Normalized sensitivity coefficients for perturbation (lower) of biochar yield for scenarios 1-12 (Table 1). Values highlighted red and yellow correspond to coefficients larger and smaller than 0.3 and -0.3, respectively (medium sensitivity).

		1	2	3	4	5	6	7	8	9	10	11	12
Impact category	Unit	flame curtain, NT	flame curtain, N	flame curtain, LS	flame curtain, LJ	retort, NT	retort, N	retort, LS	retort, LJ	earth-mound, NT	earth-mound, N	earth-mound, LS	earth-mound, LJ
Global warming	DALY	0.81	0.43	0.47	0.85	-1.16	-0.45	-0.74	-1.40	0.70	0.29	0.33	0.76
Global warming (terrestrial)	species.yr	0.81	0.43	0.47	0.85	-1.16	-0.45	-0.74	-1.40	0.71	0.29	0.33	0.76
Global warming (freshwater)	species.yr	0.81	0.43	0.47	0.85	-1.16	-0.44	-0.74	-1.39	0.71	0.29	0.33	0.76
Stratospheric ozone depletion	DALY	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01
Ionizing radiation	DALY	-0.77	-0.45	-0.08	-1.41	-1.29	-0.92	-0.09	-2.06	0.01	0.00	0.00	0.01
Ozone formation	DALY	0.14	0.01	0.02	0.13	1.33	-1.80	-1.51	1.36	1.27	-2.91	-2.45	1.29
Particulate matter formation	DALY	1.17	1.10	-1.48	1.26	1.11	1.06	-8.09	1.16	1.10	1.06	-28.90	1.14
Ozone formation (terrestrial eco)	species.yr	-0.30	-0.04	-0.03	-0.31	1.36	-2.34	-1.30	1.37	1.23	-136.44	-4.95	1.22
Acidification (terrestrial)	species.yr	0.01	0.00	0.00	0.01	-0.07	-0.01	-0.01	-0.06	-0.01	0.00	0.00	-0.01
Eutrophication (freshwater)	species.yr	2.32	-0.53	-0.15	1.37	4.63	-0.38	-0.10	1.64	0.03	0.00	0.00	0.03
Ecotoxicity (terrestrial)	species.yr	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01
Ecotoxicity (freshwater)	species.yr	-0.24	-0.04	-0.03	-0.24	-0.19	-0.03	-0.02	-0.17	0.01	0.00	0.00	0.01
Ecotoxicity (marine)	species.yr	-9.99	-1.07	-0.15	75.38	-1.63	-0.80	-0.08	-1.48	0.01	0.00	0.00	0.01
Toxicity (carcinogenic)	DALY	5.45	-0.23	-0.23	7.65	-1.17	-0.10	-0.08	-0.97	0.01	0.00	0.00	0.01
Toxicity (non-carcinogenic)	DALY	-0.48	-0.05	-0.12	-4.70	-0.20	-0.03	-0.05	-0.68	0.01	0.00	0.00	0.01
Land use (mammals)	species.yr	0.01	0.00	0.00	0.01	-13.43	-0.05	-3.30	13.56	0.01	0.00	0.00	0.01
Land use (birds)	species.yr	0.01	0.00	0.00	0.01	45.13	-1.22	-8.71	10.44	0.01	0.00	0.00	0.01
Land use (plants)	species.yr	0.01	0.00	0.00	0.01	63.04	-0.36	-9.04	10.40	0.01	0.00	0.00	0.01
Land use (amphibians)	species.yr	0.01	0.00	0.00	0.00	-460.61	-0.96	-6.24	11.11	0.01	0.00	0.00	0.01
Land use (reptiles)	species.yr	0.01	0.00	0.00	0.01	-13.42	-0.61	-3.47	13.24	0.01	0.00	0.00	0.01
Mineral resource scarcity	USD2013	1.68	1.22	-0.80	1.39	1.19	1.08	8.36	1.12	0.01	0.00	0.00	0.01
Fossil resource scarcity	USD2013	-0.19	-0.45	-0.02	-0.20	-2.16	2.65	-0.08	-1.48	0.01	0.00	0.00	0.01
Water use (terrestrial)	species.yr	0.00	-0.27	0.00	-0.03	0.00	-0.30	0.00	-0.03	0.01	0.00	0.00	0.01
Water use (freshwater)	species.yr	0.01	-0.27	0.00	0.01	0.01	-0.30	0.00	0.01	0.01	0.00	0.00	0.01
Water use	DALY	-0.08	-0.14	-0.01	-0.09	-0.07	-0.15	-0.01	-0.07	0.01	0.00	0.00	0.01
Water use, marginal	0	-0.08	-0.13	-0.01	-0.09	-0.07	-0.14	-0.01	-0.07	0.01	0.00	0.00	0.01
Eutrophication (marine)	species.yr	0.01	0.00	0.00	0.01	-0.08	-0.01	-0.01	-0.07	-0.06	-0.01	-0.01	-0.05
Human health	DALY	0.31	0.11	0.11	0.45	-2.59	-0.48	-0.46	-2.21	-0.46	-0.02	0.02	0.10
Ecosystems	species-yr	0.31	0.06	0.08	0.36	-2.53	-0.19	-0.73	-5.06	0.18	0.03	0.04	0.21
Resources	USD2013	-0.24	-0.59	-0.02	-0.26	-3.28	2.34	-0.09	-2.25	0.01	0.00	0.00	0.01

Table S39. Normalized sensitivity coefficients for perturbation (higher) of biochar yield for scenarios 1-12 (Table 1). Values highlighted red and yellow correspond to coefficients larger and smaller than 0.3 and -0.3, respectively (medium sensitivity).

		1	2	3	4	5	6	7	8	9	10	11	12
Impact category	Unit	flame curtain, NT	flame curtain, N	flame curtain, LS	flame curtain, LJ	retort, NT	retort, N	retort, LS	retort, LJ	earth-mound, NT	earth-mound, N	earth-mound, LS	earth-mound, LJ
Global warming	DALY	0.81	0.43	0.47	0.85	2.88	1.34	1.70	3.21	0.70	0.29	0.32	0.76
Global warming (terrestrial)	species.yr	0.81	0.43	0.47	0.85	2.88	1.34	1.71	3.21	0.70	0.29	0.33	0.76
Global warming (freshwater)	species.yr	0.81	0.43	0.47	0.85	2.88	1.34	1.70	3.20	0.70	0.29	0.33	0.76
Stratospheric ozone depletion	DALY	-0.01	0.00	0.00	-0.01	-0.01	0.00	0.00	-0.01	-0.01	0.00	0.00	-0.01
Ionizing radiation	DALY	-0.81	-0.45	-0.08	-1.45	-1.34	-0.92	-0.09	-2.11	-0.01	0.00	0.00	-0.01
Ozone formation	DALY	-0.93	-0.11	-0.11	-0.87	1.34	-1.79	-1.52	1.36	1.28	-2.91	-2.47	1.29
Particulate matter formation	DALY	1.17	1.10	-1.49	1.26	1.11	1.06	-8.14	1.16	1.10	1.06	-29.05	1.15
Ozone formation (terrestrial eco)	species.yr	-1.51	-0.16	-0.14	-1.52	1.37	-2.33	-1.31	1.37	1.23	-136.21	-4.98	1.23
Acidification (terrestrial)	species.yr	-0.02	0.00	0.00	-0.01	-0.01	0.00	0.00	-0.01	-0.03	0.00	-0.01	-0.03
Eutrophication (freshwater)	species.yr	2.39	-0.52	-0.16	1.39	4.82	-0.38	-0.11	1.68	-0.03	0.00	0.00	-0.03
Ecotoxicity (terrestrial)	species.yr	-0.01	0.00	0.00	-0.01	-0.01	0.00	0.00	-0.01	-0.01	0.00	0.00	-0.01
Ecotoxicity (freshwater)	species.yr	-0.27	-0.03	-0.04	-0.26	-0.21	-0.03	-0.03	-0.19	-0.01	0.00	0.00	-0.01
Ecotoxicity (marine)	species.yr	-10.22	-1.07	-0.16	76.54	-1.68	-0.79	-0.09	-1.52	-0.01	0.00	0.00	-0.01
Toxicity (carcinogenic)	DALY	5.55	-0.23	-0.23	7.75	-1.22	-0.09	-0.09	-1.00	-0.01	0.00	0.00	-0.01
Toxicity (non-carcinogenic)	DALY	-0.52	-0.05	-0.13	-4.79	-0.23	-0.03	-0.06	-0.71	-0.01	0.00	0.00	-0.01
Land use (mammals)	species.yr	-0.01	0.00	0.00	-0.01	10.75	0.04	2.64	-10.85	-0.01	0.00	0.00	-0.01
Land use (birds)	species.yr	-0.01	0.00	0.00	-0.01	-36.10	0.98	6.97	-8.35	-0.01	0.00	0.00	-0.01
Land use (plants)	species.yr	-0.01	0.00	0.00	-0.01	-50.42	0.29	7.23	-8.32	-0.01	0.00	0.00	-0.01
Land use (amphibians)	species.yr	-0.01	0.00	0.00	-0.01	368.00	0.77	4.98	-8.88	-0.01	0.00	0.00	-0.01
Land use (reptiles)	species.yr	-0.01	0.00	0.00	-0.01	10.73	0.49	2.78	-10.59	-0.01	0.00	0.00	-0.01
Mineral resource scarcity	USD2013	1.70	1.22	-0.81	1.39	1.19	1.08	8.40	1.12	-0.01	0.00	0.00	-0.01
Fossil resource scarcity	USD2013	-0.21	-0.45	-0.03	-0.22	-2.22	2.65	-0.08	-1.52	-0.01	0.00	0.00	-0.01
Water use (terrestrial)	species.yr	-0.02	-0.26	-0.01	-0.05	-0.02	-0.30	-0.01	-0.04	-0.01	0.00	0.00	-0.01
Water use (freshwater)	species.yr	-0.01	-0.26	0.00	-0.01	-0.01	-0.30	0.00	-0.01	-0.01	0.00	0.00	-0.01
Water use	DALY	-0.10	-0.14	-0.01	-0.11	-0.09	-0.14	-0.01	-0.08	-0.01	0.00	0.00	-0.01
Water use, marginal	0	-0.10	-0.13	-0.01	-0.11	-0.09	-0.13	-0.01	-0.09	-0.01	0.00	0.00	-0.01
Eutrophication (marine)	species.yr	-0.03	0.00	0.00	-0.02	-0.10	-0.01	-0.02	-0.09	-0.08	-0.01	-0.01	-0.07
Human health	DALY	0.29	0.11	0.10	0.45	3.03	0.66	0.66	3.12	-0.49	-0.02	0.01	0.09
Ecosystems	species-yr	0.30	0.06	0.08	0.34	2.87	0.28	0.77	5.27	0.16	0.03	0.04	0.20
Resources	USD2013	-0.26	-0.58	-0.03	-0.28	-3.37	2.34	-0.10	-2.29	-0.01	0.00	0.00	-0.01

Table S40. Normalized sensitivity coefficients for perturbation (lower) of biochar application rate for scenarios 1-12 (Table 1). Values highlighted red and yellow correspond to coefficients larger and smaller than 0.3 and -0.3, respectively (medium sensitivity).

		1	2	3	4	5	6	7	8	9	10	11	12
Impact category	Unit	flame curtain, NT	flame curtain, N	flame curtain, LS	flame curtain, LJ	retort, NT	retort, N	retort, LS	retort, LJ	earth-mound, NT	earth-mound, N	earth-mound, LS	earth-mound, LJ
Global warming	DALY	-0.12	-0.30	-0.50	-0.13	-5.74	-2.78	-3.92	-6.54	-0.19	-0.37	-0.63	-0.22
Global warming (terrestrial)	species.yr	-0.12	-0.30	-0.50	-0.13	-5.74	-2.78	-3.92	-6.54	-0.19	-0.37	-0.63	-0.22
Global warming (freshwater)	species.yr	-0.12	-0.30	-0.50	-0.13	-5.73	-2.78	-3.92	-6.53	-0.19	-0.37	-0.63	-0.22
Stratospheric ozone depletion	DALY	-1.02	-1.06	-1.05	-1.03	-1.03	-1.06	-1.05	-1.03	-1.02	-1.05	-1.05	-1.03
Ionizing radiation	DALY	-1.83	-1.53	-1.13	-2.51	-2.37	-2.03	-1.14	-3.18	-1.02	-1.05	-1.05	-1.03
Ozone formation	DALY	0.07	-0.92	-0.92	0.00	0.34	-2.95	-2.63	0.37	0.28	-4.13	-3.61	0.30
Particulate matter formation	DALY	0.18	0.10	-2.60	0.27	0.11	0.06	-9.53	0.16	0.10	0.06	-31.33	0.15
Ozone formation (terrestrial eco)	species.yr	-0.27	-0.98	-0.98	-0.27	0.38	-3.52	-2.41	0.38	0.23	-144.88	-6.24	0.23
Acidification (terrestrial)	species.yr	-1.02	-1.05	-1.05	-1.03	-1.18	-1.07	-1.07	-1.16	-1.05	-1.06	-1.05	-1.05
Eutrophication (freshwater)	species.yr	3.42	-2.07	-1.35	1.60	9.46	-1.88	-1.28	2.79	-2.53	-1.36	-1.16	-4.20
Ecotoxicity (terrestrial)	species.yr	-1.03	-1.06	-1.05	-1.03	-1.03	-1.06	-1.05	-1.03	-1.02	-1.05	-1.05	-1.03
Ecotoxicity (freshwater)	species.yr	-1.29	-1.09	-1.08	-1.29	-1.23	-1.09	-1.07	-1.22	-1.02	-1.05	-1.05	-1.03
Ecotoxicity (marine)	species.yr	-11.36	-2.18	-1.21	77.25	-2.72	-1.89	-1.14	-2.58	-1.02	-1.05	-1.05	-1.03
Toxicity (carcinogenic)	DALY	4.60	-1.30	-1.28	6.90	-2.25	-1.16	-1.14	-2.05	-1.02	-1.05	-1.05	-1.03
Toxicity (non-carcinogenic)	DALY	-1.53	-1.10	-1.17	-5.92	-1.25	-1.08	-1.11	-1.75	-1.02	-1.05	-1.05	-1.03
Land use (mammals)	species.yr	-1.02	-1.06	-1.05	-1.03	-36.40	-1.18	-9.72	34.63	-1.02	-1.05	-1.05	-1.03
Land use (birds)	species.yr	-1.02	-1.06	-1.05	-1.03	117.72	-4.26	-23.98	26.43	-1.02	-1.05	-1.05	-1.03
Land use (plants)	species.yr	-1.02	-1.06	-1.05	-1.03	164.82	-1.99	-24.83	26.32	-1.02	-1.05	-1.05	-1.03
Land use (amphibians)	species.yr	-1.02	-1.06	-1.05	-1.03	-1212.74	-3.58	-17.46	28.18	-1.02	-1.05	-1.05	-1.03
Land use (reptiles)	species.yr	-1.02	-1.06	-1.05	-1.03	-36.36	-2.67	-10.19	33.79	-1.02	-1.05	-1.05	-1.03
Mineral resource scarcity	USD2013	0.71	0.23	-1.89	0.40	0.19	0.08	7.71	0.13	-1.02	-1.05	-1.05	-1.03
Fossil resource scarcity	USD2013	-1.23	-1.53	-1.07	-1.25	-3.27	1.74	-1.13	-2.57	-1.02	-1.05	-1.05	-1.03
Water use (terrestrial)	species.yr	-1.03	-1.34	-1.05	-1.07	-1.03	-1.37	-1.05	-1.07	-1.02	-1.05	-1.05	-1.03
Water use (freshwater)	species.yr	-1.02	-1.34	-1.05	-1.03	-1.02	-1.37	-1.05	-1.03	-1.02	-1.05	-1.05	-1.03
Water use	DALY	-1.12	-1.20	-1.06	-1.14	-1.10	-1.21	-1.05	-1.11	-1.02	-1.05	-1.05	-1.03
Eutrophication (marine)	species.yr	-1.01	-1.05	-1.04	-1.02	-1.12	-1.07	-1.06	-1.12	-1.09	-1.06	-1.06	-1.10
Human health	DALY	-0.63	-0.75	-0.91	-0.55	-8.59	-2.36	-2.50	-8.03	-1.32	-0.86	-1.00	-0.90
Ecosystems	species-yr	-0.68	-0.95	-0.95	-0.66	-8.41	-1.62	-3.13	-15.43	-0.82	-0.98	-1.00	-0.81
Resources	USD2013	-1.79	-3.23	-0.93	-2.02	-11.06	5.32	-1.17	-9.24	-0.71	-0.82	-0.81	-0.80

Table S41. Normalized sensitivity coefficients for perturbation (higher) of biochar application rate for scenarios 1-12 (Table 1). Values highlighted red and yellow correspond to coefficients larger and smaller than 0.3 and -0.3, respectively (medium sensitivity).

		1	2	3	4	5	6	7	8	9	10	11	12
Impact category	Unit	flame curtain, NT	flame curtain, N	flame curtain, LS	flame curtain, LJ	retort, NT	retort, N	retort, LS	retort, LJ	earth-mound, NT	earth-mound, N	earth-mound, LS	earth-mound, LJ
Global warming	DALY	-0.11	-0.27	-0.45	-0.13	5.50	2.20	2.93	6.27	-0.18	-0.33	-0.58	-0.20
Global warming (terrestrial)	species.yr	-0.11	-0.27	-0.45	-0.13	5.50	2.21	2.93	6.26	-0.18	-0.33	-0.58	-0.20
Global warming (freshwater)	species.yr	-0.11	-0.27	-0.45	-0.13	5.49	2.20	2.93	6.25	-0.18	-0.33	-0.58	-0.20
Stratospheric ozone depletion	DALY	-0.98	-0.95	-0.96	-0.97	-0.98	-0.95	-0.96	-0.97	-0.98	-0.95	-0.96	-0.97
Ionizing radiation	DALY	-1.75	-1.38	-1.04	-2.36	-2.27	-1.82	-1.05	-3.00	-0.98	-0.95	-0.96	-0.97
Ozone formation	DALY	-2.72	-1.17	-1.17	-2.61	0.33	-2.66	-2.41	0.35	0.27	-3.72	-3.32	0.28
Particulate matter formation	DALY	0.17	0.09	-2.38	0.25	0.11	0.06	-8.75	0.16	0.09	0.05	-28.75	0.14
Ozone formation (terrestrial eco)	species.yr	-3.39	-1.21	-1.18	-3.39	0.36	-3.17	-2.21	0.36	0.22	-130.49	-5.72	0.22
Acidification (terrestrial)	species.yr	-0.99	-0.95	-0.96	-0.98	-0.90	-0.95	-0.95	-0.91	-1.00	-0.95	-0.96	-0.99
Eutrophication (freshwater)	species.yr	3.27	-1.87	-1.24	1.51	9.05	-1.69	-1.18	2.64	-2.42	-1.23	-1.07	-3.97
Ecotoxicity (terrestrial)	species.yr	-0.98	-0.95	-0.96	-0.98	-0.98	-0.95	-0.96	-0.97	-0.98	-0.95	-0.96	-0.97
Ecotoxicity (freshwater)	species.yr	-1.23	-0.98	-0.99	-1.22	-1.18	-0.98	-0.98	-1.15	-0.98	-0.95	-0.96	-0.97
Ecotoxicity (marine)	species.yr	-10.87	-1.97	-1.11	72.89	-2.60	-1.71	-1.04	-2.43	-0.98	-0.95	-0.96	-0.97
Toxicity (carcinogenic)	DALY	4.41	-1.17	-1.18	6.51	-2.15	-1.04	-1.04	-1.94	-0.98	-0.95	-0.96	-0.97
Toxicity (non-carcinogenic)	DALY	-1.47	-0.99	-1.08	-5.58	-1.19	-0.98	-1.01	-1.65	-0.98	-0.95	-0.96	-0.97
Land use (mammals)	species.yr	-0.98	-0.95	-0.96	-0.97	31.03	-0.84	6.89	-33.23	-0.98	-0.95	-0.96	-0.97
Land use (birds)	species.yr	-0.98	-0.95	-0.96	-0.97	-108.40	1.95	19.79	-25.82	-0.98	-0.95	-0.96	-0.97
Land use (plants)	species.yr	-0.98	-0.95	-0.96	-0.97	-151.01	-0.10	20.56	-25.72	-0.98	-0.95	-0.96	-0.97
Land use (amphibians)	species.yr	-0.98	-0.95	-0.96	-0.98	1094.82	1.33	13.89	-27.39	-0.98	-0.95	-0.96	-0.97
Land use (reptiles)	species.yr	-0.98	-0.95	-0.96	-0.97	30.98	0.51	7.31	-32.47	-0.98	-0.95	-0.96	-0.97
Mineral resource scarcity	USD2013	0.68	0.21	-1.73	0.38	0.19	0.07	7.08	0.12	-0.98	-0.95	-0.96	-0.97
Fossil resource scarcity	USD2013	-1.18	-1.38	-0.98	-1.18	-3.13	1.57	-1.04	-2.43	-0.98	-0.95	-0.96	-0.97
Water use (terrestrial)	species.yr	-0.99	-1.20	-0.97	-1.01	-0.99	-1.23	-0.96	-1.01	-0.98	-0.95	-0.96	-0.97
Water use (freshwater)	species.yr	-0.98	-1.20	-0.96	-0.97	-0.98	-1.23	-0.96	-0.97	-0.98	-0.95	-0.96	-0.97
Water use	DALY	-1.07	-1.08	-0.97	-1.07	-1.06	-1.09	-0.97	-1.05	-0.98	-0.95	-0.96	-0.97
Eutrophication (marine)	species.yr	-1.01	-0.95	-0.96	-1.00	-1.07	-0.96	-0.97	-1.05	-1.05	-0.96	-0.97	-1.03
Human health	DALY	-0.60	-0.68	-0.83	-0.52	7.08	0.88	0.71	6.84	-1.27	-0.77	-0.92	-0.85
Ecosystems	species-yr	-0.66	-0.86	-0.88	-0.63	6.67	-0.23	1.14	13.37	-0.78	-0.89	-0.91	-0.77
Resources	USD2013	-1.23	-1.51	-0.99	-1.24	-4.24	1.27	-1.05	-3.18	-0.98	-0.95	-0.96	-0.97

Table S42. Normalized sensitivity coefficients for perturbation (lower) of crop yield without biochar addition for scenarios 1-12 (Table 1). Values highlighted red and yellow correspond to coefficients larger and smaller than 0.3 and -0.3, respectively (medium sensitivity).

		1	2	3	4	5	6	7	8	9	10	11	12
Impact category	Unit	flame curtain, NT	flame curtain, N	flame curtain, LS	flame curtain, LJ	retort, NT	retort, N	retort, LS	retort, LJ	earth-mound, NT	earth-mound, N	earth-mound, LS	earth-mound, LJ
Global warming	DALY	0.08	0.28	0.33	0.10	-2.07	-0.67	-0.96	-2.36	0.13	0.35	0.42	0.16
Global warming (terrestrial)	species.yr	0.08	0.28	0.33	0.10	-2.07	-0.67	-0.97	-2.36	0.13	0.35	0.42	0.16
Global warming (freshwater)	species.yr	0.08	0.28	0.33	0.10	-2.07	-0.67	-0.96	-2.35	0.13	0.35	0.42	0.16
Stratospheric ozone depletion	DALY	0.90	0.97	0.89	0.92	0.90	0.97	0.89	0.92	0.90	0.97	0.89	0.92
Ionizing radiation	DALY	0.02	0.00	0.00	0.02	0.02	0.00	0.00	0.02	0.01	0.00	0.00	0.01
Ozone formation	DALY	1.63	1.05	0.92	1.65	-0.27	2.64	2.07	-0.31	-0.22	3.69	2.85	-0.25
Particulate matter formation	DALY	0.00	0.00	0.01	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.08	0.00
Ozone formation (terrestrial eco)	species.yr	1.83	1.03	0.79	1.98	-0.25	2.95	1.57	-0.28	-0.15	121.42	4.05	-0.17
Acidification (terrestrial)	species.yr	0.99	0.99	0.98	1.00	0.98	0.99	0.98	0.99	1.00	0.99	0.98	1.01
Eutrophication (freshwater)	species.yr	-0.80	1.24	0.34	-0.51	-2.20	1.12	0.33	-0.89	0.59	0.81	0.29	1.34
Ecotoxicity (terrestrial)	species.yr	1.01	1.00	1.00	1.01	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ecotoxicity (freshwater)	species.yr	0.97	0.93	0.83	1.06	0.92	0.93	0.82	1.00	0.77	0.90	0.80	0.85
Ecotoxicity (marine)	species.yr	2.02	1.46	0.20	-16.64	0.48	1.27	0.19	0.56	0.18	0.70	0.17	0.22
Toxicity (carcinogenic)	DALY	-3.93	1.18	1.08	-6.12	1.92	1.05	0.96	1.82	0.87	0.96	0.88	0.91
Toxicity (non-carcinogenic)	DALY	0.15	0.09	0.22	1.45	0.12	0.09	0.21	0.43	0.10	0.09	0.20	0.25
Land use (mammals)	species.yr	0.01	0.00	0.00	0.01	-12.92	-0.04	-3.17	13.04	0.01	0.00	0.00	0.01
Land use (birds)	species.yr	0.01	0.00	0.00	0.01	43.40	-1.17	-8.38	10.04	0.01	0.00	0.00	0.01
Land use (plants)	species.yr	0.01	0.00	0.00	0.01	60.60	-0.34	-8.69	10.00	0.01	0.00	0.00	0.01
Land use (amphibians)	species.yr	0.01	0.00	0.00	0.01	-442.63	-0.92	-5.99	10.68	0.01	0.00	0.00	0.01
Land use (reptiles)	species.yr	0.01	0.00	0.00	0.01	-12.90	-0.59	-3.34	12.73	0.01	0.00	0.00	0.01
Mineral resource scarcity	USD2013	-0.01	0.00	0.00	0.00	0.00	0.00	-0.02	0.00	0.01	0.00	0.00	0.01
Fossil resource scarcity	USD2013	0.01	0.00	0.00	0.01	0.03	0.00	0.00	0.02	0.01	0.00	0.00	0.01
Water use (terrestrial)	species.yr	0.94	0.00	0.46	0.65	0.93	0.00	0.46	0.65	0.93	0.00	0.46	0.63
Water use (freshwater)	species.yr	1.00	0.00	0.97	0.98	1.00	0.00	0.97	0.98	1.00	0.00	0.97	0.98
Water use	DALY	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01
Eutrophication (marine)	species.yr	0.96	0.97	0.96	0.98	1.04	0.98	0.97	1.05	1.01	0.97	0.96	1.03
Human health	DALY	0.24	0.45	0.36	0.26	-2.71	-0.15	-0.24	-2.56	0.51	0.51	0.39	0.42
Ecosystems	species-yr	0.49	0.57	0.74	0.55	-2.26	0.33	0.00	-4.65	0.58	0.59	0.77	0.67
Resources	USD2013	0.01	0.00	0.00	0.01	0.05	0.00	0.00	0.03	0.01	0.00	0.00	0.01

Table S43. Normalized sensitivity coefficients for perturbation (higher) of crop yield without biochar addition for scenarios 1-12 (Table 1). Values highlighted red and yellow correspond to coefficients larger and smaller than 0.3 and -0.3, respectively (medium sensitivity).

		1	2	3	4	5	6	7	8	9	10	11	12
Impact category	Unit	flame curtain, NT	flame curtain, N	flame curtain, LS	flame curtain, LJ	retort, NT	retort, N	retort, LS	retort, LJ	earth-mound, NT	earth-mound, N	earth-mound, LS	earth-mound, LJ
Global warming	DALY	0.08	0.28	0.33	0.09	2.25	1.24	1.65	2.56	0.13	0.35	0.42	0.15
Global warming (terrestrial)	species.yr	0.08	0.28	0.33	0.09	2.25	1.24	1.65	2.56	0.13	0.35	0.42	0.15
Global warming (freshwater)	species.yr	0.08	0.28	0.33	0.09	2.24	1.23	1.65	2.56	0.13	0.35	0.42	0.15
Stratospheric ozone depletion	DALY	0.88	0.97	0.89	0.91	0.88	0.97	0.89	0.91	0.88	0.97	0.89	0.91
Ionizing radiation	DALY	-0.02	0.00	0.00	-0.02	-0.02	0.00	0.00	-0.02	-0.01	0.00	0.00	-0.01
Ozone formation	DALY	0.51	0.92	0.79	0.59	-0.27	2.64	2.06	-0.31	-0.22	3.70	2.83	-0.25
Particulate matter formation	DALY	0.00	0.00	-0.01	0.00	0.00	0.00	-0.02	0.00	0.00	0.00	-0.08	0.00
Ozone formation (terrestrial eco)	species.yr	0.56	0.90	0.67	0.71	-0.24	2.95	1.55	-0.27	-0.15	121.66	4.02	-0.16
Acidification (terrestrial)	species.yr	0.96	0.99	0.98	0.98	1.04	1.00	0.99	1.05	0.98	0.99	0.98	0.99
Eutrophication (freshwater)	species.yr	-0.72	1.24	0.33	-0.49	-2.00	1.12	0.32	-0.85	0.54	0.81	0.29	1.28
Ecotoxicity (terrestrial)	species.yr	0.99	1.00	0.99	0.99	0.99	1.00	0.99	0.99	0.98	1.00	0.99	0.99
Ecotoxicity (freshwater)	species.yr	0.94	0.94	0.82	1.04	0.90	0.93	0.81	0.98	0.75	0.90	0.79	0.83
Ecotoxicity (marine)	species.yr	1.78	1.46	0.19	-15.43	0.43	1.27	0.18	0.52	0.16	0.71	0.17	0.21
Toxicity (carcinogenic)	DALY	-3.84	1.18	1.08	-6.01	1.87	1.06	0.95	1.79	0.85	0.96	0.88	0.90
Toxicity (non-carcinogenic)	DALY	0.12	0.09	0.22	1.36	0.09	0.09	0.20	0.40	0.08	0.09	0.19	0.24
Land use (mammals)	species.yr	-0.01	0.00	0.00	-0.01	12.92	0.04	3.17	-13.04	-0.01	0.00	0.00	-0.01
Land use (birds)	species.yr	-0.01	0.00	0.00	-0.01	-43.40	1.17	8.38	-10.04	-0.01	0.00	0.00	-0.01
Land use (plants)	species.yr	-0.01	0.00	0.00	-0.01	-60.60	0.34	8.69	-10.00	-0.01	0.00	0.00	-0.01
Land use (amphibians)	species.yr	-0.01	0.00	0.00	-0.01	442.63	0.92	5.99	-10.68	-0.01	0.00	0.00	-0.01
Land use (reptiles)	species.yr	-0.01	0.00	0.00	-0.01	12.90	0.59	3.34	-12.73	-0.01	0.00	0.00	-0.01
Mineral resource scarcity	USD2013	0.01	0.00	0.00	0.00	0.00	0.00	0.02	0.00	-0.01	0.00	0.00	-0.01
Fossil resource scarcity	USD2013	-0.01	0.00	0.00	-0.01	-0.03	0.00	0.00	-0.02	-0.01	0.00	0.00	-0.01
Water use (terrestrial)	species.yr	0.91	0.00	0.46	0.64	0.91	0.00	0.46	0.63	0.91	0.00	0.45	0.61
Water use (freshwater)	species.yr	0.98	0.00	0.96	0.97	0.98	0.00	0.96	0.97	0.98	0.00	0.96	0.97
Water use	DALY	-0.01	0.00	0.00	-0.01	-0.01	0.00	0.00	-0.01	-0.01	0.00	0.00	-0.01
Eutrophication (marine)	species.yr	0.92	0.97	0.95	0.95	1.01	0.98	0.96	1.04	0.99	0.97	0.96	1.01
Human health	DALY	0.23	0.45	0.35	0.25	3.29	1.07	0.97	3.13	0.48	0.51	0.39	0.41
Ecosystems	species-yr	0.47	0.57	0.73	0.53	3.50	0.83	1.60	6.39	0.56	0.59	0.77	0.66
Resources	USD2013	-0.01	0.00	0.00	-0.01	-0.05	0.00	0.00	-0.03	-0.01	0.00	0.00	-0.01

Table S44. Normalized sensitivity coefficients for perturbation (lower) of crop yield change when biochar is used for scenarios 1-12 (Table 1). Values highlighted red and yellow correspond to coefficients larger and smaller than 0.3 and -0.3, respectively (medium sensitivity).

		1	2	3	4	5	6	7	8	9	10	11	12
Impact category	Unit	flame curtain, NT	flame curtain, N	flame curtain, LS	flame curtain, LJ	retort, NT	retort, N	retort, LS	retort, LJ	earth-mound, NT	earth-mound, N	earth-mound, LS	earth-mound, LJ
Global warming	DALY	0.12	0.29	0.47	0.13	0.12	0.29	0.49	0.14	0.18	0.36	0.60	0.21
Global warming (terrestrial)	species.yr	0.12	0.29	0.47	0.13	0.12	0.29	0.49	0.14	0.18	0.36	0.60	0.21
Global warming (freshwater)	species.yr	0.12	0.29	0.47	0.13	0.12	0.29	0.49	0.14	0.18	0.36	0.60	0.21
Stratospheric ozone depletion	DALY	1.00	1.02	1.00	1.00	1.01	1.02	1.00	1.00	1.00	1.02	1.00	1.00
Ionizing radiation	DALY	1.79	1.48	1.08	2.44	2.32	1.96	1.09	3.10	1.00	1.02	1.00	1.00
Ozone formation	DALY	1.33	1.06	1.04	1.31	-0.34	2.85	2.52	-0.36	-0.27	3.99	3.46	-0.29
Particulate matter formation	DALY	-0.17	-0.10	2.49	-0.26	-0.11	-0.06	9.13	-0.16	-0.10	-0.06	30.00	-0.15
Ozone formation (terrestrial eco)	species.yr	1.83	1.11	1.08	1.84	-0.37	3.40	2.31	-0.37	-0.23	139.97	5.97	-0.23
Acidification (terrestrial)	species.yr	1.01	1.02	1.00	1.01	1.04	1.02	1.01	1.04	1.02	1.02	1.00	1.02
Eutrophication (freshwater)	species.yr	-3.35	2.00	1.29	-1.56	-9.27	1.81	1.23	-2.72	2.48	1.31	1.12	4.09
Ecotoxicity (terrestrial)	species.yr	1.00	1.02	1.00	1.01	1.01	1.02	1.00	1.01	1.00	1.02	1.00	1.00
Ecotoxicity (freshwater)	species.yr	1.26	1.05	1.03	1.26	1.21	1.05	1.03	1.18	1.00	1.02	1.00	1.00
Ecotoxicity (marine)	species.yr	11.13	2.11	1.16	-75.14	2.67	1.83	1.09	2.51	1.00	1.02	1.00	1.00
Toxicity (carcinogenic)	DALY	-4.51	1.25	1.23	-6.71	2.20	1.12	1.09	2.00	1.00	1.02	1.00	1.00
Toxicity (non-carcinogenic)	DALY	1.50	1.07	1.12	5.75	1.22	1.05	1.06	1.70	1.00	1.02	1.00	1.00
Land use (mammals)	species.yr	1.00	1.02	1.00	1.00	2.69	1.03	1.41	-0.70	1.00	1.02	1.00	1.00
Land use (birds)	species.yr	1.00	1.02	1.00	1.00	-4.66	1.17	2.09	-0.31	1.00	1.02	1.00	1.00
Land use (plants)	species.yr	1.00	1.02	1.00	1.00	-6.91	1.06	2.13	-0.30	1.00	1.02	1.00	1.00
Land use (amphibians)	species.yr	1.00	1.02	1.00	1.01	59.04	1.14	1.78	-0.39	1.00	1.02	1.00	1.00
Land use (reptiles)	species.yr	1.00	1.02	1.00	1.00	2.69	1.10	1.44	-0.66	1.00	1.02	1.00	1.00
Mineral resource scarcity	USD2013	-0.69	-0.23	1.81	-0.39	-0.19	-0.08	-7.38	-0.12	1.00	1.02	1.00	1.00
Fossil resource scarcity	USD2013	1.20	1.48	1.02	1.22	3.20	-1.68	1.08	2.50	1.00	1.02	1.00	1.00
Water use (terrestrial)	species.yr	1.01	1.29	1.01	1.04	1.01	1.32	1.01	1.04	1.00	1.02	1.00	1.00
Water use (freshwater)	species.yr	1.00	1.29	1.00	1.01	1.00	1.32	1.00	1.00	1.00	1.02	1.00	1.00
Water use	DALY	1.10	1.16	1.01	1.10	1.08	1.17	1.01	1.08	1.00	1.02	1.00	1.00
Eutrophication (marine)	species.yr	1.01	1.02	1.00	1.01	1.10	1.03	1.01	1.09	1.07	1.03	1.01	1.07
Human health	DALY	0.62	0.73	0.87	0.53	0.75	0.75	0.89	0.59	1.30	0.83	0.96	0.88
Ecosystems	species-yr	0.67	0.92	0.91	0.64	0.87	0.94	0.99	1.03	0.80	0.95	0.95	0.79
Resources	USD2013	1.26	1.61	1.03	1.27	4.34	-1.37	1.10	3.28	1.00	1.02	1.00	1.00

Table S45. Normalized sensitivity coefficients for perturbation (higher) of crop yield change when biochar is used for scenarios 1-12 (Table 1). Values highlighted red and yellow correspond to coefficients larger and smaller than 0.3 and -0.3, respectively (medium sensitivity).

		1	2	3	4	5	6	7	8	9	10	11	12
Impact category	Unit	flame curtain, NT	flame curtain, N	flame curtain, LS	flame curtain, LJ	retort, NT	retort, N	retort, LS	retort, LJ	earth-mound, NT	earth-mound, N	earth-mound, LS	earth-mound, LJ
Global warming	DALY	-0.06	-0.14	-0.26	-0.07	-0.07	-0.15	-0.27	-0.08	-0.10	-0.18	-0.33	-0.12
Global warming (terrestrial)	species.yr	-0.06	-0.14	-0.26	-0.07	-0.07	-0.15	-0.27	-0.08	-0.10	-0.18	-0.33	-0.11
Global warming (freshwater)	species.yr	-0.06	-0.14	-0.26	-0.07	-0.07	-0.15	-0.27	-0.08	-0.10	-0.18	-0.33	-0.11
Stratospheric ozone depletion	DALY	-0.55	-0.51	-0.55	-0.55	-0.55	-0.51	-0.55	-0.55	-0.55	-0.51	-0.55	-0.55
Ionizing radiation	DALY	-0.98	-0.74	-0.59	-1.33	-1.27	-0.98	-0.60	-1.69	-0.55	-0.51	-0.55	-0.55
Ozone formation	DALY	-0.73	-0.53	-0.57	-0.71	0.18	-1.43	-1.38	0.20	0.15	-2.00	-1.90	0.16
Particulate matter formation	DALY	0.09	0.05	-1.37	0.14	0.06	0.03	-5.02	0.09	0.05	0.03	-16.50	0.08
Ozone formation (terrestrial eco)	species.yr	-1.00	-0.56	-0.59	-1.00	0.20	-1.70	-1.27	0.20	0.12	-70.07	-3.29	0.12
Acidification (terrestrial)	species.yr	-0.55	-0.51	-0.55	-0.55	-0.57	-0.51	-0.55	-0.57	-0.56	-0.51	-0.55	-0.56
Eutrophication (freshwater)	species.yr	1.83	-1.00	-0.71	0.85	5.06	-0.91	-0.68	1.48	-1.36	-0.66	-0.61	-2.23
Ecotoxicity (terrestrial)	species.yr	-0.55	-0.51	-0.55	-0.55	-0.55	-0.51	-0.55	-0.55	-0.55	-0.51	-0.55	-0.55
Ecotoxicity (freshwater)	species.yr	-0.69	-0.53	-0.57	-0.69	-0.66	-0.53	-0.56	-0.65	-0.55	-0.51	-0.55	-0.55
Ecotoxicity (marine)	species.yr	-6.08	-1.06	-0.64	41.06	-1.46	-0.92	-0.60	-1.37	-0.55	-0.51	-0.55	-0.55
Toxicity (carcinogenic)	DALY	2.46	-0.63	-0.68	3.67	-1.20	-0.56	-0.60	-1.09	-0.55	-0.51	-0.55	-0.55
Toxicity (non-carcinogenic)	DALY	-0.82	-0.53	-0.62	-3.14	-0.67	-0.52	-0.58	-0.93	-0.55	-0.51	-0.55	-0.55
Land use (mammals)	species.yr	-0.55	-0.51	-0.55	-0.55	-1.47	-0.51	-0.78	0.38	-0.55	-0.51	-0.55	-0.55
Land use (birds)	species.yr	-0.55	-0.51	-0.55	-0.55	2.55	-0.59	-1.15	0.17	-0.55	-0.51	-0.55	-0.55
Land use (plants)	species.yr	-0.55	-0.51	-0.55	-0.55	3.78	-0.53	-1.17	0.16	-0.55	-0.51	-0.55	-0.55
Land use (amphibians)	species.yr	-0.55	-0.51	-0.55	-0.55	-32.26	-0.57	-0.98	0.21	-0.55	-0.51	-0.55	-0.55
Land use (reptiles)	species.yr	-0.55	-0.51	-0.55	-0.55	-1.47	-0.55	-0.79	0.36	-0.55	-0.51	-0.55	-0.55
Mineral resource scarcity	USD2013	0.38	0.11	-0.99	0.21	0.10	0.04	4.06	0.07	-0.55	-0.51	-0.55	-0.55
Fossil resource scarcity	USD2013	-0.66	-0.74	-0.56	-0.66	-1.75	0.84	-0.60	-1.37	-0.55	-0.51	-0.55	-0.55
Water use (terrestrial)	species.yr	-0.55	-0.65	-0.55	-0.57	-0.55	-0.66	-0.55	-0.57	-0.55	-0.51	-0.55	-0.55
Water use (freshwater)	species.yr	-0.55	-0.65	-0.55	-0.55	-0.55	-0.66	-0.55	-0.55	-0.55	-0.51	-0.55	-0.55
Water use	DALY	-0.60	-0.58	-0.56	-0.60	-0.59	-0.58	-0.56	-0.59	-0.55	-0.51	-0.55	-0.55
Eutrophication (marine)	species.yr	-0.55	-0.51	-0.55	-0.55	-0.60	-0.52	-0.56	-0.59	-0.59	-0.51	-0.56	-0.58
Human health	DALY	-0.34	-0.36	-0.48	-0.29	-0.41	-0.38	-0.49	-0.33	-0.71	-0.42	-0.53	-0.48
Ecosystems	species-yr	-0.37	-0.46	-0.50	-0.35	-0.48	-0.47	-0.55	-0.56	-0.44	-0.48	-0.52	-0.43
Resources	USD2013	-0.69	-0.81	-0.57	-0.70	-2.37	0.68	-0.60	-1.79	-0.55	-0.51	-0.55	-0.55

Table S46. Normalized sensitivity coefficients for perturbation (lower) of mineralization rate constant for the recalcitrant biochar carbon pool for scenarios 1-12 (Table 1).

		1	2	3	4	5	6	7	8	9	10	11	12
Impact category	Unit	flame curtain, NT	flame curtain, N	flame curtain, LS	flame curtain, LJ	retort, NT	retort, N	retort, LS	retort, LJ	earth-mound, NT	earth-mound, N	earth-mound, LS	earth-mound, LJ
Global warming	DALY	-0.07	-0.04	-0.04	-0.07	-0.39	-0.18	-0.23	-0.44	-0.11	-0.05	-0.05	-0.12
Global warming (terrestrial)	species.yr	-0.07	-0.04	-0.04	-0.07	-0.39	-0.18	-0.23	-0.44	-0.11	-0.05	-0.05	-0.12
Global warming (freshwater)	species.yr	-0.07	-0.04	-0.04	-0.07	-0.39	-0.18	-0.23	-0.44	-0.11	-0.05	-0.05	-0.12
Stratospheric ozone depletion	DALY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ionizing radiation	DALY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ozone formation	DALY	0.07	0.01	0.01	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Particulate matter formation	DALY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Ozone formation (terrestrial eco)	species.yr	0.08	0.01	0.01	0.08	0.00	0.00	0.00	0.00	0.00	-0.02	0.00	0.00
Acidification (terrestrial)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eutrophication (freshwater)	species.yr	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity (terrestrial)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity (freshwater)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity (marine)	species.yr	0.02	0.00	0.00	-0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toxicity (carcinogenic)	DALY	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toxicity (non-carcinogenic)	DALY	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land use (mammals)	species.yr	0.00	0.00	0.00	0.00	-1.70	-0.01	-0.42	1.71	0.00	0.00	0.00	0.00
Land use (birds)	species.yr	0.00	0.00	0.00	0.00	5.70	-0.15	-1.10	1.32	0.00	0.00	0.00	0.00
Land use (plants)	species.yr	0.00	0.00	0.00	0.00	7.96	-0.05	-1.14	1.31	0.00	0.00	0.00	0.00
Land use (amphibians)	species.yr	0.00	0.00	0.00	0.00	-58.17	-0.12	-0.79	1.40	0.00	0.00	0.00	0.00
Land use (reptiles)	species.yr	0.00	0.00	0.00	0.00	-1.70	-0.08	-0.44	1.67	0.00	0.00	0.00	0.00
Mineral resource scarcity	USD2013	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fossil resource scarcity	USD2013	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water use (terrestrial)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water use (freshwater)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water use	DALY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water use, marginal	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eutrophication (marine)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Human health	DALY	-0.08	-0.02	-0.02	-0.08	-0.55	-0.12	-0.11	-0.51	-0.18	-0.03	-0.02	-0.14
Ecosystems	species-yr	-0.03	-0.01	-0.01	-0.03	-0.43	-0.04	-0.12	-0.80	-0.03	-0.01	-0.01	-0.04
Resources	USD2013	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table S47. Normalized sensitivity coefficients for perturbation (higher) of mineralization rate constant for the recalcitrant biochar carbon pool for scenarios 1-12 (Table 1).

		1	2	3	4	5	6	7	8	9	10	11	12
Impact category	Unit	flame curtain, NT	flame curtain, N	flame curtain, LS	flame curtain, LJ	retort, NT	retort, N	retort, LS	retort, LJ	earth-mound, NT	earth-mound, N	earth-mound, LS	earth-mound, LJ
Global warming	DALY	-0.06	-0.03	-0.03	-0.06	-0.04	-0.02	-0.02	-0.04	-0.09	-0.04	-0.04	-0.10
Global warming (terrestrial)	species.yr	-0.06	-0.03	-0.03	-0.06	-0.04	-0.02	-0.02	-0.04	-0.09	-0.04	-0.04	-0.10
Global warming (freshwater)	species.yr	-0.06	-0.03	-0.03	-0.06	-0.04	-0.02	-0.02	-0.04	-0.09	-0.04	-0.04	-0.10
Stratospheric ozone depletion	DALY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ionizing radiation	DALY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ozone formation	DALY	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Particulate matter formation	DALY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ozone formation (terrestrial eco)	species.yr	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Acidification (terrestrial)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eutrophication (freshwater)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity (terrestrial)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity (freshwater)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity (marine)	species.yr	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toxicity (carcinogenic)	DALY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toxicity (non-carcinogenic)	DALY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land use (mammals)	species.yr	0.00	0.00	0.00	0.00	0.27	0.00	0.07	-0.28	0.00	0.00	0.00	0.00
Land use (birds)	species.yr	0.00	0.00	0.00	0.00	-0.92	0.02	0.18	-0.21	0.00	0.00	0.00	0.00
Land use (plants)	species.yr	0.00	0.00	0.00	0.00	-1.29	0.01	0.18	-0.21	0.00	0.00	0.00	0.00
Land use (amphibians)	species.yr	0.00	0.00	0.00	0.00	9.42	0.02	0.13	-0.23	0.00	0.00	0.00	0.00
Land use (reptiles)	species.yr	0.00	0.00	0.00	0.00	0.27	0.01	0.07	-0.27	0.00	0.00	0.00	0.00
Mineral resource scarcity	USD2013	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fossil resource scarcity	USD2013	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water use (terrestrial)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water use (freshwater)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water use	DALY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eutrophication (marine)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Human health	DALY	-0.07	-0.02	-0.02	-0.07	-0.06	-0.02	-0.01	-0.05	-0.15	-0.02	-0.02	-0.11
Ecosystems	species-yr	-0.02	0.00	-0.01	-0.03	0.02	0.00	0.01	0.06	-0.03	0.00	-0.01	-0.03
Resources	USD2013	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table S48. Normalized sensitivity coefficients for perturbation (lower) of biochar priming effect for scenarios 1-12 (Table 1). Values highlighted red and yellow correspond to coefficients larger and smaller than 0.3 and -0.3, respectively (medium sensitivity).

		1	2	3	4	5	6	7	8	9	10	11	12
Impact category	Unit	flame curtain, NT	flame curtain, N	flame curtain, LS	flame curtain, LJ	retort, NT	retort, N	retort, LS	retort, LJ	earth-mound, NT	earth-mound, N	earth-mound, LS	earth-mound, LJ
Global warming	DALY	0.07	0.29	0.06	0.02	-0.77	-0.08	-0.45	-0.94	0.11	0.36	0.07	0.03
Global warming (terrestrial)	species.yr	0.07	0.29	0.06	0.02	-0.77	-0.08	-0.45	-0.94	0.11	0.36	0.07	0.03
Global warming (freshwater)	species.yr	0.07	0.29	0.06	0.02	-0.77	-0.08	-0.45	-0.94	0.11	0.36	0.07	0.03
Stratospheric ozone depletion	DALY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ionizing radiation	DALY	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Ozone formation	DALY	0.22	0.03	0.03	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Particulate matter formation	DALY	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.03	0.00
Ozone formation (terrestrial eco)	species.yr	0.25	0.03	0.02	0.25	0.00	0.00	0.00	0.00	0.00	-0.05	0.01	0.00
Acidification (terrestrial)	species.yr	0.01	0.00	0.00	0.00	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
Eutrophication (freshwater)	species.yr	-0.01	0.00	0.00	0.00	-0.04	0.00	0.00	-0.01	0.01	0.00	0.00	0.01
Ecotoxicity (terrestrial)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity (freshwater)	species.yr	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity (marine)	species.yr	0.05	0.00	0.00	-0.24	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Toxicity (carcinogenic)	DALY	-0.02	0.00	0.00	-0.02	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Toxicity (non-carcinogenic)	DALY	0.01	0.00	0.00	0.02	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Land use (mammals)	species.yr	0.00	0.00	0.00	0.00	-5.04	-0.02	-1.24	5.08	0.00	0.00	0.00	0.00
Land use (birds)	species.yr	0.00	0.00	0.00	0.00	16.92	-0.46	-3.27	3.92	0.00	0.00	0.00	0.00
Land use (plants)	species.yr	0.00	0.00	0.00	0.00	23.64	-0.13	-3.39	3.90	0.00	0.00	0.00	0.00
Land use (amphibians)	species.yr	0.00	0.00	0.00	0.00	-172.63	-0.36	-2.34	4.16	0.00	0.00	0.00	0.00
Land use (reptiles)	species.yr	0.00	0.00	0.00	0.00	-5.03	-0.23	-1.30	4.96	0.00	0.00	0.00	0.00
Mineral resource scarcity	USD2013	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00
Fossil resource scarcity	USD2013	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Water use (terrestrial)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water use (freshwater)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water use	DALY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eutrophication (marine)	species.yr	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Human health	DALY	0.09	0.18	0.03	0.02	-1.06	-0.05	-0.21	-1.09	0.19	0.21	0.03	0.04
Ecosystems	species-yr	0.03	0.04	0.01	0.01	-1.09	-0.06	-0.30	-2.14	0.04	0.04	0.01	0.01
Resources	USD2013	0.01	0.00	0.00	0.00	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.00

Table S49. Normalized sensitivity coefficients for perturbation (higher) of biochar priming effect for scenarios 1-12 (Table 1). Values highlighted red and yellow correspond to coefficients larger and smaller than 0.3 and -0.3, respectively (medium sensitivity).

		1	2	3	4	5	6	7	8	9	10	11	12
Impact category	Unit	flame curtain, NT	flame curtain, N	flame curtain, LS	flame curtain, LJ	retort, NT	retort, N	retort, LS	retort, LJ	earth-mound, NT	earth-mound, N	earth-mound, LS	earth-mound, LJ
Global warming	DALY	0.07	0.29	0.06	0.02	0.92	0.66	0.57	0.98	0.11	0.36	0.07	0.03
Global warming (terrestrial)	species.yr	0.07	0.29	0.06	0.02	0.92	0.66	0.57	0.98	0.11	0.36	0.07	0.03
Global warming (freshwater)	species.yr	0.07	0.29	0.06	0.02	0.92	0.66	0.57	0.98	0.11	0.36	0.07	0.03
Stratospheric ozone depletion	DALY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ionizing radiation	DALY	-0.01	0.00	0.00	-0.01	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
Ozone formation	DALY	-0.22	-0.03	-0.03	-0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Particulate matter formation	DALY	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	-0.03	0.00
Ozone formation (terrestrial eco)	species.yr	-0.25	-0.03	-0.02	-0.25	0.00	0.00	0.00	0.00	0.00	0.05	-0.01	0.00
Acidification (terrestrial)	species.yr	-0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Eutrophication (freshwater)	species.yr	0.01	0.00	0.00	0.00	0.04	0.00	0.00	0.01	-0.01	0.00	0.00	-0.01
Ecotoxicity (terrestrial)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity (freshwater)	species.yr	-0.01	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity (marine)	species.yr	-0.05	0.00	0.00	0.24	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
Toxicity (carcinogenic)	DALY	0.02	0.00	0.00	0.02	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
Toxicity (non-carcinogenic)	DALY	-0.01	0.00	0.00	-0.02	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
Land use (mammals)	species.yr	0.00	0.00	0.00	0.00	5.04	0.02	1.24	-5.08	0.00	0.00	0.00	0.00
Land use (birds)	species.yr	0.00	0.00	0.00	0.00	-16.92	0.46	3.27	-3.92	0.00	0.00	0.00	0.00
Land use (plants)	species.yr	0.00	0.00	0.00	0.00	-23.64	0.13	3.39	-3.90	0.00	0.00	0.00	0.00
Land use (amphibians)	species.yr	0.00	0.00	0.00	0.00	172.63	0.36	2.34	-4.16	0.00	0.00	0.00	0.00
Land use (reptiles)	species.yr	0.00	0.00	0.00	0.00	5.03	0.23	1.30	-4.96	0.00	0.00	0.00	0.00
Mineral resource scarcity	USD2013	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Fossil resource scarcity	USD2013	-0.01	0.00	0.00	0.00	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
Water use (terrestrial)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water use (freshwater)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water use	DALY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eutrophication (marine)	species.yr	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Human health	DALY	0.08	0.18	0.03	0.02	1.28	0.42	0.26	1.13	0.18	0.21	0.03	0.03
Ecosystems	species-yr	0.02	0.04	0.01	0.00	1.16	0.14	0.32	2.16	0.03	0.04	0.01	0.01
Resources	USD2013	-0.01	0.00	0.00	0.00	-0.02	0.00	0.00	-0.01	0.00	0.00	0.00	0.00

Table S50. Normalized sensitivity coefficients for perturbation (lower) of water use for irrigation for scenarios 1-12 (Table 1). Values highlighted red and yellow correspond to coefficients larger and smaller than 0.3 and -0.3, respectively (medium sensitivity).

		1	2	3	4	5	6	7	8	9	10	11	12
Impact category	Unit	flame curtain, NT	flame curtain, N	flame curtain, LS	flame curtain, LJ	retort, NT	retort, N	retort, LS	retort, LJ	earth-mound, NT	earth-mound, N	earth-mound, LS	earth-mound, LJ
Global warming	DALY	0.00	0.00	0.00	0.00	-0.97	-0.43	-0.59	-1.10	0.00	0.00	0.00	0.00
Global warming (terrestrial)	species.yr	0.00	0.00	0.00	0.00	-0.97	-0.43	-0.59	-1.10	0.00	0.00	0.00	0.00
Global warming (freshwater)	species.yr	0.00	0.00	0.00	0.00	-0.97	-0.43	-0.58	-1.10	0.00	0.00	0.00	0.00
Stratospheric ozone depletion	DALY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ionizing radiation	DALY	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Ozone formation	DALY	0.25	0.03	0.03	0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Particulate matter formation	DALY	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.04	0.00
Ozone formation (terrestrial eco)	species.yr	0.28	0.03	0.03	0.28	0.00	0.00	0.00	0.00	0.00	-0.05	0.01	0.00
Acidification (terrestrial)	species.yr	0.01	0.00	0.00	0.00	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
Eutrophication (freshwater)	species.yr	-0.02	0.00	0.00	-0.01	-0.04	0.00	0.00	-0.01	0.01	0.00	0.00	0.01
Ecotoxicity (terrestrial)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity (freshwater)	species.yr	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity (marine)	species.yr	0.05	0.00	0.00	-0.27	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Toxicity (carcinogenic)	DALY	-0.02	0.00	0.00	-0.02	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Toxicity (non-carcinogenic)	DALY	0.01	0.00	0.00	0.02	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Land use (mammals)	species.yr	0.00	0.00	0.00	0.00	-5.78	-0.02	-1.42	5.84	0.00	0.00	0.00	0.00
Land use (birds)	species.yr	0.00	0.00	0.00	0.00	19.43	-0.52	-3.75	4.50	0.00	0.00	0.00	0.00
Land use (plants)	species.yr	0.00	0.00	0.00	0.00	27.14	-0.15	-3.89	4.48	0.00	0.00	0.00	0.00
Land use (amphibians)	species.yr	0.00	0.00	0.00	0.00	-198.20	-0.41	-2.68	4.78	0.00	0.00	0.00	0.00
Land use (reptiles)	species.yr	0.00	0.00	0.00	0.00	-5.78	-0.26	-1.49	5.70	0.00	0.00	0.00	0.00
Mineral resource scarcity	USD2013	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00
Fossil resource scarcity	USD2013	0.01	0.00	0.00	0.00	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Water use (terrestrial)	species.yr	0.93	0.00	0.46	0.65	0.93	0.00	0.46	0.64	0.92	0.00	0.46	0.62
Water use (freshwater)	species.yr	1.00	0.00	0.97	0.98	1.00	0.00	0.97	0.98	0.99	0.00	0.97	0.98
Water use	DALY	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eutrophication (marine)	species.yr	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Human health	DALY	0.00	0.00	0.00	0.00	-1.34	-0.27	-0.27	-1.27	0.01	0.00	0.00	0.00
Ecosystems	species-yr	0.03	0.00	0.00	0.01	-1.26	-0.11	-0.35	-2.46	0.03	0.00	0.00	0.01
Resources	USD2013	0.01	0.00	0.00	0.00	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.00

Table S51. Normalized sensitivity coefficients for perturbation (higher) of water use for irrigation for scenarios 1-12 (Table 1). Values highlighted red and yellow correspond to coefficients larger and smaller than 0.3 and -0.3, respectively (medium sensitivity).

		1	2	3	4	5	6	7	8	9	10	11	12
Impact category	Unit	flame curtain, NT	flame curtain, N	flame curtain, LS	flame curtain, LJ	retort, NT	retort, N	retort, LS	retort, LJ	earth-mound, NT	earth-mound, N	earth-mound, LS	earth-mound, LJ
Global warming	DALY	0.00	0.00	0.00	0.00	0.97	0.43	0.59	1.10	0.00	0.00	0.00	0.00
Global warming (terrestrial)	species.yr	0.00	0.00	0.00	0.00	0.97	0.43	0.59	1.10	0.00	0.00	0.00	0.00
Global warming (freshwater)	species.yr	0.00	0.00	0.00	0.00	0.97	0.43	0.58	1.10	0.00	0.00	0.00	0.00
Stratospheric ozone depletion	DALY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ionizing radiation	DALY	-0.01	0.00	0.00	-0.01	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
Ozone formation	DALY	-0.25	-0.03	-0.03	-0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Particulate matter formation	DALY	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	-0.04	0.00
Ozone formation (terrestrial eco)	species.yr	-0.28	-0.03	-0.03	-0.28	0.00	0.00	0.00	0.00	0.00	0.05	-0.01	0.00
Acidification (terrestrial)	species.yr	-0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Eutrophication (freshwater)	species.yr	0.02	0.00	0.00	0.01	0.04	0.00	0.00	0.01	-0.01	0.00	0.00	-0.01
Ecotoxicity (terrestrial)	species.yr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity (freshwater)	species.yr	-0.01	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity (marine)	species.yr	-0.05	0.00	0.00	0.27	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
Toxicity (carcinogenic)	DALY	0.02	0.00	0.00	0.02	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
Toxicity (non-carcinogenic)	DALY	-0.01	0.00	0.00	-0.02	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
Land use (mammals)	species.yr	0.00	0.00	0.00	0.00	5.78	0.02	1.42	-5.84	0.00	0.00	0.00	0.00
Land use (birds)	species.yr	0.00	0.00	0.00	0.00	-19.43	0.52	3.75	-4.50	0.00	0.00	0.00	0.00
Land use (plants)	species.yr	0.00	0.00	0.00	0.00	-27.14	0.15	3.89	-4.48	0.00	0.00	0.00	0.00
Land use (amphibians)	species.yr	0.00	0.00	0.00	0.00	198.20	0.41	2.68	-4.78	0.00	0.00	0.00	0.00
Land use (reptiles)	species.yr	0.00	0.00	0.00	0.00	5.78	0.26	1.49	-5.70	0.00	0.00	0.00	0.00
Mineral resource scarcity	USD2013	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Fossil resource scarcity	USD2013	-0.01	0.00	0.00	0.00	-0.02	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
Water use (terrestrial)	species.yr	0.92	0.00	0.46	0.64	0.92	0.00	0.46	0.64	0.91	0.00	0.45	0.62
Water use (freshwater)	species.yr	0.99	0.00	0.97	0.97	0.99	0.00	0.97	0.97	0.99	0.00	0.97	0.97
Water use	DALY	-0.01	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eutrophication (marine)	species.yr	-0.01	0.00	0.00	-0.01	-0.01	0.00	0.00	0.00	-0.01	0.00	0.00	0.00
Human health	DALY	0.00	0.00	0.00	0.00	1.34	0.27	0.27	1.27	-0.01	0.00	0.00	0.00
Ecosystems	species-yr	0.02	0.00	0.00	0.00	1.32	0.11	0.36	2.48	0.03	0.00	0.00	0.00
Resources	USD2013	-0.01	0.00	0.00	0.00	-0.02	0.00	0.00	-0.01	0.00	0.00	0.00	0.00

Table S52. Normalized sensitivity coefficients for perturbation (lower or higher) fraction of PM smaller than 2.5 μm for scenarios 1-12 (Table 1). Values highlighted red and yellow correspond to coefficients larger and smaller than 0.3 and -0.3, respectively (medium sensitivity).

		1	2	3	4	5	6	7	8	9	10	11	12
Impact category	Unit	flame curtain, NT	flame curtain, N	flame curtain, LS	flame curtain, LJ	retort, NT	retort, N	retort, LS	retort, LJ	earth-mound, NT	earth-mound, N	earth-mound, LS	earth-mound, LJ
Global warming	DALY	0.00	0.00	0.00	0.00	-1.36	-0.60	-0.82	-1.55	0.00	0.00	0.00	0.00
Global warming (terrestrial)	species.yr	0.00	0.00	0.00	0.00	-1.36	-0.60	-0.82	-1.55	0.00	0.00	0.00	0.00
Global warming (freshwater)	species.yr	0.00	0.00	0.00	0.00	-1.36	-0.60	-0.82	-1.55	0.00	0.00	0.00	0.00
Stratospheric ozone depletion	DALY	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01
Ionizing radiation	DALY	0.01	0.00	0.00	0.01	0.02	0.00	0.00	0.02	0.01	0.00	0.00	0.01
Ozone formation	DALY	0.35	0.04	0.04	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Particulate matter formation	DALY	1.11	1.03	-1.36	1.16	1.05	0.98	-7.57	1.08	1.10	1.06	-28.93	1.14
Ozone formation (terrestrial eco)	species.yr	0.40	0.04	0.04	0.40	0.00	0.00	0.00	0.00	0.00	-0.07	0.01	0.00
Acidification (terrestrial)	species.yr	0.01	0.00	0.00	0.01	-0.02	0.00	0.00	-0.02	0.01	0.00	0.00	0.01
Eutrophication (freshwater)	species.yr	-0.02	0.00	0.00	-0.01	-0.06	0.00	0.00	-0.01	0.02	0.00	0.00	0.02
Ecotoxicity (terrestrial)	species.yr	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01
Ecotoxicity (freshwater)	species.yr	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01
Ecotoxicity (marine)	species.yr	0.08	0.00	0.00	-0.38	0.02	0.00	0.00	0.01	0.01	0.00	0.00	0.01
Toxicity (carcinogenic)	DALY	-0.03	0.00	0.00	-0.03	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01
Toxicity (non-carcinogenic)	DALY	0.01	0.00	0.00	0.03	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01
Land use (mammals)	species.yr	0.01	0.00	0.00	0.01	-8.13	-0.03	-1.99	8.21	0.01	0.00	0.00	0.01
Land use (birds)	species.yr	0.01	0.00	0.00	0.01	27.32	-0.74	-5.27	6.32	0.01	0.00	0.00	0.01
Land use (plants)	species.yr	0.01	0.00	0.00	0.01	38.15	-0.22	-5.47	6.30	0.01	0.00	0.00	0.01
Land use (amphibians)	species.yr	0.01	0.00	0.00	0.01	-278.62	-0.58	-3.77	6.72	0.01	0.00	0.00	0.01
Land use (reptiles)	species.yr	0.01	0.00	0.00	0.01	-8.12	-0.37	-2.10	8.01	0.01	0.00	0.00	0.01
Mineral resource scarcity	USD2013	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	0.01	0.00	0.00	0.01
Fossil resource scarcity	USD2013	0.01	0.00	0.00	0.01	0.02	0.00	0.00	0.01	0.01	0.00	0.00	0.01
Water use (terrestrial)	species.yr	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01
Water use (freshwater)	species.yr	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01
Water use	DALY	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01
Eutrophication (marine)	species.yr	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01
Human health	DALY	-0.43	-0.09	-0.06	-0.26	-2.69	-0.53	-0.47	-2.24	-1.58	-0.19	-0.11	-0.76
Ecosystems	species-yr	0.01	0.00	0.00	0.00	-1.82	-0.16	-0.50	-3.47	0.01	0.00	0.00	0.00
Resources	USD2013	0.01	0.00	0.00	0.01	0.03	0.00	0.00	0.02	0.01	0.00	0.00	0.01

Table S53. Normalized sensitivity coefficients for perturbation (lower or higher) fraction of PM smaller than 2.5 μm for scenarios 1-12 (Table 1). Values highlighted red and yellow correspond to coefficients larger and smaller than 0.3 and -0.3, respectively (medium sensitivity).

Impact category	Unit	1 flame curtain, NT	2 flame curtain, N	3 flame curtain, LS	4 flame curtain, LJ	5 retort, NT	6 retort, N	7 retort, LS	8 retort, LJ	9 earth-mound, NT	10 earth-mound, N	11 earth-mound, LS	12 earth-mound, LJ
Global warming	DALY	0.00	0.00	-0.01	0.00	8.61	3.80	5.21	9.81	-0.01	0.00	-0.01	-0.01
Global warming (terrestrial)	species.yr	0.00	0.00	-0.01	0.00	8.61	3.80	5.22	9.81	-0.01	0.00	-0.01	-0.01
Global warming (freshwater)	species.yr	0.00	0.00	-0.01	0.00	8.59	3.79	5.21	9.79	-0.01	0.00	-0.01	-0.01
Stratospheric ozone depletion	DALY	-0.04	0.00	-0.01	-0.03	-0.04	0.00	-0.01	-0.03	-0.04	0.00	-0.01	-0.03
Ionizing radiation	DALY	-0.08	0.00	-0.01	-0.08	-0.10	0.01	-0.01	-0.10	-0.04	0.00	-0.01	-0.03
Ozone formation	DALY	-2.24	-0.27	-0.27	-2.10	0.01	0.01	-0.03	0.01	0.01	0.01	-0.04	0.01
Particulate matter formation	DALY	1.12	1.03	-1.39	1.17	1.06	0.98	-7.68	1.09	1.10	1.06	-29.30	1.15
Ozone formation (terrestrial eco)	species.yr	-2.53	-0.27	-0.23	-2.53	0.02	0.01	-0.02	0.01	0.01	0.47	-0.06	0.01
Acidification (terrestrial)	species.yr	-0.05	0.00	-0.01	-0.04	0.13	0.02	0.02	0.11	-0.04	0.00	-0.01	-0.03
Eutrophication (freshwater)	species.yr	0.14	0.01	-0.01	0.05	0.40	0.01	-0.01	0.09	-0.11	0.00	-0.01	-0.13
Ecotoxicity (terrestrial)	species.yr	-0.04	0.00	-0.01	-0.03	-0.04	0.00	-0.01	-0.03	-0.04	0.00	-0.01	-0.03
Ecotoxicity (freshwater)	species.yr	-0.05	0.00	-0.01	-0.04	-0.05	0.00	-0.01	-0.04	-0.04	0.00	-0.01	-0.03
Ecotoxicity (marine)	species.yr	-0.48	0.01	-0.01	2.41	-0.11	0.01	-0.01	-0.08	-0.04	0.00	-0.01	-0.03
Toxicity (carcinogenic)	DALY	0.19	0.00	-0.01	0.22	-0.09	0.00	-0.01	-0.06	-0.04	0.00	-0.01	-0.03
Toxicity (non-carcinogenic)	DALY	-0.06	0.00	-0.01	-0.18	-0.05	0.00	-0.01	-0.05	-0.04	0.00	-0.01	-0.03
Land use (mammals)	species.yr	-0.04	0.00	-0.01	-0.03	51.49	0.18	12.63	-51.97	-0.04	0.00	-0.01	-0.03
Land use (birds)	species.yr	-0.04	0.00	-0.01	-0.03	-173.00	4.67	33.40	-40.03	-0.04	0.00	-0.01	-0.03
Land use (plants)	species.yr	-0.04	0.00	-0.01	-0.03	-241.61	1.37	34.64	-39.87	-0.04	0.00	-0.01	-0.03
Land use (amphibians)	species.yr	-0.04	0.00	-0.01	-0.03	1764.61	3.68	23.89	-42.57	-0.04	0.00	-0.01	-0.03
Land use (reptiles)	species.yr	-0.04	0.00	-0.01	-0.03	51.42	2.35	13.30	-50.75	-0.04	0.00	-0.01	-0.03
Mineral resource scarcity	USD2013	0.03	0.00	-0.02	0.01	0.01	0.00	0.08	0.00	-0.04	0.00	-0.01	-0.03
Fossil resource scarcity	USD2013	-0.05	0.00	-0.01	-0.04	-0.14	-0.01	-0.01	-0.08	-0.04	0.00	-0.01	-0.03
Water use (terrestrial)	species.yr	-0.04	0.00	-0.01	-0.03	-0.04	0.00	-0.01	-0.03	-0.04	0.00	-0.01	-0.03
Water use (freshwater)	species.yr	-0.04	0.00	-0.01	-0.03	-0.04	0.00	-0.01	-0.03	-0.04	0.00	-0.01	-0.03
Water use	DALY	-0.05	0.00	-0.01	-0.04	-0.05	0.00	-0.01	-0.03	-0.04	0.00	-0.01	-0.03
Eutrophication (marine)	species.yr	-0.08	0.00	-0.02	-0.06	-0.05	0.00	-0.01	-0.03	-0.05	0.00	-0.01	-0.03
Human health	DALY	-0.46	-0.09	-0.07	-0.28	11.16	2.28	2.30	10.90	-1.65	-0.19	-0.13	-0.79
Ecosystems	species-yr	-0.04	0.00	-0.01	-0.03	11.50	1.00	3.20	22.00	-0.03	0.00	-0.01	-0.03
Resources	USD2013	-0.05	0.01	-0.01	-0.04	-0.19	0.00	-0.01	-0.11	-0.04	0.00	-0.01	-0.03

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Abstract

Spatial differentiation in evaluation of environmental impacts in life cycle assessment (LCA) may give more accurate and realistic results, especially in cases where impacts occur at a local or regional scale and where sensitivity of receiving ecosystems differs from generic conditions. However, from a decision maker's perspective it is of interest to investigate whether the use of spatially differentiated impact assessment methods in addition leads to better decisions. Biochar production and agricultural utilization in Indonesia is an example of a micro-level decision-support case where spatial differentiation could be relevant~~ for making. decision, which are related to implementation of biochar as a waste management strategy and the choice of best performing biochar production techniques, agricultural utilization systems and geographic locations~~.

To study the influence of spatial differentiation on implementation of biochar as a waste management strategy and the choice of best performing biochar production techniques, agricultural utilization systems and geographic locations~~these aspects~~, comparisons were made between four communities living on different Indonesian islands, three biochar production techniques and two types of fertilizer.

Results showed that the differences in impact scores between generic and spatially differentiated impact scores were an order of magnitude different for some of the considered impact categories. These differences influenced the identification of which system performed best when considering total damage to human health, which was mainly due to differences in accounting for impacts arising from water use. By contrast, trade-offs between impact categories combined with relatively small contribution of some spatially differentiated impacts rendered spatial differentiation less relevant with regard to total damage to ecosystems. ~~In this context, t~~Total impact scores were influenced to a greater extent by variations in inventories determining environmental burden and benefits, than by differences between generic and spatially differentiated characterization factors.

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Hence, ~~I~~irrespective of the scenario and type of damage considered, both generic and spatially differentiated assessments showed that implementing biochar technology in Indonesia is expected to bring environmental benefits. ~~In this context, total impact scores were influenced to a greater extent by variations in inventories determining environmental burden and benefits, than by differences between generic and spatially differentiated characterization factors.~~

~~Thus~~It was shown that ~~,~~ spatial differentiation in impact assessment did not necessary lead to better decisions in this case study. This may suggest that depending on the goal of the LCA, practitioners should consider potential benefits of implementing spatially differentiated life cycle impact assessment methods as opposed to potential benefits from collecting site-specific inventories.

Keywords

decision-making, decision-support, LCA, LCIA, regionalization, spatialization

1. Introduction

Life cycle impact assessment (LCIA) the part of life cycle assessment (LCA) in which the life cycle inventory of a system's material flows is translated into their potential contributions to the environmental impacts. LCIA supports the interpretation phase of the LCA, where questions posed in the goal definitions are answered (Hauschild and Huijbregts, 2015). Spatially differentiated life cycle impact assessment (LCIA) methods enable execution or regionalized life cycle assessment (LCA) studies as they take into consideration local conditions and sensitivities of receiving ecosystems. In contrast to generic methods, which should be valid on a global scale (at the expense of higher spatial uncertainty), spatially-differentiated LCIA methods are more accurate as they operate at either regional or local scales, corresponding to site-dependent and site-specific

Formatted: Font: (Default) Times New Roman, 12 pt, Font color: Auto, English (United Kingdom) assessments, respectively (Potting and Hauschild, 2006). In this paper, we studied the influence of the choice of spatially differentiated LCIA methods on the interpretation phase of an LCA.

The development of spatially differentiated LCIA methods has intensified in the past few years (Patouillard et al., 2018; Rosenbaum et al., 2018; Verones et al., 2017). A review of characterization models included in spatially differentiated LCIA methods, like IMPACT World+ (Bulle et al., 2012) or LC-Impact (Verones et al., 2016), is given in Rosenbaum (2018). Examinations of these models shows, that depending on the impact category, geographic variability in characterization factors (CF) can be higher than differences in characterization factors between substances covered by the method. Applications of such methods in LCA studies results in more accurate and realistic evaluations of environmental impacts, as was demonstrated for the few regionalized LCA studies published to date (Anton et al., 2014; Heidari et al., 2017; Henderson et al., 2017a; Mutel et al., 2011).

LCA is a decision support tool. Two (out of three) commonly used archetype goal situations (namely, situation A for micro-level decision support and situation B for meso/macro-level decision support) involve a decision context (Bjørn et al., 2018a; European Commission, 2010). It is therefore of interest to investigate whether the use of spatially differentiated LCIA methods leads to better decisions, in addition to more accurate and realistic LCIA results. Our research question is therefore: does spatial differentiation in life cycle impact assessment lead to better decisions? The answer to this research question is not obvious. Even large differences in impact scores for individual impact categories might become less influential for decision support. This could be due to potential trade-offs between impact categories (Heidari et al., 2017), due to a larger influence of spatial variability in inventory flows compared to spatial differences in characterization factors (Henderson et al., 2017b), or due to a smaller contribution of spatially-differentiated impact

Formatted: Font: (Default) Times New Roman, 12 pt, Font color: Auto, English (United Kingdom) categories to total damage. The influence of spatial differentiation in impact assessment on LCA-based decision support has not previously been investigated.

Spatial differentiation may be particularly important for application of biochar systems in tropical rural areas like Indonesia, where conditions with regard to biodiversity or water availability can vary significantly from generic characterization factors used in traditional LCA (Boulay et al., 2011; Chaudhary et al., 2015). Biochar is typically used as soil conditioner, increasing crop productivity while contributing to climate change mitigation through carbon sequestration and storage (Lehmann, 2007; Woolf et al., 2010). Biochar is produced from biomass residues, and in developing and middle-income countries often small-scale, low-cost pyrolysis technologies traditionally based on earth-mound kilns are used (Nsamba et al., 2015). Alternatively, more innovative and cleaner flame curtain ("Kon-Tiki") kilns or retort kilns made out of bricks and steel, can be used (Cornelissen et al., 2016; Sparrevik et al., 2015). Experimental studies have shown that biochar production leads to emission of toxic organic compounds and greenhouse gases (Cornelissen et al., 2016; Sparrevik et al., 2015). Environmental impacts from biochar systems have previously been assessed using LCA (e.g. Galgani and Delft, 2012; Gwenzi et al., 2015; Sparrevik et al., 2014). However, the relative immaturity of spatially differentiated LCIA approaches and their limited implementation into LCA modelling software, have restricted the use of spatially differentiated methods in these studies.

The objective of this study was therefore to assess implications of spatial differentiation in LCIA on decision support related to implementation of a biochar systems in Indonesia. For this purpose, generic and spatially differentiated impact scores were calculated and compared using a suite of relatively recent LCIA methods, which offer spatially differentiated characterization factors at the damage level. Firstly, the influence on an *absolute scale*, i.e. whether the conversion of biomass residues to biochar and its subsequent use in agriculture provides has a net positive effect compared to the current situation (no treatment of biomass residues), was investigated. Secondly, when selecting management strategies, decision makers must know in which geographic locations biochar systems are expected to perform optimally, and furthermore which biochar production technique and biochar application conditions (inorganic vs. organic fertilizer based agriculture) perform best from an environmental point of view. Thus, the effect of spatial differentiation on the *relative importance* for ranking of subsystems and technologies was assessed. Finally, decision makers may be interested in identifying potential improvements for biochar systems, and a process contribution analysis, i.e. identifying the processes with the largest environmental burden, can be used for this purpose. Thus, the impact of spatial influence on *process contribution* was examined.

2. Methods

2.1. Goal and scope

The goals of the LCA were three fold: The first goal was to assess and compare life cycle impacts of biochar systems in Indonesia in order to support decision making related to the implementation of biochar as a waste management strategy in four Indonesian island communities. The second goal was to identify the best biochar production technique and agriculture practice in these communities. The third goal was to identify improvement potentials for the biochar systems. The results of this LCA are used to discuss the effect on spatial differentiation for LCA-based decision support in the Indonesian context.

The LCA was carried out following the requirements of the ISO standards and the guidelines of the International Reference Life Cycle Data System (ILCD) handbook (European Commission, 2010; European Committee for Standardization, 2006a, 2006b) According to the ILCD guidelines, the current study is a micro-level decision support (type-A) situation, and the assessment carried out applies an attributional approach in accordance with the recommendations of the ILCD guidelines for this decision support type. A system expansion (through crediting) using average processes in this attributional approach, consistent with both ILCD and the ISO hierarchy for solving multifunctionality, was therefore applied (Bjørn et al., 2018b).

2.1.1. Functional unit and system boundaries

The primary function of the biochar systems in this context is to utilize biomass waste to produce biochar and use of this biochar as a soil conditioner. Thus, the functional unit was defined as the “treatment of 1 kg of biogenic carbon from biomass residues in rural areas in Indonesia”. This definition allows for a fair comparison between residues treated using different techniques. A secondary function of biochar when used as soil conditioner is its ability to support crop growth. In this case, the benefits from increasing yields are modelled as avoided production of crops (mainly fertilizer use). In addition, system boundaries included the complete underlying biochar production life cycle, including the construction of the biochar kilns and production of biochar from biowaste (Fig. 1). Avoided impacts from current waste management system are also relevant to considered, but in this case there is no treatment of biomass residues, which are allowed to decompose in aerobic conditions. Thus, following Sparrevik et al., (2014) no net emissions of carbon dioxide and no emission of methane during decomposition of biomass residues were assumed.

Fig. 1.

2.1.2. Biochar systems investigated

The influence of spatial differentiation was studied by using site specific inventory data from four distinct geographic locations of Indonesia (Ngata Toro on the island of Sulawesi, Napu on Sumba, Lampung on Sumatra, and Lamongan on Java) (see SI, Section S1 for details). On the basis of previous work in Nepal and Zambia, the most promising method for the production of biochar in the four villages was considered to be the flame curtain technique (Table 1, scenarios 1-4)

(Cornelissen et al., 2016; Schmidt et al., 2014). This novel production technology was compared to biochar systems based on other available alternative production technologies, such as retort kilns (the Adam retort) (Adam, 2009) and simple non-retort earth-mound kilns (Table 1, scenarios 5-12). Inorganic fertilizers (N, P, K, and urea) are used in all villages, except for Napu where compost is used. Thus, comparisons were made with compost as the sole source of nutrient input in Ngata Toro, Lampung, and Lamongan, and with inorganic fertilizers as the source of nutrient input in Napu (Table 1, scenarios 13-24).

Table 1. Overview of the compared biochar systems.

# Scenario	Sensitivity parameter	Geographic location (production and use) [a]	Biochar production technique [b]	Fertilizer type and amount [c]
1	Baseline	NT	"Kon-Tiki" flame curtain kiln	NPK and urea fertilizers
3-4	Geographic location of biochar production and use	N, LS, LJ	"Kon-Tiki" flame curtain kiln (all locations)	NPK and urea fertilizers (NT, LS, LJ); compost (N)
5-12	Biochar production technique	NT, N, LS, LJ	retort kiln (all locations); earth mound kiln (all locations)	NPK and urea fertilizers (NT, LS, LJ); compost (N)
13-24	Fertilizer type and amount	NT, N, LS, LJ	"Kon-Tiki" flame curtain kiln, retort kiln; earth mound kiln (all locations)	compost (NT, LS, LJ); NPK and urea fertilizers (N)

[a] NT: Ngata Toro; N: Napu; LS; Lampung, Sumatra; LJ: Lamongan, Java

[b] retort kiln made from bricks and steel (Adam retort) and earth-mound kiln were alternatives to steel-made "Kon-Tiki" flame curtain kiln

[c] in Lampung and Lamongan NPK and urea fertilizers were applied in higher amounts compared to Ngata Toro (see SI, Section S2 for details)

2.2. Life cycle inventory analysis

Data for background processes, like construction of kilns or (avoided) production of inorganic fertilizers are based on generic processes available in Ecoinvent, version 3.3 (Weidema et al., 2013). Ecoinvent is currently one of the most comprehensive databases of life cycle inventories. Consideration of spatial differentiation in LCIA for these generic processes was not possible, as it is not known where emissions occur in the background system. Data for foreground processes in the biochar system, such as biochar production or soil application, should be represented as accurately as possible and were thus based on primary data measured in Indonesia and reported previously (Sparrevik et al., 2014), or collected specifically in surveys carried out for this work. Spatial differentiation was used in the LCIA in all relevant processes in the foreground system. All inventory data were site-specific representative field data aggregated from seven years of biochar research activities. This data, which included biochar properties, biochar application rate, irrigation and agricultural yields, varied between sites. Outdoor emissions resulting from the production of biochar, concentrations of CO_2, CO, CH_4, NMVOC, and PM_{10} and nitrous oxides, measured in Cornelissen et al., (2016) and Sparrevik et al., (2015) were used. Emissions of nitrate, phosphate, phosphorus and metals (co-contaminants) to soils, and emissions of GHG to air from organic and inorganic fertilizers were taken from generic Ecoinvent process for production of maize. Differences in fertilizer amounts between the Ecoinvent process and amounts in these case studies were corrected for, assuming that composition of fertilizers with regard to metal content was the same. Site-specific data related to the mineralization kinetics of biochar in soil were not available for this study and as such were assumed to follow bi-exponential decay kinetics and average (geometric mean) kinetic parameters measured for six biochars representing a wide range of mineralization rate constants were therefore used (Zimmerman and Gao, 2013). Based on Woolf and Lehmann, (2012) a negative priming equal to 45% increase in soil organic carbon stock in the long-term (100 years) was used. Model parameters and underlying data are presented in the SI, Section S2. Unit processes for the foreground system are given in the SI, Section S3.

2.3. Life cycle impact assessment

To answer the research question (does spatial differentiation lead to better decisions?), spatially differentiated LCIA methods must be applied to all relevant categories of environmental impacts and must express impacts in common units. Hence, the following set of criteria was applied to choose LCIA methods: (i) a method must be published in peer-reviewed literature; (ii) it must offer modelling at damage level; (iii) it must allow a calculation of spatially-explicit impact score at sufficient resolution to be made (e.g. country- or Southeast-Asia level for regional impact categories like photochemical ozone formation, and island- or biome-level for local impact categories like land use); and (iv) it can be further adapted to specific geographic situation based on available details of the case study (e.g. adapting the particulate matter (PM) model to local exposure parameters). A comparison of impact assessment methods based on their environmental relevance or scientific robustness was not carried out here and no preference was given to one method over another for this study. Damage scores were computed allowing for weighting of impact categories contributing to total damage in two important areas of protection in LCIA: (i) human health, where impacts are expressed in disability adjusted life years, DALY; and (ii) ecosystem quality considering terrestrial, freshwater, and marine ecosystems, where impacts are expressed as loss of biodiversity (in species-years) (Hauschild and Huijbregts, 2015). The full list of LCIA methods with details of the spatial scales considered is given in Table 2. A detailed description of each method is presented in the SI, Section S5.

Table 2. Generic and site-explicit LCIA methods for the impact categories considered in this study.

Impact category	Area of protection	Impact score unit	Geographical and temporal reference unit	Reference
Climate change	Human health	DALY	Indonesia; 1-yr time steps	Levasseur et al., 2010); ReCiPe2016 (Huijbregts et al., 2016); IPCC (2013); Cherubini et al., (2016)
Climate change	Ecosystems (freshwater)	species×year	Indonesia; 1-yr time steps	
Climate change	Ecosystems (terrestrial)	species×year	Indonesia; 1-yr time steps	
Ozone depletion	Human health	DALY	Global	ReCiPe2016 (Huijbregts et al., 2016)
Ionizing radiation	Human health	DALY	Global	ReCiPe2016 (Huijbregts et al., 2016)
Particulate matter formation	Human health	DALY	Outdoor rural: Southeast Asia Indoor: air exchange rate for open building and no attenuation, measured village-specific exposure parameters (see Table S1)	(Fantke et al., 2017b)
Land use	Ecosystems (terrestrial)	species×year	Village-specific	Chaudhary et al., (2015)
Water use (distribution)	Human health	DALY	Watershed/Indonesia [a]	Boulay et al., (2011)
Water use	Ecosystems (terrestrial)	species×year	Watershed	ReCiPe2016 (Huijbregts et al., 2016), based on Pfister et al., (2009)
Water use	Ecosystems	species×year	Indonesia [b]	ReCiPe2016

Impact category	Area of protection	Impact score unit	Geographical and temporal reference unit	Reference
	(freshwater)			(Huijbregts et al., 2016), based on Hanafiah et al., (2011)
Toxicity (cancer and non-cancer effects)	Human health	DALY	Outdoor: Southeast Asia Indoor: household indoor exposure settings based on non-OECD archetype combined with village-specific exposure parameters (see Table S2)	USEtox 2.02 (Fantke et al., 2017a)
Freshwater ecotoxicity	Ecosystems (freshwater)	species×year (converted from PDF×m3×d)	Southeast Asia	USEtox 2.02 (Fantke et al., 2017a)
Terrestrial ecotoxicity	Ecosystems (terrestrial)	species×year (converted from PDF×m3×d)	Village-specific for metallic elements; Global for organic chemicals	ReCiPe2016 (Huijbregts et al., 2016); (Owsianiak et al., 2017; Owsianiak et al., 2013) for metallic elements
Marine ecotoxicity	Ecosystems (marine)	species×year (converted from PDF×m3×d)	Indonesian Sea marine ecosystem for metallic elements; Global for organic chemicals	ReCiPe2016 (Huijbregts et al., 2016) for organics; Dong et al., (2016) for metallic elements
Freshwater eutrophication	Ecosystems (freshwater)	species×year	Indonesia	ReCiPe2016 (Huijbregts et al., 2016)
Marine eutrophication	Ecosystems (marine)	species×year	Village-specific	Cosme et al., (2017; Cosme and Hauschild, 2017); Roy et al., (2014)

Impact category	Area of protection	Impact score unit	Geographical and temporal reference unit	Reference
Terrestrial acidification	Ecosystems (terrestrial)	species×year	Village-specific	ReCiPe2016 (Huijbregts et al., 2016)
Photochemical ozone formation	Human health	DALY	Region comprising Indonesia, Papua New Guinea, and East Timor	ReCiPe2016 (Huijbregts et al., 2016)
Photochemical ozone Formation	Ecosystems (terrestrial)	species×year	Region comprising Indonesia, Papua New Guinea, and East Timor	ReCiPe2016 (Huijbregts et al., 2016)
Mineral resource scarcity	Resources	USD2013	Global	ReCiPe2016 (Huijbregts et al., 2016)
Fossil resource scarcity	Resources	USD2013	Global	ReCiPe2016 (Huijbregts et al., 2016)

[a] although watershed-specific characterization factors were calculated by Boulay et al., (2011) for main watersheds (ca. 600 in total), all four villages are located outside main watersheds and thus assigned the same characterization factor

[b] although watershed-specific characterization factors were calculated by Hanafiah et al., (2011) for well-known river basins above 42° latitude (214 in total), none of the four villages could be mapped on the watershed.

2.4. Sensitivity and uncertainty analyses

A sensitivity analysis of the results of the discrete parameters as determined by scenarios presented in Table 1 (Section 2.1) was conducted by comparing impact scores without any internal normalization. For continuous parameters, sensitivity of impact scores was quantified by computing normalized sensitivity coefficients (eq 1), based on Ryberg et al., (2015):

$$X_{IS,k} = \frac{\Delta IS / IS}{\Delta a_k / a_k} \qquad \text{(eq 1)}$$

where $X_{IS,k}$ is the dimensionless normalized sensitivity coefficient of impact score (IS) for perturbance of continuous parameter k, a_k is the kth parameter value, Δa_k is the perturbation of parameter a_k, IS is the calculated impact score, and ΔIS is the change of the impact score that resulted from the perturbation of parameter a_k. Baseline parameter values were used as default in all scenarios listed in Table 1. They originate from measurements and are described in Section 2.2. Perturbed parameter values representing lower and higher ranges of parameters were defined based on variations reported earlier in other experimental studies on biochar in developing and middle-income countries (Table 3). A parameter is considered important if $X_{IS,k} \geq 0.3$, corresponding to a medium sensitivity (Cohen et al., 2013). Uncertainties in those parameters which were found important in the perturbation analysis (see SI, Section S6.5 for results of the sensitivity analysis) were assigned either normal, or triangular, or uniform distributions based on the distribution of measured values (SI, Section S4).

In addition to parameter uncertainties, uncertainties in the life cycle inventories were also considered. For the foreground processes (e.g. in material inputs or emissions) they were estimated using the Pedigree matrix approach, as illustrated in Ciroth et al., (2013) assuming that the data was log-normally distributed (Huijbregts et al., 2003). Uncertainties in the background processes were based on geometric standard deviations already assigned to flows in the ecoinvent processes used. Uncertainties in characterization factors are not provided for the majority of the methods, and were therefore not considered. Monte Carlo simulations (1000 iterations) were carried out for pairwise comparison between scenarios listed in Table 1 while keeping track of the correlations between pairs of systems. Comparisons were considered statistically significant if at least 95% of all 1000 Monte Carlo runs were favourable for one scenario.

Table 3. Uncertain, continuous model parameters for processes associated with biochar systems. Values referred to as default apply to all relevant scenarios listed in Table 1. Perturbation analysis was carried out to test the influence of a parameter value on the results for selected scenarios.

Parameter	Parameter values		Unit	Source
	Default	Perturbations (min-max)		
Biochar yield (flame curtain and earth-mound kilns)	22	17-27	%	Measured in Cornelissen et al., (2016) Error of 5.0% as measured by Sparrevik et al., (2015)
Biochar yield (Adam retort)	32	27.4-36.6	%	Measured in Sparrevik et al., (2015) Error of 4.6% as measured by Sparrevik et al., (2015)
Biochar application rate (per village) [a]	NT: 1200	1140-1260	kg/ha	Measured in Sparrevik et al., (2014) Error of 5% assumed, expected to be in realistic range of values
	N: 4000	3800-4200		
	LS: 5000	4750-5250		
	LJ: 4000	3800-4200		
Crop yield without biochar addition (per village) [a]	NT: 6500	5655-7345	%	Measured in Sparrevik et al., (2014) (NT) and in this study (for the other locations). Error of 13% based on values reported in Zambia by Sparrevik et al., (2013)
	N: 2000	1740-2260		
	LS: 6000	5220-6780		
	LJ: 8000	6960-9040		
Crop yield change when biochar is used (per village)	NT: 10	7.1-11.6	%	Measured in Sparrevik et al., (2014) (NT), in this study (N and LS) or assumed (LJ) equal to 10%, which is a conservative estimate (Jeffery et al., 2017, 2011). Perturbation ranges based on measurements in Napu (N) were scaled to other villages assuming equal variance
	N: 248	176-287		
	LS: 100	71-116		
	LJ: 10	7.1-11.6		
Mineralization rate	8.58E-04	9.2E-06 -	yr^{-1}	Measured in Zimmerman and Gao, (2013) for

constant for the recalcitrant pool		6.1E-03		six different biochars. Default (geometric mean), minimum, and maximum values were used
Priming effect	45	30-60	%	Modelled in Woolf and Lehmann, (2012) Increase in soil organic carbon stock in the long-term (100 years) was used. Perturbation values are ranges reported (Woolf and Lehmann, 2012)
Water use for irrigation (per village) [a]	NT: 0.155	0.11-0.20	m^3/kg output	Measured in this study. Perturbation values assumed 30% increased and decrease, which is in realistic range of values
	N: 0	0-0		
	LS: 0.155	0.11-0.20		
	LJ: 0.155	0.11-0.20		
Fraction of PM smaller than 2.5 µm	0.92	0.73-0.95	kg/kg	Measured for residential wood combustion as reported in Humbert et al., (2011) Value of 0.73 is for low-stack emissions, value of 0.95 is in higher range of measured values for various sources (Humbert et al., 2011)

[a] NT: Ngata Toro; N: Napu; LS; Lampung, Sumatra; LJ: Lamongan, Java

3. Results

3.1. Comparison between generic and spatially differentiated impacts

Figure 2 shows the comparison between generic and spatially differentiated impacts from biochar produced using a flame curtain kiln and used in agriculture, as influenced by geographic location of the field and fertilizer type (scenarios 1-4 and 13-15 in Table 1). Impact scores for individual impact categories either increased or decreased compared with generic scores, depending on the impact category (see also SI, Section S6.1). The largest consistent increase (by ca. 2 orders of magnitude) was observed at all locations for the *human health impacts from water use* (except Napu). Spatially differentiated characterization factors for human health impacts in the watersheds are equal to 0 DALY/m^3 for all sites except Napu where the characterization factor is higher and reflects water scarcity problems on Sumba. However, current agricultural practice does not rely on irrigation in this village. This explains why there are no apparent benefits in terms of water used impacts when the system is credited for increasing crop yields in Napu for both spatially differentiated and generic assessments. The comparison between spatially differentiated and generic impacts also shows that there is some reduction in human health impacts stemming from emissions of PM2.5 (difference up to factor of 2), mainly because the site-specific intake of PM2.5 resulting from emissions are smaller at the site-specific level at these rural sites, than the default value used in global-generic assessment.

The largest consistent decrease when spatial differentiation was used (by ca. 1 order of magnitude) was observed at all locations for *land use impacts on birds and mammals.* Indonesian ecoregions are among the most biodiverse globally, and characterization factors are generally one order of magnitude higher in all villages when compared to global-generic values (Chaudhary et al., 2015). Changes in impact scores for other impact categories ranged from small (below 10%) to large (up to a factor of 5) when spatial differentiation was considered, but these differences were largely non-conspicuous as the contribution of these impacts categories to total damage was often very small (less than 1% of total damage). Statistically significant differences between regionalized and generic impacts were found in nearly all impact categories, except for freshwater eutrophication. Similar trends were observed for other kilns (see SI, Section S6.2). The major differences between spatially differentiated and generic impacts were, again, due to significantly smaller (but not equal to zero) contributions from water use impacts on the terrestrial ecosystem (Fig. 2b). Here, the very high resolution of watersheds used in the method of Pfister et al., (2009) which includes relevant minor watersheds, allowed each village and its corresponding watershed to be mapped. In addition, there was an increase in impact scores for terrestrial acidification due to a small alkaline buffering capacity of the soils, making them more vulnerable to acidic emissions. Figure 2b also shows that there is some reduction in ecotoxicological impacts stemming from using soil-specific characterization factors for metallic elements (like Cd or Zn) emitted together with fertilizer as co-contaminants. Terrestrial ecotoxicity characterization factors for these elements are generally higher (approximately twice as high) compared to generic values because acidic soils have a higher bioavailable metal concentration and thus a higher toxicity potentials in soils (Owsianiak et al., 2017; Owsianiak et al., 2015).

When aggregating impacts at the human health and ecosystem level, the impact of spatial differentiation was less pronounced. The spatially differentiated damage to human health was approximately 3 to 5 times higher when compared to generic scores, except for Napu where total damage was comparable between approaches (Fig. 2a). For aggregated potential impacts on ecosystems, the effect of spatial differentiation was not significant (Fig. 2b), although impact scores varied by up to one order of magnitude for the individual impact categories. This is mainly caused by the small absolute numbers for the impact categories mostly influenced by spatial differentiation (such as marine eutrophication or ozone formation) (see SI, Section S6.1), as well as trade-offs between categories, where an increase in impact scores for some categories was compensated by a decrease in others. For example, the increase in impact from water use and acidification in the regionalized assessment was compensated by increased benefits from land use impacts on plants. These benefits roughly doubled when compared with the global-generic assessment.

Fig. 2.

4. Discussion

4.1 Relevance of spatial differentiation for decision support

Results presented in Fig. 2 and in Section S6.1 of the SI show that spatially differentiated impact assessments resulted in more accurate and realistic results than generic assessments. This finding is consistent with earlier regionalized LCA studies demonstrating the use of spatially differentiated LCIA methods. Mutel et al., (2011) already showed that spatially differentiated ecosystem damage and human health scores of coal-based power generation in America were 30% higher and 38% lower, respectively, compared to generic scores. Anton et al., (2014) reported that regionalized human toxicity impacts of tomato agriculture in Spain were one order of magnitude higher than those determined from generic assessment. More recently, Henderson et al., (2017) demonstrated that spatial differentiation resulted in a nearly double water stress for American food production when compared to a generic assessment.

This is the first regionalized comparative LCA study where influence of spatial differentiation on decision support was investigated. While this study ~~collaborates~~ corroborates earlier regionalized LCA studies in terms of influence of spatial differentiation on impact scores, it demonstrates that the benefits of spatial differentiation for decision-support are closely connected to the goal of the LCA. ~~-~~The discussion below therefore relates to various aspects in a decision support context, using the application of biochar technology as the example.

4.1.1 Evaluation at an absolute scale

In order to make decisions about the implementation of a new biowaste management strategy, information about overall environmental performance of the technology is needed. In this study, impact scores were negative in most (but not all) of the individual impact categories, and the total damages were all negative (Fig. 2). Thus, environmental benefits from increased crop productivity outweighed the environmental burden of biochar production, which can include human health impacts from particulate matter and emission of toxic carcinogenic compounds. This holds true for all of the geographic locations, biochar production techniques, and fertilizers compared, suggesting that spatial differentiation does not influence decisions about implementing biochar systems in Indonesia. This study showed that a crop productivity increase as low as 10%, such as in Lampung and Ngata Toro (and lower than 25% as reported in a recent meta-analysis for tropical soils (Jeffery et al., 2017), is sufficient to make spatial differentiation irrelevant with regards to making decisions about the implementation of biochar-based management strategy for biowaste in Indonesia. Burden and benefits can also be determined by the current waste management practice that is replaced by the new biowaste management strategy (Owsianiak et al., 2016). In the biochar context, spatial differentiation is therefore expected to be less relevant in cases where the replaced waste management system is based on the polluting methods composting or landfilling, which emit the potent greenhouse gas methane (Laurent et al., 2014).

The increase in crop productivity of 10% may, however, be sufficient to make spatial differentiation relevant for certain chars where production and/or transportation to the field are important contributors to total impacts, as has been shown to be the case for hydrochars (Owsianiak et al., 2017). This may also hold true for biochars made on an industrial scale (and thus off-site). It is therefore important to see spatial differentiation in connection to the quality of the inventory, which for most relevant processes in this study used site-specific data.

4.1.2 Relative ranking

One plausible management decision from the LCA would be a relative feasibility ranking of villages to assess the benefit of implementing biochar technology in that specific region. For human health damage, both generic and spatially differentiated assessments identified Lampung as the village performing best, while Napu and Ngata Toro/Lamongan were identified as least optimal in both the generic and site-specific assessments (Fig. 3 and SI, Section 6.3). This difference is due to different quantities of water used for irrigation. Further, different villages were identified as best in scenarios with alternative fertilization strategies. This makes spatial differentiation relevant to consider in cases where detailed rank information is desirable. For total ecosystem damage however, Lampung and Lamongan performed best in both generic and spatially differentiated assessments, with no statistically significant difference between them. This was mainly due relatively large geographic differences in life cycle inventories between villages, which were larger than geographic differences in characterization factors. Indeed, the good performance of Napu (relative to the other villages) is explained by the very high productivity increase when biochar is amended to soils (250% increase compared to the control; Table 2). The relatively good performance of Lampung is explained by the high productivity increase (100% increase compared to the control; Table 2) which in turn reduces the need for inorganic fertilizers, combined with the fact that the absolute yield was relatively high for agricultural practices without biochar.

To isolate the effects of variability in life cycle inventories from spatial differences in characterization factors, inventory flows in all villages were set to be the same, and equal to that of Ngata Toro. Spatially differentiated LCA carried out showed that a different village performed best when considering total damage to human health (Lamongan, against Lampung for site-specific inventories) (Table S36). This further emphasizes that differences in ranking between villages were mainly caused by variability in life cycle inventories between villages. Henderson et al., (2017) also showed that in addition to spatial differences in characterization factors, variability in inventories of water used for irrigation explained a large part of the differences in water deprivation impacts from corn production and from milk production between different geographic locations within the U.S.

4.1.3. Process contribution

Finally, decision makers are interested in identifying improvement options in the biochar life cycle. At the total damage level, spatial differentiation was generally not important in determining which processes contributed most to overall benefits (here, agricultural benefits from increasing yields or sequestration and storage of carbon). Only in one case (scenario 1) were the largest benefits attributed to increases in crop productivity in the generic assessment, while both the productivity increase and biochar production (specifically, sequestration of carbon) contributed nearly equally to human health benefits in regionalized assessment (SI, Section 6.4). However, spatial differentiation did influence the identification of processes with the largest environmental burdens in some individual impact categories. For example, it identified biochar use as a major driver of freshwater eutrophication (due to direct emissions of phosphorus together with the biochar added to soil) in the generic assessment, while in the spatially differentiated assessment the contribution of this process was smaller and comparable to that of biochar production. Thus, spatial differentiation could still be relevant to support decision about improving environmental performance of a given biochar system by suggesting changes in processes which decision-makers have influence on (foreground processes). In this particular case, the decision-maker could focus on reducing P emissions by using biochar with smaller content of P, but more accurate and realistic assessment of environmental impacts as offered by spatially differentiated impact assessment is needed to determine whether such improvement is valuable.

Fig. 3.

4.2. Practical implications

This study corroborates earlier studies showing that spatial differentiation is particularly relevant in cases where geographic variability in characterization factors is large (e.g., land or water use), and where total impact is dominated by one or few flows contributing to that impact category (e.g. irrigation or land occupation) (Chaudhary et al., 2016; Henderson et al., 2017b). As product life cycles are global, emissions in the life cycles can occur anywhere, making spatially differentiated LCA the preferred option if accuracy and realism of impacts are important for the goal of the LCA. This includes cases where the intended application is identification of weak points in the product system as a basis for environmental optimization. In this case, different conclusions were drawn related to potential improvement options in the biochar system to address eutrophication impacts on freshwater ecosystems.

Due to trade-offs between burden and benefits spatial differentiation had no relevance for decisions related to whether a new biochar-based waste management strategy should be implemented. Thus, in this aspect of the goal definition, spatial differentiation in LCIA did not lead to better decision support. This conclusion is expected to hold for systems where environmental benefits largely outweigh burdens, including the use of other chars in agriculture (Owsianiak et al., 2017) or technologies which replace inefficient waste management systems or allow reducing food losses (Fabbri et al., 2018).

Large geographic variability in life cycle inventories, combined with trade-offs between impact categories, resulted in spatial differentiation having a limited relevance for decisions about identification of best biochar production techniques and agricultural use conditions for ecosystem damage. Heidari et al., (2017) also showed that for pasta production in Iran the impact of ozone formation was up to a factor two larger than the generic determined impact, while impacts for land use and acidification were up to a factor of three smaller. Trade-offs between impact categories like those presented in this study and earlier in Heidari et al., (2017) are expected to occur for other product systems if they are located in dry and not very biodiverse regions (e.g. Iran), or in water-rich and biodiverse areas (like the majority of the Indonesian islands). However, in less extreme conditions with regard to water availability and biodiversity status (e.g. in Europe), similar trade-offs may not occur, and other impact categories may become dominant contributors (e.g. marine eutrophication impacts in Baltic Sea are expected to be higher compared with the Indonesian Sea marine ecosystems) (Cosme et al., 2017). Further, tradeoffs between impact categories were less relevant for total damage to human health. In addition, species can be weighted differently in LCIA, influencing trade-offs between impact categories (Verones et al., 2015). Thus, spatial differentiation is recommended to be considered as a default approach in comparative LCA studies.

4.3. Limitations of the study

Execution of this case study required implementation of regionalized characterization factors for most impact categories into the modelling software employed (SimaPro) and a subsequent matching of them with regionalized input and output flows. This practice, although perhaps the most straightforward from the LCA practitioner's perspective, has some limitations.

Uncertainties in characterization factors were not considered due to incomplete knowledge related to them and the limited ability of the modelling software to consider them. If these uncertainties had been considered, the number of pairwise comparisons with statistically significant differences between regionalized and generic assessments is expected to be smaller. It is a challenge for LCA practitioners to determine whether uncertainties in characterization factors combined with inventory and parameter uncertainties are larger than geographic variability in life cycle inventories. Henderson et al., (2017) showed that for water use impacts, spatial variability may be larger than uncertainty.

The second limitation is that the selection of the spatial scale for the impact assessment was based on a simple method of matching regionalized inventories with available respective characterization factors at the smallest scale possible. This limitation is not expected to influence conclusions because geographic locations of each village are accurate and because locations of respective ecoregions, watersheds and agricultural fields corresponding to each village were known. This allowed for both accurate and precise quantification of impacts for relevant impact categories, including water use, land use, and ecotoxicity emissions. Thus, aggregating grid-specific characterization factors in these categories, as proposed by Mutel et al., (2011) is not expected to reduce uncertainty in this case study. Selection of appropriate spatial scale of impact assessment could be relevant however, for some regional impact categories such as freshwater eutrophication. In this case eutrophication relied on the use of country-specific characterization factors, but this impact category was not important contributor to total damage.

5. Conclusions

This first regionalized LCA study where spatially differentiated LCIA methods were consistently applied to all relevant impact categories at damage level~~Application of spatially differentiated LCIA methods to all relevant flows in the foreground system and to all relevant categories of environmental impacts at the damage~~ level showed that although spatial differentiation improved accuracy and realism of environmental impacts, it did not necessarily lead to better decisions. This finding was unexpected considering that conditions in Indonesia with regard to biodiversity are very different compared to generic conditions. Geographic variability in life cycle inventories, combined with small contribution of some impact categories to total damage and tradeoffs between impact categories influenced the role of spatial differentiation for decision-support in this case study.

Although extrapolation of these findings to other cases is not straightforward, this study may suggest that depending on the goal of the LCA, practitioners should consider potential benefits of implementing spatially differentiated LCIA methods as opposed to potential benefits from collecting site-specific inventories. This study indicates that the former should be the priority in studies where accuracy and realism are required (e.g. in weak point analyses and eco-design LCA studies), but also in comparative LCA studies, while the latter should be the priority in studies where environmental performance of a system is expected to be mainly determined by trade-offs between burden and benefits.

The findings presented in this study raise several additional questions. First, it is unknown whether environmental benefits from implementation of biochar systems are larger than environmental burdens in other regions of the World. Second, it is unknown whether the findings generally apply to other comparative LCA case studies. Third, an intelligent approach needs to be developed to determine which of the flows in the foreground system are relevant to consider for spatially differentiated impact assessments, and which can be omitted. Forth, in this study, spatial differentiation was considered for all flows in the foreground system, but this can be challenging if more complex systems are modelled. Finally, the use of spatially differentiated LCIA methods depends on the ability of LCA modelling software to consider them, and solutions are needed to enable easy and consistent use of spatially differentiated LCIA methods in LCA of products and systems in the future.

Supplementary material

Details of case studies, model parameters, unit processes, details of uncertainty analysis, details of LCIA methods, and additional results.

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