

Biochars in soils: new insights and emerging research needs

Introduction and background

The quantity, quality and breadth of research connected to biochar have grown rapidly since 2009/2010 when a number of books and reviews were published, some with policy support (Lehmann & Joseph, 2009; Shepherd, 2009; Sohi *et al.*, 2009; Verheijen *et al.*, 2010), and a European Commission biochar event was held at the COP15 meeting in Copenhagen in 2009. Bi-annual conferences organised by the IBI (International Biochar Institute: <http://www.biochar-international.org/>) have been superseded by sessions and symposia at many disciplinary conferences. Research networks have emerged, notably a European COST action as well as a number of journal special issues (*Pesquisa Agropecuária Brasileira*, 2012, 47(5); *Global Change Biology Bioenergy*, 2013, 5(2); *Agronomy*, 2013, vol. 3(2); *Carbon Management*, 2014; and a virtual special issue of *Soil Biology & Biochemistry*. This special issue of the *European Journal of Soil Science* is the fruit of biochar sessions at the EUROSOIL 2012 conference (held at Bari, Italy).

At the time of writing, 1038 articles which included the word 'biochar' or 'bio-char' in the topic had been indexed in the ISI Web of Science from 2005 to 2012, of which 698 included 'soil' in the topic (Figure 1). Approximately one third of all biochar publications do not include 'soil' as a topic (black bars in Figure 1), despite soils being their suggested direct or indirect objective. Analysis of key words of these non-soil related biochar publications reveals that the main subject areas are chemical engineering and energy. This possibly reflects a search for better understanding of biochar as a material and the co-production of energy and biochar.. From 2010, the proportion of soil-related biochar publications increased (green bars in Figure 1). To put these numbers into context, we compared the number of biochar publications against a well-established and related topic, that of crop residue return and impact on soil. The red line in Figure 1 (the secondary y-axis) shows publications with 'biochar & soil' in the topic as a proportion of publications with 'crop residue & soil' in the topic, increased from 5% in 2005 to 37% in 2012.

The increasing interest in biochar in soil science stems predominantly from its potential for increasing crop productivity (Atkinson *et al.*, 2010; Jeffery *et al.*, 2011) at the same time as efficiently sequestering carbon in soils (Woolf *et al.*, 2010). Nevertheless, there is a range of additional soil functions and land uses, as well as reports on direct and indirect interactions between soils, biochar and biota. These include, among others, contaminated soil remediation (Beesley *et al.*, 2011; Ennis *et al.*, 2012), restoration

of grasslands (Ohsowski *et al.*, 2012); forest management (Zwart & Kim, 2012; Stavi, 2013), promotion of mycorrhizal activity (Warnock *et al.*, 2007), seed germination (Solaiman *et al.*, 2012), plant disease suppression (Elad *et al.*, 2010; Meller Harel *et al.*, 2012), interactions with soil fauna (reviewed by Lehmann *et al.*, 2011; Ameloot *et al.*, 2013) and impacts on pesticides (Kookana, 2010; Graber *et al.*, 2011). It is now firmly understood that as well as influencing soil fertility by improving nutrient retention and exchange, addition of biochar to soils can affect numerous other soil properties and processes, including abiotic and biotic interactions. With biochar production and application to soil increasing in most parts of the world, for scientific research purposes as well as a burgeoning interest for commercial purposes, the need to understand how biochar additions affect soil properties and processes in order to inform regulation has become urgent. Given its wide-ranging effects and longevity and reactivity in the soil, acquiring such an understanding requires contributions from all relevant soil science disciplines and as well as environmental science and plant science disciplines. As a step towards providing a platform for interdisciplinary exchange, a session titled 'Effects of Biochar on Soil Properties, Processes and Functions' was convened at the EUROSOIL 2012. A total of 85 oral and poster presentations were made, constituting the third largest session at the conference after the classical sessions on soil erosion and soil organic matter. Twenty-four manuscripts based on session presentations were submitted to this EJSS peer-reviewed special issue. The 16 accepted manuscripts submitted from Africa, Asia, Australia & New Zealand, Europe, North and Latin America and the Middle East, describe the latest findings on how biochar affects auto- and heterotrophic soil respiration, nutrient dynamics, sorption of soil contaminants, water dynamics, redox reactions, and rhizosphere interactions. The methodologies employed span multiple spatial scales including field plots, root-box experiments, lysimeters and greenhouse and laboratory experiments, and also studies that compare effects between different scales. Temporal scales of experiments ranged from 1 day to 21 months (the median was 100 days), while one study compared charcoals added to the soil over 770 years.

New insights

The 16 papers of this Special Issue are a snapshot of a dynamic international research community. The wide range of disciplines, methodologies, spatio-temporal scales, fundamental and applied research questions, is entirely appropriate for advancing our

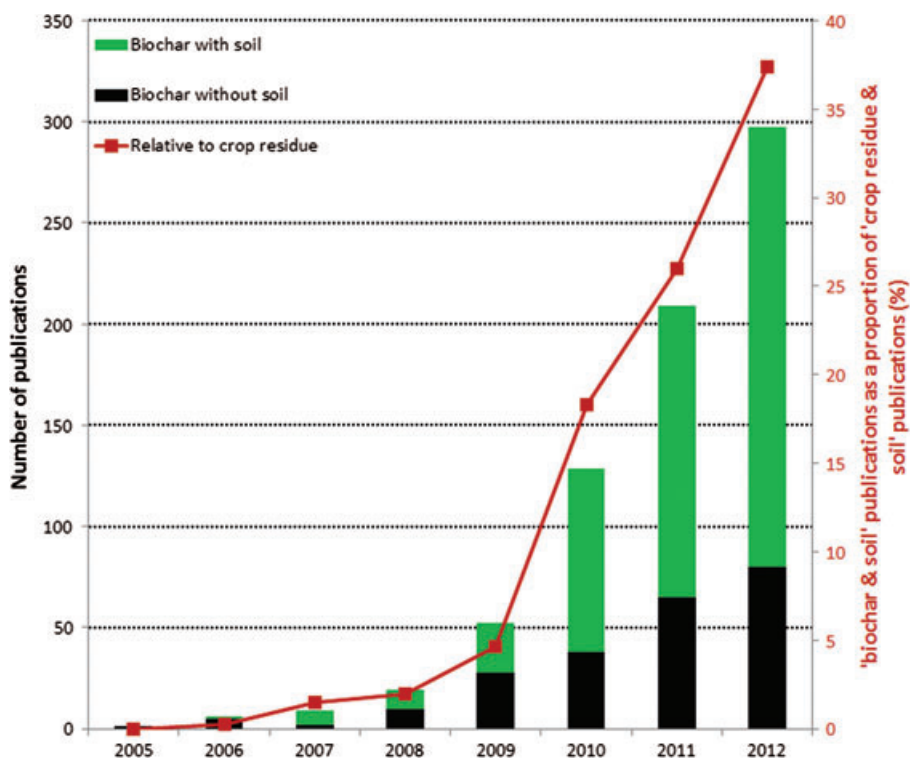


Figure 1 Biochar publications in scientific journals between 2005 and 2012. The bars (primary y-axis) indicate numbers of publications of published ISI articles in Web of Science (Web of Science™©). The black bars represent non-soil-related biochar publications, and the green bars represent soil-related biochar publications. The red data and line (read on the secondary y-axis) represent the biochar publications ('biochar' and 'soil' in the topic) as a proportion of crop residue publications ('crop residue' and 'soil' in the topic).



Figure 2 Word cloud based on the 16 abstracts in this special issue. The frequency of occurrence is expressed by the relative size of the words. The terms 'biochar' and 'soil' were omitted (including their plural forms). Created with Wordle™.

scientific understanding and for the urgently needed contribution of science to policy and society on this topic. Figure 2 shows the relative frequency of words used in the abstracts in this special issue. Terms associated with soil respiration and biochar stability, particularly 'microbial', and to a lesser degree 'incubation', are most numerous. Terms involving water dynamics and the N-cycle follow in second place and include 'water', 'leaching' and 'ammonium'. For the last two groups, 'metal dynamics' and 'root dynamics', a few specific terms can be found ('reducing', 'metals', and 'root'). In the sections below, a brief introduction of the papers in this special issue is given, organized by topic.

Soil respiration and biochar stability

In the opening paper, Gomez *et al.* (2014) mixed biochar (oak; 550°C) to four temperate soils at a range of application rates

and measured effects on soil microbial biomass and community structure. Their work shows that microorganisms used biochar as a substrate to a limited extent only, while suggesting that a fraction of the biochar, possibly the inorganic C content, was degraded abiotically. These authors also found that biochar can reduce PLFA extraction efficiency and recommend that future studies account for this in microbial community structure evaluations. Watzinger *et al.* (2014) investigated the same effects but used laboratory and pot experiments where they mixed ¹³C-depleted biochar (wheat and willow; 525°C) to contrasting soils (sandy Planosol and calcareous Chernozem) at fixed application rates. They also found that the soil microbiota degraded the biochar to a limited extent (2% biochar-C in the total microbial biomass). In addition, they noted that interference with negative priming and carbonates confounded the effects. Bruun *et al.* (2014) investigated the role of carbonates in CO₂ released from soil samples after addition of ¹⁴C-labelled biochar (barley; 400–600°C). They showed that carbonates from the biochar are released during the first days of incubation and can contribute to substantial amounts of the total CO₂ released. Fang *et al.* (2014) studied biochar stability from the perspective of four contrasting soil types, by adding biochar (eucalypt; 450–550°C) at 2% weight/weight to four Australian soils contrasting in chemistry and mineralogy (Inceptisol, Entisol, Oxisol and Vertisol). The total biochar-C mineralized during 1 year ranged from 0.30 to 2.71%. Soil properties influenced biochar-C mineralization, more pronounced for the 450°C biochar, with biochar-mineral interactions having been proposed as the likely mechanism candidate alongside chemical recalcitrance of biochar. Bamminger

et al. (2014) compared the stability of two chars (maize silage) made by different technologies (either pyrolysis at 600°C or hydrothermal carbonization at 220°C), in a forest and an arable soil. They showed that 13–16% of the hydrothermal char was mineralized in 8 weeks, with a positive priming effect on the mineralization of the native soil organic matter (SOM). However, mineralization of the (pyrolysis) biochar was significantly less (1.4–3%) and caused a negative priming effect on native SOM (–24 to –38%). The last paper in this section introduces a methodology to study biochar stability. Calvelo-Pereira *et al.* (2014) investigated the stability of charcoals from a mix of woody feedstocks in pre-European Māori gardens (mostly sandy soils) of New Zealand that were 329–770 years old, and combined the study with laboratory incubations. They showed clearly that weakly-charred lignocellulosic material had a residence time in the soil of several centuries. They also highlighted the limitations of using archaeological charcoals in the study of biochar stability with respect to the lack of information on charcoal formation factors and to the unknown changes in environmental factors to which that the charcoal has been subjected.

Water dynamics and the nitrogen (N)-cycle

Ulyett *et al.* (2014) mixed biochar (mixed woody feedstock; 600°C) into two soils (Luvisol and Cambisol) that had been managed conventionally and organically, respectively, and found that biochar significantly increased the available water capacity by 0.3 and 1.3%, at 60 t ha⁻¹ biochar application at 0 to –50 kPa matric potential. The authors recommended that future studies were required on the drier end of the water retention curve up to –1500 kPa. Kameyama *et al.* (2014) monitored the soil moisture content of a clay soil (Typic Hapludalf) amended with 3% weight/weight biochar (sugarcane bagasse; 400, 600 and 800°C) with TDR probes. They found that the electrical resistivity of biochar greatly decreased as pyrolysis temperature increased from 600 to 800°C. Their results suggest that TDR-based measurements over-estimate soil water content in soils amended with biochar formed at high temperatures, because of conductive and dielectric loss and propose a correction procedure to avoid this over-estimation. Sika & Hardie (2014) studied how biochar (pine; 450°C) added incrementally to sandy soil in laboratory columns may affect leaching of inorganic N. Although they found strong reductions in leached N, ranging from 12 to 96% for ammonium and nitrate ions, respectively, the amount of exchangeable ammonium and nitrate left in the biochar-amended soils was smaller than in the control soil, which they suggest may be caused by physico-chemical or microbial mechanisms. In addition, they noted a trade-off between reducing N leaching and over-liming when adding biochar to sandy soils. Raave *et al.* (2014) produced an activated carbon (coconut shell; 900°C, steam) to test the effect on N leaching when added to a sandy loam soil using mini lysimeters in the field. The authors also found that the nitrate leaching was reduced in the amended soil. However,

in contrast to the study by Sika & Hardie (2014), Raave *et al.* (2014) did not find a significant effect on ammonium leaching. The reduction in nitrate leaching found by Raave *et al.* (2014) was also related to a reduction in leachate in the amended soil. The laboratory experiments of Sika & Hardie (2014) simulated intense rainfall (60 mm hour⁻¹) typical for the Western Cape, South Africa, which is roughly the monthly average rainfall for the Estonian field site of Raave *et al.* (2014). In addition to N leaching, Raave *et al.* (2014) also found that phosphorus leaching was reduced, but potassium leaching increased because of the large extractable potassium content of the activated carbon itself. Felber *et al.* (2014) combined field and laboratory experiments to study the effect of biochar (green waste; 750°C) on N₂O emissions from a Stagnic Cambisol. They found that N₂O emissions decreased with biochar addition by 22% in the field study and 47–58% in the laboratory study and suggested that this discrepancy was probably caused by more homogeneous mixing of the biochar with soil in the laboratory experiment. This is an important finding and indicates that integration of studies at multiple scales may be required to advance our understanding.

Metal dynamics

Wagner & Kaupenjohann (2014) compared the suitability of a biochar (maize; 750°C) and a hydrothermal carbonization (HTC) char (poplar, 200°C) for the immobilization of heavy metals in a former sewage field. The HTC char had no effect on metal mobility, although it did decrease crop yield (perhaps by decreased N availability). The biochar reduced plant uptake of metals, particularly of zinc and cadmium. However, it also increased the metal concentration in leachates, particularly lead and copper. Wagner & Kaupenjohann (2014) suggested that organic complexation or formation of mobile colloids may explain these observations. Rees *et al.* (2014) also investigated the effect of biochar (mixed wood; 450°C) on the mobility and sorption kinetics of copper, cadmium and nickel in metal-contaminated soils (Redoxic Cambisols) in the north of France. They reported effective metal immobilization in biochar-amended soils, whereas biochar particle size distribution and soil pH increase appeared to control short-term sorption rate of these metals. Graber *et al.* (2014) tested the hypothesis that soluble biochar components influence redox-mediated reactions in soils. To this end they tested the reducing capacity of water extracts from eucalypt wood, olive pomace and greenhouse waste biochars (350, 450, 600 and 800°C), and the solubilization of manganese and iron from four soils in biochar extracts over a range of pH values. They found that water extracts from biochars had smaller redox potentials than water and reduced and solubilized soil manganese and iron. At a given pH, the lower temperature biochars solubilized more manganese than higher temperature biochars. As a fundamental soil property, altered soil redox potential may have implications for a wide range of biotic and abiotic soil processes.

Root dynamics

Prendergast-Miller *et al.* (2014) investigated biochar-root interactions in a rhizobox mesocosms study where they grew spring barley in a sandy loam soil amended with willow biochar (450°C) and miscanthus biochar (700°C) at 10 t ha⁻¹. They found that after 28 days, plants in biochar-amended soil had larger rhizosphere zones than those in control soil, and that the rhizosphere contained more biochar particles than the bulk soil. It was suggested that plant roots are attracted to biochar particles because of their nutrient or water content, but more research is needed to unravel specific mechanisms. Ventura *et al.* (2014) also considered the interactions between biochar and roots, specifically the contribution of root respiration to total soil respiration. Biochar (mixed wood; 500°C) was added to the Haplic Calcisol of an apple orchard at 10 t ha⁻¹ and partitioned soil respiration was monitored over 2 years. The authors also observed a rhizosphere increase in biochar-amended soil and root length intensity approximately doubled. However, root respiration was decreased, possibly because of decreased root metabolic activity.

Emerging research needs

Harmonization

The studies in this special issue illustrate important patterns and trends in research on biochar-soil interactions. There is a clear heterogeneity with regard to the soil type and its characteristics used in current research. Despite being useful to study soil-biochar interactions using local feedstocks and soil types, the lack of standardization, whether it is in relation to biochar feedstock, pyrolysis conditions, soil types, biochar application rates or analytical methods, confounds the comparison between observations and ultimately the unravelling of underlying mechanisms. One way of addressing harmonization can be through integrating the use of reference soils (alongside the study soils) in future experimental designs. Various standard soils, natural (LUFAs) or artificial (OECD soils) are now widely available from a range of EU and international organizations, including the EUROSIL range proposed by the European Commission (Caetano *et al.*, 2012). Adding a standard soil or a standard biochar to an experimental design might increase the workload and costs, thus perhaps its use should be dependent on the research aim and anticipated scope of results. This is unlikely to be a popular recommendation when scientists are already struggling to limit the variables in their experiments, and although several standard soils are currently available, a standard biochar is not. This is a worthwhile discussion for the scientific community, since the collective benefit may outweigh the individual drawbacks. In addition, it is becoming apparent that existing analytical methods may need to be modified for biochar studies (Tsechansky & Graber, 2014). Pertinent examples from this special issue are the over-estimation of soil moisture content when using TDR probes in biochar-amended soils (Kameyama *et al.*, 2014) and the decreased PLFA extraction efficiency observed by Gomez

et al. (2014). It can be expected that many more examples remain unaddressed at present including DNA and enzyme extraction, CEC and ash content.

Timeframe

A second observation that can be made from the 16 studies presented here and which is largely echoed by the overall body of biochar literature, is that the time factor is an issue. The laboratory and field experiments periods ranged from 1 day to 21 months, after which there is a gap of several centuries to the studies on archaeological charcoals, which have additional issues for relevance to biochar (Calvelo-Pereira *et al.*, 2014). However, it is the long mean residence time that has made biochar of interest from the perspective of mitigating climate change, while making it fundamentally distinct from traditional SOM amendments, such as crop residues or manures. Therefore, it seems imperative that new methods and methodologies be designed to fill this time gap. Simulated weathering (Prendergast-Miller *et al.*, 2014) and aging (combining the biological, chemical and physical perspectives) of biochar in soils (Hale *et al.*, 2011) integrated over several scales, need to be considered in future studies to bridge this vital gap.

Integration

A third trend that can be observed is the need for further integration in biochar studies, in terms of disciplines, spatial and temporal scales and effects/mechanisms. Reductionist approaches are useful to unravel specific mechanisms behind effects, but more integrated approaches are required to test how different mechanisms may interact to create a net effect. The concept of 'trade-offs' between effects, described by Jeffery *et al.* (2013) as a 'trade-off between potential wins', is a useful consideration. An example in this special issue can be found in Sika & Hardie (2014), which showed evidence of a trade-off between reducing N leaching and over-liming for a sandy soil. Trade-offs can be expected between effects as well as between different mechanisms behind a specific effect, or behind different effects. Inter-disciplinarity is required to achieve the assessment of trade-offs between 'wins', while supported by further reductionist research to elucidate underlying mechanisms. Extension to other scientific disciplines within studies may also be required. For example, a number of papers in this special issue report changes in leaching in biochar-amended soils. However, effects on downstream aquatic systems and ground waters remain under-researched (Jaffe *et al.*, 2013). Optimizing progress also depends on effective communication and data sharing between scientists, as well as between scientists and stakeholders. Jeffery *et al.* (2011) identified the main weaknesses in the scientific evidence in a quantitative meta-analysis on the effect of biochar on crop productivity. As well as timeframe, these were (i) environmental/management representativeness, (ii) auxiliary data and (iii) statistical reporting of observations. If journals do not provide the option of hosting of datasets, then alternatives have to be sought. Jeffery *et al.* (2011) made their database publicly available in the European Soil Data Centre (ESDAC, 2010), although this

mostly focuses on European scale data. The COST action TD1107 'Biochar as Option for Sustainable Resource Management' (http://www.cost.eu/domains_actions/fa/Actions/TD1107) is a network that aims to improve data sharing and communication between scientists and stakeholders, and is therefore a useful platform in Europe. Similarly, the International Biochar Initiative (IBI) also supports the dissemination of biochar information in all its aspects.

We hope that identifying current research needs will help to spur biochar research towards enough understanding to build a sustainable biochar regulation framework. The research presented in this special issue provides the reader with a snapshot of recent developments in biochar-soil interactions. We also hope that this special issue will also inspire the reader to participate in scientific discourse on how to address emerging research needs and on how the scientific community can organise itself to facilitate this.

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F. G. A. VERHEIJEN

Department of Environment and Planning, Centre for Environmental and Marine Studies (CESAM), University of Aveiro, 3810-193 Aveiro, Portugal

E. R. GRABER

Institute of Soil, Water and Environmental Sciences, The Volcani Center, Agricultural Research Organization, POB 6, Bet Dagan 50250, Israel

N. AMELOOT

Department of Soil Management, Ghent University, Coupure Links 653, 9000 Gent, Belgium

A. C. BASTOS

Department of Biology, Centre for Environmental and Marine Studies (CESAM), University of Aveiro, 3810-193 Aveiro, Portugal

S. SOHI

UK Biochar Research Centre, School of Geosciences, University of Edinburgh, Edinburgh EH9 3JN, UK

H. KNICKER

IRNAS-CSIC, Avda Reina Mercedes, 10, 41080 Sevilla, Spain

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