1

Biochar for Environmental Management: An Introduction

Johannes Lehmann and Stephen Joseph

What is biochar?

Simply put, biochar is the carbon-rich product obtained when biomass, such as wood, manure or leaves, is heated in a closed container with little or no available air. In more technical terms, biochar is produced by so-called thermal decomposition of organic material under limited supply of oxygen (O_2), and at relatively low temperatures (<700°C). This process often mirrors the production of charcoal, which is one of the most ancient industrial technologies developed by mankind – if not the oldest (Harris, 1999). However, it distinguishes itself from charcoal and similar materials that are discussed below by the fact that biochar is produced with the intent to be applied to soil as a means of improving soil productivity, carbon (C) storage, or filtration of percolating soil water. The production process, together with the intended use, typically forms the basis for its classification and naming convention, which is discussed in the next section.

In contrast to the organic C-rich biochar, burning biomass in a fire creates ash, which mainly contains minerals such as calcium (Ca) or magnesium (Mg) and inorganic carbonates. Also, in most fires, a small portion of the vegetation is only partially burned in areas of limited O_2 supply, with a portion remaining as char (Kuhlbusch and Crutzen, 1995).

The question as to what biochar actually is from a chemical point of view rather than from a production point of view is much more difficult to answer due to the wide variety of biomass and charring conditions used. The defining property is that the organic portion of biochar has a high C content, which mainly comprises so-called aromatic compounds characterized by rings of six C atoms linked together without O or hydrogen (H), the otherwise more abundant atoms in living organic matter. If these aromatic rings were arranged in perfectly stacked and aligned sheets, this substance would be called graphite. Under temperatures that are used for making biochar, graphite does not form to any significant extent. Instead, much more

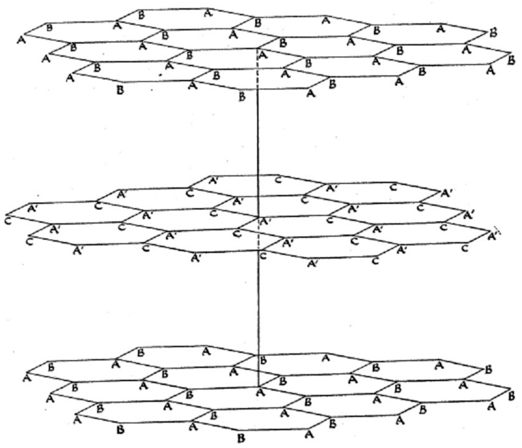

Figure 1.1 *Structure of graphite as proven for the first time by J. D. Bernal in 1924*

Source: Bernal (1924), with permission from the publisher and the estate

irregular arrangements of C will form, containing O and H and, in some cases, minerals depending upon the feedstock. Until now, biochar-type materials have largely escaped full characterization due to their complexity and variability (Schmidt and Noack, 2000). One of the first attempts to characterize the crystal structure of graphite was undertaken in the 1920s by John D. Bernal. Using X-ray diffraction, Bernal (1924) demonstrated the hexagonal structure and layering of graphene sheets in a pure graphite crystal (see Figure 1.1). The much more irregular biochar-type organic matter was only successfully investigated much later by Rosalind Franklin in the late 1940s (Franklin, 1950, 1951), and efforts to characterize the chemistry of biochar are ongoing and are discussed in detail in Chapters 2 to 4.

Biochar terminology

The term 'biochar' is a relatively recent development, emerging in conjunction with soil management and C sequestration issues (Lehmann et al, 2006). This publication establishes and uses 'biochar' as the appropriate term where charred organic matter is applied to soil in a deliberate manner, with the intent to improve soil properties. This distinguishes biochar from charcoal that is used as fuel for heat, as a filter, as a reductant in iron-making or as a colouring agent in industry or art (see historical definitions in Chapter 7).

The term 'biochar' has previously been used in connection with charcoal production (e.g., Karaosmanoglu et al, 2000; Demirbas, 2004a). The rationale for avoiding the term 'charcoal' when discussing fuel may stem from the intent to distinguish it from coal. Indeed, coal is formed very differently from charcoal and has separate chemical and physical properties, although in very specific cases the differences in properties can become blurred (see Chapter 17). In spite of this, the term 'charcoal' is long established in popular language and the scientific literature, and will also be used in this book for charred organic matter as a source of energy.

The establishment of the term 'agrichar' is closely related to that of biochar, with the desire to apply charred organic matter to soil, but is not used further in this book. 'Biochar' is preferred here as it includes the application of charred organic matter in settings outside of agriculture, such as promoting soil remediation or other environmental services. And the term emphasizes biological origin, distinguishing it from charred plastics or other non-biological material.

'Char' is a term that is often used interchangeably with charcoal, but is sometimes applied to refer to a material that is charred to a lesser extent than charcoal, typically as a product of fire (Schmidt and Noack, 2000). The term is used in this book to refer to the charred residue of vegetation fires. Both terms, char and charcoal, are extensively employed in this volume because much of the available information on charred organic matter has been generated in studies on charcoal production for fuel and on char as a result of fires. In most instances, this body of literature provides information that is relevant to biochar management.

'Activated carbon' is a term used for biochar-type substances, as well as for coal, that have been 'activated' in various ways using, for example, steam or chemicals, often at high temperature (>700°C) (Boehm, 1994). This process is intended to increase the surface area (see Chapter 2) for use in industrial processes such as filtration.

The term 'black C' is much wider and includes all C-rich residues from fire or heat. Fossil fuels such as coal, gas and petrol, as well as biomass, can produce black C. The term includes the solid carbonaceous residue of combustion and heat, as well as the condensation products, known as soot. Black C includes the entire spectrum of charred materials, ranging from char, charcoal and biochar, to soot, graphitic black C and graphite (Schmidt and Noack, 2000).

The term 'charring' is used either in connection with making charcoal or in connection with char originating from fires. The term 'pyrolysis' is typically used either for analytical procedures to investigate the organic chemistry of organic substances (Leinweber and Schulten, 1999) or for bioenergy systems that capture the off-gases emitted during charring and used to produce hydrogen, syngas, bio-oils, heat or electricity (Bridgwater et al, 1999). In contrast, the term 'burning' is typically used if no char remains, with the organic substrate being entirely transformed to ash that does not contain organic C. Often, substances called 'ash' in reality contain some char or biochar, significantly influencing ash properties and behaviour in technology and the environment.

Burning is very different from charring and pyrolysis, not only with respect to the solid ash residue versus biochar and related substances, but in terms of the gaseous products that are generated. Therefore, these two processes should be carefully distinguished from each other.

The terminology surrounding biochar may evolve. However, the definition provided here serves as a starting point for future development. Other terms such as gasification or liquefaction that are used in conjunction with biochar are explained elsewhere (Peacocke and Joseph, undated).

The origin of biochar management and research

While both research and development of biochar for environmental management at a global scale is a somewhat recent development, it is by no means new in certain regions and has even been the subject of scientific research for quite some time. For example, Trimble (1851) shared observations of 'evidence upon almost every farm in the county in which I live, of the effect of charcoal dust in increasing and quickening vegetation'. Early research on the effects of biochar on seedling growth (Retan, 1915) and soil chemistry (Tryon, 1948) yielded detailed scientific information. In Japan, biochar research significantly intensified during the early 1980s (Kishimoto and Sugiura, 1980, 1985).

The use of biochar has, for some time, been recommended in various horticultural contexts – for example, as a substrate for potting mix (Santiago and Santiago, 1989). In 1927, Morley (1927) writes in the first issue of *The National Greenkeeper* that 'charcoal acts as a sponge in the soil, absorbing

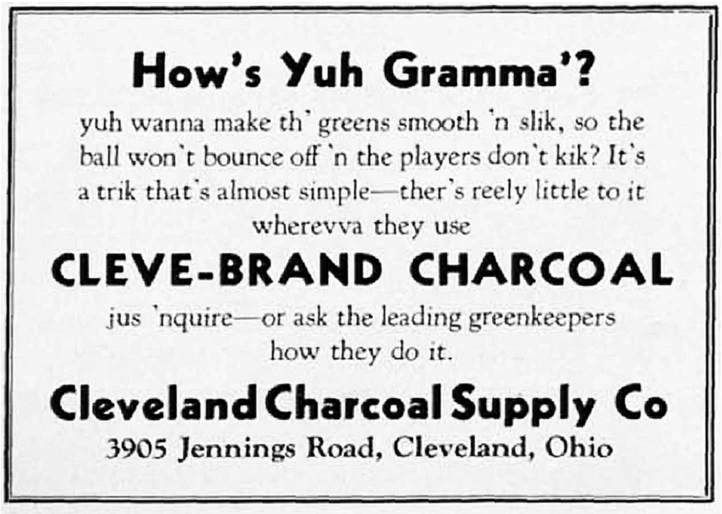

Figure 1.2 *Advertisement for biochar to be used as a soil amendment in turf greens*

Source: The National Greenkeeper (1933)

and retaining water, gases and solutions'. He even remarks that 'as a purifier of the soil and an absorber of moisture, charcoal has no equal' (Morley, 1929), and charcoal products are being marketed for turf applications in a 1933 issue of the same magazine (see Figure 1.2). Young (1804) discusses a practice of 'paring and burning' where soil is heaped onto organic matter (often peat) after setting it on fire with reportedly significant increases in farm revenue. Also, Justus Liebig describes a practice in China where waste biomass was mixed and covered with soil, and set on fire to burn over several days until a black earth is produced, which reportedly improved plant vigour (Liebig, 1878, p452). According to Ogawa (undated), biochar is described by Miyazaki as 'fire manure' in an ancient Japanese text on agriculture dating from 1697 (pp91–104). Despite these early descriptions and research, global interest in biochar only began in the past few years.

The basis for the strong recent interest in biochar is twofold. First, the discovery that biochar-type substances are the explanation for high amounts of organic C (Glaser et al, 2001) and sustained fertility in Amazonian Dark Earths locally known as Terra Preta de Indio (Lehmann et al, 2003a). Justifiably or not, biochar has, as a consequence, been frequently connected to soil management practised by ancient Amerindian populations before the arrival of Europeans, and to the development of complex civilizations in the Amazon region (Petersen et al, 2001). This proposed association has found widespread support through the appealing notion of indigenous wisdom rediscovered. Irrespective of such assumptions, fundamental scientific research of Terra Preta has also yielded important basic information on the functioning of soils, in general, and on the effects of biochar, in particular (Lehmann, 2009).

Second, over the past five years, unequivocal proof has become available showing that biochar is not only more stable than any other amendment to soil (see Chapter 11), and that it increases nutrient availability beyond a fertilizer effect (see Chapter 5; Lehmann, 2009), but that these basic properties of stability and capacity to hold nutrients are fundamentally more effective than those of other organic matter in soil. This means that biochar is not merely another type of compost or manure that improves soil properties, but is much more efficient at enhancing soil quality than any other organic soil amendment. And this ability is rooted in specific chemical and physical properties, such as the high charge density (Liang et al, 2006), that result in much greater nutrient retention (Lehmann et al, 2003b), and its particulate nature (Skjemstad et al, 1996; Lehmann et al, 2005) in combination with a specific chemical structure (Baldock and Smernik, 2002) that provides much greater resistance to microbial decay than other soil organic matter (Shindo, 1991; Cheng et al, 2008). These and similar investigations have helped to make a convincing case for biochar as a significant tool for environmental management. They have provided the breakthrough that has brought already existing – yet either specialized or regionally limited – biochar applications and isolated research efforts to a new level. This book is a testament to these expanding activities and their results to date.

The big picture

Four complementary and often synergistic objectives may motivate biochar applications for environmental management: soil improvement (for improved productivity as well as reduced pollution); waste management; climate change mitigation; and energy production (see Figure 1.3), which individually or in combination must have either a social or a financial benefit or both. As a result, very different biochar systems emerge on different scales (see Chapter 9). These systems may require different production systems that do or do not produce energy in addition to biochar, and range from small household units to large bioenergy power plants (see Chapter 8). The following sections provide a brief introduction into the broad areas that motivate implementation of biochar, leading to more detailed information presented in the individual chapters throughout this book.

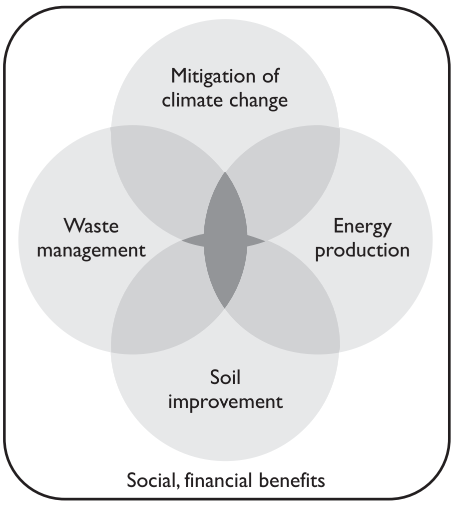

Figure 1.3 *Motivation for applying biochar technology*

Source: Johannes Lehmann

Biochar as a soil amendment

Soil improvement is not a luxury but a necessity in many regions of the world. Lack of food security is especially common in sub-Saharan Africa and South Asia, with malnutrition in 32 and 22 per cent of the total population, respectively (FAO, 2006). While malnutrition decreased in many countries worldwide from 1990–1992 to 2001–2003, many nations in Asia, Africa or Latin America have seen increases (FAO, 2006). The 'Green Revolution' initiated by Nobel Laureate Norman Borlaug at the International Centre for Maize and Wheat Improvement (CIMMYT) in Mexico during the 1940s had great success in increasing agricultural productivity in Latin America and Asia. These successes were mainly based on better agricultural technology, such as improved crop varieties, irrigation, and input of fertilizers and pesticides. Sustainable soil management has only recently been demanded to create a 'Doubly Green Revolution' that includes conservation technologies (Tilman, 1998; Conway, 1999). Biochar provides great opportunities to turn the Green Revolution into sustainable agroecosystem practice. Good returns on ever more expensive inputs such as fertilizers rely on appropriate levels of soil organic matter, which can be secured by biochar soil management for the long term (Kimetu et al, 2008; Steiner et al, 2007).

Specifically in Africa, the Green Revolution has not had sufficient success (Evenson and Gollin, 2003), to a significant extent due to high costs of agrochemicals (Sanchez, 2002), among other reasons (Evenson and Gollin, 2003). Biochar provides a unique opportunity to improve soil fertility and nutrient-use efficiency using locally available and renewable materials in a sustainable way. Adoption of biochar management does not require new resources, but makes more efficient and more environmentally conscious use of existing resources. Farmers in resource-constrained agroecosystems are able to convert organic residues and biomass fuels into biochar without compromising energy yield while delivering rapid return on investment (see Chapter 9).

In both industrialized and developing countries, soil loss and degradation is occurring at unprecedented rates (Stocking, 2003; IAASTD, 2008), with profound consequences for soil ecosystem properties (Matson et al, 1997). In many regions, loss in soil productivity occurs despite intensive use of agrochemicals, concurrent with adverse environmental impact on soil and water resources (Foley et al, 2005; Robertson and Swinton, 2005). Biochar is able to play a major role in expanding options for sustainable soil management by improving upon existing best management practices, not only to improve soil productivity (see Chapters 5 and 12), but also to decrease environmental impact on soil and water resources (see Chapters 15 and 16). Biochar should therefore not be seen as an alternative to existing soil management, but as a valuable addition that facilitates the development of sustainable land use: creating a truly green 'Biochar Revolution'.

Biochar to manage wastes

Managing animal and crop wastes from agriculture poses a significant environmental burden that leads to pollution of ground and surface waters (Carpenter et al, 1998; Matteson and Jenkins, 2007). These wastes as well as other by-products are usable resources for pyrolysis bioenergy (Bridgwater et al, 1999; Bridgwater, 2003). Not only can energy be obtained in the process of charring, but the volume and especially weight of the waste material is significantly reduced (see Chapter 8), which is an important aspect, for example, in managing livestock wastes (Cantrell et al, 2007). Similar opportunities exist for green urban wastes or certain clean industrial wastes such as those from paper mills (see Chapter 9; Demirbas, 2002). At times, many of these waste or organic by-products offer economic opportunities, with a significant reliable source of feedstock generated at a single point location (Matteson and Jenkins, 2007). Costs and revenues associated with accepting wastes and by-products are, however, subject to market development and are difficult to predict. In addition, appropriate management of organic wastes can help in the mitigation of climate change indirectly by:

- decreasing methane emissions from landfill;
- reducing industrial energy use and emissions due to recycling and waste reduction;
- recovering energy from waste;

- enhancing C sequestration in forests due to decreased demand for virgin paper; and
- decreasing energy used in long-distance transport of waste (Ackerman, 2000).

Strict quality controls have to be applied for biochar, particularly for those produced from waste, but also from other feedstocks. Pathogens that may pose challenges to direct soil application of animal manures (Bicudo and Goyal, 2003) or sewage sludge (Westrell et al, 2004) are removed by pyrolysis, which typically operates above 350°C and is thus a valuable alternative to direct soil application. Contents of heavy metals can be a concern in sewage sludge and some specific industrial wastes, and should be avoided. However, biochar applications are, in contrast to manure or compost applications, not primarily a fertilizer, which has to be applied annually. Due to the longevity of biochar in soil, accumulation of heavy metals by repeated and regular applications over long periods of time that can occur for other soil additions may not occur with biochar.

Biochar to produce energy

Capturing energy during biochar production and, conversely, using the biochar generated during pyrolysis bioenergy production as a soil amendment is mutually beneficial for securing the production base for generating the biomass (Lehmann, 2007a), as well as for reducing overall emissions (see Chapter 18; Gaunt and Lehmann, 2008). Adding biochar to soil instead of using it as a fuel does, indeed, reduce the energy efficiency of pyrolysis bioenergy production; however, the emission reductions associated with biochar additions to soil appear to be greater than the fossil fuel offset in its use as fuel (Gaunt and Lehmann, 2008). A biochar vision is therefore especially effective in offering environmental solutions, rather than solely producing energy.

This appears to be an appropriate approach for bioenergy as a whole. In fact, bioenergy, in general, and pyrolysis, in particular, may contribute significantly to securing a future supply of green energy. However, it will, most likely, not be able to solve the energy crises and satisfy rising global demand for energy on its own. For example, Kim and Dale (2004) estimated the global potential to produce ethanol from crop waste to offset 32 per cent of gasoline consumption at the time of the study. This potential will most likely never be achieved. An assessment of the global potential of bioenergy from forestry yielded a theoretical surplus supply of 71EJ in addition to other wood needs for 2050 (Smeets and Faaij, 2006), in comparison to a worldwide energy consumption of 489EJ in 2005 (EIA, 2007). If economical and ecological constraints were applied, the projection for available wood significantly decreases (Smeets and Faaij, 2006). However, even a fraction of the global potential will be an important contribution to an overall energy solution. On its own, however, it will probably not satisfy future global energy demand.

In regions that rely on biomass energy, as is the case for most of rural Africa as well as large areas in Asia and Latin America, pyrolysis bioenergy provides opportunities for more efficient energy production than wood burning (Demirbas, 2004b). It also widens the options for the types of biomass that can be used for generating energy, going beyond wood to include, for example, crop residues. A main benefit may be that pyrolysis offers clean heat, which is needed to develop cooking technology with lower indoor pollution by smoke (Bhattacharya and Abdul Salam, 2002) than is typically generated during the burning of biomass (Bailis et al, 2005) (see Chapter 20).

Biochar to mitigate climate change

Adding biochar to soils has been described as a means of sequestering atmospheric carbon dioxide (CO_2) (Lehmann et al, 2006). For this to represent true sequestration, two requirements have to be met. First, plants have to be grown at the same rate as they are being charred because the actual step from atmospheric CO_2 to an organic C form is delivered by photosynthesis in plants. Yet, plant biomass that is formed on an annual basis typically decomposes rapidly. This decomposition releases the CO_2 that was fixed by the plants back to the atmosphere. In contrast, transforming this biomass into biochar that decomposes much more slowly diverts C from the rapid biological cycle into a much slower biochar cycle (Lehmann, 2007b). Second, the biochar needs to be truly more stable than the biomass from which it was formed. This seems to be the case and is supported by scientific evidence (see Chapter 11).

Several approaches have been taken to provide first estimates of the large-scale potential of biochar sequestration to reduce atmospheric CO_2 (Lehmann et al, 2006; Lehmann, 2007b; Laird, 2008), which will need to be vetted against economic (see Chapters 19 and 20) and ecological constraints and extended to include a full emission balance (see Chapter 18). Such emission balances require a comparison to a baseline scenario, showing what emissions have been reduced by changing to a system that utilizes biochar sequestration. Until more detailed studies based on concrete locations reach the information density required to extrapolate to the global scale, a simple comparison between global C fluxes may need to suffice to demonstrate the potential of biochar sequestration (see Figure 1.4). Almost four times more organic C is stored in the Earth's soils than in atmospheric CO_2. And every 14 years, the entire atmospheric CO_2 has cycled once through the biosphere (see Figure 1.4). Furthermore, the annual

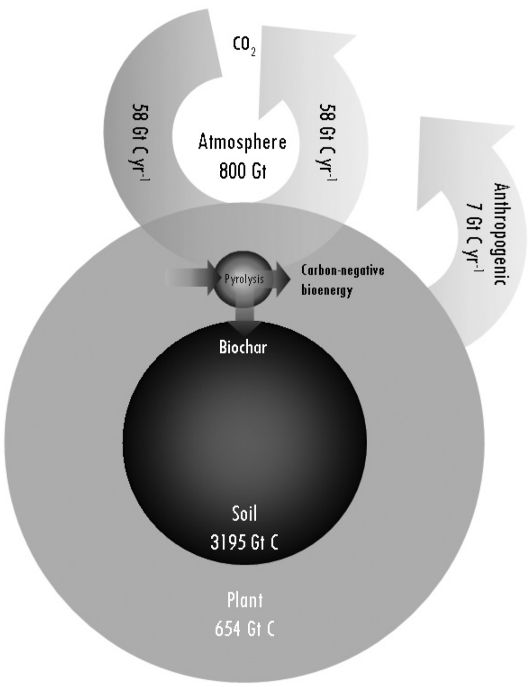

Figure 1.4 *The global carbon cycle of net primary productivity (total net photosynthesis flux from atmosphere into plants) and release to the atmosphere from soil (by microorganisms decomposing organic matter) in comparison to total amounts of carbon in soil, plant and atmosphere, and anthropogenic carbon emissions (sum of fossil fuel emissions and land-use change)*

Source: data from Sabine et al (2004)

uptake of CO_2 by plants is eight times greater than today's anthropogenic CO_2 emissions. This means that large amounts of CO_2 are cycling between atmosphere and plants on an annual basis and most of the world's organic C is already stored in soil. Diverting only a small proportion of this large amount of cycling C into a biochar cycle would make a large difference to atmospheric CO_2 concentrations, but very little difference to the global soil C storage. Diverting merely 1 per cent of annual net plant uptake into biochar would mitigate almost 10 per cent of current anthropogenic C emissions (see Chapter 18). These are important arguments to feed into a policy discussion (see Chapter 22).

Adoption of biochar for environmental management

Adopting biochar-based strategies for energy production, soil management and C sequestration relies primarily on individual companies, municipalities and farmers (see Chapter 21). But national governments and international organizations could play a critical role by facilitating the process of technological development, especially in the initial phases of research and development. Although biochar has great potential to become a critical intervention in addressing key future challenges, it is best seen as an important 'wedge', contributing to an overall portfolio of strategies, as introduced by Pacala and Socolow (2004) for climate change. Such an approach does not apply only to global warming, but also to large-scale efforts to deliver food security to more people worldwide, to produce energy and to improve waste management.

Adoption may occur in multiple sectors to varying extents because biochar systems serve to address different objectives (see Figure 1.3) and operate on different scales, and can therefore be very different from each other (see Chapter 9).

Concerns over using biomass resources that would otherwise fulfil ecosystem services or human needs have to be taken into full consideration. Possible conflicts of producing energy and biochar versus food as a consequence of massive adoption of biochar technologies have to be considered, as discussed for bioenergy in general (Müller et al, 2008). But the minimum residue cover required to protect soil surfaces also needs to be established in conjunction with biochar management of soil organic matter. While biochar will undoubtedly improve soil quality and productivity, some soil cover is required to keep water and wind erosion at a minimum. Therefore, plant residues cannot be entirely removed for biochar production. Other tasks that lie ahead are technological issues, such as refining methods for production, transportation of biochar and its application to soil, while avoiding unacceptable dust formation or health hazards (see Chapters 8 and 12). These are merely examples of questions that need to be addressed in the near future and that are discussed in more detail in individual chapters.

Much information certainly must still be gathered, and several such challenges have to be addressed (Lehmann, 2007a; Laird, 2008). But the tasks ahead are of such magnitudes that they can be solved alongside implementation. In fact, biochar research requires working under conditions of economically feasible enterprises in order to investigate the processes at the scale at which they are to be implemented. Much has already been achieved, and the basic information on which biochar for environmental management rests is available. This book documents that information and serves as the starting point for scaling up biochar management to become a global strategy.

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