Biochar for Environmental Management

Biochar is the carbon-rich product which occurs when biomass (such as wood, manure or crop residues) is heated in a closed container with little or no available air. It can be used to improve agriculture and the environment in several ways, and its persistence in soil and superior nutrient-retention properties make it an ideal soil amendment. In addition to this, biochar sequestration, in combination with sustainable biomass production, can be carbon-negative and therefore used to actively remove carbon dioxide from the atmosphere, with potentially major implications for mitigation of climate change. Biochar production can also be combined with bioenergy production through the use of the gases that are given off in the pyrolysis process.

The first edition of this book, published in 2009, was the definitive work reviewing the expanding research literature on this topic. Since then, the rate of research activity has increased at least ten-fold, and biochar products are now commercially available as soil amendments. This second edition includes not only substantially updated chapters, but also additional chapters on: environmental risk assessment; new uses of biochar in composting and potting mixes; a new and controversial field of studying the effects of biochar on soil carbon cycles; traditional use with very recent discoveries that biochar was used not only in the Amazon but also in Africa and Asia; changes in water availability and soil water dynamics; sustainability and certification. The book therefore continues to represent the most comprehensive compilation of current knowledge on all aspects of biochar.

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Johannes Lehmann and Stephen Joseph

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Preface

At the writing of the first edition, the term 'biochar' was hardly known even in scientific circles that specialize in bioenergy, waste management, site remediation, climate change mitigation or soil fertility. This has changed over the past five years and scientific inquiry has increased remarkably, while the first commercial biochar products are found on shelves in retail stores. This book not only captures the recent advances made in our understanding of biochar properties, behaviour and effects on agriculture and the environment, but also develops fundamental principles and frameworks of biochar science and application.

This book serves as an introduction to biochar for students, scholars and lay persons, as well as a comprehensive textbook for anyone who wants to gain a deeper understanding of biochar. At the same time, it highlights new insights at the frontier of biochar science, develops new concepts for its investigation and use, and identifies knowledge gaps and future research needs. It is intended to provide essential information available to date to land use planners, home owners, trainers, policy makers, regulatory agencies, project or business developers.

The interest in biochar is constantly shifting between stakeholders, since in spite of its ancient roots biochar is a relatively new industry and topic of science for an increasing and broader group of people. Regional and local groups have been founded in many countries, and the international networks of scientists, industry, project developers and policy makers interested in biochar have advanced the discourse and sustainable development of biochar under the auspices of the International Biochar Initiative (IBI). These networks have advanced frameworks for commercializing biochar such as setting standards of what safe biochar is and how it can be used sustainably to address environmental issues while recognizing social and economic constraints. This book contributes to rigorous scientific inquiry and hopes to motivate development of realistic and sustainable biochar application. It attempts to lay out the complexity of biochar systems, covering both the detailed science as well as the broad developmental and policy picture, and develop concepts for further inquiry and realistic and achievable implementation.

The book is divided into five main areas: (i) History and fundamentals of biochar investigation, production and use; (ii) Basic physical and chemical properties of biochar and their classification; (iii) Persistence, changes and movement of biochar in the environment; (iv) Plant productivity and environmental processes that are affected by biochar including soil biota, nutrient and carbon transformations and movement, greenhouse gas emissions, soil water and pollutant dynamics in soil (such as organic pollutants, heavy metals, herbicides); (v) Implementation of biochar that requires assessments of biochar contents, its use in commercial products and as part of wider biochar systems, greenhouse gas accounting, certification, economics and commercialization.

We are extremely grateful to the numerous referees who spent a significant amount of their time to give expert opinions that ensured the high scientific quality of this publication. In particular, we want to thank Samuel Abiven, Teri Angst, Elizabeth Baggs, Julia Berazneva, Luke Beesley, Catherine Brewer, Anthony Bridgwater, Sander Bruun, Marta Camps-Arbestain, Chih-Hsin Cheng, Tim Clough, Gerard Cornelissen, Annette Cowie, Andrew Crane-Droesch, Andrew Cross, David Crowley, Thomas DeLuca, Xavier Domene, John Field, Elizabeth Fisher, Yves Gelinas, Brent Gloy, Sarah Hale, Jim Hammond, Christopher Higgins, Philippe Hinsinger, Andreas Hornung, Michael Hedley, Rachel Hestrin, William Hockaday, Joeri Kaal, Claudia Kammann, Markus Kleber, Heike Knicker, David Laird, Jens Leifeld, Isabel Lima, Min Malla, Caroline Masiello, Neil Mattson, Mark Milstein, Joseph Pignatello, Debbie Reed, Cornelia Rumpel, Klaus Schmidt-Rohr, Michael Sesko, Simon Shackley, Joff Silberg, Bhupinder Pal Singh, Dawit Solomon, Magnus Sparrevik, Kurt Spokas, Christoph Steiner, Janice Thies, Wolfgang Wilcke, William Woods, Dongke Zhang, Lukas van Zwieten, and several anonymous referees. We are indebted to Kelly Hanley who proofread and formatted several of the chapters.

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Finally and most importantly, we want to thank our families and friends for all their patience with the frenzy of organizing this volume and all the late-night writing, and their full support, without which we would not have been able to put together this book.

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May 2014

Foreword

The climate problem is now extremely large. Each year, humanity disgorges 43 billion tonnes of CO_2 into the atmosphere, a volume 25 per cent greater than just a decade ago. Scientists have calculated a carbon budget for Earth. If we wish to have a 75 per cent chance of keeping warming to less than 2 degrees, we can emit just 1,000 billion tonnes of CO_2 over the first half of this century. Yet our carbon emissions had grown so fast that by 2013 we had already used almost 40 per cent of that budget. At that rate, we'll be out of budget by 2028. So, the time we have to address the climate crisis is limited, and the remaining years of this decade are particularly critical. Just 16 months from now, in December 2015 in Paris, humanity will face a tough challenge – developing a global treaty sufficient to deal with the climate crisis. Following the failure of our previous attempt in Copenhagen, many are sceptical that it will be a success. In any case, many scientists argue that a treaty, if agreed, will come too late to avoid profound climate disruption. Already, our planet is warming at a rate consistent with the worst case scenarios developed by the Intergovernmental Panel on Climate Change. Yet, with economic growth and the thirst for energy in China and India seemingly unstoppable, reducing the burning of fossil fuels is a task of the utmost difficulty. Moreover, progress cannot be made at the cost of our food or energy security. What is needed in this twenty-first century of ours are solutions that deal with several of our major problems at once. And they must be deliverable quickly, and at a scale able to make a real difference.

This book, I believe, provides the basic information required to implement the single most important initiative for humanity's environmental future. The biochar approach provides a uniquely powerful solution: it allows us to address food security, the fuel crisis and the climate problem, and all in an immensely practical manner. Biochar is both an extremely ancient concept and one very new to our thinking. Amazonian Indians used it to produce the Terra Preta soils of the Amazon Basin, which, 1000 years after their creation, remain more fertile than surrounding lands. Despite its benefits, few farmers living today consider producing it. Worse, our political debates about climate change continue in ignorance of it, while industries that could benefit immensely have only taken the smallest first steps in developing it at scale.

The key element in the biochar technologies is charcoal-making, which involves the heating of organic matter in the absence of oxygen. Rather than a single technology, biochar is a common thread running through various technological approaches, which can be varied to emphasize a particular outcome or opportunity. This book therefore describes a series of innovations whose products and outcomes are myriad and beneficial. Yet, it goes much further than that, for this work is essentially a 'how to' manual of biochar, providing expert analyses on biological, technical, economic, political and social aspects of the approach. There are many important products of the charcoal-making processes, including synthetic gas that can be used to generate electricity, a substitute for diesel fuel and the charcoal itself.

One of the most important aspects of biochar is the scale at which it can be deployed. If we turned all of the world's annual production of forestry and agricultural waste into biochar, and stored the carbon, we'd remove around 4 gigatonnes of CO_2 from the atmosphere. This makes biochar production potentially one of the most effective engines atmospheric cleansing we possess. Indeed, it is one of the finalist technologies in the Virgin Earth Challenge, the world's richest prize, which is aimed at fostering technologies that are capable of pulling a gigatonne or more of carbon out of the atmosphere annually.

Among the most valuable outcomes of the application of the biochar technologies are greatly increased economic efficiency in agriculture, enhanced crop yields and slowing the return to the atmosphere of carbon captured by plants. The result is diverse and clean energy supplies, more food per unit of input and a chance at climate security. In simple terms, this is what the biochar revolution offers us. The biochar technologies described in this volume are potentially worldwide in their applicability. Grain production and many other forms of agriculture, livestock production, forestry and even the disposal of human waste will, I'm convinced, be profoundly transformed by the processes described in these pages, and the impact will be both swift and radical. The driver, at least initially, is likely to be the climate crisis.

Approximately 8 per cent of all atmospheric CO_2 is absorbed by plants each year. If just a small proportion of the carbon captured by plants can be pyrolysed and transformed into charcoal, humanity's prospects will be much brighter, for this will buy us time as we struggle to make the transition to a low emissions economy. With its careful evaluation of every aspect of biochar, this book represents a cornerstone of our future global sustainability. I'm convinced that its message is every bit as important as that of Rachel Carson's *Silent Spring*, and potentially every bit as politically powerful as Al Gore's *An Inconvenient Truth.* If it finds a wide enough readership, it will change our world forever, and very much for the better.

Tim Flannery
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August 2014

1

Biochar for environmental management: an introduction

Johannes Lehmann and Stephen Joseph

What is biochar?

Biochar is the product of heating biomass in the absence of or with limited air to above 250°C, a process called charring or pyrolysis also used for making charcoal (Chapter 3). The material distinguishes itself from charcoal or other carbon (C) products in that it is intended for use as a soil application or broader for environmental management. In some instances, the material properties of biochar may overlap with those of charcoal as an energy carrier, but many types of biochar do not easily burn and charcoals are typically not made to address soil issues (Nomenclature in Box 1.1). An important defining feature of biochars, similar to charcoal, is a certain level of organic C forms, called fused aromatic ring structures (Chapter 6). These structures are formed during pyrolysis and are key to biochar properties with respect to mineralization (Chapter 10) or adsorption (Chapter 9). Therefore, biochar is typically enriched in C (Figure 1.1), and even more in phosphorus (P) or other metals such as calcium (Ca) or magnesium (Mg) and sometimes even nitrogen (N). The chemical properties of the organic C structure of biochars are fundamentally different from those of the material that the biochar was produced from and depleted in oxygen (O) and hydrogen (H). In contrast, the macro-morphological characteristics of biochars typically resemble those of the starting material, which means that it typically looks the same, apart from its black color. The intended use as a soil amendment also requires that biochars do not contain harmful levels of heavy metals or organic

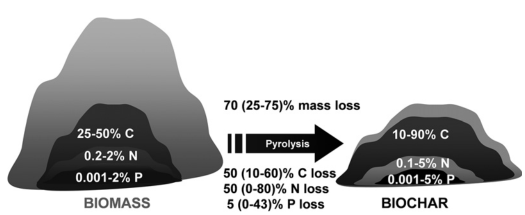

Figure 1.1 *Conversion efficiency of biomass, C, N and P during pyrolysis (data from Enders et al (2012); typical losses followed by range in brackets)*

contaminants (IBI, 2013), in keeping with related efforts to make composts and other soil amendments safe for soil. Despite these common criteria, it would be wrong to conclude that biochar is a narrowly defined material. In fact, biochars can have very different properties, which have to be recognized, as discussed throughout this book.

Box 1.1 Nomenclature of biochar and related materials in comparison to pyrogenic C structures

Johannes Lehmann, Joseph J. Pignatello, Michael Bird, Stephen Joseph

The following nomenclature for biochar and related terms has been adopted in this book and may provide guidance for achieving greater clarity. In some instances, clarity in conversation may also improve conceptualization and scientific advances, which is intended to promote understanding of biochar properties and its behavior in the environment.

Biochar: Biochar is the solid product of pyrolysis, designed to be used for environmental management. IBI (2013) defines biochar as: 'A solid material obtained from thermochemical conversion of biomass in an oxygen-limited environment. Biochar can be used as a product itself or as an ingredient within a blended product, with a range of applications as an agent for soil improvement, improved resource use efficiency, remediation and/or protection against particular environmental pollution and as an avenue for greenhouse gas (GHG) mitigation.' In addition, to be recognized as biochar according to IBI (2013) or Delinat (2012), the material has to pass a number of material property definitions that relate both to its value (e.g., H/Corg ratios relate to the degree of charring and therefore mineralization in soil) and its safety (e.g., heavy metal content). This publication uses the term biochar even when citing publications that use other terms but clearly refer to the use of such materials in the context defined for biochar.

Hydrochar: Hydrochar is the solid product of hydrothermal carbonization (HTC) or liquefaction (sometimes referred to as HTC material), and is distinct from biochar due to its production process and properties (Libra et al, 2011). It typically has higher H/C ratios (Schimmelpfennig and Glaser, 2012) and lower aromaticity than biochar as well as little or no fused aromatic ring structures. Hydrochar is not covered in this publication and only occasionally discussed in comparison to biochar.

Pyrogenic Carbonaceous Material (PCM): PCM is introduced here as the umbrella term for all materials that were produced by thermochemical conversion and contain some organic C, such as charcoal, biochar, char, black carbon, soot, activated carbon. The term refers to the material and not the C atom.

Char: Char is defined for the purpose of this publication as the material generated by incomplete combustion processes that occur in natural and man-made fires.

Charcoal: Charcoal is produced by thermochemical conversion from biomass (mainly but not exclusively wood) for energy generation. The term is sometimes used in the context of other uses, e.g., medicine, filtration, separation etc. If processed further by any form of activation, use of the term 'activated carbon' is proposed.

Activated carbon: Activated carbon denotes a PCM that has undergone activation, for example by using steam or additions of chemicals. It is used in filtration or separation processes, sometimes in restoration and for specialized experiments in soil (competition, inoculation, etc). 'Carbon' in this context should not be abbreviated to 'C', since it does not refer to the C atom in activated carbon, but to the material (which also contains other atoms than C). The acronym 'AC' for activated carbon will be used in this publication only if needed repeatedly, but the preferred spelling is 'activated carbon'. Clarification is needed in those instances where biochars were modified after production for which some sources use the term 'activation'. Such treatment of biochars is typically ill defined and it should be explained in detail what 'activation' of biochars means in a particular study. The use of the term 'activated biochar' is discouraged.

Black carbon: The term black carbon (carbon spelled out) is extensively used in the atmospheric, geologic, soil science and environmental literature to refer to PCMs dispersed in the environment from wildfires and fossil fuel combustion. The term should be taken to refer to the entire material, not just the fused ring fraction or the C atom. The use of this term is discouraged (or be used only if absolutely necessary and in the context described here), to avoid confusion with 'black C', which is defined below.

Soot: Soot is a secondary PCM and a condensation product (Chapter 3). Chars, charcoal, biochars, black carbons (and, to a limited extent, also activated carbon) may contain soot, but soot can also be identified as a separate component resulting from gas condensation processes.

Ash: Ash is the operationally defined fraction of biomass or PCM (according to ASTM D1762-84) and typically includes inorganic oxides and carbonates (Enders et al, 2012). For the purposes of this publication, the term does not describe the solid residue of combustion which commonly contains some residual organic C.

When referring to the C atoms of the PCM, the letter C should be used as in 'pyrogenic C' or 'black C'. A selection of terms referring to C forms in PCM relevant to this publication includes:

- 'Black C' spelled with 'C' and not 'carbon' refers to the C atom, and not to the material that also contains H, O, N and ash minerals (Figure 1.2). 'Black C' should not be abbreviated to BC as this can be confused with biochar (which is in some publications abbreviated to BC; the acronym BC is therefore not used here).
- 'Pyrogenic C' (abbreviated to PyC after first use) is synonymous with black C. It should be used preferentially to 'black C'.
- PyC (or black C) should refer to the (non-inorganic) C atoms that have undergone pyrogenic or thermal transformation, and by this definition only include C present in fused rings, including C on surfaces of fused aromatic C that may also bind to other atoms than C such as C-O/N, non-protonated C and protonated C. In this publication, the term does not include non-transformed C present in residual carbohydrates or lignin structures, or in tars, or in functional groups bound to fused aromatic C such as carboxyl groups. Different methods to quantify PyC (or black C) typically attempt to capture this C fraction (Chapter 24), but do so with varying success or intentionally capture a portion of it (e.g., only the fused aromatic C without the surface C). When referring to a certain analytically defined fraction, the method should be stated in conjunction with the term PyC (e.g., PyC quantified by CTO-375).

- 'Total Organic Carbon' (abbreviated TOC) refers to the entire organic C component of any material, and is similarly defined for PCMs (Chapter 8), including all thermally altered organic C as well as remaining untransformed organic C. 'Total inorganic carbon' (abbreviated TIC) mainly includes carbonate and possibly other compounds such as oxalates (Figure 1.2).
- In some cases 'soot C' is appropriate to indicate the C atom properties of soot (which is a secondary PCM as defined above).

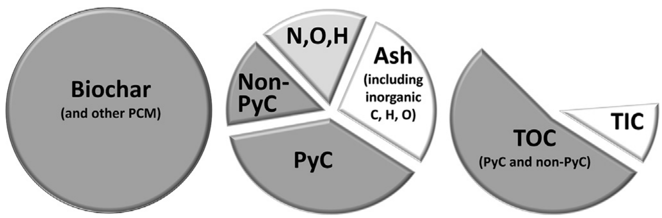

Figure 1.2 *Illustrative sketch of a possible distribution of different C forms and other atoms in biochar (component and acronyms explained in text)*

A brief history of biochar research and application

Valuing biochar-rich soils and the concept of adding biochar to soil and in potting mixes reaches back several centuries (Chapters 2 and 12) and has found entry into some traditional management concepts in many regions worldwide (Chapter 2). Even though some notable research was done, the historic reports and scientific studies started as mostly observational and were initially in large part gathered from plant growth responses on former charcoal storage sites (Chapter 12). Biochar application was discussed in major agricultural textbooks (Allen, 1846) and in scientific journals (Anonymous, 1851) and developed into commercial products as a form of 'manure' in the mid 1800s, but with varying success as seen for biochar made from peat (Durden, 1849). By the second half of the nineteenth century, scientific studies on biochar had increased substantially, not the least due to Justus von Liebig's publications (Liebig, 1852) providing quantitative proof combined with theoretical underpinning of why biochar may improve nutrient availability. This interest in biochar continued into the twentieth century (e.g., Retan, 1915; Morley, 1927), but most of the research and development subsequently ceased by the middle of the twentieth century, possibly trailing the development and marketing of inorganic fertilizers. Notable research and development on biochar started again in the 1980s in Japan (Ogawa and Okimori, 2010). The present interest in biochar research and development was mainly motivated by research on Amazonian Dark Earths (also called *Terra Preta de Indio*; Mann, 2002; Marris, 2006). These soils found in the Amazon Basin were created by Amerindian populations several hundred to a few thousand years before present, but maintained their fertility largely due to the high proportion of biochar-type organic matter (Glaser and Birk, 2012). Even though *Terra Preta* soils do not provide a direct analogue to biochar management (Lehmann, 2009) and are by far not the only soils containing biochar (Chapter 2), they can be credited for spurring recent investigation into whether biochar can provide broader soil benefits in its own right (Glaser et al, 2002). In parallel, naturally produced chars from vegetation fires are becoming re-appreciated as the reason for the high fertility attributes of some soils such as those in the U.S. midwest (Mao et al, 2012).

The term 'biochar' was introduced only recently, first as a term to distinguish activated carbon made from fossil fuel and activated carbon made from biomass (Bapat et al, 1999), and shortly thereafter to replace the term 'charcoal' as a fuel (Karaosmanoglu et al, 2000) and to distinguish it from coal. Biochar, as the term used in this book and by now more widely accepted globally in the context of a soil amendment, was introduced in 2006 (Lehmann et al, 2006) based on conversations with Peter Read.

Research on *Terra Preta* and on naturally occurring chars (often under the term black C) dominated the scientific literature on biochar-relevant topics ten years ago, but in 2008 the number of articles in academic journals on purposeful application of biochar to soil started to increase (Figure 1.3). The term charcoal continues to be used in the context of a soil amendment, but with a decreasing proportion. The publication activity of biochar in the scientific literature now exceeds that in the more established subject of compost science (Figure 1.3). Similarly, citations of scientific articles on biochar have risen and are also higher than those on compost for the ten most-cited journal articles published since 2006 (on ISI Web of Knowledge in August 2013, http://apps.webofknowledge.com), which may be taken as an indicator of scientific interest in biochar research. For a number of key scientific journals relevant to the soil application of biochar (e.g., *Plant and Soil*, *Organic Geochemistry*, *Biology and Fertility of Soils*, *Australian Journal of Soil Research*, *Soil Biology and Biochemistry*), several publications on biochar are among the ten most-cited articles on any subject covered in those journals over the past five years.

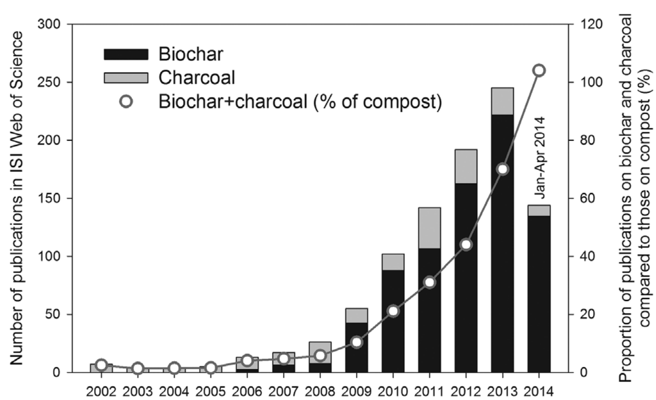

Figure 1.3 *Number of publications in scientific journals listed in the ISI Web of Knowledge (http://apps.webofknowledge.com) with the term biochar or charcoal in the title of the article and studied in the context of soil management in comparison to those with compost or composting in the title (book chapters, abstracts and reports were not considered, nor publications that contain relevant research but where the terms were not used in the title; also publications with the terms black C or pyrogenic C were not considered even if they are relevant to soil application of biochar; the numbers reported here are therefore conservative)*

Figure 1.4 *Title of the animated film* Waste No More*, an education resource for schools developed by MindFuel in 2013, featuring 'biochip', a biochar particle who engages in a conversation with a girl who competes in a contest to turn waste into value. (www.wonderville.ca/asset/wastenomore)*

In addition to the scientific output, the development of biochar over the past years can also be traced by examining patents, membership in professional organizations, products in the market place or the number of interest groups. Groups of interested stakeholders started to form in 2006 and regional and national groups have constituted themselves by now. Patents were in appreciable numbers only published after 2010. Biochar has become part of educational curricula (Figure 1.4) and dedicated seminars. The connection with *Terra Preta* soils in the Amazon has provided a narrative that has stimulated a general interest in soils for those who may otherwise have less interest in agriculture.

Biochar as a system

In a narrow sense, biochar is the term for a range of materials. But actually, any benefits that the production and use of biochars is able to generate can often be realized only if biochars are perceived as a systems approach. A wide variety of biomass can be used to produce a wide variety of biochar materials, each with its own opportunities and constraints. Some biomass is a valuable commodity for other purposes such as food and construction wood, or has environmental value for soil protection, shade or as wind breaks. In each specific circumstance, the use or abuse of biomass has to be critically evaluated. When the biomass is heated to a point where pyrolysis occurs, the energy generated by the pyrolysis is sufficient to continue the reaction (Figure 1.5). However, depending on the moisture

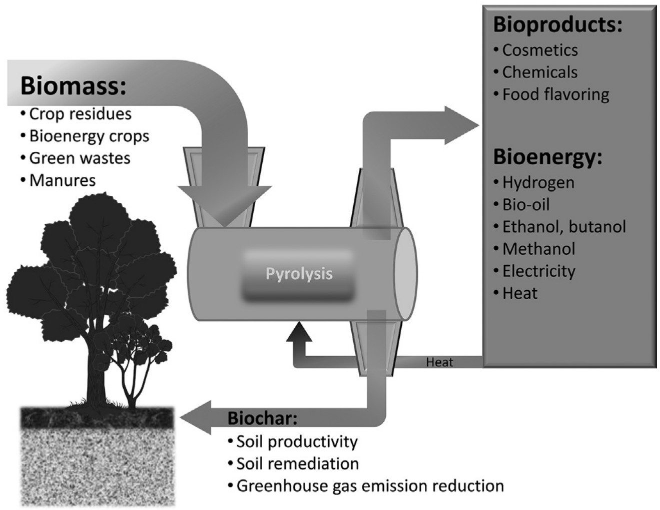

Figure 1.5 *Schematic of a basic biochar system*

content of the biomass, the heat can be sufficient to maintain the pyrolysis or require more energy to dry than is contained in the biomass. The rest of the energy that is released can be utilized to produce a wide variety of products, including energy but also other bioproducts such as food flavoring. The energy can have various forms owing to the comparatively low temperature used in comparison to combustion or gasification, and ranges from heat and electricity to hydrogen, converted using microorganisms to ethanol or butanol or using catalysis to methanol or bio-oil. Biochar is the solid product with about a third of the mass yet containing half the C originating from the biomass (Figure 1.1).

For biomass input, bioenergy or bioproduct and biochar output, many different permutations of the system are possible (Chapter 26). Biomass input may not only include plants grown for their sole purpose as feedstock for pyrolysis, but also residues from crop production or food and energy processing. Therefore, the motivation or entry point for a biochar system can be very different. It is useful to distinguish between four broad groups of objectives: soil improvement, mitigation of climate change or nutrient pollution, waste management and energy generation (Figure 1.6).

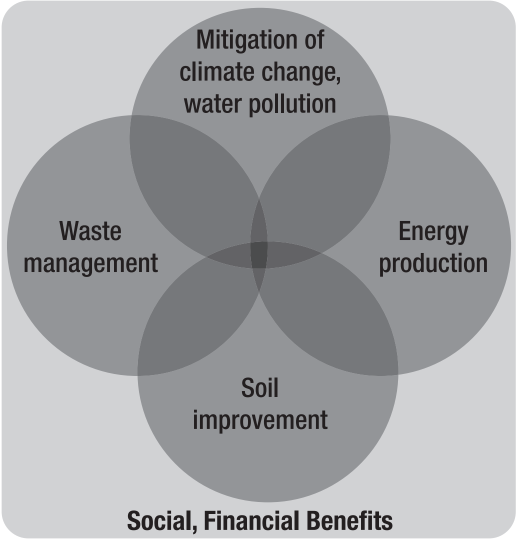

Figure 1.6 *Motivation for applying biochar systems*

Soil improvement

Soil improvement using biochars may target not only: (i) crop productivity through improvements of soil nutrient availability (Chapters 7, 15 and 18), soil physical properties and specifically water relations (Chapters 5 and 19), or plant-microbe interactions (Chapters 13 and 14); but also (ii) soil remediation (Chapters 20 and 22). The potential value of biochars in a particular soil is in the first instance related to properties that can also be addressed by additions of other organic matter such as compost or manure, albeit with important nuances. Obviously, not all soil constraints can be addressed with biochar, and if soil properties do not constrain productivity and the soil is very fertile, then biochar additions will likely not improve crop yields. The fact that biochars can have very different properties depending on the material they were produced from and their production conditions also changes their utility to address any existing soil constraints. In addition, biochar use in soil-less planting media, as compost additive, in animal feed with subsequent use of the manure in soil, as admixtures in fertilizers or in green roofs among others (Chapter 25) may require very different properties than in soil.

The ability to target biochars with very different attributes affords the possibility to design biochars for certain purposes ('fit for purpose', 'designer biochar'; Chapter 31) in a potentially very effective way. For example, biochars made from the same feedstock can have pH values of less than 4 or above 12 (Chapter 7), one being potentially able to address fertility of soils with pH values that are either too high or too low for optimum productivity. However, the wide variety of biochar materials also hampers effective communication in science, public and the market place: biochar does not equal biochar to the extent that a common term may even provide a hurdle. Classification is therefore needed to distinguish different biochars (Chapter 8) and it may even prove prudent to develop a nomenclature of different subsets of biochars with different properties and use to facilitate communication with and between stakeholders.

Soil improvement is possibly the defining feature of a biochar system. Biochar may be added without benefit to soil that is already fertile or that has received sufficient nutrients and water, if the primary objective is to sequester C; however, the lack of gaining social or financial capital through soil application may provide a disincentive. Biochar can also be used as a charcoal fuel, and greater energy gains may provide greater reductions in greenhouse gas emissions, if no soil benefits can be realized (Gaunt and Lehmann, 2008; Woolf et al, 2010). In fact, reduced greenhouse gas emissions from soils or greater plant growth may need to be achieved for a biochar system to have a preferable emission balance compared to biochar use as a charcoal fuel (Roberts et al, 2010; Woolf et al, 2010). Revenues from increased crop yields may prove critical for financial viability.

Mitigation of climate change and nutrient pollution

The opportunity to reduce greenhouse gas emissions clearly shows the need to perceive biochar management as a system rather than a material (Chapter 27). The lower mineralization of biochars than the original material that it was produced from (Chapter 10) reduces the CO_2 emissions from the system and is indeed key to climate change mitigation with biochar (Chapter 27). However, the CO_2 capture is delivered by plants through photosynthesis, and whether an old-growth forest or a decomposing crop litter is used to produce biochar dramatically changes the C balance (Whitman et al, 2010). Not only the C balance, but the emissions generated or reduced in the entire system determine the life-cycle greenhouse gas budget and include nitrous oxide or methane emissions from soil (Chapter 17) or from the decomposing biomass, as well as from transportation, infrastructure, indirect land use change and others (Chapter 27). Even though the technical or theoretical potential is substantial on a global scale (Woolf et al, 2010) and on par with many alternatives, the actual mitigation that will be achieved clearly depends on environmental sustainability, social acceptance, technological implementation and economic competitiveness compared to other mitigation options. This cannot be evaluated without some commercialization at a meaningful scale. Similar to several other agricultural C sequestration strategies (e.g., reducing tillage), certain financial, environmental and societal benefits can be realized through building soil health, which will create lasting value for crop productivity or clean water beyond C sequestration.

Efforts in mitigating excessive nutrient export from agricultural watersheds may benefit from pyrolysis of animal manures or the use of appropriate biochars in reducing leaching of phosphates and nitrates contained in soil or co-applied manures (Chapter 18). The first affords the ability to densify nutrient-rich manure by drying and pyrolysing, with weight losses by at least one order of magnitude. The latter leverages the ability to produce biochars that can adsorb cations and phosphates (Chapter 9). It is not clear whether nutrient trading schemes will be able to make use of this mechanism.

Waste management

Processing of wastes is a relatively established use of pyrolysis, even if the use of biochar as a soil amendment is not widespread at present. The generally lower processing temperatures and the higher organic C contents of the solid residue compared to incineration or gasification (Chapter 3) facilitate operations. These have to be weighed against longer processing times in the case of slow pyrolysis and different limitations with respect to size and type of installations (Chapter 4). Typically, the range of materials that can be processed by various permutations of pyrolysis technology is large and includes woody biomass, leaves, grasses, manures, sludge or crop residues (nut shells, pits, stones, bagasse, rice hulls, straw, etc.). High moisture contents can make some feedstocks less attractive if there is a need for net energy generation. The choice for a particular type of waste may be more limited by the requirement to produce a biochar that is: (i) safe to apply to soil; as well as (ii) appropriate for effectively addressing soil constraints relevant at a project or regional level. Waste management is a common entry point for biochar systems and the economics often dictate the use of materials that are in need of disposal with low or even negative costs sometimes even generated at a single location (Chapters 29 and 30). Biochar production may be an attractive alternative in those situations where no local disposal is available and the biomass (e.g., yard wastes, animal manures) has to be otherwise transported over long distances. Especially with efforts to close the nutrient and C cycle between urban and agricultural regions, long transportation distances are prohibitive to cost-effective recycling, and it remains to be seen whether biochar technology can provide an alternative. In addition, appropriate management of organic wastes can help in the mitigation of climate change indirectly by: (i) decreasing methane emissions from landfill; (ii) reducing industrial energy use and emissions due to recycling and waste reduction; (iii) recovering energy from waste; (iv) enhancing C sequestration in forests due to decreased demand for virgin paper; and (v) decreasing energy used in long-distance transport of waste (Ackerman, 2000).

Energy production

Pyrolysis is a recognized and long-standing technology to provide energy (Chapters 3 and 4). In addition to heat energy, pyrolysis is also able to generate a variety of high-value liquid and gaseous energy carriers. Furthermore, a range of products can be produced from food flavoring to agrochemicals, fertilizers, cosmetics, medicine, adhesives and others. In the early twentieth century, pyrolysis was the only technology to produce methanol, acetone or acetic acid, in addition to some liquid fuels (Goldstein, 1981).

Prioritizing energy or other non-solid products will in most cases constitute a trade-off to biochar production. However, from a life-cycle perspective, a maximization of energy generation may be less preferred than weighing soil health and environmental benefits against energy generation. It is theoretically possible that securing the production base by prioritizing soil fertility in a pyrolysis bioenergy project through biochar additions to soil will in the long term achieve greater energy gains than maximization of biomass offtake.

Bioenergy may on its own not be able to satisfy the growing global energy demand under realistic constraints to biomass production (Smeets et al, 2007; Kraxner et al, 2013; Pogson et al, 2013). But it may significantly contribute to a future energy solution (Dornburg et al, 2010) and possibly be competitive for distributed production of liquid or gaseous fuels and bioproducts. Pyrolysis in particular may prove capable in addressing constraints for many bioenergy approaches posed by varying availability of feedstock types, either between different locations or different times of the year, because of its versatility in accepting a wide variety of organic materials.

Similar to combustion technology, pyrolysis technology can be operated at different scales, from stoves to cook meals or heat individual homes to large bioenergy installations that generate liquid fuels (Chapter 4). The specific technology solution will need to vary considerably to meet different objectives. The upper limit for the scale of individual pyrolysis reactors will likely remain smaller than that of biomass combustion or fossil fuel-based conversion technologies (Chapter 4). This may mean that pyrolysis may also for this reason be best utilized for distributed energy generation.

Current state of biochar science, development and projections: a reality check

Scientific activity has undoubtedly accelerated significantly over the past five years (Figure 1.3), and the number of research publications can be expected to increase further in the near future. Even though the scientific output is currently high and much information on biochar is by now available, several critical knowledge gaps are only being filled over time and are identified in each chapter of this book. Of particular note is the lack of a decision tool to identify biochar types suitable to address certain soil constraints. While a comprehensive tool will only be available with a more mature state of science that considers all or at least most of the permutations of possible biochar properties and application, useful milestones can already be reached at present by identifying those biochars (Chapters 7, 10, 12, 20, 21) and biochar systems (Chapter 26) that are sufficiently investigated. The analytical framework is under development for characterizing both the material properties of biochars (Chapter 8) and the systems benefits (Chapters 27 and 28). In this context, scientific studies require careful planning to implement valid comparisons of tested biochar applications to either standard biochars available to the global scientific community, a control without adding biochar or additions of equivalent amounts of crop residues or composts (Jeffery et al, 2015). The alternative to biochar applications typically is not to apply, but to apply a different type of organic matter, and the alternative to compost applications may not be applications of biochar on its own but together with compost or inorganic fertilizers. On the one hand, a systems comparison of biochar effects on greenhouse gas emissions from soil (Chapters 17, 26, 27) may only succeed if it is compared to applications of unpyrolysed biomass considering the conversion of biomass to biochar (Chapter 3). Mechanistic insights, on the other hand, about how biochar influences greenhouse gas emissions from soil can only be obtained using comparisons on the same mass or C basis. The modification of biochars post-production may deserve particular attention to isolate specific effects by keeping others (e.g., pH) constant (Cayuela et al, 2013; Joseph et al, 2013). Random variation between biochars may often not provide the necessary parameter space to identify the mechanisms by which biochars affect soil processes (Rajkovich et al, 2012). Such necessary refinement of experimental designs and development of clear and testable hypotheses require prior knowledge. Formulating appropriate expectations can, by now, build on a sufficient body of published research as summarized in this publication.

Despite the impressive increase in the number of scientific studies, relevant knowledge gaps may need to be addressed by experimentation at scale of implementation, notably in the area of life-cycle evaluation of environmental impact and specifically greenhouse gas emissions (Chapter 27), economic evaluation (Chapters 29 and 30) and production technology (Chapter 4). Commercial-scale production and application will also generate the opportunities to address needs for longer-term data sets of biochar effects on crop productivity (Chapter 12) and on off-site impacts through leaching and erosion (Chapters 11 and 18). Fully investigated systems at a relevant scale are a prerequisite for regional or global implementation.

The large variety of possible biochar products requires due diligence on the part of research to discover unintended consequences (e.g., Chapters 21–23) and on the part of producers to comply with best management practices and ethical as well as biophysical standards to offer a safe product. The regulatory frameworks must be in place, both to provide incentive and point out limits. Only a rational and considered discussion will provide the assurance that biochar systems develop in a sustainable way.

Important questions arise whether only one motivation or entry point (waste management, mitigation of climate change and nutrient pollution, energy generation, soil improvement; Figure 1.6) is sufficient to generate the necessary social and financial benefits for a biochar system to operate sustainably; or whether two or even all four value streams are needed. Can, for example, greenhouse gas emission reductions alone be financially viable or socially acceptable, and conversely, is soil improvement socially acceptable even if greenhouse gas emissions are not reduced or even increase? And if several entry points have to generate value, how many opportunities exist that warrant research and development? In addition, trade-offs may occur between different value streams: a greater biochar production may in the first instance reduce the amount of energy generated (Jeffery et al, 2015), unless soil is sufficiently improved that biomass and therefore feedstock production increases. Many questions such as these have to be answered to develop biochar systems at a larger scale.

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