Biochar for sustainable agricultural development

A critical review of biochar for carbon management
and the improvement of agricultural production systems

Socrates Schouten, 2010

Supervisors:
Sven Sielhorst (Solidaridad, Utrecht)
Denyse Snelder (Institute of Environmental Sciences, Leiden)

Preface

This dissertation was realized to obtain the degree of MSc in Biology (track 'Sustainbility & Biodiversity') at Leiden University, the Netherlands. It is the product of a seven month internship at Solidaridad, a Dutch non-governmental organisation focussed on reducing poverty through the transformation of production chains towards sustainable modes. The internship did not only include the literature study that resulted in this report, but also the coordination of a series of expert meetings aimed at designing potential pilot projects. In September 2010 I was given the opportunity to travel to Brazil where I attended the 3rd International Biochar Conference (12-15 September, www.ibi2010.org) with subsequent field excursion to Terra Preta sites alongside the Amazon river. Immediately afterwards a visit to Misiones, Argentina, was scheduled. There I joined Josefina Eisele (Solidaridad Latinoamerica) in investigating the possibility for Solidaridad to get industries and other parties to join hands and engage in biochar.

Sven Sielhorst deserves the greatest of thanks. If it weren't for his professional curiosity for new concepts in international cooperation, I would not have had such a great graduation project. My gratitude to Jan Maarten Dros and Nico Roozen, for giving me the opportunity to spend time in the house of Solidaridad and share thoughts, is grand. I am much indebted to Denyse Snelder (CML, Leiden) for warmly accepting my appeal for her academic supervision. Josefina, thank you for the fun time in rainy Misiones.

Next to the internship at Solidaridad, I performed laboratory soil experiments at Wageningen University in the Netherlands, which allowed me to really get the full view of biochar. Many thanks to Maria Luz Cayuela and Jan Willem van Groenigen who immediately accepted my abrupt entry in the Soil Quality group and provided supervision that was first-class and fun. Finally, a loud thank you to Hans van Veen, who was so kind to overseeing the grading formalities of my dual project, which was, admittedly, a tad complex.

Abstract

Biochar is a charcoal-like material created by pyrolysis ('burning in absence of oxygen') of biomass. Incorporation of biochar into soils increases the amount of stable organic matter in the soil and thereby improves its fertility. Soil amelioration with biochar is largely inspired by the ancient 'Terra Preta' ('black earth') soils found in the Amazon region, which are to date considerably more productive than similar, unamended soils. The demand for agricultural products is deemed to increase greatly in the coming decades, not only for food, but also for production of alternatives for fossil fuels. Soil degradation is already a widespread phenomenon that troubles food production and depresses agricultural incomes and rural livelihoods. Techniques that actually improve soil fertility, instead of merely increasing productive inputs such as artificial fertilizers, have not found their way into agriculture to any satisfactory extent. Biochar is a substance that has been shown to have multiple benefits to crop production and increasing the efficiency of inputs. As biochar can be made from biomass such as crop rest-products that are present on the farm, it could prove to be a practical means of addressing soil fertility.

Biochar has recently gained strong attention because biochar soil amendment is also a form of carbon sequestration: the carbon contained in biochar is stable on long time scales, probably in the order of millennia. This could make biochar the sole form of carbon sequestration that is feasible on large scales and produces additional benefits. Beside the sequestration of carbon, biochar may reduce the climate impact of agriculture by suppressing emissions of methane and nitrous oxide and by lessening the amount of artificial fertilizer needed for crop growth.

Biochar is created by pyrolysis of biomass, a process that not only yields a solid product (the char), but also a liquid (bio-oil) and gaseous (bio-gas) product. The ratio between these product phases depends on plant design and process conditions. The co-products can be used to generate energy for local application, or fed to a grid. A reverse approach is also possible: central heating devices that yield biochar as a by-product. By subsequently sequestering the biochar, this form of energy production can be made 'carbon-negative' (i.e. having net negative CO_2 emissions).

Biochar unveils a band of dilemmas associated to the management of carbon. Climate mitigation is largely built around the idea of reducing carbon use and its emission to the atmosphere. Refraining from carbon use is the most straightforward option, but not a realistic one, since the demand for carbon-containing products is increasing, globally. The use of biological carbon is bound to rise strongly, substituting for fossil resources that are undesirable to combust. This, however, requires agricultural production to be intensified, which generally leads to deterioration of ecosystem quality and services. Nature itself needs carbon for the maintenance of ecosystem functioning. It can be said that carbon is a currency, and earth is on a tight budget, with energy, food and ecosystems competing for it while climate considerations rather have it not be spent. Biochar is not unequivocally a solution to this problem, but does sequester carbon while assisting agricultural production and co-producing energy. It is therefore an interesting technology for the current century.

There is still rather much uncertainty associated with biochar. There is little practical experience to date; results on yield increases are neither consistent or predictable. The feasibility of biochar systems, i.e. the factors controlling its potential widespread adoption, is of particular interest. Studies that assessed the availability of feedstock for biochar use similar data as studies that assessed biofuel feedstock availability. However, if feedstock is used for biochar, less carbon is available for bioenergy. Also the assumptions underlying these assessments are critical. The two important contributors to the proposed biochar feedstock are both controversial. The first class, agricultural by-products, are often already in some sort of use such as animal feed or soil protection. The second class, biochar crop plantations, assume large amounts of degraded land are available to take into cultivation. The actual extent of these areas, and that proportion on which cultivation is feasible, is difficult to determine.

Biochar projects in developing countries are likely to be very different from those in the global north. In the latter, R&D opportunities are abundant, fine-tuned biochars can be developed and sold, and allow verifiable GHG reductions to be quantified and traded. Realities in developing countries are different; where capital and infrastructure are less available, biochar systems will become more artisanal and less accountable. A climate focus on biochar for developing countries is therefore problematic, while diverting attention from food and soil challenges. Seeing that the biochar community predominantly consists of developed world organisations of which a considerable part is focused on engaging in projects in the south, involvement and consultation of target communities is more than essential. Project intentions need to be in synchrony with this requirement: development should be placed before carbon reductions.

In conclusion, biochar is a promising technology of which much still has to be resolved. The link it creates between soil and climate is of particular interest. Climate change is one of the major topics of this century and can, through biochar, unlock attention and means to address soil fertility problems. The scope for biochar's systemic approach extends beyond the agroecosystem to include the management of carbon for climate mitigation. How and how much biochar can assist in achieving sustainability goals should be discovered by doing science and practice in parallel. The uncertainties should not lead to restraint, but the exact direction into which biochar develops requires to be closely followed.

Contents

1. Introduction

Climate change, ecosystems and agricultural production have a certain element in common. That element is carbon. Carbon is the backbone of life, of biological energy and of much of human society. Energy consumption and land clearing have released great amounts of carbon to the atmosphere. Meanwhile, demands for plant and animal products, in which atmospheric carbon is assembled, experience another century of explosive growth. Maintaining soils in a fertile, productive state remains a challenge that is becoming more and more urgent to solve.

Recently, the problems just mentioned sparked attention for a substance that might very well contribute practically to the solution to many of them. This substance, biochar, consists largely of biological carbon in stabilized form. Biochar may be seen as a highly manageable form of carbon that could deliver services in soil, and remains there, instead of returning to the atmosphere. This hub position of carbon with agricultural benefits touches closely upon the challenges of the 21st century, making it worth a serious perusal, which is undertaken in this report.

1.1. Why biochar?

Biochar is a fine-grained charcoal-like material created by pyrolysis ('burning in absence of oxygen') of biomass, and differs from charcoal primarily in the sense that its primary use is not for fuel, but as a soil amendment for biosequestration and soil improvement (Figure 1.1). While the latter property was already known and put into practice in agriculture in the 1900s, the interest in biochar invigorated only recently. The basis for this lapse in interest is twofold. First, the discovery that biochar-type substrates are at the basis of the anthropogenic Amazonian dark earths that are rich in organic carbon (C) and are remarkably more fertile than the otherwise unwieldy tropical soils. Second, biochar is a stable conversion product of biomass; applied to soils it will retain most of the formerly photosynthesised organic C. Hence, it is a form of carbon capture and sequestration and might therefore be a tool in climate mitigation. Biochar is also cited as a tool in (agricultural) waste management (wastes formerly difficult to dispose of can be converted to biochar) and in energy production (biochar or its by-products can serve as source or carrier of energy).

Soil amelioration with biochar is largely inspired by the ancient 'Terra Preta' soils found in the Amazon region (Glaser *et al.* 2001, Lehmann 2009; Photos in Appendix II). While tropical soils are otherwise severely leached and low in organic carbon, Terra Preta soils are artificially enriched with black carbon and are locally known for their high productivity. Because of this, there are current examples of Terra Preta mining (for sale) and nutrient depletion from overexploitation (Lehmann *et al.* 2003: 395-6). It is unsure how the enrichment has taken place. All Terra Preta sites date back to pre-Columbian times and are associated with ancient habitation through the presence of pottery sherds. It may be that the perceivable fertility brought about by soil incorporation of charcoal from kitchen and garden activities had promoted the spread of Terra Preta (Lehmann *et al.* 2003). It is unknown how much was added (and therefore what percentage actually remains), over what time span the additions have taken place (and therefore how long it took before Terra Preta soils became fertile), and so forth (Glaser *et al.* 2004).

Given the enormity and inaccessibility of the Amazon rainforest, the extent of Terra Preta can only be guessed. Terra Preta fields are seen to occur widely along many Amazon river branches, with typical plot sizes of ~1 ha (Lehmann *et al.* 2003: Ch 4), while Glaser *et al.* (2001) cites 20 ha as the average. Contiguous Terra Preta areas of >100 ha have also been found.

Beside Terra Preta soils, artificial enrichment of soils with charcoal is largely anecdotal. Examples have been found in Japan, the U.S. and Ethiopia (J. Lehmann, pers. comm. 2010). There is no present-day evidence of autonomous and systematic charcoal addition to soils; current biochar applications all take place in the context of the renewed interest and are oriented towards research and demonstration. Most of this renewed interest is generated by western academia and sustainability ventures, trickling down to the more innovative among farmers and farming organisations. The number of start-ups aiming at biochar and pyrolysis commercialization is rapidly expanding. Very encouraging results in soil fertility and carbon sequestration are reported indeed in scientific (especially in the tropics, e.g. Glaser *et al.* 2001) and 'grey' (e.g. via IBI website: www.biochar-international.org) literature.

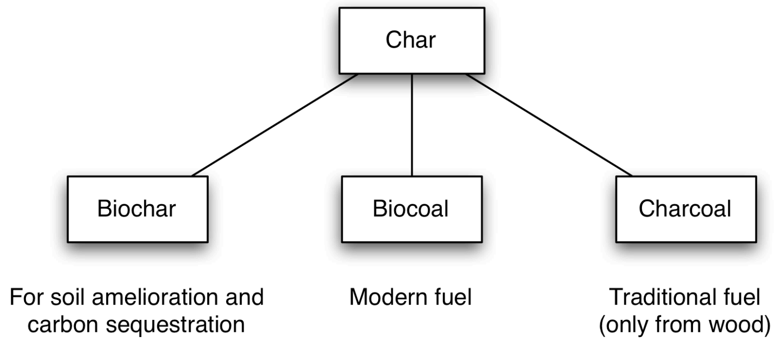

Figure 1.1. Nomenclature for chars used in this report. A *char* is a solid decomposition product of a natural or synthetic organic material, after light gases and tar have been driven out or released, usually thermally. *Charcoal* is the pyrolysis (carbonization) product of wood, usually to be used as a fuel. Biochar is produced with the intention of application to soils to deliver fertility and climate benefits. The development of new pyrolysis technologies for biomass allows for a range of modern chars that are well suitable as fuel; for these chars, *biocoal* is an appropriate name. Biochar and biocoal are largely similar products, but may be made from a range of biomass types other than wood, and will differ in details due to their different pyrolysis conditions (see Section 3.1).

1.2. Purpose and structure of the report

This report assesses the potentials and constraints of biochar and the factors controlling widespread biochar adoption, given the current state of knowledge and current developments, and focuses mostly on application in the developing world. Before setting out on the exploration of biochar's practical feasibility, a more conceptual approach is taken. Chapter 2 first presents an overview of the sustainability issues confronting agricultural production including its links to other environmental fields. This serves to create a fundament on which the assessment of biochar can further be built, as biochar touches upon a range of issues that should be well comprehended. Chapter 3 offers a predominantly technical description biochar, including its production and the various properties of biochar as tool in energy production, soil improvement and climate mitigation. Chapter 4 contains a conceptual discussion of the role biochar could fulfil in carbon management, i.e., the balancing of the needs of human society, nature and the global climate. Chapter 5 carries the assessment to the practical level. It explores the scope for biochar feedstock and evaluates the values, benefits, requirements and risks associated to widespread adoption of biochar. A particular focus is on application in the global south, given that arguably all addressed problems are more acute in underdeveloped regions. In Chapter 6, the findings of the report are brought to a conclusion, including an outlook to further development of biochar.

2. Food, agriculture and the environment

The need for increasing agricultural production is regaining public and policy attention. Recently, the soaring food prices of 2007-08 have assisted in increasing awareness of the need for systematic sustainable intensification. As food supply patterns have been shifting gradually away from local to global, food security has become an international affair. At the same time, environmental issues such as climate change and ecosystem degradation, both closely related to the practice of cultivation, have also gained global proportions. This chapter outlines the main topics of agriculture and environmental degradation that are relevant for the biochar concept.

2.1. Increasing demand for agricultural products

The world population is expected to reach 7 billion in 2011, 8 billion by 2025 and 9 billion by 2050 (UN ESA website, accessed 25 August 2010). Currently, Asia accounts for about 60% of the global population, while growth rates are highest in Latin America, the Middle East and Sub-Saharan Africa. Especially these regions have intolerable levels of malnutrition and require significant growth in food production to cope with their increasing population. On top of that, increases in welfare are expected to boost the amount of food consumed per capita per year from 2789 kcal (1999-2001 average) to some 3130 kcal in 2050 (Alexandratos *et al.* 2006), globally. Especially in developing and transition countries, a growing part of food consumption will consist of animal proteins, which require a proportionally greater amount of land for a similar calorific quantity of food (Steinfeld *et al.* 2006). The 2009 Declaration of the World Summit on Food Security therefore includes the statement that "[t]o feed a world population expected to surpass 9 billion in 2050, it is estimated that agricultural output will have to increase by 70 percent between now and then" (FAO 2009b).

Beside food production, there are increasing demands for energy and raw materials. Meanwhile we face the challenge of producing these from renewable resources instead of fossil resources. Many governments have indeed set ambitious targets on the proportion of energy that should come from renewable (often agricultural) sources (Fischer 2009). Meeting these targets would not only be advantageous in reducing oil dependency, also net greenhouse gas emissions would decline. Fuels and energy from biomass (bioenergy) have therefore been put prominently on the sustainability agenda for the current century. However, the ambitions for substituting a significant share of fossil resources by biomass raises sustainability issues by itself. Agriculturally productive areas will have to yield a great amount of biomass on top of the increasing demand for food. Is this possible without depleting nutrients and degrading the environment?

2.2. Agriculture and ecosystem services

The UN Millennium Ecosystem Assessment (Alcamo & Bennett 2003) has strongly contributed to the widespread adoption of the term 'ecosystem services'. The study pointed out the negative consequences of ecological deterioration for the well-being of our own species. Ecosystem services are the benefits that people obtain from ecosystems; agricultural products (food, biofuel, fiber) mentioned in the introduction of this chapter are part of the provisioning services (Table 2.1). Other, non-priced services are manifold and their maintenance for natural and human well-being require strong, coordinated management (Tilman *et al.* 2002, Foley *et al.* 2005, Boyd 2010).

The relationship between agriculture and the environment is intricate. Agricultural fields can be seen as simplified, homogenized ecosystems, maintained in a productive state rather than being allowed to reach equilibrium (Odum 1969). Crop and biomass production compete with output of ecological services. However, a reduction in ecological quality also affects crop production: the provisioning ecosystem services (agriculture) cannot exist without the regulating and supporting services providing the right conditions. When agricultural land is managed in such a way that essential ecosystem services are deteriorated and productivity dwindles, *land degradation* occurs. This term refers to the overall reduction in the capacity of the land to produce goods and services (*land* here includes landscape, terrain, vegetation, water and local climate) (Eswaran *et al.* 2001).

Protection of ecosystem functioning in agricultural settings is cumbersome for various reasons. Firstly, with the exception of the initial conversion of an ecosystem to a cultivated field (land use change), land degradation caused by agriculture is a *gradual* process. Meanwhile, field productivity responds quickly and visibly to fertilizer additions and other inputs. This introduces incongruity in land management: the short-term and readily perceivable benefits of intensive, homogenized farming systems outweigh and conceal land degradation, which affects productivity in the long run (Scoones *et al.* 1996). Secondly, the effects of land degradation also extend beyond the local scale (e.g. downstream effects of fertilizer application or water depletion), diluting the land manager's perception of the degradation caused by his actions. Thirdly, ecosystem services other than crop production are rarely traded in markets and thus lack observable prices (Boyd & Banzhaf 2007). Therefore, incentives to balance the supporting and regulating functions of ecosystems against their provisioning services do not follow automatically from market forces, but should be created with informed and persistent deliberation (Tilman *et al.* 2002).

Table 2.1. Classification of ecosystem services (Alcamo & Bennett 2003). Ecosystem services can be divided into provisioning, regulating, cultural and supporting services. Supporting services are necessary for the production of all other ecosystem services. Provisioning services are those that are most easily valued and traded.

Provisioning Services	**Regulating Services**	**Cultural Services**
Products obtained from ecosystems	*Benefits obtained from regulation of ecosystem processes*	*Nonmaterial benefits obtained from ecosystems*
■ Food	■ Climate regulation	■ Spiritual and religious
■ Fresh water	■ Disease regulation	■ Recreation and ecotourism
■ Fuelwood	■ Water regulation	■ Aesthetic
■ Fiber	■ Water purification	■ Inspirational
■ Biochemicals	■ Pollination	■ Educational
■ Genetic resources		■ Sense of place
		■ Cultural heritage

Supporting Services
Services necessary for the production of all other ecosystem services
■ Soil formation ■ Nutrient cycling ■ Primary production

2.3. Soil degradation

Soil degradation is a specific category of land degradation, defined as "a decrease in soil quality as measured by changes in soil properties and processes, and the consequent decline in productivity in terms of immediate and future production" (Johnson *et al.* 1997). Soil quality is determined by chemical, biological and physical parameters (Table 2.2). These include levels of available nutrients and organic matter, presence of beneficial soil biota and water holding capacity. These and other factors determine the ability of vegetation to root and obtain water and nutrients. In turn, vegetative cover and rooted earth stabilize the soil and prevent erosion by wind and water. Dying and decaying plant material replenishes the nutrients and organic matter in the soil. These two parameters, nutrient levels and soil organic matter, are highly relevant to understand how biochar may improve soil fertility, and are discussed in more detail below.

The global extent of soil degradation is difficult to quantify. The 1987-1990 Global Assessment of Soil Degradation (Oldeman *et al.* 1990) indicated that 15% of land was degraded, the highest proportions being in Europe (25%), Asia (18%) and Africa (16%). Degradation of agricultural soils was especially high in Africa (65%) and Central America (75%). A recent global land degradation study (Bai *et al.* 2008) estimated 24% of global land is degrading, of which one fifth is cropland and 20-25% is rangeland.

Table 2.2. Parameters of soil quality, divided in chemical, biological and physical domains. This overview neglects the excess of interactions between all phenomena of soil quality and soil degradation.

Type	Parameters	Problems
Chemical	Nutrient level Soil organic matter (SOM)	Nutrient depletion Leaching and acidification Loss of SOM Salinization
Biological	Diversity of microorganisms and soil invertebrates	Loss of beneficial soil organisms
Physical	Bulk density Water holding capacity	Soil compaction (mainly by agricultural activities) Waterlogging (too wet conditions) Low moisture levels Erosion

2.3.1. Nutrient depletion

In contrast to natural ecosystems, most biomass produced in agricultural systems is harvested and does not return to the land. This process creates a gap in the nutrient cycle causing a deficit in mineral and organic nutrient reserves in the soil. The replenishment of nutrient reserves requires sources of nutrient-rich material of which the useful compounds can be extracted by soil organisms and plants. Fertilizers may be expensive, however, and taking care of the right dosage and mix of additives is impeded by cost, availability and knowledge restraints. This results in farmers either fertilizing too little, or applying too much of an inadequate fertilizer.

In developing countries, fertilization is generally insufficient, leading to negative nutrient balances. The removal of nutrients at crop harvest can represent a significant part of agricultural domestic product. In Sub-Saharan Africa, erosion and crop harvest together cause most nutrient depletion; according to Drechsel et al. (2001), they constitute about 70% of nitrogen (N) losses, nearly 90% of potassium (K) losses and 100% of phosphorus (P) losses. They note that with erosion, runoff and leaching set at zero, N and K balances are still negative through crop harvest; inputs do currently not (even) suffice to balance vegetation removals only. Such *nutrient mining* on average accounts for about 7% of the agricultural share in the GDP of Sub-Saharan countries, with national values ranging up to 25%. This signifies that a significant share of agricultural earnings is not sustainable and will be curtailed either because productivity diminishes or costly investments will have to be made.

Second to 'NPK', calcium (Ca), sulphur (S) and magnesium (Mg) are essential macronutrients that need renewal, as well as a range of micronutrients. Leaching and acidification seem relatively more important for deficiencies here than with the 'big three', NPK, but soil balance characteristics differ widely per nutrient and per location. Beside crop growth and health, micronutrient deficiency links strongly to malnutrition: the human body is as responsive to a lack of essential nutrients and compounds as are plants (Alloway 2008).

Table 2.3. Major input and output parameters for determining the soil nutrient balance (adapted from Bindraban *et al.* 2000). In natural situations, 'organic fertilization' by recycling of plant litter accounts for 90-95% of nutrient inputs, except for calcium (circa 65%).

Input	Output
Mineral fertilizer	Crop products
Organic fertilizer	Crop residues
Wet and dry deposition	Leaching
Nitrogen fixation	Gaseous losses
Sedimentation	Soil erosion by wind and water

2.3.2. Loss of soil organic matter

Soils typically contain 1-5% organic matter (SOM). SOM derives from decaying plant and animal cell material (the largest contribution to animal material coming from microfauna (micro-organisms) and mesofauna (soil invertebrates)). SOM plays an important role in the formation of fertile soils, by acting as a soil aggregation agent (Bronick & Lal 2005). Soil aggregates are complexes of mineral and organic particles, micro-organisms and other substances that give fertile soils their typical 'crumbliness'. Whereas the longer lived types of SOM (most notably humus) are important for soil structure and water retention, shorter lived organic compounds provide nutrition for soil flora and fauna (Janzen 2006).

Higher OM levels are associated with higher fertility and productivity. Soils typically lose 15-30% of OM in the first few years after they are taken into cultivation (Janzen *et al.* 1997). Soil organic matter levels can be controlled by a range of management options (Bronick and Lal 2005). Replenishment of SOM and nutrients can originate from 'non-renewable' resources (fertilizers based on fossils, sediments or minerals) or organic sources and techniques (animal manure, fallowing, green manure and cover crops, agricultural residues, other residues). There is concern that, with agricultural residues becoming gradually more economically valuable, increasing biomass removal from the land will lead to widespread depletion of the soil organic carbon (SOC) pool (Lal 2005). The possibility of using agricultural residues for production of energy or raw materials therefore raises the urgent question of how to deal with declining SOC levels.

2.4. Climate change

Climate change is widely regarded to be one of the major challenges of the 21st century. Human activities, most notably combustion of fossil fuels, are shifting the balance of the global climate system. It is estimated that since pre-industrial times, the atmospheric concentration of carbon dioxide (CO_2) increased by 36%, methane (CH_4) by 148% and nitrous oxide (N_2O) by 16% (Forster and Ramaswamy 2007). The increased concentrations of these greenhouse gases (GHGs), together with other changes in the climate system, may increase the global average temperature up to +6ºC by 2100. It is increasingly accepted that a 2°C temperature increase is the upper acceptable limit, beyond which catastrophic climate and ecosystem alterations may take place. Worryingly, staying below a 2°C limit probably implies that, even having reduced emissions by 90% by 2050, CO_2 has to be actively removed from the atmosphere (Weaver *et al.* 2007). There is a very limited scope of technologies capable of 'sinking' carbon on considerable scales without generating deleterious side-effects (Woolf 2008, Lal 2008b). Agriculture is an important source of GHG emissions: N_2O emissions are primarily associated to the use of artificial fertilizers and CH_4 emissions to animal husbandry, rice cultivation and waste management. Changes in agricultural management may considerably reduce agriculture-associated GHG emissions, and added to that, even offer scope for environmentally benign C sequestration (Johnson *et al.* 2007, Obersteiner *et al.* 2010). Biochar, as will be shown in subsequent chapters, explicitly takes the approach of sequestering C in ecosystems while aiming to generate ancillary benefits.

3. Biochar: production, properties and uses

3.1. Production

Biochar is obtained through pyrolysis of biomass: thermochemical decomposition of condensed substances by heating under oxygen-limited conditions. Pyrolysis is widely used in industry for a range of chemical conversions. Generally, pyrolysis of biomass or fossil hydrocarbons yields three phases: a *gaseous*, a *liquid* and a *solid* phase. Charcoal production is an example of pyrolysis where the liquid (vapour) and gaseous phase are lost to the atmosphere; carbonized wood is the ultimate product. Other important applications are for the production of activated carbon (char with particularly fine pores and reactive inner surfaces), 'liquid smoke' for barbecue flavour, PVC production and cracking of hydrocarbons from oil.

Multiple chemical reactions occur during pyrolysis (Amonette & Joseph 2009, Masek & Brownsort 2010). At increasing temperatures, certain reactions progress towards completion and new reactions commence. Under 120°C, only drying occurs. Lignocelluloses start to decompose above this temperature, forming amorphous aromatic structures. This process is called 'torrefaction' and involves roasting rather than true carbonization of the product. Above 300°C, heavier volatile compounds are released. Above 600°C carbonization consolidates the char into graphene-like structures, which increasingly stabilizes the carbon in the solid product. Even higher temperatures allow for the gasification of a large part of the macromolecules, stripping carbon atoms to produce syngas while reducing yield of bio-oil and biochar (Table 3.1).

The optimization of reactor technology to produce a specific band of pyrolysis products involves much more than just temperature. Beside the highest heating temperature (HHT), the heating rate is a key feature, related to feedstock residence time (Table 3.1). Reactor design also includes reactor feed, mixing, catalysis, media, product separation and cleaning, process energy and so forth. The above indications on temperature only serve as elucidations on the principles of pyrolysis. Novel reactor technologies may be expected to deliver product mixtures different from those currently encountered.

Table 3.1. Liquid, solid and gas yields of pyrolysis processes at different, typical process conditions. References: (Sohi *et al.* 2009, Masek & Brownsort 2010).

Process name and conditions	**Liquid (bio-oil)**	**Solid (biochar)**	**Gas (syngas)**
SLOW PYROLYSIS Low-moderate temperature (350-400 °C) Long residence time (minutes to days)	30% (70% water)	35%	35%
INTERMEDIATE PYROLYSIS Low-moderate temperature (350-450 °C) Residence time 1-15 minutes	50% (50% water)	25%	25%
FAST and FLASH PYROLYSIS Moderate temperature (450-550 °C) Short hot vapour residence time (1-5s)	75% (25% water)	12%	13%
GASIFICATION High temperature (>800 °C) Long vapour residence time	5% tar 5% water	10%	85%

3.2. Biochar energy systems

Biochar energy systems can be divided into two different types: those that rely on the excess heat of the pyrolysis process, and those that use the products themselves as fuel (in which case the char is referred to as 'biocoal'). Pyrolysis processes are usually exothermic, i.e. after the process has been activated, they self-propagate. Part of the biomass is burned, yielding the heat necessary for pyrolysis. Heat and electricity are valuable co-products that can make the case for certain pyrolysis applications very strong. Whether energy recovery is effective and practical depends both on the feedstock and on the design of the pyrolysis facility.

As said, the other approach is to use the physical pyrolysis products as fuel. All three phases (solid, liquid and gas) are combustibles. In this approach, pyrolysis is used to convert the feedstock to products with improved fuel properties, making it an alternative to other biofuel systems (Figure 3.1). It should be noted that, in the bioenergy sector, the term 'pyrolysis' is often used for processes that are optimized to yield bio-oil. Biocoal is best produced by selecting lower temperatures and longer retention times (see Section 3.1). When pyrolysis is used to produce biocoal, rather than biochar that is meant for soil incorporation, torrefaction becomes an option. Torrefaction, as shortly noted in the previous section, involves roasting of biomass at temperatures of 200-250ºC. At these conditions the char (biocoal) yield can range up to 90% compared to 35% for conventional pyrolysis. This is caused by the low degree of 'volatilization' of lightweight compounds present in the feedstock. Hence, torrefied biomass is said to be rich in 'volatiles'. These compounds have good fuel value, but are likely to have a negative impact on soil fertility (Deenik *et al.* 2010).

As a fuel, char has some notable advantages compared to untreated biomass. Pyrolysis conversion greatly increases uniformity, allowing for feedstock flexibility. Biocoal moisture content is virtually nought, cancelling the risk of corrosion of transportation and storage vessels and increasing combustion efficiency. Moreover, biocoal does not biodegrade, is able of long-term storage and has a high calorific value (18-22 MJ/kg). Upon compaction the energy density can be over 18 MJ/m^3, compared to 10 MJ/m^3 for wood pellets. In case of industrial application, it can be combusted in conventional coal-fired plants.

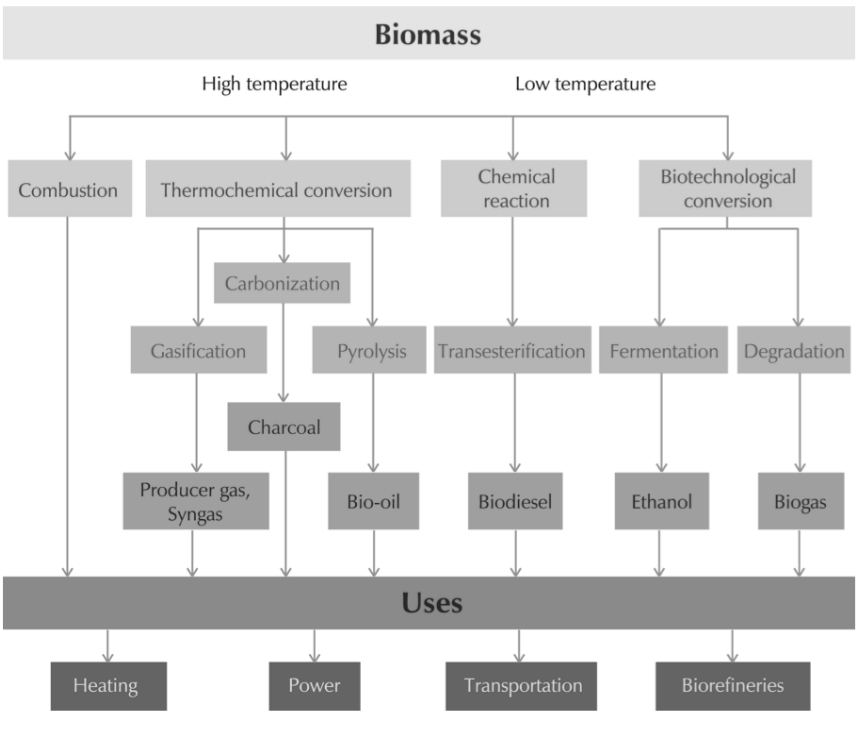

Figure 3.1. Main technology routes for bioenergy production. (ISPRE 2009)

3.3. Biochar for soil improvement

Biochar is a very particular organic product with high microporosity and low levels of degradable carbon. Biochar is believed to benefit crop production through three primary mechanisms (Sohi 2009):

1. Direct modification of soil chemistry through its intrinsic elemental and compositional make up (e.g. availability of nutrients and light organic molecules and decrease in soil acidity);
2. Providing chemically active surfaces that modify the dynamics of soil nutrients or otherwise catalyse useful soil reactions (e.g. increasing the cation exchange capacity of the soil);
3. Modifying physical character of the soil in a way that benefits root growth and/or nutrient and water retention and acquisition (e.g. reduction of soil bulk density, creation of stable macro-aggregates, improved tilth, provision of shelter for microorganisms).

The degree of (beneficial) modification of soil chemistry depends on the composition of biochar supplied to the soil. The prominent principle behind biochar is that it is recalcitrant to microbial degradation and therefore stable in soils. Hence, most biochars will contribute only marginally to replenishment of the soil nutrient base. However, any short-term and short-lasting effects of biochar through the first mechanism (i.e. fertilization) may be very important to incentivise soil biochar amendments for farmers, especially since the long-term benefits of biochar (improvement of the physical and chemical properties of bulk soil) are expected to be expressed only after a number of years' weathering has taken place (Sohi 2009).

3.4. Biochar stability, soil sequestration and climate mitigation

The process of carbonization of biomass stabilizes the carbon into structures that persist degradation for potentially thousands of years (Glaser *et al.* 2001, Glaser *et al.* 2003, Forbes *et al.* 2006). The principle of biochar sequestration for climate mitigation is based hereupon. The evidence for the long-term stability of biochar is largely derived from the observation of age-old charcoal found in soils all over the world, again with the Terra Preta soils as a notable example (Neves *et al.* 2004, Woolf 2008). Not only substance itself, but also the increased soil fertility associated to char remain centuries after Terra Preta sites were enriched (Glaser *et al.* 2001). However, as noted in the Introduction, researchers remain irresolute on how (much) char was added to Terra Preta soils; the efficiency of carbon sequestration in Terra Preta is therefore unknown.

Biochar soil sequestration does not guarantee full carbon retention or the total absence of greenhouse gas emissions. Firstly, biochar does not consist purely of stable carbon. A small proportion of the char, depending on production conditions, is 'labile' and will be decomposed either rapidly or within a few years' time. Decomposition rate of the labile fractions present in biochar will depend on the specific nature of these fractions and the properties of the soil and microclimate. Nevertheless, the labile fraction in biochar will be much less than that of the original feedstock, so that the carbon sequestration potential of biochar is considerably higher (Figure 3.2).

Also, the assumption of millennia-scale recalcitrance of the stable carbon is not uncontested. Gaps in the known 'black carbon cycle' suggest that significant amounts of black carbon from pyrogenic origin (i.e. wildfires) are lost from the soil, in order to explain the lower-than-expected amounts of black C in soils and ocean sediments (Masiello 2004, Forbes *et al.* 2006). It should be held for possible that soil black C is lost via oxidation by subsequent fires or by microbial action (Czimczik *et al.* 2003), both of which are of concern to biochar sequestration programs. (Major *et al.* (2010) identified surface runoff as an important contributor to loss of black carbon, but this has no bearing on stability of the carbon *per se*.)

Beside keeping C in a stable form, biochar is expected to offset greenhouse gas (GHG) emissions by a number of other pathways. Firstly, heat and energy are co-produced with biochar, which could mitigate the use of fossil fuels. Pyrolysis systems do not necessarily produce net energy, but in practical cases they are likely to, as evaluated by a recent life cycle analysis (Roberts *et al.* 2009).

Secondly, crop growth is generally promoted so that more CO_2 is drawn from the atmosphere. This could allow for faster cycling of carbon back and forth between the atmosphere and the economy, which is a prerequisite for increasing the share of biomass in energy and raw material production (see discussion in Section 4.1). Thirdly, improved fertility should reduce the need for chemical fertilizers, and therefore the emissions associated to their production (Gaunt *et al.* 2008). Fourthly, many studies show that biochar amended soils have suppressed emissions of CH_4 and N_2O (ibid.), two GHG species that are 25 and 298 times more potent than CO_2, respectively (100y radiative forcing equivalent; Forster and Ramaswamy 2007). However, much research has still to be done before these reductions can be reassured and predicted. Finally, biochar is said not only to be sequestered itself, but also to promote the build-up of non-biochar C in the soil. This is perhaps the most controversial of effects, although much of the controversy was caused by a single paper (Wardle *et al.* 2008) that has since been refuted by many researchers (e.g. Lehmann and Sohi 2008).

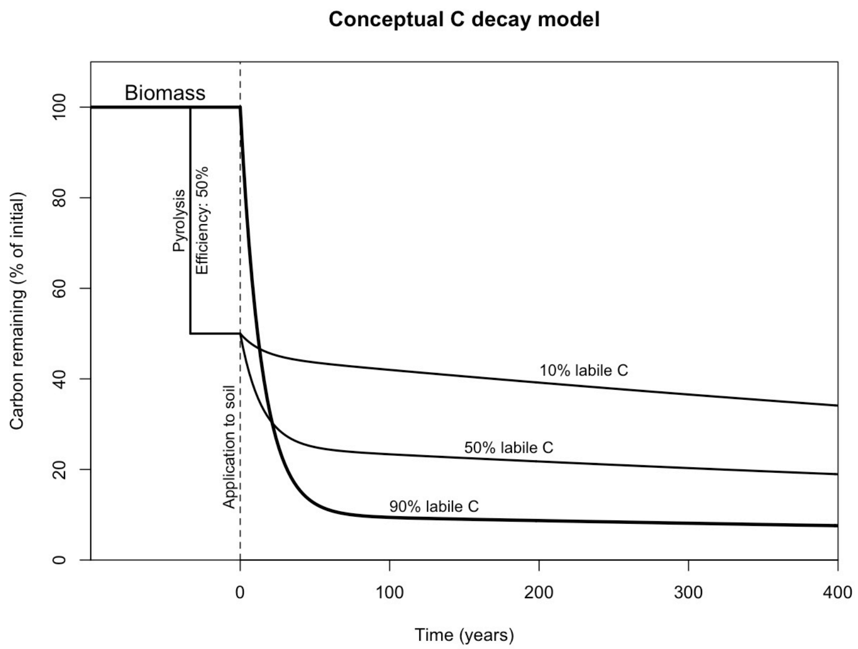

Figure 3.2. Conceptual carbon decay model. In the pyrolytic conversion of biomass to biochar, a quantity of C in the order of 50% is lost, but the remainder is much more stable than its untreated counterpart. Shown are two hypothetical biochars with 90% and 50% stable C and raw biomass with an assumed 10% stable C. Used values for mean residence times are 10y for labile C and 1000y for stable C. (Replicated from Lehmann *et al.* 2009)

4. Carbon management: how big is the biochar bonus?

Just as one dollar can only be spent once, a quantity of carbon can not be used in multiple ways simultaneously. When, for example, an amount of biomass is harvested and used as a fuel, it is no longer available for food, to be sequestered in the soil, or to decompose and nourish the ecosystem. Such trade-offs are due to gain in importance this century as both man and nature require more nourishment – man because of its growing numbers, and nature because it has been deprived from it in recent decades. The human intervention in the global carbon cycle has become so large that there is urgent need for new paradigms concerning the 'problem' of carbon.

This chapter philosophises on three carbon trade-offs: that of locked (sequestered) vs. used C, digestible (decomposable) vs. recalcitrant (stable) C, and that of product (e.g. food or fuel product) vs. non-product C. The role of biochar will be shown to be ambiguous in all cases. There is scope for a simultaneous positive contribution to all of food, fuel, climate and nature, but this very much depends on the magnitude of the positive feedback it generates. The concept of positive feedbacks and indeed the fulfilling of multiple needs in carbon management emerges as a key theme for the current century.

4.1. Sequestered vs. used carbon

Typically, carbon is emitted to the atmosphere upon use, either directly as CO_2 or other greenhouse gas (GHG), or with some delay as decomposable waste. This implies that climate ambitions in the end constrain total carbon consumption ('use'). Climate mitigation therefore comes in two shades: using a new source of carbon that is less GHG-intensive than an old one, or not using carbon at all[1]. Typical carbon offset schemes henceforth consist of either replacing fossil resources by renewable, or keeping a certain amount of C in stock – upon which it is not available to replace a lesser form of C. Here, typical climate mitigation strategies are reviewed in order to grasp the dilemmas in place, after which the role of biochar can be better understood.

Plantations (afforestation)
The extent to which plantations qualify as carbon offsets has been a matter of discussion. Earlier years sprouted carbon offsetting initiatives that provided individuals and organisations the possibility to compensate the climate impact of their consumption (e.g. flights) by donating money for plantation construction. Plantations have also been credited in voluntary and European carbon markets. The carbon effect of plantations is in the storage of carbon in standing trees, either through longer-term rotation periods or permanent afforestation, and enlargement of the C pool in the soil underneath them. The baseline[2] therefore consists of land use with less C stored in vegetation and soils. Wildfires, natural disasters, degradation and (illegal) logging are events that threaten the assumption of permanence[3] of the reduction (given a certain crediting period, which is not longer than 100y in the case of plantations (Reijnders 2009)). Large scale plantations will be needed if plantations are to become a significant carbon sink, but even the largest imaginable afforestation program will have only a modest contribution to climate mitigation (Nilsson & Schopfhauser 1995). Furthermore, activity shifting of land users to unclaimed forested areas may undo the enlargement of fixed C in the plantation ('indirect land use change', Gnansounou *et al.* 2008). This would boil down to financing the replacement of valuable natural forests by ecologically low-grade plantations (Smith 2002).

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[1] I disregard two other options, carbon capture and sequestration (CCS) and improving efficiency, because these have no fundamental implications for the system.
[2] 'Baseline' refers to the business-as-usual situation against which the emissions reduction is measured. For example, if 100 t gasoline equivalent of biofuel is used, it is assumed that the use of the same 100 t gasoline equivalent of a fossil fuel is offset.
[3] 'Permanence' is a critical criterion for the success of sequestration-type offset schemes: carbon sequestration in forests and other types of land cover is potentially reversible, i.e. the reduction may be lost.

Prevention of deforestation
Saving existing forests rather than creating new low-grade ones makes practical, economical and ecological sense. Deforestation is a problem in itself: still 13 Mha of natural forest are cleared every year, affecting biodiversity, local climate control and livelihoods of (near) forest-dwelling people (FAO 2009). Greenhouse gas emissions from deforestation make up 15-30% of total annual emissions, to a large extent owing to disturbance of the soil C pool that has built up over the centuries (Fargione *et al.* 2008). Exactly because of these reasons, implementation of deforestation prevention activities is pursued under the title of 'Reducing Emissions from Deforestation and Forest Degradation' (REDD). Such activities still have permanence and activity shifting problems like with afforestation. Moreover, it only performs relative to a negative baseline: no new carbon is stored, only old carbon is secured (be it carbon with an abundance of important values held in the biodiversity it harbours).

Crop and plantation biofuels
Using plantation biomass and energy crops to fulfil part of the global energy demand reduces the amount of fossil fuels combusted ('avoided fossil'). The C storage in trees and crops is then terminated and released to the atmosphere. As vegetation carbon was recently taken up from the atmosphere, as opposed to fossil carbon; biofuels are 'carbon-neutral'. Searchinger (2008, 2010) points out that the *direct* effect of biofuels is nil: the same amount of fuel is combusted, only fossil is replaced by bio. This substitution can only be realized by additional cultivation of higher-yielding and faster-growing crops and increasing turnover of biomass in the 'technosphere' (this is further explained in Figure 4.1). However, beside driving up agricultural intensification, more land is likely to be used for crop production. Generally, grassland or forest is sacrificed in the process, which could tip the GHG balance to undesired outcomes. (In addition, fossil inputs are used in cultivation that negatively affect the efficiency of biofuels relative to fossil fuels.)

Bioenergy from agricultural and forestry residues
Agricultural and forestry residues can be converted to bioenergy. Unused residues usually undergo biological decomposition, releasing GHGs to the atmosphere. Using these residues for bioenergy production emits about the same amount of GHGs. The greenhouse advantage is found in the avoided use of fossil fuel. However, using residues for bioenergy may compete with other uses of residues. These other uses will not cease to exist; other feedstocks will need to be addressed to fulfil all demands, shifting resource use and concomitant emissions to other areas. Literature on the amount of biomass waste that has absolutely no current use and would genuinely induce no activity shifting, is absent. The discussion on the availability of agricultural resources is continued in Section 5.1.1.

Biochar sequestration
Biochar that is used for energy is similar to bioenergy from crop and plantations and from agricultural and forestry residues (above). Only soil sequestration of biochar, or any other permanent storage of biomass, are carbon-negative: CO_2 is removed from the atmosphere and then sequestered (assuming sequestration last sufficiently long[4]). With pyrolysis, biochar and energy can be co-produced, enabling energy production to be carbon-negative through sequestration of its co-product.

[4] Ideally, carbon should remain fixed for timescales that "would make decomposition of biochar a negligible effect on the global climate compared to other geological processes" (Woolf 2008). In order to be a climate asset, however, biochar does not need to be locked up in eternity. If black carbon is stored a multitude longer than its fresh counterpart, and preferably at least in the order of hundreds of years, the function of bridge towards a low-carbon future where advanced climate management technologies are available could be fulfilled.

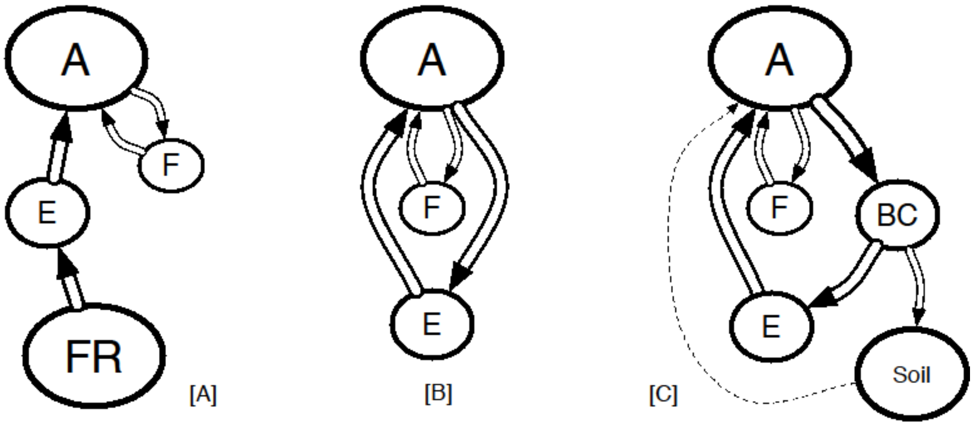

Figure 4.1. A bio-based economy needs to create 'additional carbon' (Searchinger 2010) in the 'fast' agriculture-technosphere C cycle. Reducing emissions from fossil resources given the same energy demand will require agriculture to become more productive, i.e., biomass carbon harvested per unit of time should be increased. The emissions reduction actually takes place at the point where the increased total demand for agricultural products is supposed to increase agricultural yields, magnifying the agricultural and technological C pool. [**A**] Baseline situation: biomass is used predominantly for food, represented by the atmosphere (A) – food (F) loop. Meanwhile, energy (E) from fossil reserves (FR) add more and more C to the atmosphere (A). [**B**] Bio-based scenario where all energy is from biomass. No fossil C is added to the atmosphere, but the amount of biological C that circulates through atmosphere via agriculture to technosphere has been hugely increased. [**C**] Scenario where, in addition to the switchover to bio-based, part of atmospheric carbon is buried as biochar (BC). This extra stream is another addition to the demands for food (F) and energy (E). Carbon has entered a 'slow' C cycle: over millennial timescales part will biologically active pools.

The first two mechanisms, afforestation and prevention of deforestation, only maintain or increase the standing stock of unused (unharvested) biomass; material or energy use is not affected. In a bio-based economy, biomass substitutes for fossil resources in the production of energy and materials. This way, no new carbon is added to the 'fast carbon cycle' of biosphere, technosphere and atmosphere, keeping atmospheric carbon more or less constant. The flow, or throughput, of biomass through this cycle for materials and energy will have to increase spectacularly to fulfill this demand. The only ways by which this is possible, is by reallocating current biomass use to bioenergy production (putting stress on food production), or by increasing the volume of grown biomass in time and space: shortening cultivation cycles, increasing yield and taking more land into production. Any of these options should take the same spectacular proportion as the surge in demand that calls for them (Figure 4.1 A-B). If, in addition to the biomass produced for food, energy and biomaterials, significant amounts of additional carbon are desired to produce biochar for sequestration, an even greater carbon turnover has to be achieved (Figure 4.1 C). The only way by which this proposition could be challenged is when bioenergy and biochar are produced from unused biomass wastes that would otherwise be left to decompose ('true wastes'), or from biomass grown on degraded land; these are viable but constrained in their potential (see Section 5.1). Table 4.1 gives a summary of the discussed aspects of carbon offsets.

4.1. Digestible vs. recalcitrant carbon

The climate merit of biochar is largely provided by its recalcitrance, i.e. its ability to be sequestered in soils for extended periods of time (Section 3.4). While the need to greatly enlarge stable soil C pools, both for soil quality and more recently for climate mitigation, is stressed frequently, much of the value of organic matter in soils derives from its *decay* (Janzen 2006). As carbon macromolecules are broken down, they release organic compounds and nutrients that nourish soil biota and the vegetation rooted

Table 4.1. Overview of basic carbon offsets. 'Baseline reduction' is the point of reference for the emission reduction. Biochar sequestration * has a more complex baseline reduction: it could consist of foregone biomass decomposition, or extra CO_2 could have been removed from the atmosphere. In addition, other biochar climate benefits are present. 'C balance' is expressed here in climate-positive terms: carbon negativity of biochar is good (++) for the climate. 'Permanence' involves the risk of losing the reduction, e.g. by chopping down an afforested plot a decade after creation. 'Leakage' includes activity shifting and indirect land use change. 'Additional benefits' is a measure of other merits the carbon offset offers. For example, plantations and biofuel crops *may* improve biodiversity and ecological services, but can also induce deterioration. Note that if additional benefits actually accrue to the project owner, such as productivity increases of biochar soil amendments, the additionality criterion of an offset project may be compromised.

	Baseline reduction	**C balance**	**Permanence**	**Leakage**	**Additional benefits**
Plantations	Low-carbon land use	0	--	--	+/-
REDD	Deforestation and degradation	0	-	-	++
Crop biofuels	Fossil combustion	0/-	0	--	+/-
Residue biofuels	Fossil combustion	0/-	0	-	+/-
Biochar production and sequestration	*	+/++	++	-	0/++

in the soil; recalcitrant C does no such thing. As identified in Section 3.3, amendments other than biochar will remain important to maintain and improve soil fertility. Soil organic matter (SOM) consists of a wide variety of organic fractions, ranging from very short-lived molecules to humified substances that persist degradation for ages (Section 2.3.2). The less varied SOM is, the less fertile and resilient the soil. Biochar primarily tends to improve the *structure* of the soil; fertilization still is necessary to replenish nutrients, and fresh organic residues to structure the soil food web and provide good tilth. Hence, some of the 'win–win' character of sequestering C in soils must be considered critically, because recalcitrant C is not going to contribute to the carbon pool that provides its services through its decay. On the other hand, biochar is likely to have beneficial effects on soil CEC, pH and other characteristics. Furthermore, in Section 3.4 a number of indirect climate mitigating properties of biochar were related to its effects in soil and on plant growth; not purely stemming from its stability, but from its structural contributions. If these extra benefits 'pay back' the initial investment of carbon in recalcitrant biochar C, there is a positive feedback compensating for the biological cost of returning degradation resistant C to the soil.

4.2. Product vs. non-product carbon

Another trade-off exists in the allocation of carbon, or biomass, or ecosystem productivity between harvested product and other services (see Section 2.2). Higher productivity can be achieved through an increase in yield or an increase of the area harvested. By optimizing growing conditions and crop species, product yield can be improved by realizing, per unit of area, increases in:

1. product mass: investments are devoted to maximize the amount of product successfully grown and harvested, for example by breeding crops that have less residue and bigger product-parts, or by combating consumption by pest animals;
2. crop mass: the amount of grown whole-crop is increased, for example by cropping more densely, by optimizing water and nutrient supply and by combating crop disease;
3. all arable phytomass: all vegetation (including weeds and fringe vegetation) grown on the field is increased, possibly by more holistic optimization of nutrient supply and soil and water conservation.

In the past half century (1961-2008), crop yields have on average increased by 111%, while harvested area has grown by only 30% (FAOSTAT, accessed 2010). Most yield increases have been achieved by shifting crop mass (and therefore C allocation) towards the product and away from roots and residues; photosynthesis has not been improved in itself (Evans & Fischer 1999). Non-product biomass has therefore been reduced strongly relative to product biomass. Such a technological approach focuses on the first and second of the three yield increase options given above, while a more ecological approach focuses on the third. Increasing total arable productivity means that not only the biomass of crop species is enhanced, but also biomass of protective vegetation and primary production available for organisms higher up the food chain, either as food or habitat. Among the conserved biodiversity may be species that are beneficial for pest control or pollination. Non-harvested biomass is important for control of soil erosion, multiple indicators of soil quality, and replenishment of soil carbon and nutrients available for next crops.

If extra biomass is to be used for biochar production, either by cultivating a dedicated crop or using agricultural by-products, less fresh organic material will be available for the ecosystem, but biochar is added. Similarly to the allocation questions mentioned earlier, the final question is: How big is the positive feedback for biochar? Does it already pay off significantly in terms of climate and soil fertility to pyrolyse a quantity of biomass that does not infringe upon other services drawn from it?

5. Assessment of biochar potential

The key idea behind biochar is the (economically favourable) enrichment of soils with stable organic carbon compounds. Chapter 3 introduced the workings of biochar and shown a range of likely benefits resulting from this enrichment. On the soil side, biochar could improve soil structure and vitality to benefit the agricultural ecosystem. On the climate side, biochar seeks to combat global warming by introducing a 'carbon-negative' technology in the band of mitigation strategies that are considered. Chapter 4 demonstrated that the conceptual advantage of biochar is in the potential positive feedbacks it delivers to productive nature. Biochar systems that exploit these and other benefits should not only function conceptually, but also in practice. This chapter assesses the potential and feasibility of biochar systems by addressing the following questions:

1. What is the scope for the typical feedstock availability?
2. What benefits are conceivable?
3. What are the environmental and socio-economic implications of the system?

5.1. Feedstock sourcing

What types and volumes of biomass feedstock are available for biochar production? What are possible constraints? In this section, feedstock flows that are eligible for biochar production are discussed in three main categories:

- Medium to large biochar systems that concentrate on agricultural by-products as source for their conversion to biochar and application to the soils in the native agricultural system;
- Dedicated large-scale plantations for biochar feedstock production;
- Biochar systems based on 'thinly distributed feedstock' produced by smallholders.

This section comments on recent viewpoints and assessments that are typical and highly cited in the biochar or otherwise the bioenergy debates.

5.1.1. Agricultural by-products

Agricultural by-products are organic solid and liquid substances that are co-produced the agricultural product of intent, most notably crop residues (corn stalks, rice husks, empty oil palm fruit bunches, etc.) and animal manures. Some by-products are economically valuable and are sold to generate additional income for the farm, but most by-products are processed to return their nutrients and organic matter to the land. Many agricultural systems are already nutrient limited and will not sustain if residues are exported (Lal 2005, Lal 2008a). Otherwise, many residues are used locally as cooking fuel, soil protection (mulch), animal bedding or animal feed.

Studies that assess the potential biomass quantity available for bioenergy usually include agricultural by-products next to dedicated (first and second generation) energy crops. Some authors prefer by-products over dedicated crops because cropland ought to be spared for food production (e.g. Righelato & Spracklen 2007). Others stress the necessity to return residues to the land and argue that second generation biofuel crops are best candidates (Tilman *et al.* 2006, Lal 2008a). This discussion points at a fundamental sustainability dilemma. Agricultural by-products are already being claimed for conflicting purposes: local uses (soil fertility maintenance, mulch, feed, cooking fuel) on the one hand, and modern bioenergy production on the other. The question remains what is left for biochar. A recent paper (Woolf *et al.* 2010) assessing global biochar potential attempted to overcome the availability problem by estimating the share of by-products that is freely available, i.e. not competing with other uses that people depend upon for their livelihoods. More specifically, their criteria required that residues 'be extracted at a rate and in a manner that does not cause soil erosion or soil degradation' and those 'currently in use as animal fodder not be used as biochar feedstock'. These criteria reduced wheat straw and corn stover availability to 8-14% of total residues generated, 20-30% in the case of rice husks and paddy rice straw and 62.5% for sugarcane. Including 12.5% of global animal manure, some 500 Mt (megaton) C from agricultural residues is available for external use (bioenergy as well as biochar) annually (Figure 5.1). Averaged over the global crop acreage of 1.5 Gha, this amount would allow for annual biochar additions using 0.33 t/ha, or about 0.1 t/ha biochar considering pyrolysis efficiency; much less than typically suggested application rates of 5-50 t/ha.

Undeniably, there are plenty cases of cultivation where by-products are produced that are not used or used far from optimally. Some residue streams are already being concentrated along with product harvest or similar operations; others are left in the field to decompose without being managed so that they contribute well to soil fertility. For these biomass streams, conversion to biochar can be an excellent option. I conclude that the success of biochar systems based on agricultural by-products will be system-specific, rather than attributable to any aggregate quantity of by-products.

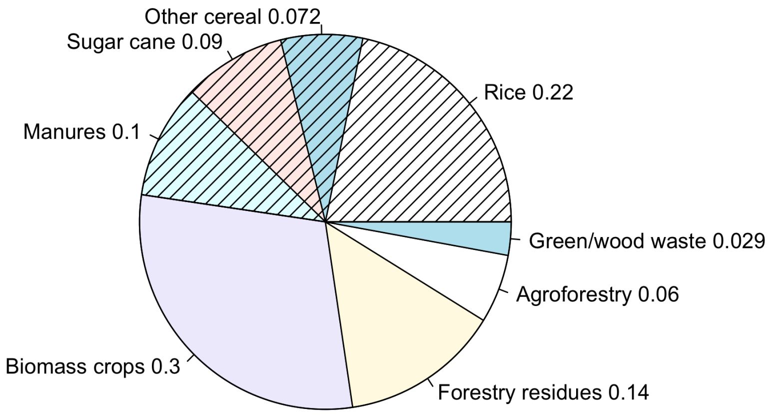

Figure 5.1. Annual globally sustainable biomass feedstock availability from Woolf et al. (2010; Alpha scenario). Data in Pg C (1.000 Mt C) per year; total available biomass amounts to 1.01 Pg C. Shaded area represents the share of agricultural by-products. In an alternative scenario ('Beta') that assumes higher availability, especially the share of biomass crops and agroforestry increase (new total: 1.64 Pg C) (Woolf et al., 2010).

5.1.2. Biochar crop plantations

Thirty per cent of the global annual sustainably available feedstock from Woolf et al. (2010) stems from biomass crops (Figure 5.1). Aware of the controversy surrounding the land requirement for biofuel production, the authors preclude crops for which new lands are taken into production or taken out of food production. Furthermore they require that 'minimal carbon debt be incurred from land-use change or use of feedstocks with a long life expectancy'. In the end, only 'degraded and abandoned cropland' apply for new biomass crop cultivation – these have been in production, but have since been deserted and not taken into use again. Earlier papers already pointed at this land category as being the sole lands where true climate benefits from biomass production for biofuels can be achieved (Field *et al.* 2008), because other ecosystems have great amounts of carbon in store that will be lost upon conversion (Fargione 2008, Tilman 2006, Lal). Also from a habitat conservation perspective, all but severely degraded lands are candidate for conversion into biomass plantations.

Three questions accompany the issue of biomass production on degraded and abandoned cropland. First, the idea has only recently been proposed and still dwells in a conceptual stage; the performance of such plantations are unknown. Tilman et al. (2006) for example proposed a 'low-input high-diversity grassland' scheme where a mixture of grass species would increase biodiversity and be high-yielding at the same time, but their findings and generalizations were not without controversy (e.g. Russelle *et al.* 2007). In addition, potential yields of biomass production on degraded land should not be overestimated (Field *et al.* 2008, Campbell *et al.* 2008).

Second, the estimation of the extent of such lands is complicated. The calculus by Field et al. delivers a figure of 386 Mha world wide – a little under the total agricultural area of the U.S. – that has been abandoned and has not had forest regrowth or used for settlements or food production. They assert that, given the expected rise in food demand, this land may become economically eligible for food production again, but do not take this further in their analysis. However, would current and future food demand indeed not provide an incentive to take these lands into cultivation again, the likeliness that they be attractive for biomass production without the support of rigorous carbon schemes may be very low. Woolf et al.'s (2010) assumption that 50% of degraded and abandoned cropland could be used for biochar production in their conservative Alpha scenario may be a high bet. Moreover, using these lands to grow biochar crops reduces their scope for producing bioenergy.

Lastly, the suggestion by Woolf et al. to use abandoned arable land for biochar production on such scales sparked fierce objection by a number of non-governmental organisations, claiming that these lands are often not truly 'abandoned', but may be in some sort of traditional or subsistence use not recognized by official administrative organs (Anon. 2010). Similar groups earlier opposed the use of such lands for cultivation of biofuel crops.

5.1.3. Thinly distributed feedstock

Woolf et al. (2010) did not include farm residues other than cereal and sugarcane residues in their analysis because of either (1) excessive risk of erosion, (2) unsuitably high moisture contents or (3) insignificance in volume. In practice however, the large variety of cultivated crops will include many anonymous cases where excess agricultural residues could find valuable use through pyrolysis. Smallholders anywhere, both in developed and developing countries, may generate small amounts of agricultural by-products that are not economical to concentrate for processing in large, high-tech pyrolysis machines (Frogner & Taylor 2010), but may be economical to process at a low-cost pyrolysis technology basis. This way, biochar production can provide an additional way of dealing with by-products and realizing soil fertility benefits.

5.2. Benefits of biochar systems

The previous sections in this chapter discussed three basic approaches to source feedstock for biochar and subsequently apply it. In general, biochar and pyrolysis offer valuable services such as soil improvement and energy co-production, or even serving as a fuel (biocoal) itself. Whether biochar will be widely adopted depends chiefly on the feasibility and economics of the actual concentration of the feedstock, and the relative value of one application of by-products versus the other. Here, the potential value of biochar will be discussed, dissected in three pillars: soil, energy and climate.

5.2.1. Soil

Biochar's potential soil benefits, that were summarized in Section 3.3, could be substantial. It is acknowledged that the extent to which these benefits materialize depends on the combination of biochar type, soil type and the crop of consideration. Some soil/crop combinations will benefit strongly lest the biochar that is used meets certain requirements and is applied in sufficient volumes. In this respect, there is currently a substantial knowledge gap to be overcome. The effect of pyrolysis conditions on biochar characteristics has been discussed in Section 3.1, but the influence of what feedstock is used is at least as great. Resultant biochars vary widely in stability of C, porosity, water retention, pH, salinity, nutrient richness, recalcitrance, macrostructure etcetera, and subsequently, in how well they perform on the site of application.

If biochar soil benefits prove to be substantial in developed countries, it is likely that commercial biochar production ("bespoke biochar") will dominate, since fine-tuning of biochars for different arable conditions is R&D-intensive. Added to that, agricultural legislation in developed countries is very strict. It may take a long way before biochar is approved as soil amendment, especially for biochar feedstocks that were formally considered to be 'waste' prior to their pyrolysis. The way the biochar product is amended to soil will also require due attention. In dry, fine-grained form, biochar may blow away upon application by 25% even in calm weather conditions (Laird *et al.* 2009, Cook & Sohi 2010) or erode when not properly tilled. Some biochars have been reported to spontaneously combust during storage or transportation (Laird *et al.* 2009). Biochar products could be designed to eliminate such risks by fitting a specific cultivation scheme. For instance, in breeding of perennial crops or horticulture, biochar cannot blow away or erode. In other cases, processing biochar as a slurry (e.g. mixed with manure) overcomes spontaneous ignition and similarly prevents particles to erode by wind. Probably such products could also be considerably more valuable than pure biochar.

Arguably, biochar could generate greatest benefits in the least developed parts of the world. Poverty, malnutrition, water shortages, extreme weather events, starvation and degraded soils are among the major problems that keep pestering still many countries and many millions of people. Any easily available technology that can lift some of the strain off of these people is one that should be pursued duly. However, modern technology is often more difficult to obtain, use and maintain when circumstances are cumbersome and capital is absent. In these settings, only 'low-tech' devices will survive: fine-tuned, high-tech options are unlikely to make it into developing countries. Affordable pyrolysers may not produce biochars that are highly tailored for specific soil/crop combinations, but may be a good buy for farmers that then can cheaply convert agricultural by-products into a biochar that will meet at least the primary soil improvement needs.

In situations where incomes are low and food production is insecure, the benefits brought by the adoption of such apparatus should be evident and achievable within a short time span. The benefits become evident when the required costs and investments (producing/obtaining a low-tech pyrolyser, collecting feedstock and distributing biochar) are clearly and rewardingly offset by agronomic measures (improved yields, better water retention, lower fertilizer requirement). In many cases, co-production of energy will be a decisive system component (see below).

5.2.2. Energy

Heat is often co-produced with biochar and can be used directly or (partially) converted to electricity. In the latter case, a pyrolysis facility may be connected to the grid, either centrally or decentralized. 'Combined heat and biochar' devices could provide heating for buildings such as schools or for industrial purposes. In principle, such devices could very well be low-tech, but obtaining ample locally grown biomass could instead be a bottleneck.

Biocoal production could be seen as a technological sequel to charcoal production. Both industrially and domestically, charcoal production is on the rise. Worldwide production in 2008 was 49.35 million tonnes (Table 5.1); in comparison, worldwide annual production of coal was 135x higher (6,597 million tonnes). A huge commercial leap may be made when biocoal co-firing is supported or obliged for energy companies.

Concerning traditional fuels, fresh fuelwood is used more than charcoal: 2008 worldwide production of 1,892 million m^3 corresponds to about 1,230 million tonnes (= 25x charcoal production). However, much wood mass is lost in the production of charcoal from fresh wood inefficient pits and kilns. Assuming an average conversion efficiency of 15-20%, the amount of wood converted to charcoal is 250-350 million tonnes, equal to at least 20% of harvested fuelwood. Interestingly, the growth rate of charcoal production has been four times that of fuelwood since 1961 (see Figure 5.2). More efficient carbonization and the possibility to combust/pyrolyse other biomass than wood makes a strong case for dissemination of modern pyrolysis techniques.

A particular case of interest involves biochar-producing cookstoves. Hundreds of millions of people still collect branches or manure to fuel traditional three-stone stoves. Besides being associated with deforestation in many parts of the world, the workload of fuel collection is often high, and primitive

indoor cooking is causing respiratory disease with an estimated 2 million casualties annually (Fullerton *et al.* 2008). The necessity to get people to use improved cookstoves is gaining widespread attention; recently, U.S. public and private organisations teamed up to raise $250m for this purpose (The Economist, Sep. 25 2010, p67). Modern cookstoves can be designed to pyrolyse the fuel rather than to fully combust it. In other words, while meals are being prepared without emitting harmful substances, biochar is produced that can be returned to the land. In Tamil Nadu, India, the application of stove-produced biochar to agricultural fields delivered clear production increases (D. Friese-Greene, pers. comm. 2010). Similarly, farmers in Senegal achieved 50% yield increase for onions and 180% for maize (website Pro-Natura, www.pro-natura.org, accessed Oct 15, 2010). Improved stoves also enable the use of a wider range of fuels, thereby possibly reducing the pressure on nearby stands of forest (e.g. D. Torres (pers. comm. 2010) reported a 30% reduction in wood use in Kenya). Interesting cases can be made in (peri)urban settings where relatively high-value products are traded and a great concentration of people may benefit from improved stoves (either by producing biochar, or combusting biocoal which forgoes the consumption of less sustainable charcoal).
Appendix I includes some examples of both low- and high-tech biochar stoves.

Table 5.1. Global production of fuelwood and charcoal in 2008.

2008, FAOSTAT	Fuelwood (million cubic metres)	Charcoal (million tonnes)
Africa	637.6	27.78
Latin America	285.9	12.44
Asia	753.7	7.59
Other	214.9	1.55
World total	1,892.0	49.35

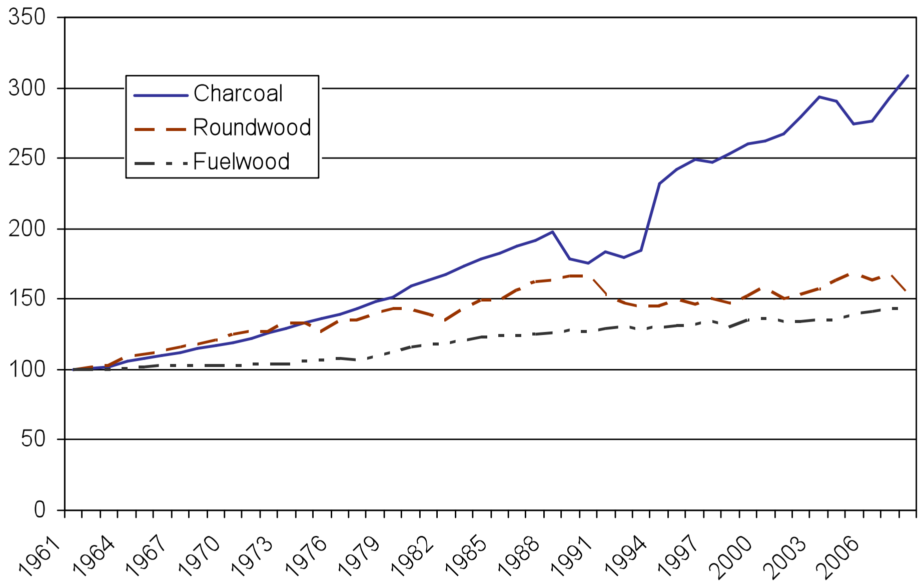

Figure 5.2. Index (1961 = 100) of global charcoal, roundwood (wood for material purposes) and fuelwood production 1961-2008. Source: FAOSTAT online database (accessed 2010).

5.2.3. Climate

Biochar would not have received such widespread attention if it did not hold the potential of offering a significant climate mitigation strategy (see Section 3.4). To generate the economic incentive for climate projects, a number of trading systems are in place or under development, together referred to as the “carbon marketplace”. They allow parties (most often private companies) to fulfil their compulsory or voluntary emission reduction targets by purchasing reductions achieved by another institution. In a mechanism such as the Clean Development Mechanism under the Kyoto Protocol, credits generated in projects in developing countries are traded, opening an otherwise unaffordable path to sustainable (clean) development. This way, developed countries gain access to lower-cost emission reductions, increasing cost efficiency of global GHG reductions (Whitman & Lehmann 2009).

With the cooperation of the International Biochar Initiative, Leading Carbon Ltd. is currently in pursuit of an ISO-type 'biochar characterisation standard' scheme to open up the carbon marketplace for biochar offset projects (www.biochar-international.org/characterisationstandard). This standard in its first draft will be restricted to the certification of stabilized biochar-C, and provide a framework for later addition of other biochar-induced reductions (to the extent that they can be proven).

Biochar could be part of a massive carbon sequestration effort to reduce atmospheric CO_2. Such an approach bears similarity to 'geoengineering' propositions. Recently, geoengineering was defined as "deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change" (Royal Society 2009). The two basic strategies are removal of C and reflection of sunlight. The sole aim is to shift the climate balance without intervening in a human system that causes climate pressure. Some propositions involving biochar sequestration do focus strongly on the burial side of the equation and are rather optimistic about the magnitude of the GHG reduction that could be achieved. Often, the soil improving properties of biochar are advanced as justification, but not further elaborated. A strong bias toward the climate mitigation function of biochar bears the risk of yielding a behemoth biochar movement that satisfy the climate obligations of the developed world, instead of solving soil degradation, productivity declines and unsustainable modes of agriculture, which are especially severe in the global south. There are concerns that when insufficient care is taken, the irreversibility of biochar applications becomes a significant risk. The current experimental phase is imperative, since *beyond* the small scale of experimentation, irreversible interventions in soils that go awry are impermissible.

In the case of thinly distributed feedstock and small-scale projects in developing countries, the scope for and necessity of carbon payments remain in question. Small-scale carbon projects incur significant transaction costs, especially if their aggregation turns out to be problematic. In a recent policy study, Whitman, Schulz and Lehmann (2010) stress the importance for biochars to be 'characterized', i.e. to express the quality of a biochar in several measurable parameters, to allow biochar projects to earn carbon credits. However, the requirement to have biochars characterized is at odds with the practical reality that biochar systems in the global south will be artisanal and extremely fragmented, which makes certification difficult. Also, the reliance of techniques that improve livelihoods on (sustained) international funding, be it through conventional development aid or clean development mechanisms, brings the risk of project failure on the longer term. Preferably, pyrolysis systems and biochar application should be worthwhile for farmers in its own right, otherwise outcomes may be skewed. Smith and Scherr (2003) showed that trade-offs exist between social benefits of carbon forestry projects and their cost-effectiveness: socially beneficial projects incur higher transaction costs and require dependable enabling policies. Also the 'innovativeness-needs' paradox general to innovation-driven development applies to biochar projects: those who are most in needs of the benefits brought by an innovation are the least likely to adopt, simply because they are least endowed and lack adoption capability (Tschakert *et al.* 2007, De Pinto *et al.* 2010). Hence, after the first hurdles have been taken (for which climate funding could be of great assistance), biochar systems that work endogenously instead of externally driven are preferable.

6. Conclusion and outlook

System level approach to agricultural sustainability
Biomass in general is gaining economic value since demand for food is rising and technological developments enable its use for energy and material production (Section 2.1). At the same time, the ecological value of carbon is increasingly recognized, as land degradation proliferates. Not all primary production can be employed for the direct benefit of man; some must be judiciously managed to maintain fertility of the agroecosystem (Section 2.2). The availability of chemical inputs provided, besides agronomic stimulus, a partial solution to the decline in organic quality of agroecosystems. A more integrated approach to agriculture is necessary to preserve productivity in economic and ecological terms for the future. Interestingly, biochar is implied to have both economic value as be instrumental to the questions of nutrient cycling and soil quality.

Linking climate and agroecosystems
Climate change is one of the major topics of this century and can, through biochar, unlock attention and means to address soil fertility problems. Biochar could be seen as a type of climate geoengineering that does not exclusively involve the rather unsophisticated act of removing carbon or reflecting sunlight, but generates ancillary benefits. The scope for biochar's systemic approach extends beyond the agroecosystem to include the management of carbon for climate mitigation.

Soil benefits likely but variable
Enough proof has been gathered to conclude that significant soil fertility benefits can be expected from biochar application in different agricultural systems. Soil rehabilitation may also be greatly facilitated. In other words, pursuit of dedicated biochar applications is a worthwhile investment. Biochar does not *generically* improve soils and deliver its 'win–win' capacity: each case will need new analysis whether profits are achieved and if returns are economical. Some soils will profit substantially, others marginally; some other side-effects may even be ill. In many cases, limited scale and means constrain the potential to research, tailor and monitor the characteristics and performance of biochar. Biochar quality was deemed "very important" by Laird et al. (2009): its performance depends on the ability to address the specific needs of a particular system by the development of a particular biochar product. Results may be disappointing when too much is expected from the treatment, especially because the required application rates may turn out to be high. Biochar is no magic substance that solves all soil-related problems, but rather one that may take the best out of all other substances (nutrients, water, soil biota, etc.) present – lest these are present indeed, for which other soil conservation practices need to be in place.

Widespread use may be constrained by availability of biomass
A major uncertainty is found in biomass availability. In Section 5.1, the validity of estimates in biochar potential studies was questioned; in the foreseeable future, the cumulative magnitude of realized biochar projects will likely be at least one order of magnitude smaller. Also system complexity infringes upon predictability; many agree that no single biomass feedstock or product will suffice because of the disparate economic, environmental, soil-related, climatic, technological, and logistical factors involved. It should be borne in mind that the biomass value chain is strongly evolving presently, and the development of biochar is subordinate to this process.

Biochar systems in the developing world
Biochar produced in low-tech pyrolysis machines by small communities was shown to contribute to yield improvements and energy provision (Section 5.2). Smallholders managing a mixed cropping system may improve its nutrient and organic matter cycles through pyrolysis and biochar application. Meanwhile, the urgency for improved cookstoves is high, and those that produce biochar while cooking may be very useful. In other cases, pyrolysis may increase the value and usefulness of previously wasted agricultural and silvicultural by-products such as wood waste if other techniques do

not suffice or are too expensive. When larger value chains are involved, biochar can contribute to the pursuit of a sustainability agenda, recycling nutrients and organic matter to production sites. Biochar projects in developing countries are likely to be very different from those in the global north. In the latter, R&D opportunities are abundant, fine-tuned biochars can be developed and sold, and through their characterization allow GHG reductions to be quantified and traded. Realities in developing countries are different; with less available capital and infrastructure, biochar systems will become more artisanal and less accountable. Poor smallholders, so to speak, will not have them be done Life Cycle Analyses or carbon accounting studies. A climate focus on biochar for developing countries is therefore problematic, while diverting attention from food and soil challenges. Seeing that the biochar community predominantly consists of developed world organisations of which a considerable part is focused on engaging in projects in the south, involvement and consultation of target communities is more than essential. Project intentions need to be in synchrony with this requirement: development should be placed before carbon reductions, as already pronounced by Whitman *et al.* (2010).

Dealing with uncertainty

In this paper, biochar has been identified as a promising technology, but particularly rich in uncertainties. Concerns that large-scale biochar application may involve unforeseen and irreversible negative side-effects, ought to be taken seriously. Even if the risk of such side-effects occurring is found to be small, once public debate goes awry, the image of biochar may be tarnished permanently. On the other hand, too much restraint will not benefit anything or anyone. Land degradation, climate change and sustainable agricultural development are modern issues that are interlinked, urgent, of high stake, and rife with uncertainty (Funtowicz *et al.* 1998); an approach in which science leads and practice follows is unaffordable. How and how much biochar can assist in achieving sustainability goals should be discovered by doing science and practice in parallel.

Finding the correct role for biochar

The exact way in which the biochar movement develops deserves meticulous attention. First, I identified a potential divide between low- and high-grade biochars and biochar systems. While implementation in the developing world, where regulation is scanty, may be easiest, it is also most risk-prone. Second, the outcomes of biochar projects will be the result of their design and intent, and a trade-off between soil and social performance on the one hand, and climate and cost-effectiveness on the other, may occur. Finally, biochar will need to find its role in the context of other developments in nutrient recycling (e.g. phosphorus recovery), soil fertility (e.g. integrated soil fertility management, ISFM) and broader rural development.

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Appendix I: Biochar production machines

Examples of biochar-producing apparatus.
TOP: BioChar Engineering's B-1000
(http://www.biocharengineering.com)
ABOVE: WorldStove's Fan Free LuciaStove
(http://www.worldstove.com). ABOVE RIGHT:
Anila stove; RIGHT: 'TLUD' biochar stove
(http://biocharinnovation.wordpress.com/category/gasification-stove-designs/)

Appendix II: Terra Preta photos

UPPER : ground cores of a Terra Preta soil.
LOWER LEFT: Terra Preta soil profile.
LOWER RIGHT: large charcoal particles from a Terra Preta soil.

Photos by the author.