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REVIEW ARTICLE

Biochar research activities and their relation to development and environmental quality. A meta-analysis

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Abstract Biochar is the solid product that results from pyrolysis of organic materials. Its addition to highly weathered soils changes physico-chemical soil properties, improves soil functions and enhances crop yields. Highly weathered soils are typical of humid tropics where agricultural productivity is low and needs to be raised to reduce human hunger and poverty. However, impact of biochar research on scientists, politicians and end-users in poor tropical countries remains unknown; assessing needs and interests on biochar is essential to develop reliable knowledge transfer/translation mechanisms. The aim of this publication is to present results of a meta-analysis conducted to (1) survey global biochar research published between 2010 and 2014 to assess its relation to human development and environmental quality, and (2) deduce, based on the results of this analysis, priorities required to assess and promote the role of biochar in the development of adapted and sustainable agronomic methods. Our main findings reveal for the very first time that: (1) biochar research associated with less developed countries focused on biochar production technologies (26.5 ± 0.7%), then on biochars' impact on chemical soil properties (18.7 ± 1.2%), and on plant productivity (17.1 ± 2.6%); (2) China dominated biochar research activities among the medium developed countries focusing on biochar production technologies (26.8 ± 0.5%) and

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on use of biochar as sorbent for organic and inorganic compounds (29.1 ± 0.4%); and (3) the majority of biochar research (69.0±2.9%) was associated with highly developed countries that are able to address a higher diversity of questions. Evidently, less developed countries are eager to improve soil fertility and agricultural productivity, which requires transfer and/or translation of biochar knowledge acquired in highly developed countries. Yet, improving local research capacities and encouraging synergies across scientific disciplines and countries are crucial to foster development of sustainable agronomy in less developed countries.

Keywords Sustainable development goals · Soil fertility · Plant productivity · Carbon sequestration · Agriculture · Food security

Contents

1 Introduction

The world's population is expected to reach 9 billion by 2050 (Godfray et al. 2010), which will require an increase of >50% in agricultural food supply to meet the growing demand (Mueller et al. 2012; FAO 2013a; Paul et al. 2009; FAO 2009). Over the same period, climate change, water scarcity and land degradation are expected to negatively impact agricultural productivity, which may severely challenge our ability to meet this required demand of food production (FAO 2013a). People that are already poor and vulnerable may be the worst affected, despite having contributed least to climate change. Since the global challenges of hunger, nutrition and climate justice are strongly connected (Gregory et al. 2005; FAO 2009), it is critical to minimize further land use change, land degradation and greenhouse gas (GHG) emissions. The complex interrelationship of agricultural production, water availability, and soil health will underpin the possibilities for achieving the Sustainable Development Goals of the United Nations Sustainable Development Solutions Network (Sustainable Development Solutions Network 2015). Managing land degradation is a central challenge that simultaneously addresses environmental and development objectives.

The literature often reports that the majority of land degradation is caused by human activity (e.g., overgrazing, deforestation, agricultural mismanagement or mining) that stimulates the loss of organic matter due to erosion, physical and chemical soil deterioration of the soil (Jie et al. 2002; Barman et al. 2013; Oldeman 1994; Oldeman et al. 1991). This in turn reduces soil productivity and the provision of crucial ecosystem services (ELD Initiative 2015; Barman et al. 2013). Moreover, agriculture is one of the major GHG emitters (i.e. CO_2, CH_4, N_2O) accelerating global warming (IPCC 2013, 2000), which almost certainly will negatively impact agriculture (Gregory et al. 2005). This contribution will even be enhanced with future climate change by positive feedback effects of elevated CO_2 on non-CO_2 GHG formation (van Groenigen et al. 2011), rising temperatures and more extreme weather events, such as droughts and flooding. Thus, agricultural management requires adaptation and mitigation strategies to reduce GHG emissions while simultaneously increasing crop productivity (UN 2015; FAO 2013a; Gregory et al. 2005).

One adaptation strategy is to apply organic matter to agricultural lands. Application of organic matter has shown to improve the properties of soils and agricultural productivity (Lal 2006; Lal et al. 2007; FAO 2013a). However, soil organic matter can decompose quickly (Kögel-Knabner and Amelung 2014; Schmidt et al. 2011; von Lützow et al. 2006), necessitating repeated applications (Gattinger et al. 2012; Lal 2006). Thus, the usage of stable compounds such as biochar as soil amendments, or as part of organic amendments such as compost or manure, may be a cost-effective and low-risk alternative to improve agricultural productivity and to mitigate climate change over the long-term (Gurwick et al. 2013; Glaser et al. 2002; Crane-Droesch et al. 2013; Borchard et al. 2014a; Hernández-Soriano et al. 2015).

Among the long-term soil restoration techniques, biochar and all its modified forms (e.g. loaded with nutrients, activated to change porosity and chemical properties) belong to the more promising soil GHG mitigation amendments (Joseph et al. 2013; Novak et al. 2014; Kammann et al. 2015; Schmidt et al. 2015; Mukherjee et al. 2014). Biochar is the solid product that results from pyrolysis of organic materials (Verheijen et al. 2010; Sohi et al. 2010; Keiluweit et al. 2010) having properties that depend on used technology and feedstock (Keiluweit et al. 2010; Libra et al. 2011; Enders et al. 2012). How biochar affect soil properties and plant performance has been reasonably assessed (Crane-Droesch et al.

2013; Jeffery et al. 2011; Sohi et al. 2010; Liu et al. 2013). Many investigations have shown that the application of biochar to soil influences soil physico-chemical properties and improves soil functions such as water and nutrient holding capacity (Crane-Droesch et al. 2013; Mukherjee and Lal 2013; Ajayi and Horn 2016; Jeffery et al. 2011; Haider et al. 2016). These characteristics make biochar, applied alone or as its mixture with other organic amendments (e.g. compost, manure, digestate etc.), a potentially attractive tool to improve agricultural productivity (Schulz et al. 2013, 2014; Prost et al. 2013; Liu et al. 2013). Recently, Joseph et al. (2013) and Novak and Busscher (2013) introduced tailor-made and designer biochars having specific properties adapted to their potential use. Despite the uncertainty about exact mechanisms of improvement, biochar has been most successful at improving crop yields on highly weathered soils (Crane-Droesch et al. 2013; Liu et al. 2013; Schulz et al. 2013; Jeffery et al. 2011; Lehmann and Rondon 2006; Cornelissen et al. 2013; Obia et al. 2016). Highly weathered soils are typical for humid (e.g. tropical) zones where low agricultural productivity needs to be improved to reduce poverty (Barrett and Bevis 2015; Folberth et al. 2016; Lal 2006). Thus, it is essential to transfer/translate knowledge about the use of biochar as soil amendment to scientists, politicians and end-users in poor tropical countries, where improved soil management strategies in combination with new crop varieties (e.g., drought-tolerant ones) can likely maximize beneficial effects on crop yield and climate, fostering further implementation of climate-smart agricultural practices.

There are several examples where biochar programs or activities bridge research, policy and end-users (Fig. 1). For example, the International Biochar Initiative (www.biochar-international.org), the British Biochar Foundation (www.britishbiocharfoundation.org), and the Alberta Biochar Program in Canada (www.albertatechfutures.ca) are providing organizational structure for these outreach activities. Additionally, there are numerous research networks (e.g. European Biochar Research Network [www.cost.european-biochar.org]; UK Biochar Research Centre [www.biochar.ac.uk], Biochar for Sustainable Soils (B4SS) project [http://biochar.international]) and numerous local efforts (see also http://www.biochar-international.org/network/communities) that are incorporating biochar as an axis of research and dissemination. Undoubtedly, dissemination is important to convey scientific knowledge of biochar uses and its potential benefits to policy makers and practitioners. Designing and implementing new technologies (e.g. engineered biochar) and selecting biochars to address specific soil limitations requires scientific exchange of results and information among scientists, stakeholders, and potential users (Fig. 1). Creating regional and worldwide scientific exchange networks (e.g. African Biochar Expert Group [http://www.siani.se/expert-groups/african-biochar], Design Char4Food [https://www.faccejpi.com/content/download/4466/41944/version/1/file/Designchar4Food.pdf]), will guide the development of integrated soil management strategies into a coherent global policy platform that may sustain agricultural productivity and ensure food security in the challenging times ahead (Fig. 1). To our knowledge, there has been no citable literature that has closely examined the extent of biochar adoption by countries. Moreover, information on current funding levels for biochar research by individual countries or states is sparse in the literature.

Based on the critical need for promoting the sound adoption of biochar in agricultural practices around the world, we report on biochar research activities on a global scale to identify countries that promote and fund biochar research. Information on countries' socio-economic status and their impact on the environment were used to assess how human development and environmental properties and characteristics affected biochar research. Biochar research itself is a young research discipline (Gurwick et al. 2013), thus we assumed that the countries' interest and investment in promoting biochar research would be manifested in international publication activity.

2 Material and methods

2.1 Literature search and topical classification of biochar research

An exhaustive systematic literature search (Uman 2011) was conducted for peer-reviewed articles published between January 1, 2010 and September 20, 2014 in the Web of Science database (Thomson Reuters) using the term "biochar" in the "topic" field. We excluded search results that were published in languages other than English (n = 16), or for which only an abstract was available. The remaining pool of 1250 articles was categorized into three publication types: (a) Original research, (b) Reviews, or (c) Editorials/Comments. Editorials/Comments included notes and short communications presenting brief and novel scientific findings.

From the publication database, we also extracted information about "country of origin" of the research, "country/origin of funding" and "country of institution to which authors are affiliated". Compiling "country of origin" was simple for publications indicating location or multiple locations of research (e.g. field trial, laboratory etc.). In case of lacking information on the "country of origin" we assumed that research (e.g. laboratory experiment) was performed in the first author's country (i.e. affiliation) or, in case of multiple affiliations in country, where majority of authors was affiliated. Screening articles published within 5 years (see above) may risk a publication bias due to time lag until publication and significance or novelty of biochar research results (Jennions et al. 2013),

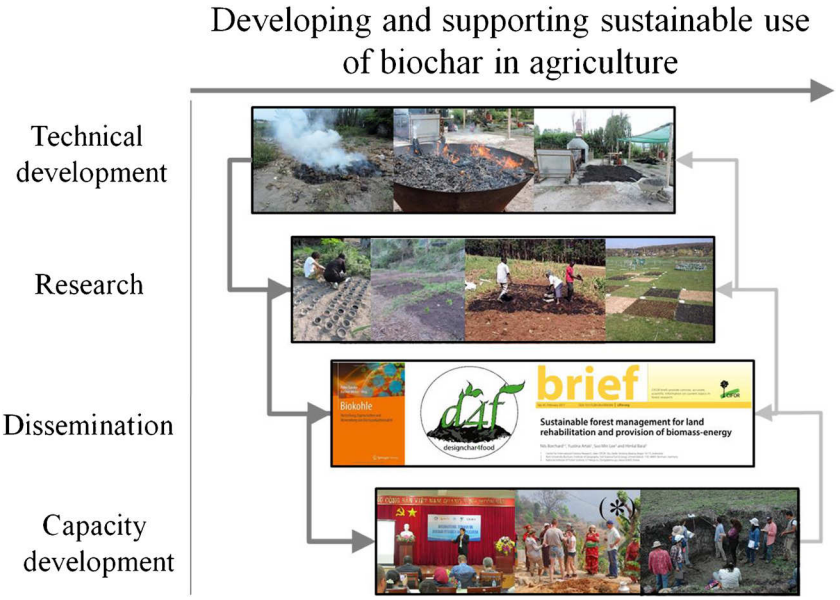

Fig. 1 Developing sustainable agriculture adapted to cultural and geophysical circumstances requires complex approaches that include technical development, research, knowledge transfer/translation and capacity development. Increasing agricultural productivity, improving food quality and reducing greenhouse gas emissions from agriculture are global challenges as demonstrated by initiatives that assess, promote and teach methods for using biochar in agriculture. *Arrows* indicate simple relations and feedback loops between technical development, research, knowledge transfer/translation and capacity development. A *single asterisk* indicates the photo: Hand-Peter Schmidt, Ithaka Institute for Carbon strategies, Switzerland

which may affect publication activity. Typically, as knowledge gaps have been addressed, new research must be more sophisticated, in terms of methods applied and hypotheses tested, which may make it difficult for developing country researchers to publish their research if they are lacking in expertise and facilities to undertake process-oriented research. Thus, time related publication bias was addressed in this study by assessing publication activity also annually. Assessing "country/origin of funding" required an acknowledgment that clearly addressed funding source, which was linked to a country or multiple countries. The authors' affiliations were explicitly added into our data base for authors affiliated to institutions located in developing countries. However, we had to accept bias due to hidden relation of authors to developing countries, e.g. a research student originally from China, but affiliated to an institution in Australia is considered to be an Australian. Multiple entries were allowed in case of multiple countries of origin, funding and authors' affiliation. Thus, the final dataset contained country-related information and topic classification.

Relative values (R) of environmental and socio-economic indices explained in section 2.2 and results shown in Figs. 4 and 5 were determined using Eq. (1):

$$R = \left(\frac{n_i}{n_t}\right)^{*} 100 \quad (1)$$

Where n_i is the number of research activities related to a specific biochar research topic and n_t is the total number of research activities found. Means are shown with their standard errors.

2.2 Compiling and aggregation of environmental and socio-economical indices

Additional information was gathered to link biochar research topics to socio-economic development and environmental indices of the 77 countries that contributed to biochar research. For this purpose, global reports and databases were evaluated for easily available, widely accepted and representative corresponding indices that reflect human development, food security and environmental circumstances (Table 1) (Lysenko et al. 2010; Steinberger et al. 2012; Organisation for Economic Co-operation and Development 2008; IPCC 2007; UNDP 2010; Sustainable Development Solutions Network 2015). Indices that reflect human development were the human development index of 2009 and its change between 2009 and 2010 (UNDP 2010), contribution of agriculture to gross domestic product in 2009 (UNSTAT, www.unstat.un.org/unsd/snaama/dnllist.asp, last update December 2013) as well as total population and its growth rate in 2009 relative to 2008 (World Bank, www.worldbank.org, 19th September 2014). Indices related to agriculture and food security were the global hunger index of 2009 (von Grebmer et al. 2013), prevalence of undernourishment (FAO, Food security indicators, www.fao.org, last update 20th December 2013), depths of the food deficit (FAO, Food security indicators, www.fao.org, last update

Table 1 Metric indices used in this study. We included five indices related to human development, eight indices representing different aspects of agricultural performance and food security and additional eight indices indicating impact on the environment and atmosphere

Topic	Index
Human development	• HDI: human development index in 2009 (UNDP 2010); four classes and their score ranges in 2010: (i) low HDI ranging between 0 and <0.480, (ii) medium HDI ranging between 0.480 and <0.670, (iii) high HDI ranging between 0.670 and <0.785 and *iv*) very high HDI ranging between 0.785 and 1 • HDI_{rel}: change of HDI between 2009 and 2010 (UNDP 2010) • AGDP: Contribution of agriculture on gross domestic product in 2009 (UNSTAT, www.unstat.un.org/unsd/snaama/dnllist.asp, last update December 2013) • Population: total population (World Bank, www.worldbank.org, 19th September 2014) • $Population_{rel}$: populations growth rate in 2009 relative to 2008 (World Bank, www.worldbank.org, 19th September 2014)
Agriculture and food security	• GHI: Global hunger index in 2009 (von Grebmer et al. 2013) • PoU: prevalence of undernourishment (FAO, Food security indicators, www.fao.org, last update 20th December 2013) • DoFD: depths of the food deficit (FAO, Food security indicators, www.fao.org, last update 20th December 2013) • PoFI: prevalence of food inadequacy (FAO, Food security indicators, www.fao.org, last update 20th December 2013) • CPC: crop land per capita (FAO 2013b); "per capita" is usually used in socio-economic sciences to indicate relation to total population or per person • N: N Fertilizer consumption in 2009 (FAO 2013b) • P: P Fertilizer consumption in 2009 (FAO 2013b) • K: K Fertilizer consumption in 2009 (FAO 2013b)
Environment, global warming and land use intensity	• EF: ecological footprint per capita in 2009 (Global Footprint Network 2014) • BC: total bio-capacity per capita in 2009 (Global Footprint Network 2014) • $CO_{2\ AGRI}$: total greenhouse gas emissions from agriculture in 2009 (FAO, FAOStat Emission Database, www.faostat.fao.org) • $CO_{2\ AGRI\ rel}$: relative (i.e. per capita) greenhouse gas emissions from agriculture in 2009 (FAO, FAOStat Emission Database, www.faostat.fao.org) • $CO_{2\ FOR}$: total greenhouse gas emissions from forestry in 2009 (FAO, FAOStat Emission Database, www.faostat.fao.org) • $CO_{2\ FOR\ rel}$: relative (i.e. per capita) greenhouse gas emissions from forestry in 2009 (FAO, FAOStat Emission Database, www.faostat.fao.org) • $CO_{2\ FFC}$: total greenhouse gas emissions from fossil fuel combustion in 2009 (IEA 2013) • $CO_{2\ FFC\ rel}$: relative (i.e. per capita) greenhouse gas emissions from fossil fuel combustion in 2009 (IEA 2013)

20th December 2013), prevalence of food inadequacy (FAO, Food security indicators, www.fao.org, last update 20th December 2013), crop land per capita and fertilizer (i.e. N, P, K) consumption per ha in 2009 (FAO 2013b). Environmental aspects relating to global warming and land use intensity were total ecological footprint per capita (i.e. "A measure that represents the productive area required to provide the renewable resources humanity is using and to absorb its waste".) and total bio-capacity per capita (i.e. "ability of an ecosystem to produce useful biological materials and to absorb carbon dioxide"; www.footprintnetwork.org) of 2009 (Global Footprint Network 2014), and GHG emissions from individual sources of agriculture, forestry and fossil fuel combustion in 2009 (FAO, FAOStat Emission Database, www.faostat.fao.org; IEA 2013).

Since the selected country-specific indices were all descriptive and intercorrelated, an aggregation of the data into fewer factors was justified (Pavlovic and Mandel 2011). We used exploratory factor analysis to identify common, uncorrelated latent variables from the larger pool of correlated indices (Fabrigar and Wegener 2012). This permitted us to deduce the major indicators and to find groups of relationships among these primary indicators by examining the factor loadings.

Exploratory factor analysis was applied on all indices using generalised least squares (GLS) which handles Heywood cases effectively (Jöreskog and Goldberger 1972). Heywood cases are factor estimates >1, which renders the factor analysis unreliable. GLS weighs the residual matrix by the inverse of the correlation matrix. This gives a greater weight to weakly correlated variables and prevents distortion of results due to collinearity of independent variables. For interpretation, the factors were rotated using VARIMAX rotation. VARIMAX rotation maximizes the variance of the loadings, which ensures that for each factor the loadings are stretched into small and high loadings (Kaiser 1958).

Based on the eigenvalues calculated by the exploratory factor analysis we chose four factors of the aggregated indices. This decision was supported by a screeplot, which displayed the eigenvalues depending on the number of factors. At the point where the eigenvalues levelled off, we determined the

number of factors (Cattell 1966). According to the distribution of the loading values within each factor, we defined the factors as follows (Table 1, Fig. 2):

Factor 1 (*Development*) explained 50% of the data variability and included socio-economic and environmental indices from countries that contributed to biochar research activities (i.e. country of origin and funding by country; Table 2). This factor indicates development as shown by high loadings of (i) human development index, (ii) relative change of the human development index between 2009 and 2010, (iii) ecological footprint, (iv) contribution of agriculture to gross domestic product, (v) global hunger index, (vi) CO_2 emissions from fossil fuel combustion relative to total population, (vii) population growth rate between 2008 and 2009, (viii) prevalence of undernourishment, (ix) depths of the food deficit and (x) prevalence of food inadequacy. In detail, developed countries are characterized by high human development combined with large CO_2 emissions from fossil fuel combustion and a high impact on Earth's ecosystems, whereas countries, where agriculture is usually an important component of gross domestic product, are facing food scarcity and malnutrition, rapid population growth and development change.

Factor 2 (*GHG emissions*) explained 21% of the data variability and indicates countries with high (i) total population, (ii) total GHG emissions from agriculture and (iii) emissions from combustion of fossil fuels relative to total population. Countries having larger Factor 2 scores are for instance Brazil, China, India and the USA.

Factor 3 (*Environmental resilience*) explained 15% of the variability in the level of biochar research activity and indicates environmental capacity of countries to renew biotic resources used by humans and to mitigate impacts (e.g. emitted CO_2) as well amount of agricultural land relative to total population. As indicated by high loadings for (i) bio-capacity, (ii) crop land relative to total population and (iii) GHG emissions from agriculture relative to total population this factor is large for countries that have large areas of agricultural land causing substantial emissions of GHGs from agriculture. Countries having higher values that fit these criteria are for instance Argentina, Australia, Brazil and the USA.

Factor 4 (*Intensity of agriculture*) explained also 15% of the data variability and relates to intensity of agriculture, which is indicated by high loadings for (i) N and (ii) P fertilizer use as well as by (iii) CO_2 emissions from agriculture relative to total population. Countries like New Zealand, Singapore and Ireland fit these criteria and have larger values, while Australia and Canada have low values.

These factors represent country-specific indicators that relate to *Development*, *GHG emissions*, *Environmental resilience* and *Intensity of agriculture,* which were then related to common biochar research topics (see above; Atkinson et al. 2010; Sohi et al. 2010; Leach et al. 2012). Thus, aggregated socio-economic and environmental indices were used to assess relationships between biochar research topics and country-specific development and environmental quality.

2.3 Relation between biochar research topics and aggregated environmental and socio-economic indices

We estimated the influence of a country's socio-economic development and environmental quality for each biochar research topic (see below) and their interaction with country-specific activities (i.e. "country of origin", "country/origin of

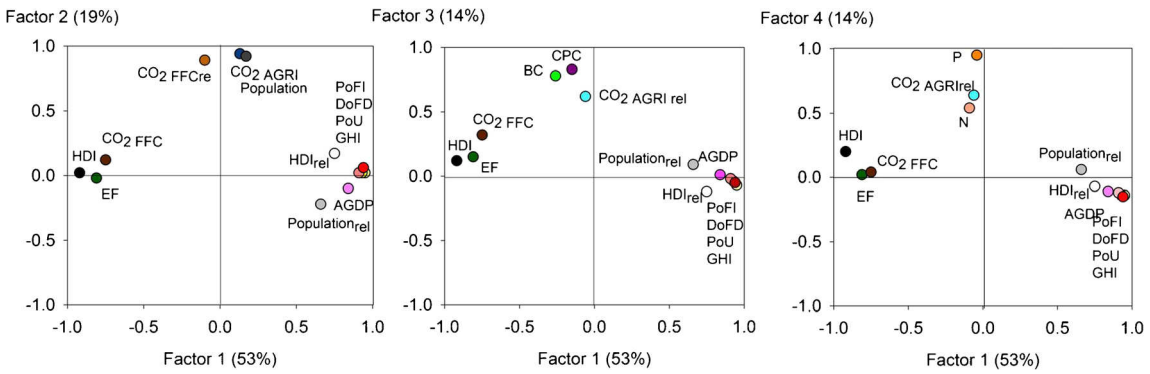

Fig. 2 Factor loading vectors showing the correlations between the socio-economic parameters obtained from global databases and datasets (Table 1), explained variance in parentheses. Values with loadings >0.60 are shown. HDI: human development index of 2009 (*black circle*) and its change between 2009 and 2010 (HDI_{rel}; *white circle*); AGDP: Contribution of agriculture on gross domestic product in 2009 (*light purple circle*); population: total population (*grey circle*) growth rate in 2009 relative to 2008 (population $_{rel}$; light grey circle); GHI: Global hunger index of 2009 (*light yellow circle*); PoU: prevalence of undernourishment (*yellow circle*); DoFD: depths of the food dedicate (*light red circle*); PoFI: prevalence of food inadequacy (*red circle*); CPC: crop land per capita (*purple circle*); **N**: N Fertilizer consumption in 2009 (*light orange circle*); P: P Fertilizer consumption in 2009 *(orange circle*); EF: Ecological footprint per capita (*green circle*); BC: total bio-capacity per capita of 2009 (*light green circle*); total and relative (i.e. per capita) greenhouse gas emissions from agriculture in 2009 ($CO_{2\ AGRI}$,$CO_{2\ AGRI\ rel}$; *blue* and *light blue circles*); total and relative (i.e. per capita) greenhouse gas emissions fossil fuel combustion of 2009 ($CO_{2\ FFC}$,$CO_{2\ FFC\ rel}$; *brown* and *light brown circles*)

Table 2 Relationships between aggregated socio-economic as well as environmental indices (i.e. factors) of countries hosting and/or funding biochar research and research activities in different biochar research topics. The results shown are based on a two-step approach: (i) aggregation of 21 socio-economic and environmental indices by explanatory factor analysis to four factors (see below table footnotes; *Development, GHG emissions*, *Environmental resilience*, *Intensity of agriculture*; Chapter 2.2; Table 1) and (ii) assessing the relation between these factors and biochar research activities (i.e. *Chemistry & fertility*, *Physics*, *Biology*, *Plant performance*, *GHG & climate*, *Sorption*, *Technology*) by a regression model described in Chapter 2.3. Significant relations are indicated by a "yes" and corresponding probability level

Biochar research activities	Chemistry & fertility	Physics	Biology	Plant performance	GHG & climate	Sorption	Technology
Factors	Country of origin						
Development	"yes"***	"yes"***	"yes"***	"yes"**	"yes"***	"yes"***	"yes"***
GHG emissions	"yes"***	"yes"***	"yes"***	"yes"***	"yes"***	"yes"***	"yes"***
Environmental resilience	"yes"*	n.s.	"yes"***	n.s.	"yes"***	"yes"***	"yes"***
Intensity of agriculture	n.s.	n.s.	n.s.	n.s.	n.s.	"yes"*	n.s.
Factors	Funding by country						
Development	"yes"***	"yes"***	"yes"***	"yes"***	"yes"***	"yes"***	"yes"***
GHG emissions	"yes"***	"yes"***	"yes"***	"yes"***	"yes"***	"yes"***	"yes"***
Environmental resilience	n.s.	n.s.	"yes"*	n.s.	n.s.	n.s.	n.s.
Intensity of agriculture	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Development: Factor 1 indicates country development; *GHG emissions*: Factor 2 relates to countries having high population and vast GHG emissions from agriculture and combustion of fossil fuels; *Environmental resilience*: Factor 3 indicates environmental capacity of countries to renew biotic resources used by humans and to absorb their wastes (e.g. emitted CO_2) as well as impact of agriculture; *Intensity of agriculture*: Factor 4 relates to intensity of agriculture, which is indicated by high loadings for N and P fertilizer as well as by CO_2 emissions per capita from agriculture

n.s. not significant

Probability level: ***<0.001, **<0.01, *<0.05

funding" and "country of institution with which authors are affiliated") with regression analysis.

Biochar research activities were grouped into seven research topics (Atkinson et al. 2010; Sohi et al. 2010). Each article addressed at least one of the following biochar research topics:

1) Effect of biochar on soil chemistry and fertility *(Chemistry & Fertility)*: publications that presented chemical soil properties affected by biochar additions, which reflect impacts on element cycles (i.e. C, N), nutrients (e.g. K, N, P, etc.), cation exchange capacity and soil pH. Thus, this topic is related to soil fertility, which connects to plant nutrition and growth.
2) Effect of biochar on soil physical properties *(Physics)*: publications that provided information of soil physical properties altered by biochar application. This topic includes effects on soil hydrology (e.g. water holding capacity, water hydraulics), soil structure (e.g. aggregation, erodibility) and energy balance (e.g. albedo).
3) Effect of biochar on soil biology *(Biology)*: this topic includes publications that presented effects on soil biota (e.g. bacteria, fungi, earthworms) and soil enzymes.
4) Effect of biochar on plant performance *(Plant performance)*: biochar may affect total biomass yield and mass of plant organs (e.g. root, grain). Additionally, effects on plant health and any alteration of its compositional character (e.g. proteins, sugar, nutrients) are part of this topic.
5) Biochar application to mitigate climate change and sequester carbon *(GHG & Climate)*: Publications that presented effects on GHG emissions (i.e. CO_2, CH_4, N_2O) and C-sequestration after soil application are included into this topic.
6) Biochar as a sorbent *(Sorption)* of organic and inorganic compounds: Here we included publications that studied or reviewed effects on inorganic and organic soil compounds (e.g. retention, immobilization, degradation).
7) Biochar production and economic assessment *(Technology)*: This topic covers publications that presented technologies to produce modified and treated biochars. Formation and handling of biochar may also affect economic aspects, thus, this topic also included in the category of biochar production and economic assessments. This meta-analysis, however, considered only publications that presented technologies to produce modified and treated biochars without further assessments to prevent repetition of research (see also section 1).

The response of the regression model (i.e. the number of publications within the specific research topic) was related to the extracted factor scores from the exploratory factor analysis. Since the response variable is the counted number of publications, we used a general linear model coupled to a logistic link function and a Poisson distributed error structure (Crawley 2002). Some of the general linear models experienced over-dispersion as assessed by the test of Cameron

and Trivedi (2005); this might eventually underestimate the standard errors of the coefficients and thus overestimate the statistical significance of the factors (Fitzmaurice 1997). In the case of overdispersion, a negative binomial general linear model with full maximum likelihood estimation was applied (Hilbe and Robinson 2013; Venables and Ripley 2003).

3 Results and discussion

We identified and screened a total number of 1250 publications (i.e. research papers, reviews, short communications and notes) to assess relations between biochar research topics and overall indicators derived from 21 country-specific socio-economic and environmental indices. Sources of funding were mentioned in 1010 publications (81%). In 474 publications (38%), authors were from countries in a development status lower than "very highly developed" (Table 2; UNDP 2010). Due to multiple entries for experiments that (i) were performed in multiple countries, (ii) were supported by multiple funders or (iii) were written by authors from multiple countries, the final dataset consists of 1430 observations (i.e. rows). Most research associated with countries with a less development score (i.e. low and medium human development) was performed to study *biochar production* and to do *economic assessments* accounting 27 ± 1% of all research activities in these countries. Another focus of biochar research in less developed countries was the study of impact of biochar on *chemistry & fertility* and *plant performance*, which accounted for 19 ± 1% and 17 ± 3% of total research activities, respectively. Less research was recorded for *GHG & climate* (15 ± 1%), *sorption* (15 ± 2%) and *biology* (6 ± 1%). Very little research was performed to assess effects of biochar on soil *physics* accounting for only 2 ± 1% of the total research activities, which might be a result of slow soil formation processes (e.g. formation of soil aggregates) and/or capabilities required to assess them (Ajayi and Horn 2016; Obia et al. 2016).

Biochar research is anticipated to support climate-smart agriculture, food security and livelihoods for poor farmers (Leach et al. 2012; FAO 2013a), but effectiveness has not been conclusively and systematically assessed. Linking all 21 indices to biochar research activities is a promising way to test whether socio-economic development and environmental quality interact to determine biochar research activities. Our findings revealed that global biochar research activities differed among countries depending on their level of *development* and their *GHG emissions* (see above and Table 2, Fig. 3). As country *development* and *GHG emission* levels increased so did research activity and funding for all biochar research topics mentioned above (Table 2) and illustrated in Fig. 3 for the most popular biochar research topics: *chemistry & fertility* (i.e. 18 ± 1%) and *technology* (30 ± 0%). *Environmental resilience* and *impact of agriculture* correlated with a few biochar research topics (Table 2). For *biology* both data sets revealed a correlation with the countries' *environmental resilience*, while further correlations were found exclusively for the "*Country of origin*" dataset.

3.1 Influence of development on biochar research

The most important factor 1 in this analysis (*Development*) correlated strongly with all biochar research topics (Fig. 2, Table 2). The individual factor scores of the countries in this dataset correlated (i.e. Spearman) strongly with the human development index (Table 1; $P < 0.05$; $R = -0.83$). Hence, the widely accepted and commonly used human development index was used in this study to assess the relation between human development and biochar research activities.

Countries low on the human development index (Table 1; UNDP 2010) undertook biochar research in four areas: *chemistry & fertility* (24%), *plant performance* (22%), *GHG & climate* (27%) and *technology* (27%). Similarly, surveyed funding activities revealed an intense support of biochar research on *chemistry & fertility* (22%), *plant performance* (33%), *GHG & climate* (22%) and *technology* (22%), but just 1.1% of mentioned funding sources originated from countries low on the human development index. Only three publications mentioned funding from countries with low human development index (Table 1; Ali et al. 2012; Deal et al. 2012; Sparrevik et al. 2013; UNDP 2010). Each of these three studies was devoted to the area of *plant performance* and 2 of the 3 assessed also effects on *chemistry & fertility*, *GHG & climate* and *technology*. Thus, the majority (~99%) of surveyed funding originated from funding sources in highly developed countries (HDI > 0.480; UNDP 2010). Limited funding from countries with low human development index scores may be the result of limited financial resources (Delmer 2005). Therefore, a small number of studies were published, but they revealed that low developed countries focused on assessing potential use of biochar to improve agronomic production as reflected by large proportion of studies related to the research topics *chemistry & fertility* and *plant performance*. This interest probably relates to findings reporting that biochar can increase biomass and crop yields especially on low fertility soils in the tropics, which are common in developing tropical countries (Crane-Droesch et al. 2013; Glaser et al. 2002; Liu et al. 2013; Barrett and Bevis 2015; Cornelissen et al. 2013; Obia et al. 2016). Therefore, developing countries in the tropics suffering from hunger and poverty supported biochar research with the aim to increase agronomic productivity (Barrett and Bevis 2015; Folberth et al. 2016; Mueller et al. 2012), which clearly links to the *zero hunger* and *reducing poverty* Sustainable Development Goals (UN 2015).

Biochar research topics in countries ranked medium on the human development index (Table 1; UNDP 2010) differed to those of low development countries due to higher interest in the topics *sorption* (27 ± 0%) and *technology* (28 ± 1%)

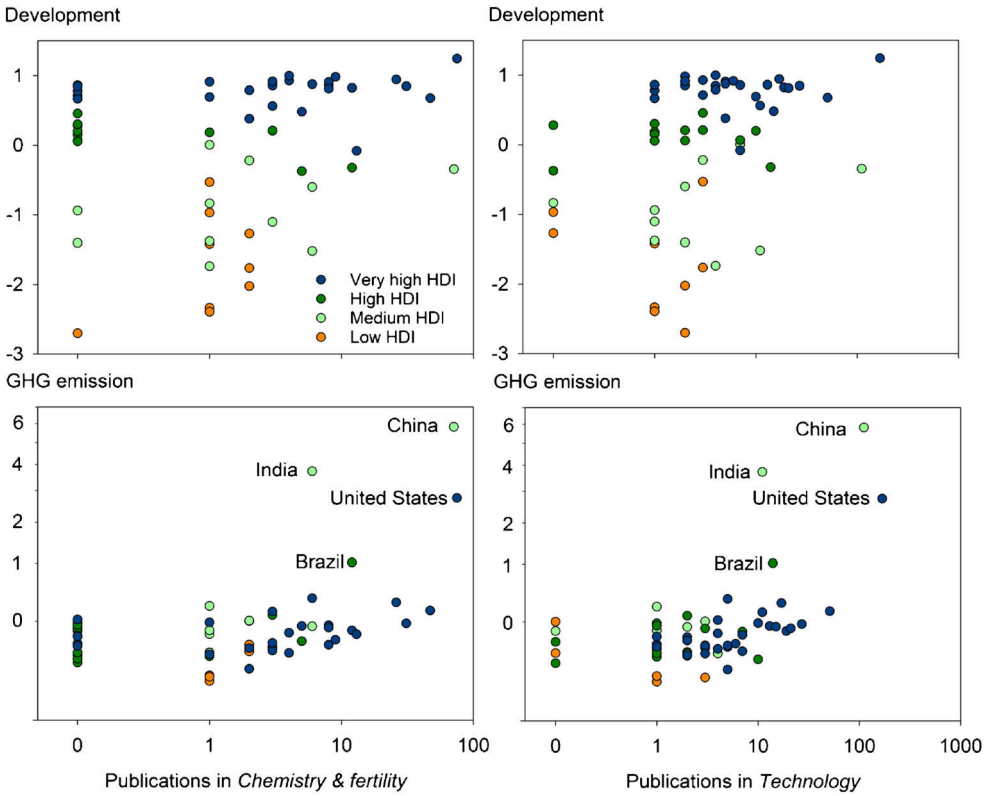

Fig. 3 Biochar research activities on *chemistry & fertility* and *technology* in terms of total number of publications and their relation to the countries' *development* (i.e. larger number implies higher development) and their *GHG emissions* (i.e. larger number implies higher impact on GHG emissions) (see also Table 2)

compared to lower interest in *chemistry & fertility* (15 ± 2%) and *plant performance* (10 ± 0%). It is interesting to note that biochar research activities and funding for countries with a medium human development index score were dominated by Chinese research and funding activities, ranging between 75 and 95% among all research topics (Figs. 4 and 5). Between 2010 and 2014 China's contribution to biochar research increased continuously and more strongly than in other countries with intermediate development scores (Fig. 5). Especially, the latter reflects efforts by China to protect the environment and to restore degraded/polluted land (Zhang et al. 2016; Albert and Xu 2014) using biochar (Kong et al. 2014; Ahmad et al. 2014; Zhang et al. 2013). Other countries in this group (e.g. India, Pakistan and South Africa) focused their research on *chemistry & fertility* (16 ± 2%) and *technology* (36 ± 3%), and to a lesser extent on *plant productivity* (14 ± 0%) (Fig. 4). Their research activities often combined aims of sustainable food and energy production while assessing potential use of secondary resources (e.g. organic wastes) (Saranya et al. 2011; Singh and Sidhu 2014; Liu et al. 2014; Naeem et al. 2014; Bolan et al. 2013). It is important that wastes are free of contaminates to prevent any negative impact on the environment and food chain (Kookana et al. 2011; Kusmierz and Oleszczuk 2014; Lucchini et al. 2014).

Although authors from 21 countries with development scores lower than high (i.e. HDI < 0.670; UNDP 2010) conducted research on biochar, their output in form of publications was low relative to countries having high and very high human development. Publications prepared entirely by authors associated to institutions in countries with a human development index of <0.670 was low (18%), but it clearly indicates a successful scientific South-South cooperation due to collaboration among these countries (e.g. Demisie et al. 2014; Ibrahim et al. 2013; Zhang et al. 2012). Similarly, contribution of mixed groups (i.e. North-South cooperation) was also low, accounting for only 15% of all publications (e.g. Deenik et al. 2011; Deal et al. 2012; Nelissen et al. 2014; Ahmad et al. 2013), while contribution of authors linked to institutions in countries with high and very high human development index was very high accounting for 67% of the published research. The enormous body of literature produced by countries with high and specifically with very high Human Development Indices covers all biochar research topics mentioned above (Figs. 4 and 5). However, the majority of supported and conducted research assessed effects on *chemistry & fertility* (18 ± 1%) and *technology* (34 ± 1%). These countries also did research on *biology* (10 ± 1%), *plant performance* (11 ± 0%), *GHG & climate* (13 ± 1%), and *sorption* (12 ± 0%). In addition, research was done to study the effects of biochar on soil *physics* (3 ± 1%). The higher the countries' human development score, the higher was the diversity of biochar research topics and outputs, which is crucial to develop sustainable strategies to improve plant productivity and adaptation to climate change (FAO 2013a; Bouma 2014). Thus, biochar research activities in highly developed countries were more intense,

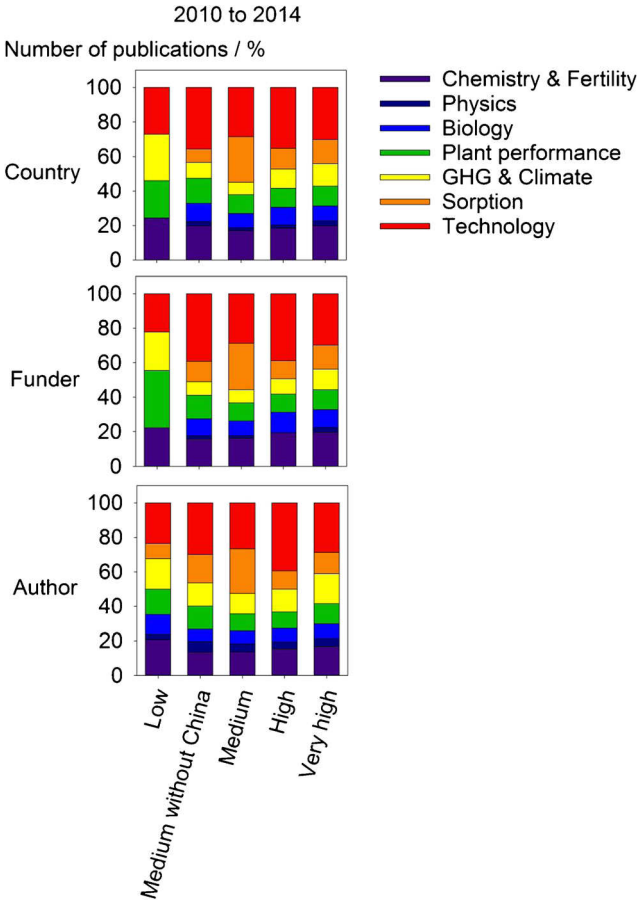

Fig. 4 Biochar research related publication activity in 2010 to 2014 sorted by biochar research topics (see Material & Methods section) and research country, funding country and author's country (i.e. their affiliation). Research topics were assessed and sorted in accordance to the countries' human development index of 2009 (Table 1); low human development <0.480, medium human development <0.670, high human development <0.785 and very high human development ranges between 0.785 and 1 (UNDP 2010)

diverse, and due to overlapping activities, more complex than in low and medium developed countries.

Das (2015), OECD (2012), and Pietrobelli and Rabellotti (2011) explained low or even lacking acquisition of new technologies and innovations in developing countries by the following factors: (i) lacking diversity of research actors (i.e. governmental and higher education sector >> business enterprise sector); (ii) inadequate research infrastructure and weak interaction with the local business enterprise sector; and (iii) lack of knowledge, equipment, human and financial resources. However, developing sustainable growth strategies (e.g. climate-smart agriculture combined with biochar) requires removing existing knowledge gaps, capacity and policy barriers by (i) establishing reliable technology transfer/translation, capacity building, funding mechanisms and (ii) promoting local research and interaction between research actors by improving research policy, education and research infrastructure (Dinesh et al. 2016; Delmer 2005; Calderón and Fuentes 2012; Garb and Friedlander 2014). Evidently, biochar research coordinated and conducted by research groups from highly developed countries (e.g. Australia, Norway, USA) has already produced a huge body of knowledge on how biochar affects soil properties and plant productivity in the sub-tropics and tropics (Macdonald et al. 2014; Cornelissen et al. 2013; Novak et al. 2009). Thus, effort is now required to transfer/translate biochar knowledge, to change behaviour and encourage implementation of agricultural biochar strategies in the tropics.

3.2 Influence of GHG emission on biochar research

This analysis shows that countries that are large primary producers of agricultural products (i.e. Brazil, China, India and USA; Fig. 3) are interested in offsetting and reducing greenhouse gas emission from agriculture by using biochar (FAO 2012; Laird 2008; IPCC 2000; Cayuela et al. 2010; Mukherjee and Lal 2013). Notably, these four countries emitted in 2009 about 51% (i.e. Brazil 10%, India 15%, China 19% and USA 9%) of total GHG emissions from agriculture (FAO, FAOStat Emission Database, www.faostat.fao.org; Table 1) from the 77 countries assessed in this study. Additionally, Brazil and the USA produced large quantities of GHGs from combustion of fossil fuels (IEA 2013), which were large even when expressed in per capita terms (Brazil: 12.5 Mg CO_2 capita^{-1}, USA: 16.9 Mg CO_2 capita^{-1}). Relative emission from fossil fuel combustion in India (1.4 Mg CO_2 capita^{-1}) and China (5.1 Mg CO_2 capita^{-1}) was in the middle of the data utilized, ranging between 1.3 and 8.5 Mg CO_2 capita^{-1} (IEA 2013). Reducing emissions from fossil fuel combustion and agriculture is a global task and requires contributions from all countries to mitigate climate change, and to adapt the energy sector and land use (i.e. agriculture and forestry) to the changing climate (FAO 2009; IPCC 2000, 2013; Hallegatte et al. 2016). Recently, Wollenberg et al. (2016) stated that agriculture can contribute to the 2 °C target for limiting global warming, but reliable strategies and technologies are required to manage, e.g. agricultural emissions of CH_4 and N_2O (IPCC 2013). Although it is clear that biochar can reduce emissions of GHGs (Cayuela et al. 2014; Borchard et al. 2014c), stabilize labile organic matter (Borchard et al. 2014a) and remain in agricultural soils for at least decades (Preston and Schmidt 2006; Borchard et al. 2014b) contradictory findings (Wardle et al. 2008; Borchard et al. 2014c; Zimmermann et al. 2012) elucidate needs to assess mechanisms controlling GHG emissions in more detail across varying environments and climatic zones (Schmidt et al. 2011).

3.3 Influence of environmental resilience and agriculture on biochar research

Assessing relations between both the countries' *environmental resilience* and *impact of agriculture* to the biochar research activities revealed an inconsistency between location of research

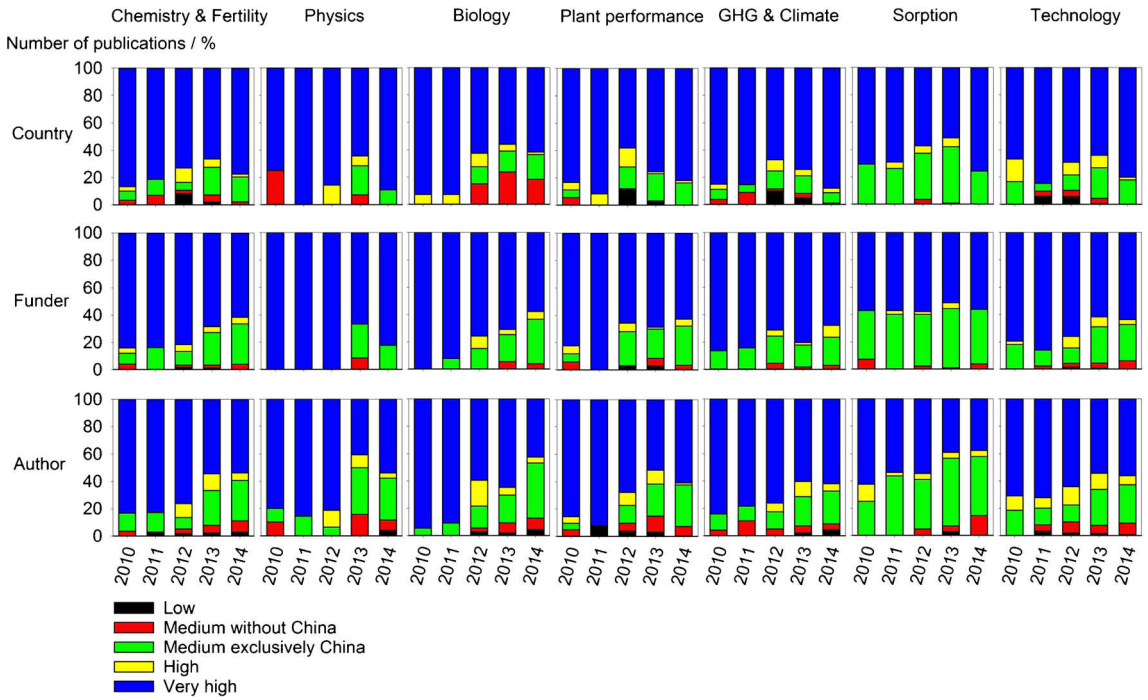

Fig. 5 Biochar research related publication activity for each year in 2010 to 2014 sorted by biochar research topics (see Material & Methods section), research country, funding country and author's country (i.e. their affiliation). Research topics were assessed and sorted in accordance to the countries' human development index of 2009 (Table 1); low human development <0.480, medium human development <0.670, high human development <0.785 and very high human development ranges between 0.785 and 1 (UNDP 2010)

(i.e. country of origin) and funding by country (Table 2). A smaller number of acknowledged funding resources may explain non-significant relations between funding sources from countries scored by their *environmental resilience* and *impact of agriculture* to almost all biochar research topics. Countries with high scores for *environmental resilience* and areas with very low population densities (Argentina, Australia, Brazil, Canada, and New Zealand) hosted research assessed impact of biochar on *chemistry & fertility*, *GHG & climate*, *sorption* and *technology* (Table 2 "Country of origin"). The countries' interest in assessing impacts of biochar on these issues can be related to their efforts to improve soil fertility, to sequester carbon and to use pesticides efficiently in agriculture (Kookana 2010; Blackwell et al. 2010; Jablonowski et al. 2012). Assessing effects of biochar on soil biota was clearly related to the countries' *environmental resilience* as reflected by significant relations to the country of origin and funding (Table 2) and their ability to promote and facilitate biological research that required more sophisticated methods and equipment (Delmer 2005).

4 Conclusion and implication for future activities

This meta-analysis presents for the first time results on global biochar research activities and their relation to socio-economic development of the countries hosting/funding the research. Biochar research activities are concentrated in very highly developed countries, with little effort in poor tropical countries. However, those countries in which poor soils are abundant may benefit substantially from agricultural innovations that include biochar (Crane-Droesch et al. 2013; Barrett and Bevis 2015; FAO 2013a). Further, the lack of research being done in poor tropical countries may result in researchers missing local and indigenous innovations that could enhance biochar efficacy where it is most needed (van Vliet et al. 2012; Nigh and Diemont 2013; Miltner and Coomes 2015). Thus, to realize the potential benefits of biochar in poor tropical countries we need cooperation (e.g. interdisciplinary research, knowledge transfer/translation) and investments (e.g. research equipment and infrastructure) in countries that are interested in doing integrated research that includes biochar as a tool to improve crop productivity and to mitigate climate change (Calderón and Fuentes 2012; Das 2015; Garb and Friedlander 2014). Biochar research activities can contribute substantially to the 2 °C target for limiting global warming (Wollenberg et al. 2016; FAO 2013a; Leach et al. 2012). Further global efforts in biochar research are required to understand and manage nutrient dynamics and impacts on GHG emissions. Therefore, based on the results of this review, we identify the following research priorities to assess and promote the role of biochar in development of adapted and sustainable agronomic methods:

1. Intensify transfer/translation of existing knowledge, and capacity building required to conduct climate-smart agronomic research across countries of different development

levels. It is important to educate and train local experts in science, policy and best-practice examples (e.g. Schmidt et al. 2015) to ensure effective research and successful implementation of new technologies and methods including biochar in poor tropical countries.

2. Enhance research investments and technical cooperation used to conduct agronomic research across countries of different development levels. In developing countries, research is often limited to simple (and often labour-intensive) objectives (e.g. plant growth, but not plant physiology) restricting depth and complexity of their biochar research activities. However, to understand the complex interactions among biochar, soil and plants, and to develop methods applicable for end-users, a mixture of simple and high-tech methods is required and has been initiated recently by research networks (e.g. the Biochar for Sustainable Soils project [http://biochar.international//]).
3. Sustainable and climate-smart agriculture using biochar needs knowledge about soil chemistry and plant productivity that is required to manage nutrient application. However, soil biology and physical properties are also drivers that affect nutrient and water availability and thus plant productivity. Therefore, agronomic research using and managing soil biology and physics to enhance plant productivity are needed, but rarely performed.
4. Finally, agronomic research must be interdisciplinary to ensure greatest benefit from soil and biochar research. Cooperation among several scientific disciplines (e.g. plant science, soil science, and hydrology) is required to facilitate development of sustainable agronomic methods.

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