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BIOCHAR - A SURVEY

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Abstract

The scientific study of biochar (charcoal) as soil amendment has increased in recent years, partly because of its potential as carbon sink. The aim of this review is to present biochar in its whole diversity, illuminating past, present, and possible future impacts on human life and its environment. The review starts with a look back into history and continues with a detailed overview about production methods, resulting properties and the versatile use of biochar. The following chapter puts the gained insights into a global perspective and calculates implications on carbon and nutrient cycles, as well as on mankind's energy needs. The final chapter focuses on the current research about biochar and provides further references on this topic.

This work provides hopefully the big picture, which could prove valuable in every specialized research on biochar. It shall also help to trigger some new thoughts and eventually initiate new projects.

Preface

I was already interested in biochar for more than two years and I thank the Department of Energy and Process Engineering to grant me a complete freedom of choice concerning the topic and the content of this paper.

I am also very grateful for the scientific infrastructure of my guest university, which gave me access to nearly every paper, which was ever written about my topic.

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Abbreviations

B	boron
C	carbon
Ca	calcium
CEC	cation exchange capacity
Cl	chloride
Cu	copper
Fe	iron
GHG	greenhouse gas
K	potassium
Mg	magnesium
Mn	manganese
Mo	molybdenum
N	nitrogen
OC	organic carbon
P	phosphorus
S	sulfur
SOC	soil organic carbon
SOM	soil organic matter
Zn	zinc

1 Introduction

The motivation for this work came from the wish to get a precise overview about biochar, including the latest in research. Although there are many papers published, especially since its acknowledgment as possible factor in climate policies, these are often only from one point of view. This is understandable since it is an interdisciplinary topic, involving chemistry, thermodynamics, agriculture and some more. Specialized work has to be done and will always be necessary. But in this review it is aimed to shed light on the connections between different aspects and focus as often as possible on the big picture.

In this survey biochar is used as generic term for any biomass derived char, although it is often solely associated with the use as soil amendment. Depending on specific viewpoints and themes in literature, many different terms are used for biochar, these include charcoal, biocoal, agrichar and black carbon.

2 A short history

Biochar was used by humans since mankind learned to control fire. In this chapter some applications and scientific advancements throughout history are presented. In addition, some developments are looked at, which are not directly connected to biochar at that time, but which strongly influence today's research on it.

2.1 From prehistory to the 19th century

The probably oldest testament of the use of biochar by men are drawings in the Grotte Chauvet, which are older than 38,000 years (Antal, Gronli 2003). Such cave drawings were likely made with charred sticks taken from a fire and not with completely charred wood (Harris 1999). However, it can be concluded that the first application of biochar was as an artistic medium, which allowed to deliver some of our ancestors' culture to posterity.

The beginnings of biochar production on a larger scale took place together with the invention of metallurgy, approximately 3000 BC. Plain wood, with its high content of water and volatiles, can hardly generate sufficient high temperatures to smelt metals. Biochar on the other side allows temperatures well over 1000°C and produces little smoke, ideal conditions for smelting and working. Oxide ores of copper were the first to be reduced by biochar, initiating the era of the Bronze Age. Iron is more difficult to smelt, demanding higher temperatures and a greater blast of air. This was first achieved in around 1200 BC, which marks the beginning of the Iron Age. The earliest production of biochar took place in pit kilns, by the slow burning of wood in a shallow pit, covered with soil. Later also above ground forest kilns came in use, where wood was piled up in a hemispherical way and then covered with soil or turf. This, in Europe well known method, was common until the mid twentieth century. (Harris 1999) A deeper look at various pit and kiln designs will be given in Chapter 3.2.

Biochar is an important constituent of gunpowder, which has its origins in the ninth century China, when alchemist invented it by chance while searching for the secrets of life. Gunpowder should influence history on a large magnitude, beginning with the military revolution through gunpowder weapons during the fifteenth-sixteenth century, and not ending with its introduction as blasting powder in mining, in the early seventeenth century. (Buchanan 2006)

During the Renaissance many artists used biochar for making preparatory drawings. But only since the end of the 15th century it is known to make such drawings long-

lasting by immersing them in baths of gum. Without such a treatment the marks on the paper are rather impermanent. While for many artists biochar drawings were pure preparatory work, some like Albrecht Dürer, began to consider them as finished art (Figure 1 left). This trend has not stopped with 20th century artists like Matisse and Picasso (Figure 1 middle and right). Even today biochar is regarded as an important artist's material. Although its structure does not allow an easy gliding over paper, or fine lines, it has the advantage to give a perfect blackness. In contrast a graphite pencil, which comprises another form of carbon, that will produce a more grayish and metallic look. (Harris 1999)

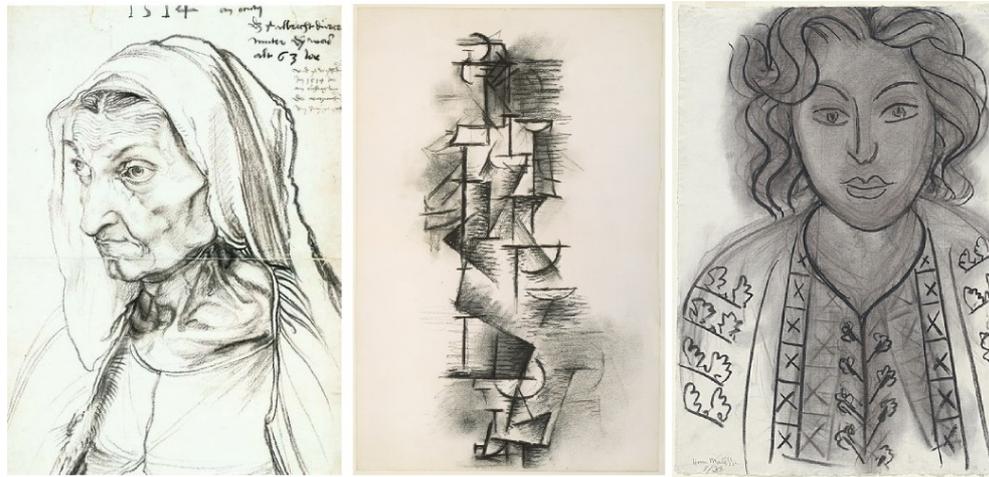


Figure 1: Biochar drawings by Dürer, Picasso and Matisse (Wikipedia Commons)

Albeit its importance to some painters, the quantities used in art were negligible compared to the demand from metallurgy. All iron production till around 1700 based on biochar. Therefore the increasing metal production led to a higher deforestation, which became a significant problem throughout Europe. Coal was available but unsuitable, because its impurities, especially sulfur, would transfer to the metal. In 1709 the English iron worker Abraham Darby produced coke out of bituminous coal, which from then on replaced biochar to a great extent. (Harris 1999) However, till today biochar is the most valued reductant of the metallurgical industry. Besides that, it has always been a favorite fuel for cooking too. (Antal, Gronli 2003).

The adsorptive properties of biochar were already used by the old Egyptians at around 1500 BC. They applied it to putrefying wounds to adsorb malodorous vapors. In Europe, in the late 18th century the Swedish scientist Carl W. Scheele was the first who made a scientific study about the adsorptive qualities of biochar. Because of the low interest in adsorptive materials, except for few specialized areas like sugar refining, his work was hardly continued during the 19th century. It should take till after the introduction of poison gas to military warfare that Scheele's work was pursued. (Harris 1999)

An early mention of a biochar influenced soil took place in the mid 1870s. At that time, Cornell professor Charles F. Hartt and his student Herbert H. Smith brought Amazonian Dark Earths to the attention of the scientific community (Lehmann et al.). These patches of unusual fertile soil, also called Terra Preta de Indio, should have far reaching influences for today's research. Their origin lies in the Precolumbian times of the Amazon, which are illuminated in the following chapter.

2.2 Precolumbian Amazon

In this chapter, some biochar related information about the Amazon region, before and after European contact, are presented. In contrast to the former and the following chapter, this will not be in chronological order, but rather in comparison between those days in general and today. Firstly, this will provide a better understanding of the importance of Terra Preta. Secondly, it is owed to the fact that only few biochar related information can be connected directly with historical events from that period.

When Francisco de Orellana led the first expedition along the Amazon in 1541, Friar Gaspar de Carvajal accompanied him. His job was to impress the king of Spain with his writing about their voyage. He described extensive settlements along the river, like in Figure 2, and encounters with thousands of warriors. His many fanciful descriptions however undermined his credibility. There is also the fact that no European after them witnessed the described civilization. When Charles Marie de la Condamine traveled the Amazon in 1743, he characterized the Indians as isolated bands of people, who struggled for existence in the most basic circumstances. Many subsequent visitors had the same impression. Therefore, generations of historians had dismissed Carvajal's records as pure fantasies. (Bush 2007)



Figure 2: Artwork visualizing the lost civilization of the Amazon (BBC 2002)

Nowadays, the Pre-Columbian populations of the Amazon are estimated between one and eleven million. Recent papers support often the higher figures. It is known that between 1520 and 1600 the population collapsed by roughly 95%, caused by epidemic

diseases, originating from the first Europeans. While the Spanish described scenes of bodies piled up in abandoned Andean villages, it is not known what exactly happened in the Amazon lowlands. However, Indians in the lowlands had the same susceptibility to European diseases. Since they had trade contacts with Andean communities, and because of dense populations along major rivers, it is very likely that they were similarly devastated. (Bush 2007) It can be concluded that Carvajal's writing was more than just fantasy and that he probably experienced a great civilization shortly before its fall. But how is it possible that the Amazon region could sustain more people in those days than it can today?

Some settlements were occupied for thousands of years and although fish was undoubtedly an important part of the daily food, so was manioc and maize too. It is known that on most Amazonian soils the yields from intensive agriculture decrease drastically within two till three years, because the soil will lose essential nutrients. A fallow period of 20 - 30 years is needed before it can support crops of maize again. (Bush 2007) This necessity led to the development of the contemporary slash-and-burn agriculture. After the soil has lost its capacity to support corn-growing, the farmer moves on to the next patch of land, cuts trees and removes shrubs. The ash from the burning of the residues provides some fertilization. This method is firstly not very productive and secondly it was not available to the Pre-Columbian population. According to William Denevan, the lack of steel axes necessitated to stay much longer on a patch of land than today. Charles R. Clement added that the precontact Indians therefore probably practiced a kind of agroforestry. (Mann 2002) Agroforestry, the production of crops between trees, offers some advantages. The soil stays in place, the crops are sheltered from intensive sun, rain and wind, and microfauna and microflora are stimulated. But even if the increased competition for sunlight and nutrients would be neglected, agroforestry alone could not have been the basis of life for millions of people in the Amazon area. Not without reason the Amazon is called by some scientists a wet desert.

The answer to a sustainable high corn production lies beneath men's feet. Archaeological excavations revealed on several sites an unusual soil, dark in color, owing to its biochar content, and also comprising potsherds, pieces of bone and organic residues. It was therefore concluded that this soil was strongly influenced by man. The usual soils of the Amazon are yellow or red (Figure 3 right), and are highly weathered and poor in nutrients. In stark contrast to them, the black soils, called Terra Preta (Figure 3 left) by the indigenous population, provide enormous crop yields and therefore are also utilized by local farmers.



Figure 3: Typical profiles of Terra Preta (left) and Oxisol (right)
(Glaser et al. 2001)

Terra Preta soils usually occur in areas averaging 20 ha, but there were also sites reported up to 350 ha. Radiocarbon ages of 740 - 2,460 years BP of biochar in 30 - 40 cm soil depth proved the Precolumbian origin. Also chernozems and other black earth like soils were reported to be enriched by biochar. Terra Preta soils contain higher concentrations of nitrogen, phosphorus, potassium and calcium than adjacent natural Oxisol-soils. The increased nutrient holding capacity is partly owed to carboxylic groups on the surface of biochar, which originate from superficial oxidation. In addition to the nutrient holding capacity, Terra Preta shows also a higher pH value and retains more water (Kim et al. 2007). All this contributes to the above mentioned high productivity. The polycyclic aromatic structure of biochar hinders biological decomposition and chemical oxidation, which explains its persistence over centuries in the environment. (Glaser et al. 2001)

Terra Preta explains how the usually unfertile Amazon could sustain dense populations on rather small patches of land. The question remains, how much land is covered with it? Answering this question would give some indication on the size of the Precolumbian society, and even more importantly, on today's potential for a sustainable agriculture in this region.

In the Amazon there are a lot of Terra Preta sites, as can be seen in Figure 4, but according to (Bush 2007), it is not advisable to extrapolate these phenomena across scales. Terra Preta sites mean a local intensive land use. The widespread sites throughout the Amazon indicate a large net of communities but do not prove an intensive human impact on large areas. Therefore, the likelihood that the Amazon region in Precolumbian times was strongly influenced by intensive agriculture is rather low. (Bush 2007) However, recent archaeological excavations in the upland and headwaters region revealed a net of towns and villages, which covers an area the size of Belgium. The structures indicate a sophisticated system of regional planning. This

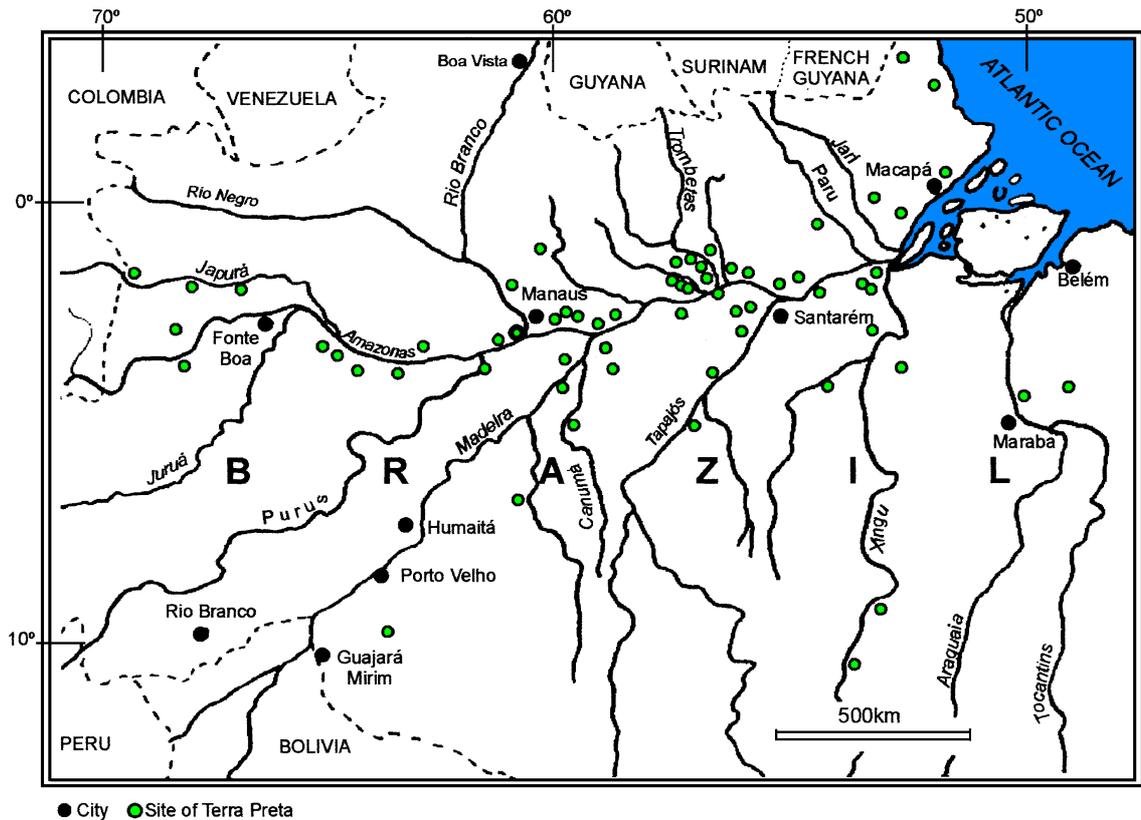


Figure 4: The distribution of known Terra Preta sites (Lima et al. 2002)

system based on decentralized communities, was connected by well planned road networks, and embedded in a matrix of agricultural land. The nearest comparison to modern days would be Ebenezer Howards garden cities, which he proposed in the early 20th century. (Mann 2008) So it can be concluded that in contrast to modern days the population was not concentrated in few big cities, but allocated in a great many decentralized towns. This gives a hint, which settlement patterns might be more sustainable, but it answers not the question how much area is covered by Terra Preta, even if some archaeologists did estimate it could be up to 10% of the Amazon. Till there are no comprehensive informations about the spatial distribution of Amazonian soils, the area cannot be precisely quantified. The composition of Terra Preta, especially the quantity of biochar in it, can be given with more certainty.

Biochar amounts measured at a Terra Preta site were 25 ± 10 tons per hectare (Mg ha^{-1}) in a soil depth of 0 - 30 cm and 25 ± 9 Mg ha^{-1} in 30 - 100 cm. These findings were corroborated by a former site where biochar was found in the upper 50 cm of soil, measurements showed the same order of magnitude as above mentioned. The high concentrations of biochar in the soil are unlikely a product of slash-and-burn and, therefore, support the theory that slash-and-burn is only a modern development. After a calculation by Phillip M. Fearnside in 1992, it would take 25 times of burning a primary forest to yield a biochar amount of 50 Mg ha^{-1} . (Glaser et al. 2001) It is highly likely that the biochar in Terra Preta originates from low-heat smoldering fires, which

indigenous population used for cooking and heating (Glaser et al. 2001). In Chapter 6.1 an imitation of Precolumbian practices is mentioned, which would mean a change from the current devastating slash-and-burn agriculture to a more sustainable approach.

2.3 The twentieth century

In the context of biochar, the twentieth century begins with some facts concerning agriculture. In Japan during the 1910s several books were published about the use of carbonized rice husks (i.e. biochar), called Kuntan. In and outside of Japan, they were applied to rice nurseries, were used as culture medium for ornamental plants, and were a component of growth media for hydroponics. Furthermore, Kuntan was used for water purification, and as an absorptive material for moisture and gas. Research about Kuntan and its benefits for rice based agriculture is continued today. (Haefele et al. 2008)

The twentieth century was also the century of two devastating world wars. The shift of great deals of economic and scientific power to conquest and defense triggered at least also one advancement, which involved biochar. The introduction of poison gas to the battlefields of World War I in 1915, led to the fast development of gas masks, in which activated biochar was used as adsorbent. Although the first models used biochar from wood, later research showed that coconut shells were the ideal feedstock. This is because of their more macroporous structure, which produces a biochar that allows an increased air flow rate. (Harris 1999)

In the mid-century the structure of biochar was hardly understood. It was known that, like graphite, this form of carbon contained hexagonal carbon rings, but how they were linked together remained unknown. Rosalind Franklin, known for her work about the structure of DNA, published a paper about her studies on the structure of chars in 1951. She proposed a model where 65% of the carbon is contained in individual graphite layers, highly perfect in structure, whereas the rest is disordered. Although this model does not represent a complete description of the nature of biochars, it was for many years the best model available. In her paper, she also presents the key distinction between char and coke. While coal derived coke can be transformed to crystalline graphite under very high temperatures, biomass derived chars cannot be turned to this most thermodynamically stable form of solid carbon. (Harris 1999)

Not only since the last decades of the century scientists have wondered if it is a good idea to blow such enormous amounts of carbon (C) into the atmosphere. Already in 1939 Guy S. Callendar published a paper in which he stated that man throws some 9,000 Mg (metric tons) of carbon dioxide (CO₂) into the air every minute. This equals around 2,500 Mg C min⁻¹. He connected the measured increase in atmospheric carbon dioxide, originating from increased coal burning, with the significant upward trend in temperatures since 1900. (Janzen 2004) But in the early 20th century it was also known that the oceans contain 50 times more dissolved CO₂ than the atmosphere. Therefore, it

was concluded that the oceans would prevent a serious impact of industrial activity to the CO₂ level of the atmosphere. This view prevailed until 1961, when more precise measurements by Charles D. Keeling revealed an increase of free atmospheric CO₂ by 0.8 parts per million per year (ppm yr⁻¹), at that time. (Archer, Brovkin 2008) In 2005, mankind emitted roughly 54,000 Mg CO₂ min⁻¹, which equals around 15,000 Mg C min⁻¹ (US Energy Information Administration 2007) and the atmospheric CO₂ level reached 377 ppm, from a preindustrial level at around 280 ppm (U.S. Department of Commerce 2008). Chapter 5.1 presents a deeper look at the global carbon cycle, and how it can be influenced by biochar.

In the late 19th century, Charles F. Hartt introduced Terra Preta to the scientific community. Around 90 years later in 1966, a dedicated soil scientist, Wim Sombroek published the book “Amazon Soils - A reconnaissance of the soils of the Brazilian Amazon region”. With it began the scientific study of Terra Preta (Marris 2006), which involved not only soil sciences but also archeology. Sombroek's vision was it to create a Terra Preta Nova, a new black and fertile soil, which would allow sustainable land use on soils that would not support continuous cultivation without large quantities of fertilizer (Lehmann et al.).

At least since Keeling's measurements of rising atmospheric CO₂ levels, more scientists thought about how to stop this trend, and therefore mitigating a possible climate change. In 1977, the quantum physicist Freeman J. Dyson made the first proposal to increase the amount of carbon, stored in vegetation and soil (Janzen 2004). Ever since, this concept has been discussed and cultivated alongside the other two ways to slow down the increase in atmospheric CO₂, which is firstly, the reduction of CO₂ release from energy use, and secondly, the replacement of fossil fuels with biofuels. In Chapter 5.1 some comparative informations about these approaches are given. Nowadays, the idea of terrestrial carbon sinks is also proposed in the Kyoto Protocol as a strategy to offset greenhouse gas emissions (Lehmann, Gaunt & Rondon 2006).

In 1992, Sombroek published his first paper on the potential of Terra Preta as a terrestrial carbon sink (Marris 2006). This was probably the foundation which led to the enormous increase in biochar research at the beginning of the 21st century, driven mainly by the potential dangers of climate change, and to a lesser degree, but not less important, by increasing soil degradation and dwindling fossil fuels. The work of the 2003 deceased Sombroek is carried on by a dedicated group of scientists around the world. In Chapter 6 some examples of current research are presented, and references for further reading are given.

3 Production and properties

Properties of biochar depend on the feedstock, and on the production method. The former is mainly subject to the availability of a suitable biomass. It is to say that most biomass is usable for biochar production, even if, or especially when it is not suitable for other conversion processes, like alcoholic fermentation, or anaerobic digestion to biogas. The production methods are based on pyrolysis, a thermal degrading process in the absence of oxygen and at temperatures around 350 – 500°C. The process has endothermic and exothermic phases. The quantity and quality of pyrolysis products, i.e. biochar, tars, oils, and non-condensable vapors depends mainly on the maximum temperature, and the heating rate, but also on pressure and gas flow.

Biochar can be defined by various properties, these include moisture content, calorific value, elemental composition (e.g. fixed carbon), hardness (abrasion resistance), compressive strength, bulk and true densities, surface area, porosity and pore volume distribution, electrical resistivity, and reactivity. There are extensive tables with properties of biomass derived chars. (Antal, Gronli 2003)

The worldwide annual amount of biochar produced is, according to Antal and Gronli (2003), not easy to estimate. They found a wide variation in literature, ranging from a few Tg (million metric tons) to around 100 Tg. The United Nations Statistic Division estimated a worldwide production of 49,7 Tg, for 2006 (UNSD 2008b). The Food and Agriculture Organization (FAO) on the other side, estimated only 43.5 Tg. According to the FAO, Africa produced the largest amounts with 23.7 Tg, followed by South America with 12.0 Tg and Asia with 6.4 Tg (FAOSTAT). Less industrialized countries cannot afford to buy fossil fuels, or have no means to utilize them. Their populations depend mainly on biomass for heating and cooking. This is one reason that their biochar production and consumption is very high, compared to industrialized countries.

3.1 Effects of pyrolysis on biochar properties

As mentioned above, different parameters of the pyrolysis process affect quantity and quality of its products. While the focus lies on biochar, the effects on co-products have to be mentioned too, because they may be of importance for energetic and socio-economic evaluations of biochar production systems.

The peak temperature controls a wide range of properties of biochar, like volatile matter content, pore structure, surface area and adsorption capabilities (Antal, Gronli

2003). In Figure 5, it is shown at which temperature zones different pyrolysis processes occur, and whether they are endo- or exothermic. These zones are not fixed, but can shift a little depending on different parameters, like pressure and heating rate (Lehmann, Joseph 2009). Unfortunately, according to Antal and Gronli (2003), there are no reported kinetic models in literature that embody the complex effects of pressure, vapor-phase residence time, and thermal pretreatments.

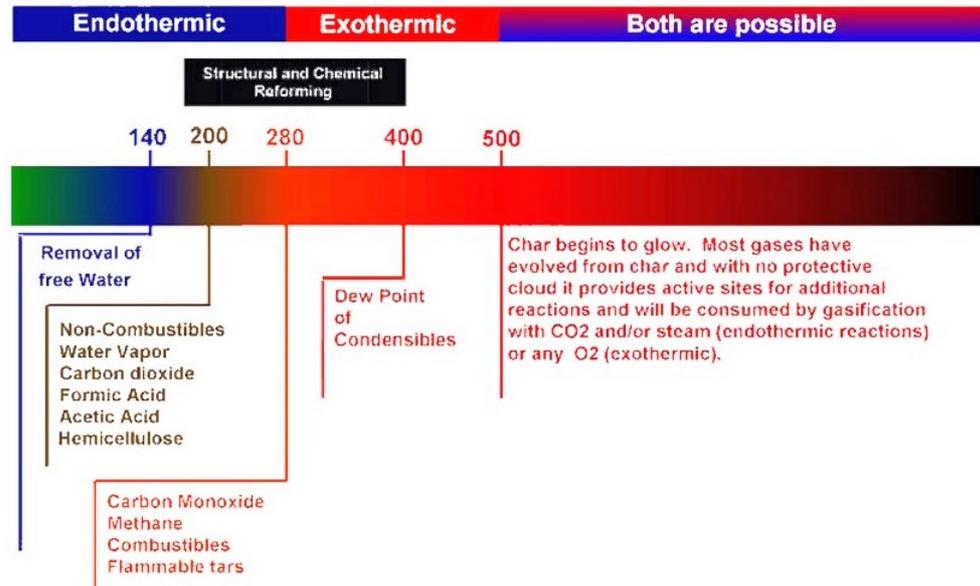


Figure 5: Temperature zones of pyrolysis (Day 2005)

Pyrolysis of biomass is a process of primary and secondary pyrolytic reactions. Primary reactions proceed in solid-phase, while secondary reactions proceed in a liquid phase. In the latter, organic vapors (tar-like) decompose onto the carbonaceous solid to secondary charcoal, which is as reactive as primary charcoal. Low gas flow provides more time for organic vapors to react with the carbonaceous solid and thus increases charcoal yields, while reducing oil and gas yields. Elevated pressures also promote secondary reactions, under higher pressure the tarry vapors have a smaller volume and can remain longer between the solid particles, and thus, have a longer time to decompose to secondary charcoal. Additionally the higher partial pressure of the tarry vapors is increasing their reaction rate. (Antal, Gronli 2003)

Through pyrolysis most chemical bonds of the biomass are broken. Since the primary phase involves no liquefaction, these broken bonds remain in a dangling state. These dangling bonds are responsible for the chemisorption properties of biochar. Through the chemical absorption of oxygen, which leads to oxides and peroxides at the surface, the charcoal becomes hydrophilic. In addition, a higher oxygen content increases the electrical resistivity of carbon. (Antal, Gronli 2003)

The amount and volume of pores in biochar is increased through volatilization, which is supported by high temperature, heating rate, and gas flow, as well as by low pressure. The decrease of pore volume and amount occurs through closing of pores,

through sintering and melting, which is supported by very high temperatures, high pressure, and low gas flow. (Lehmann, Joseph 2009)

A high content of inorganic materials in the biomass feedstock can block micropores in the biochar. De-ashing of the biomass can reduce this effect, and therefore increase the surface area. Steam pyrolysis removes highly reactive carbon, and thus, allows a larger pore volume. (Antal, Gronli 2003)

The biochar yield can be raised with an elevated moisture content, under conditions with higher pressure and negligible flow of gas. The detailed underlying chemistry of such higher yields is however not yet understood. Research in this area could lead to the development of more efficient biochar reactors. While the density of the feedstock is proportional to the biochar's density, resins can increase the density when they are coked during pyrolysis. Additionally, the biochar yield from coniferous woods can be sometimes considerably higher than from deciduous woods. Also, biomass with higher lignin content allows a higher biochar yield, because lignin preferentially forms char through pyrolysis. (Antal, Gronli 2003)

After pyrolysis, biochar has to cool down before it can come in contact with oxygen, or it would ignite and burn off. But even at ambient temperatures, biochar stays a highly reactive substance, which can show pyrophoric behavior, especially when biochar fines are tightly packed and when the content of volatiles is high. The fact that even wet biochar can autoignite, is not yet understood. Such an autoignition is not very common, but especially during the transport and storage of large amounts of biochar, precautions like as less dense packing, should be considered. (Antal, Gronli 2003)

3.2 Production methods

There are some fundamental differences between biochar production methods. The first one is the heat source for pyrolysis. It is possible to put the biomass in a closed vessel and provide the necessary energy from burning some extra biomass to heat the vessel and its content. Such a vessel should prevent the inflow of oxygen and would have to be heat conductive for the outside burning, or the hot fluegases had to be channeled into the vessel.

But to build such an apparatus would be quite an effort, and it would be difficult to move. Transportation was difficult in earlier times, and biochar was made at places where suitable raw material was abundant. Therefore, an easier way to provide the necessary heat was used. Biomass was put together tightly and coated with an airtight layer of earth. Then a small part of the biomass was burned up. To keep a productive balance between burning and pyrolysis, the air-flow was controlled through little openings in the earth layer. Where the soil was deep and dry enough, pits were dug, like in Figure 6. On stony soils or when groundwater levels were too high, kilns like in Figure 7 were constructed.

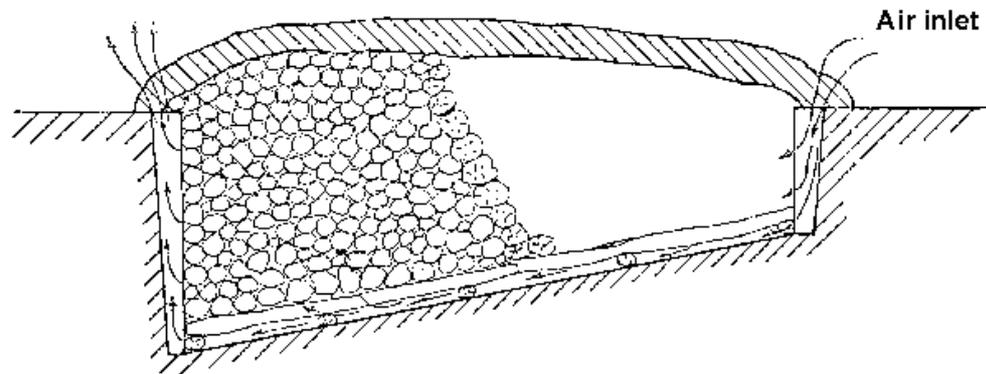


Figure 6: 30 m³ earth pit - longitudinal section (FAO Forestry Department 1987)

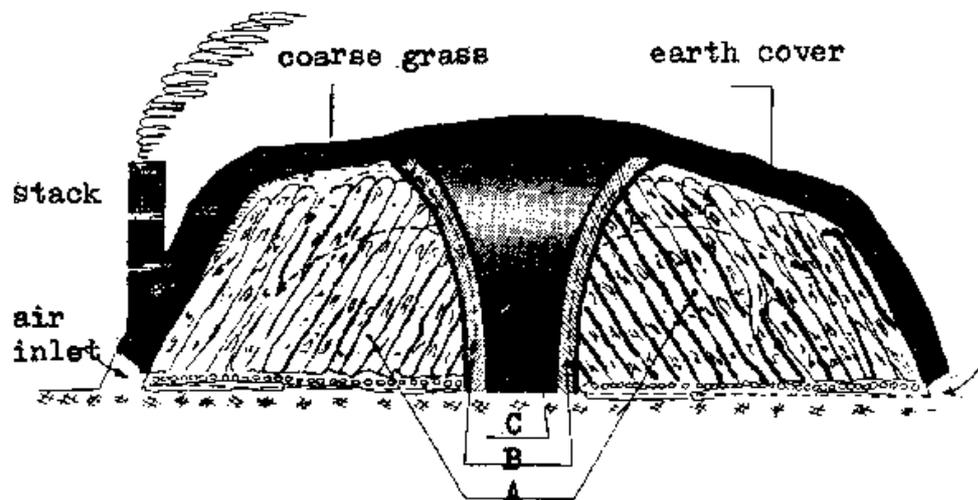


Figure 7: Swedish earth kiln with chimney (FAO Forestry Department 1987)

On more permanent production sites, also brick kilns were developed. These kilns were better insulated, and allowed a better airflow control, which allowed higher biochar yields.

In the 1930's, transportable, cylindrical metal kilns were developed in Europe and became popular in the 1960's, in developing countries. They are often made out of oil drums, and are more easily to handle than traditional pits. The sealed container allows a high control of airflow, and the biochar can easier be recovered. (FAO Forestry Department 1987)

Another fundamental differences between production methods lies in the recovery of co-products. While often this is not considered in the production process, the point of view can sometimes turn around completely. After the oil crisis of 1971, efforts where shifted to enhance bio-oil and syngas production, and to reduce charcoal yields to a pure byproduct (Antal, Gronli 2003).

The easiest way to use co-products is to burn them and use the generated heat to drive the pyrolysis process. For this way, a forced airflow is mostly necessary,

especially with bigger production facilities. This is not the case with special biochar generating cooking stoves, developed by Professor U.N. Ravikumar, from Mysore University in India. The “Anila-stove” combines the principle of providing heat from extra biomass burning, with the utilization of the pyrolysis gases for heat recovery. As shown in Figure 8, the pyrolysis gases are burnt in the combustion tube in the middle of the stove, simultaneously providing heat, not only for cooking, but also for the ongoing pyrolysis.

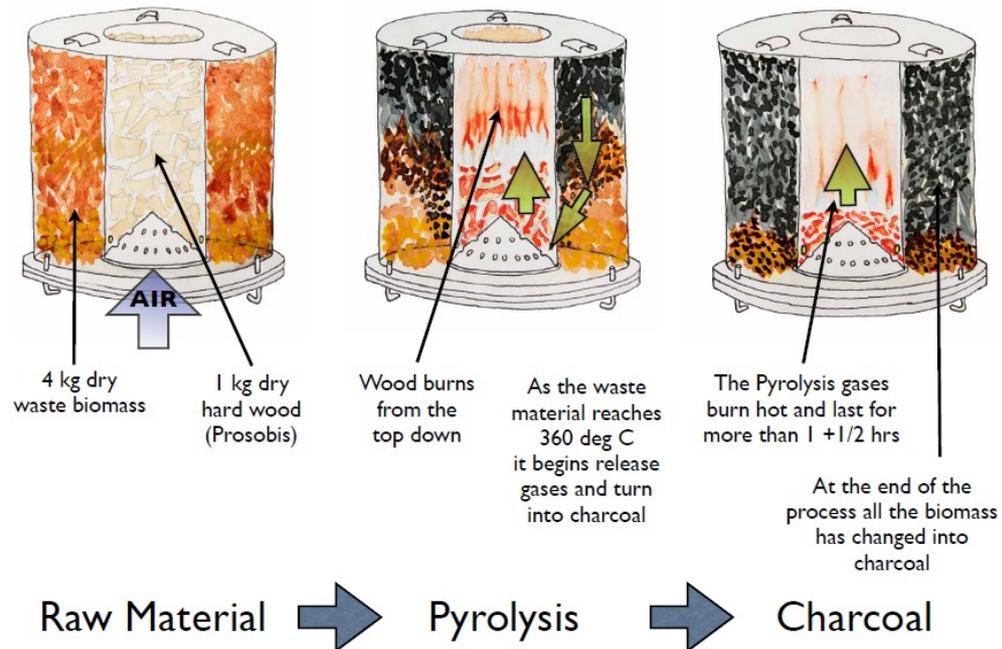


Figure 8: Anila stove combustion cycle (Freese-Green 2008)

Aside from inventions for household uses, like the “Anila-stove”, research efforts are also directed to increasing efficiency in traditional biochar production. Lin (2006) combined a Brazilian beehive kiln (0.3 m³) with a modified updraft fixed bed gasifier, with embedded combustor. In this case, hot flue gas from the gasifier is blown into the beehive kiln, and provides there the heat for pyrolysis without any burning of the biomass. The fluegas is low in oxygen (0.2 vol-%), and high in temperature (up to 1320°C), which allowed biochar yields of 35% in only 4 h, compared to 15-25% in 160 h, with the conventional approach. Unfortunately, the author did not attempt to compare the overall energy costs of his approach (kiln + gasifier + blower) with the conventional one (only kiln). But in light of the high biochar yield, it can be assumed that the overall process is more efficient too.

A more complex system for the co-production of a special biochar-fertilizer and syngas was developed by Day (2005). The system uses agricultural, forestry, and waste biomass to produce a nitrogen enriched biochar for soil amendment, as well as biofuels, which become carbon negative through the biochar co-product.

Traditional biochar production emits large amounts of smoke, sometimes this smoke is condensed to wood vinegar (Pyroligneous Acid), a fluid composed mostly of acetic acid, but also methanol (wood alcohol), acetone, wood oils, and tars in varying amounts. Unvaporised bio-oils and tars can also be recovered, with the use of appropriate production methods. It would be generally advantageous, when a biochar production system could easily be shifted to increase different product yields, depending on market demand.

4 Applications

As described in Chapter 1, biochar was used in many ways throughout history. Here, two main applications of our days are examined, the use as solid fuel and the utilization for purification and filtration. In addition, it will also be given a short overview about biochar as soil amendment.

4.1 Solid fuel and reductant

As mentioned above, biochar plays an important role as energy source for cooking and heating, especially in developing countries, where many people depend on biomass as their only fuel source. This widespread use of biochar can threaten natural forests, especially when the demand exceeds the natural forest resources. Such a situation can be worsened, when the wood to biochar conversion is done with inefficient traditional methods, which sometimes yield only around 10% dry biochar, on a dry biomass basis (Antal, Gronli 2003).

Biochar has the advantage of a high calorific value of 25 – 30 MJ kg⁻¹, compared to around 15 MJ kg⁻¹ for not processed biomass. This reduces transport and storage costs, and decreases the ash residue. The fact that most volatiles of the original biomass are driven out during pyrolysis, allows a hot and nearly smokeless burning. The high carbon (C) content on the other side, requires a sufficient oxygen supply, or too much toxic carbon monoxide (CO) is created, threatening lives when cooking indoors.

But not only in developing countries, the utilization of biochar is a viable alternative to expensive fossil fuels. In every region, where enough biomass is available, which at the same time is sustainably managed, biochar can play an important role as reliable and efficient solid fuel.

For example, in Japan, Horio (2009) developed a biochar combustion heater for household utilization, which can process biochar dust, made out of wood, biological wastes, or other biomass. Its thermal efficiency of 60 - 88%, depending on the biomass source, is high, compared with 46 – 54% of “improved biomass stoves”, which were cited in this study. This high efficiency is of course only relevant, when the biochar production itself is efficient too and uses the emerging volatiles for centralized heating or other purposes.

As described in Chapter 1, the entry into the Metal Ages depended directly on biochar. Fortunately, the ever higher demand for this heat source and reductant, which led often to deforestation, could be diverted to coke. But still today, some biochar is

used as reductant.

The Norwegian ferrosilicon industry imported in 1998 between 70 and 100 Gg biochar to reduce silica to silicon. The price per Mg fixed C can be as high as \$440, which is expensive compared to \$140 – 270 per Mg fixed C for washed coal and coke. The reason for this high value of biochar (made from wood) is its low nitrogen and ash content, and the virtually absence of sulfur and mercury. While this is also depending on the pyrolysis process, and the biomass feedstock, it can be said that many biochars represent a purer form of carbon than most natural graphites. (Antal, Gronli 2003).

The raw material for coke is coal, which is the fossil fuel with the biggest global reserves. However, future generations will maybe again depend solely on biochar, when they want to reduce metal oxides, and smelt and process metal. But this will probably not happen in the next decades. In 2006, the global iron and steel industry consumed approximately 106 Tg coke. In contrast, only 49.7 Tg biochar were produced in this year (UNSD 2008b). Considering today's coke demand, the abundance of coal, and the global net deforestation, it is unlikely to replace coke with biochar in the near future. An exception is the Brazilian iron and steel industry, which consumed not only 8,5 Tg coke, but also an enormous amount of 8 Tg biochar in 2006 (UNSD 2008b). This exceptional position is based on the fact, that Brazil, as industrial country, has virtually no coal deposits, but still large forests, even if they are dwindling fast.

4.2 Purification and filtration

Activated carbon and its feedstock biochar, has been used in sugar refining, brewing, and as a filter in the purification of many products such as gelatin, lard, oils, fats, fruit juices, sorghum syrup, and water for the soft drink industry (Rogers 1977). Additionally, it has a well known capability to adsorb toxins (Hsieh 2007), and therefore, it has also applications in medicine. The worldwide trade volume of activated carbon was approximately 0.67 Tg in 2006 (UNSD 2008a).

The activation, i.e. the increase of pore volume and quantity, of biochar can be done chemically, or by hot steam and gas flows. Today, biochar is most times only seen as the feedstock for activated carbon, but biochar itself can also provide important purification functions.

For example, in a lab scale biological wastewater treatment, biochar as media has shown better capabilities of removing ammonia nitrogen than haydite. This was because the ammonia reducing nitrobacteria were more apt to grow on biochar than on haydite. (Zhou 2008)

4.3 Soil amendment

The application of biochar to soils is nothing new, but it was never done in larger scales, except maybe for Amazonian Terra Preta, hundreds of years ago. The positive effects of

biochar are known to many home gardeners. It makes the soil 'sweet', which has to do with its liming effect (pH increase).

Many experiments have illustrated the improvement of soils through:

- higher water holding capacity,
- higher nutrient availability,
- larger amounts and higher diversity of microorganisms, and
- higher pH-values,

especially on poor soils with low organic carbon contents, which are therefore, either too dense, or too loose.

These effects occur not always in the same magnitude, and depend on the pyrolysis process, as well as on the feedstock. Not less important is the soil itself, the same biochar applied to different soils can have different impacts. Physical, chemical, and biological properties of soil and biochar influence each other. For example, the cation exchange capacity, which is important for the availability of nutrients, is low in freshly produced biochars, and increases only through oxidative processes in soils. Therefore, the soil improving facts cannot be generalized. On some poor soils the increase in biomass yield can be several hundred percent. But there are also a few reports on experiments, where plant growth was suppressed by biochar (e.g. Gundale, DeLuca 2007). So is it possible that the liming effect can suppress some acidophilic microbial communities, which are useful for plant growth, or a freshly produced biochar can adsorb most available nutrients and induce a temporary nutrient deficiency.

5 Natural cycles and anthropogenic influences

Anything cycles, more or less, and in shorter or longer periods. On earth, nothing is static, and it is important to understand the cycles, in order to understand possible future effects of things we do today. This is also the case with biochar as soil amendment. Since it comprises up to 90 % of carbon, it is useful to take a look on the global carbon cycles and its possible influences on them. Biochar makes fertilizer more effective, therefore the global nutrient cycle is also of importance. Finally, biochar production releases more energy than necessary for the pyrolysis process, and the end product is also an energy carrier. This makes it necessary to take a look on the global energy cycle. It is to mention that there are several connections between all of these three cycles.

5.1 Carbon

Most of the earth's carbon is stored in the lithosphere, for example as carbonate mountains like the Dolomite Alps. The cycling of such carbon compounds is very slow and can hardly be influenced by man. Only 0.1 % of all carbon is stored in, and cycles between oceans (39,000 Pg), biosphere (500 Pg), pedosphere (1 m depth) (2000 Pg), and atmosphere (760 Pg), as can be seen in Figure 9. Atmospheric carbon, in form of carbon dioxide (CO_2) plays an important role in the natural greenhouse effect, although

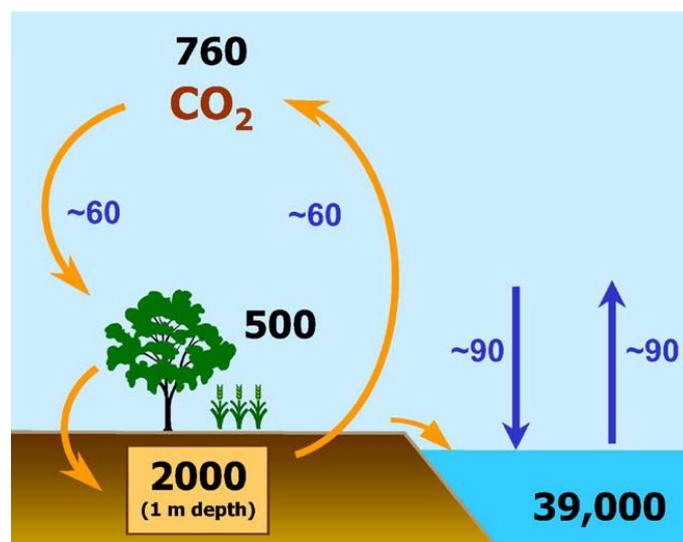


Figure 9: The global carbon cycle in the 1990's, values for stocks in Pg C, values for flows in Pg C per year (Janzen 2004)

it stands only for $\sim 0.04\%$ of all gases in the atmosphere. CO_2 is the most important nutrient for terrestrial plants, which is illustrated by the uptake by plants, worth of 60 Pg of pure carbon, as can be seen in Figure 9. All lifeforms on earth are based on carbon compounds, and when they are decomposed, the carbon is released as CO_2 and returns to the atmosphere.

Soils are full of life and also of dead organic matter, which will be eventually decomposed. The huge amount of 200 Pg C stored in soils is noteworthy and should loose the fixation on the things which grow above the earth. The management of soils is therefore very important, since their C content can be influenced very much, in positive or negative ways.

The oceans contain the largest amount of C, but only around 1,000 of the 39,000 Pg are relevant, since the rest stays in deep ocean layers and takes no part in the active cycle, or only over very long periods. The solved CO_2 in the water has a big influence on the acidity, which can have impacts on calcifying organisms, which stand often at the beginning of oceanic food chains (Doney 2009).

The carbon cycle connects atmosphere, land, and oceans, as can be seen in Figure 9. Depending on the partial pressure of CO_2 in the atmosphere and the oceans, there will be fluxes to reach an equilibrium. That is also the case with the atmosphere-land-connection. When more CO_2 is available in the atmosphere, the plants can take up more for their growth, provided that no other factors hinder plant growth.

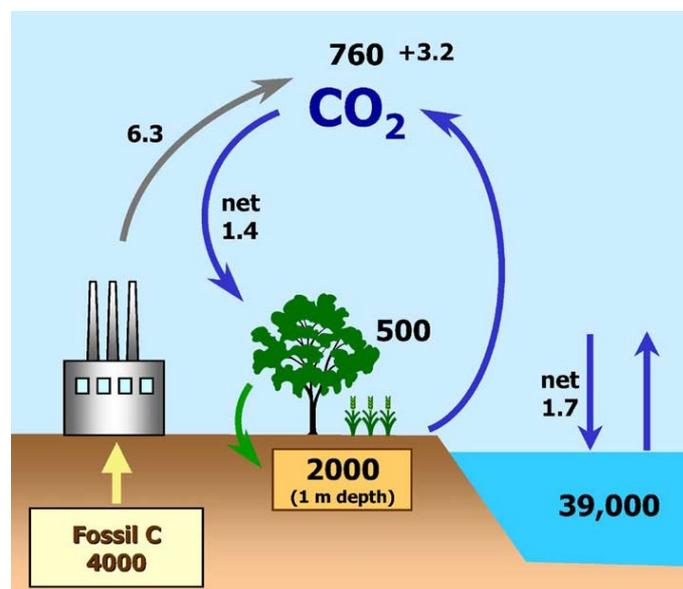


Figure 10: Global carbon cycle with fossil C stocks and fate of the emitted CO_2 , values in Pg C or Pg C per year (Janzen 2004)

The anthropogenic influences on the carbon cycle are illustrated in Figure 10. While the output of carbon from fossil fuels and the increase in atmospheric carbon are relatively well known, the C uptake by oceans and land ecosystems is afflicted with

more uncertainty. However, it can be said that not all emitted CO₂ stays in the atmosphere, and that land and oceans act as buffers. Because buffers act not instantly, which is noted in Figure 11, the interactions between these buffers can be very complex. Furthermore, the uptake of these buffers depends on their capacity, which is not exactly known, and the uptake slows down with an increasing load. If mankind would immediately stop the release of carbon dioxide from fossil sources, it is likely that the acidification of the oceans would go on until an equilibrium between atmosphere and oceans is reached. And if it were possible to sequester so much CO₂ out of the atmosphere to reach preindustrial levels, the oceans and land ecosystems would buffer back, and the atmospheric levels would rise again.

	Inventory, Gton C	Response time
Atmosphere	700	
Ocean	38,000	Exchanges with atmosphere in centuries
Land biosphere	500	Responds to climate in decades
Unfrozen soil	15,000	Decades
Permafrost soil	400	Melts and peat degrades over centuries
Ocean methane hydrates	1,000–10,000	Millennia or longer
Oil	200	Will be depleted in decades
Natural gas	200	Decades
Coal	5,000	A few centuries at current rates

Figure 11: Carbon reservoirs, their sizes (Gton = Pg), and response times (Archer, Brovkin 2008)

The burning of fossil fuels can be mitigated by the use of biomass as regenerative fuel, or by the reduction of energy use, respectively the efficiency increase in energy use. But fossil fuels are not the only source for carbon releases. Past land use changes account for around 200 Pg C. This offers a big opportunity when it is compared to an annual release of 6.3 Pg C from fossil sources. (Janzen 2004)

The change of land management, especially the increase of organic carbon (OC) in soils could offset much of the current emissions. And this would bring more benefits than the mitigation of greenhouse gases. More organic carbon makes soils more fertile, and enhances biodiversity. Therefore the small costs of land use change, compared with other mitigation strategies, would generate big increases in agricultural yields and support food security.

There are several ways to increase the OC content of soils, but the principle is to influence the OC in- and outputs of soils, as shown in Figure 12. It is to notice that the given values represent an average of all continental areas, but not all areas have vegetation, and far less consists of arable land. However, if annually 4 Mg C is bound as organic carbon, than it is advisable to remove only as much biomass that enough OC remains in the soil, and it is not to forget that also most soil organic carbon (SOC) will be mineralized eventually (that is the output of 4 Mg C). To increase SOC permanently, the land management has to pay attention to provide an annually surplus of SOC.

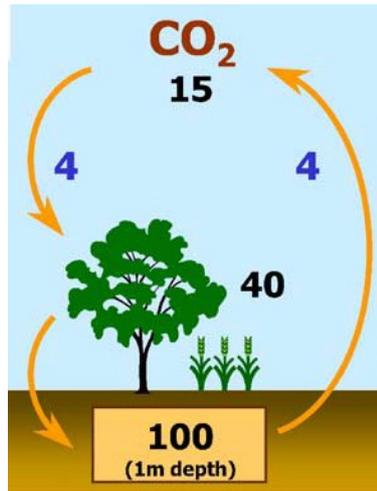


Figure 12: Average Carbon cycle of continental areas, in Mg C per ha (Janzen 2004)

Biochar as the most stable form of OC would it make easier to increase SOC over very long periods of time. The principle of biochar as soil amendment is shown in Figure 13. The 4 Mg C ha⁻¹ from Figure 12, is represented in Figure 13 by the 50% stream of OC, which would naturally completely decompose or be used in agricultural systems (left side). With pyrolysis (right side), around 50% of the OC can be converted to biochar, this would equate 2 Mg C per hectare and year. In regions with higher yields than the continental average, the annual biochar production could also be higher. Therefore, it would not need 100 years to reach biochar contents of 50 Mg ha⁻¹, like in Amazonian Terra Preta.

When biochar is regarded as a carbon storage device, which could offset GHG emissions, then a simple comparison can clarify the possibilities. As mentioned above, the burning of fossil fuels releases annually 6.3 Pg C in form of CO₂ into the atmosphere. The highest estimates of commercial biochar production are around 0.1 Pg, and the C content might be at around 80%, which would multiply to 0.08 Pg C. And it is not to forget that this biochar will probably be used as fuel, or reductant, and not as soil amendment. However, Lehmann, Gaunt, and Rondon (2006) calculated, that a change in land use, from slash-and-burn to a biochar system, could offset 0.21 Pg C annually, and the use of agricultural and forest wastes could add a conservatively estimated 0.16 Pg C yr⁻¹. To offset the CO₂ emissions of an average Finn, 5 Mg biochar had to be applied to soil annually (see Appendix 7.1).

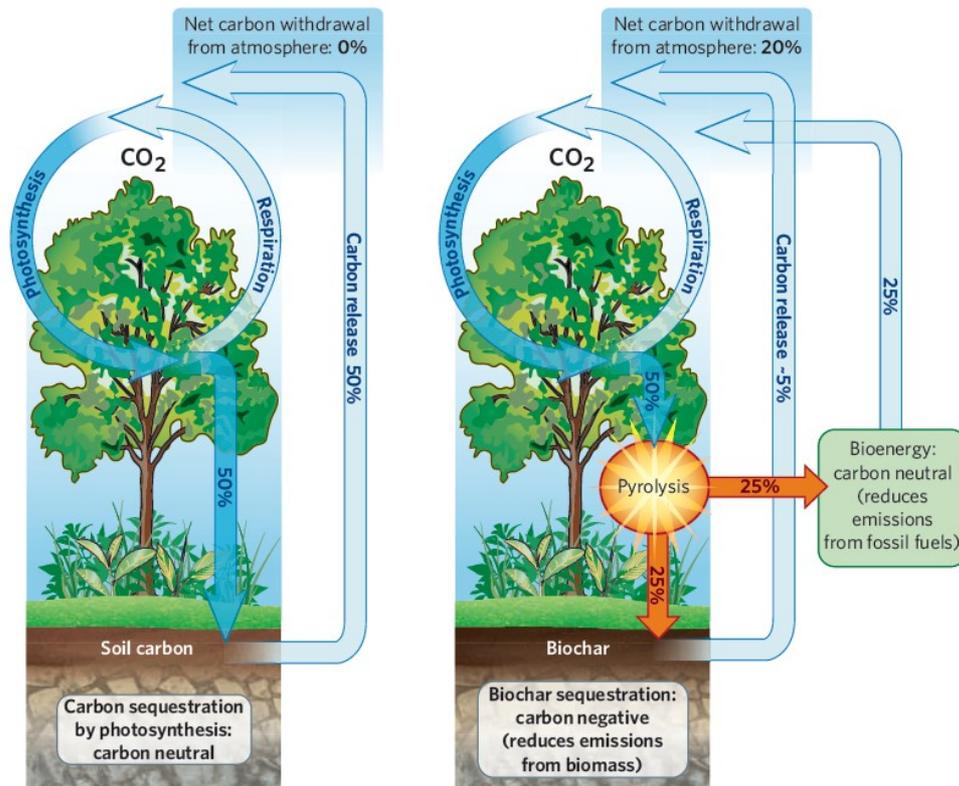


Figure 13: Natural C cycle (left) and C sequestration with biochar (right) (Lehmann 2007)

Additionally, the stored C in form of biochar is not only a passive sink. Biochar can support plant growth, and with that, also the active uptake of C from the atmosphere. Also, the soil release of methane (CH₄), which has a 25 times greater global warming potential than CO₂, can be reduced. This is probably because of better aeration through the low density of biochar, and thus lesser anaerobic conditions in soils (Lehmann, Gaunt & Rondon 2006). In 2004, CH₄ constituted around 14% of global GHG emissions, counted in CO₂ equivalents (CO_{2e}), and while some soils, especially under anaerobic conditions emit CH₄, globally, soils consume 5% of the annual load of CH₄ to the atmosphere, and are therefore a net sink. Biochar application to soils could increase this sink. (Lehmann, Joseph 2009)

5.2 Nutrients

Besides water, carbon dioxide and oxygen, plants need mineral nutrients for a healthy growth, as symbolized in Figure 14. The six major nutrients are nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), and sulfur (S). In addition, there are seven more micronutrients, boron (B), iron (Fe), chlorine (Cl), copper (Cu), manganese (Mn), molybdenum (Mo), and zinc (Zn). (Schroeder 1992)

Many of these nutrients become plant available through the decomposition of minerals. A recycling occurs through the uptake by plants in ionic form, and the

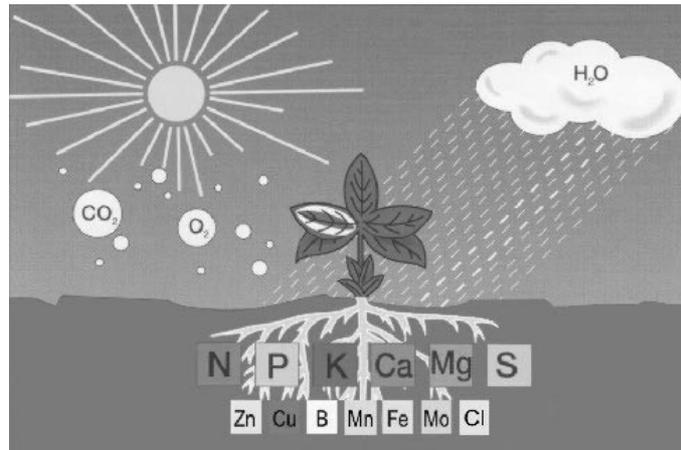


Figure 14: Plant nutrients (Döhler et al. 2007)

decomposition of these plants and their consumers along the food chain. Mineral and organic fixations of nutrients are dominant. Usually, less than 2 % of all nutrients in soil are plant available as exchangeable ions or cations, or as free ions. Therefore, an important measure for nutrient availability is the cation exchange capacity (CAC) of the soil. A major influence on the nutrient cycle has also the hydrogen ion concentration (pH), since it can hinder or promote nutrient fixation, as well as nutrient release. (Schroeder 1992)

Today's high productive and industrialized agriculture depends on synthetic fertilizers. Their worldwide production accounts for approximately 1.2 % of the world energy demand (Jenssen, Kongshaug 2003). Around 164 Tg synthetic NPK-fertilizer was used in 2006 (IFA 2009). One necessity for this extra soil input is the uneven natural distribution of nutrients in the world's soils, depending on different pedogenesis, but also on bad agricultural practices. The other big problem is the lacking recycling of nutrients. Although the nutrients in biological wastes are often recycled to compost and are therefore not lost, the nutrients in the excrements of millions of people do not return to the soil. Either they fertilize the waterways and finally the oceans, or they are mineralized in sewage treatment plants under high energy costs.

The nutrient contents of biochar depend on the biomass input and the pyrolysis process. The ranges of N and P contents cover wider ranges than that of other organic fertilizers, like compost, or fermentation sludges (Lehmann, Joseph 2009). Because of its high surface area, and CEC, it can store a large amount of plant available nutrients, and the usually high pH promotes microbial activity. All this reduces leachate of nutrients, especially from synthetic fertilizers, and thus prevents accumulations in groundwater, and surface water reservoirs, which can be harmful to water quality, and biological balances (i.e. eutrophication). This means also that less fertilizer is necessary to maintain soil productivity.

Studies have shown, that biochar increases the biological N_2 fixation of leguminous plants (Rondon et al. 2007). It is likely that also free N_2 fixing bacteria (diazotrophs) are

supported, because biochar offers them a favorable habitat (Lehmann, Joseph 2009).

Also the reduction of nitrous oxide (N_2O) emissions from soils could be shown, although the mechanisms behind are not fully understood yet (Lehmann, Gaunt & Rondon 2006). This reduces not only the loss of nitrogen, but reduces also the release of this potent greenhouse gas (298 x the impact of CO_2) to the atmosphere. In 2004, N_2O contributed around 8% of global GHG emissions (CO_2e), and agriculture was responsible for 42% of this total (Lehmann, Joseph 2009).

Biochar is no substitute for fertilizer, nor for good farming practices, but it supports both. If it is included in a good land management, then today's high and costly nutrient flux can decrease, without compromising food security, and with less pollution through leaching mineral fertilizers.

5.3 Energy

The worldwide consumption of primary energy in 2006 was approximately 498.66 EJ, which would equal an average energy consumption rate of 15.8 TW. Around 92% of this energy derived from fossil fuels (86%), and nuclear fission (6%). (EIA 2008)

The sun provides earth with enormous amounts of energy, which results not only in direct and indirect solar radiation, but also drives wind and water cycles. In Figure 15, this is expressed as the latent heat in water vapor, as well as in conduction and rising air.

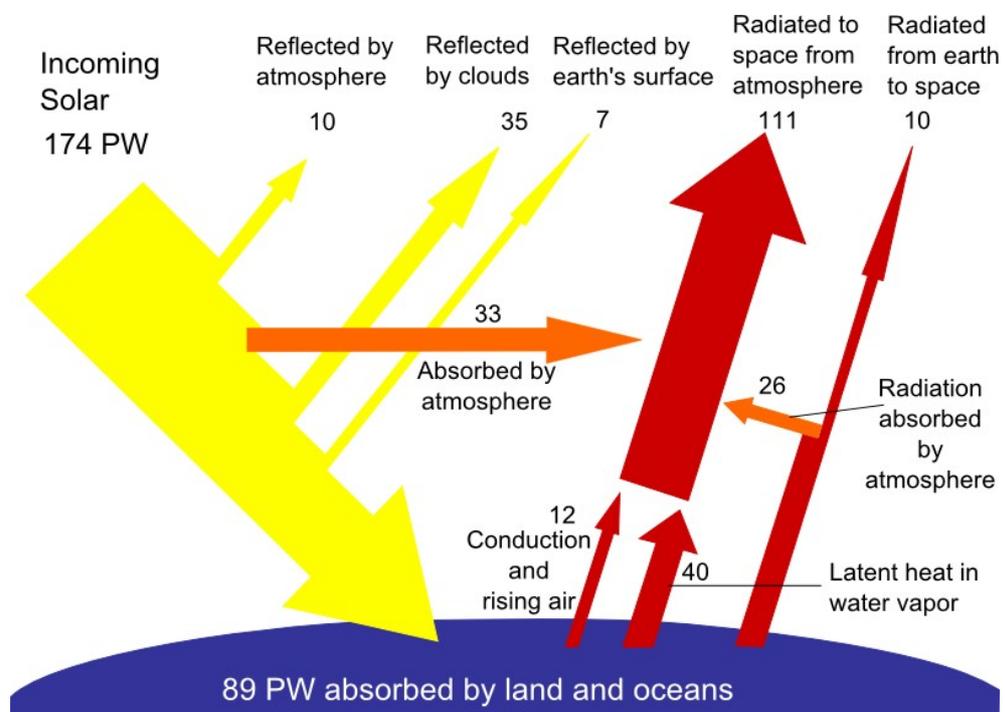


Figure 15: Breakdown of the incoming solar energy (Frank van Mierlo 2008)

It could seem surprising that our energy demand of around 16 TW is nearly completely met by the use of dwindling fossil fuels, while less than 0.02% of the global

solar radiation (~89,000 TW) could secure this demand. But fossil fuels have a big advantage, they have a very high energy density and this makes it economically much more profitable to exploit them. Another advantage is, that fossil fuels are easy to store, and therefore, available whenever needed; not like sun, wind, and even water. Sunlight radiates annually an energy equivalent of 7.9 GJ on one 1 m² of land, if an average of 250 W/m² over 24 hours is assumed. In comparison, 1 Mg of crude oil has a chemical potential energy of 41.9 GJ, and that oil can be retrieved in much shorter times than one year.

However, when fossil fuels become less available, and therefore, economically unfeasible, then there are only two alternatives. The first is to reduce the energy use and the second is to change the energy sources, although a combination of both ways seems likely. The prevention of rising atmospheric CO₂-levels would also command these two ways, even if some emissions could be offset by other measures, like land use change.

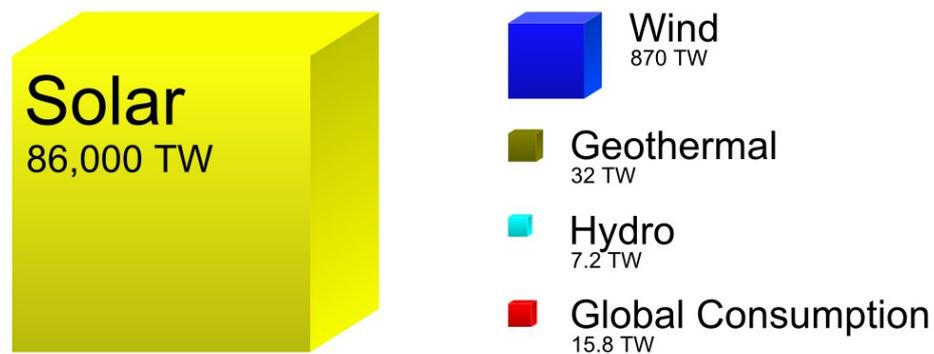


Figure 16: Available renewable energy (values from (Hermann 2006)) in comparison with the global consumption (value from (EIA 2008)) (the author)

Figure 16 illustrates the great potentials, which renewable energies offer, although not all the potential energy can be utilized. Energy from biomass is not included in this figure, because it has to be considered more careful than the other renewables. Biomass is much more than an energy source, as explained in Chapter 6.1.

Biochar has a calorific value of up to 30 MJ kg⁻¹. In combination with the highest assumption of a worldwide production of 0.1 Pg a⁻¹, biochar would represent 0.6% (3 EJ or 0.1 TW) of the global primary energy use. This calculation is not fully correct, since charcoal represents no primary energy, that would be the biomass for its production, but the numbers give a notion about today's relevance of biochar as an energy carrier. Nonetheless, as already mentioned, for less industrialized countries the importance of biochar is very high, compared to fossil fuel depending industrial countries.

6 Concerns and current research

In the following subchapters, some discussions and controversies are compiled, regarding the use of biochar as soil amendment. Some of the biggest concerns about biochar are addressed in the first subchapter. The selection was made by the author in regard to his impressions during literature research. In the second subchapter, the current most important research efforts are stated. Some necessary research originates directly from the first chapter, but not all biochar concerns are based on the lack of scientific knowledge, but are a problem of communication. Finally, in the third subchapter, the interested reader will find some references to biochar initiatives and working groups.

6.1 Biggest concerns about biochar

The biggest concerns, regarding biochar, are:

- the possible promotion of deforestation,
- the possible competition to food production,
- the uncertainty of its persistence in soils, and to a lesser degree,
- the competition between the use as soil amendment and as cooking fuel, and
- the possible competition with other organic soil amendments, like compost.

There is also the problem that the carbon sequestration through biochar could be used as a fig leaf, while not addressing the necessary reduction of carbon emissions from fossil fuel use. However, this concern has nothing to do with the technology itself, and is therefore not discussed in here.

The feedstock for biochar is biomass, and in a more traditional view this biomass is mostly wood. Therefore, biochar can be seen as a potential promoter of deforestation. Indeed, in some countries, like Tanzania, biochar production for household cooking and heating threatens natural forests. The high demand, combined with low yielding production methods, and the unsustainable use of the feedstock lead to this threatening situation (Mwampamba 2007). But even the biochar production with wood from pristine forests can reduce the thread of deforestation. An example is Brazil with its currently ongoing, devastating slash-and-burn practice. More and more people burn down natural rain forests for establishing small farms. The remaining ash fertilizes the poor soil enough for two or three years of good harvest, but then nearly every nutrient is washed out and the farmer has to burn down a new patch of forest. A change to slash-and-char could stop this devastation. When the wood is not burned but charred, then the biochar could be applied to the poor soil and turn it into a long lasting, high yielding

soil, similar to Terra Preta. The farmer could stay on his land and would not need to burn down more and more forest. Besides the protection of biodiversity and Indian cultures, this would also have positive impacts on the global climate change.

But nearly any biomass can be a feedstock for biochar. This brings it in connection to the growing market of biofuels, which can be a competitor to food production. The fundamental difference between biofuels and biochar for soil amendment is their target. The former tries to replace the use of fossil fuels with biofuels, in regard of declining fossil deposits, and in order to reduce CO₂ releases. The latter tries to increase soil productivity, with the side effect of sequestering carbon from the atmosphere. Interestingly, the latter could make the former more productive, but the question arises if the replacement of fossil- with biofuels makes sense, even if it is economically reasonable today. Besides all economics, the biofuel concept seems not to be the best solution, at least not at a large scale. The solar conversion factor for major crops in the US is around 1% (Zhu, Long & Ort 2008), the thermal conversion, or even alcoholic fermentation, leaves less energy behind. At the worst end, bioethanol could be burned in a car with an efficiency of around 30%. It might be wiser to provide energy from direct solar conversion, like photovoltaics with a conversion factor of around 10%, or from wind, water, and geothermal sources. Arable land, which is hardly threatened by these technologies, should be primarily used for the production of food and biochemicals. Of course, the conversion of biomass to energy is still a viable option for regions with an abundance of biomass, and when this use is not competing, but complementing necessary food production.

The lifetime of biochar in soils is not exactly known, there are estimates ranging from hundred to thousands of years. These estimates originate from archaeological findings and short term soil experiments. While for agricultural applications, this matter is not very important, it has great influence on the importance of biochar as carbon storage. In 2008, there was a controversial debate about a rare longterm soil experiment, concerning the stability of biochar. Wardle et al. (Wardle, Marie-Charlotte Nilsson & and Olle Zackrisson 2008) did a ten year field trial in a boreal forest soil. They measured the loss of mass, C and N, as well as the biological activity of a half and half mixture of biochar and humus, compared to only humus, and only biochar. The measurements of the mixture showed significant higher values than the mean of the single substrates, but were never higher than the values for only humus. This can be explained by the promotion of microorganism (MO) activity through biochar (Kim et al. 2007), which accelerates degradation of SOM. Since biochar is a very stable substrate (Glaser et al. 2001), Wardle et al. attributed the C loss mainly to the degradation of humus. Lehman and Sohi (2008) argued that biochar too could attribute to that loss, especially in the first year when mass losses peaked. Further, they added that the C loss might have happened not only in form of CO₂, but also in form of solubles, which can form stable compounds with underlying clay. Wardle et al. (2008) agreed to the latter

argument but pointed out, that the high MO activity suggests a degradation to CO₂. They did not agree to a significant degradation of biochar, since it is very stable and the biochar-only substrate did not show significant losses. On the other side, only biochar also showed a low MO activity, whereas in the mix, the high MO activity could have biologically degraded some biochar fractions. Despite these arguments the results of the trial showed an increased degradation of humus when mixed with biochar. Therefore, the C sequestration with biochar in boreal forests and, on a larger scale, in soils with high SOM might be partially offset by a higher CO₂ release. In short terms, this means, a partial replacement of SOM C with biochar C. (Lehmann, Gaunt & Rondon 2006). So, this debate underlined not only lifetime concerns, but accidentally highlighted possible negative effects on 'natural' SOC.

Besides the debate about the longevity of biochar in soils, the lifetime of biochar can instantly be shortened when it is used as fuel. The importance as cooking fuel in many regions makes it valuable. Therefore, the benefits as soil amendment have to be demonstrated to local farmers, or they will simply not use it as such.

There are also some concerns that biochar could be a competitor to compost. The big advantage of biochar is its longevity, compared to compost, which has to be applied on a periodical basis. Compost contains ordinarily large amounts of nutrients, whereas the nutrient contents of biochars have a very wide range, depending primarily on its feedstock. In the end, there has not to be a competition between compost and biochar. Both are valuable soil conditioners and they can complement each other, even at the production level. So has the feedstock for compost naturally a higher moisture content, while the feedstock for pyrolysis should be relatively dry. But biochar can also be used as compost additive, where it can accelerate the composting process ((Yoshizawa, Tanaka & Ohata 2007).

In future, there might be even more concerns about biochar, like with every new technology. Some can be eliminated by communication, and others have to be resolved through scientific research.

6.1 Most important research efforts

The currently most important research efforts address:

- the optimal combination between different biochars and soils,
- the necessary feedstock and pyrolysis parameters to produce 'adequate' biochars,
- a classification for biochars,
- suitable soil application methods, and
- the stability of biochar in soils.

This list claims not to be complete, nor is there any order of priority. Biochar as soil amendment and carbon storage is a quite young field of science, and therefore, intensive research has to aim in many different directions.

The diversity of soils, combined with a variety of biochar feedstocks and several pyrolysis parameters, makes it necessary to conduct a large number of soil experiments. Even when the processes during pyrolysis are understood better, and the mechanical and chemical properties of biochars are known in more detail, the interactions between biochar and soil can be very complex. Especially the biological component in relation to changes in properties over longer periods, make field trials indispensable.

To be able to develop 'adequate' biochars for soil amendment, it is important to record feedstocks and pyrolysis parameters of biochars used in soil experiments. Till now, most informations about biochar characteristics originate from the production for fuel or reduction purposes. These informations are helpful but not sufficient.

To establish a large scale application for biochar, it is necessary to classify the product. The user of biochar needs to know, which biochar is optimal to enhance his soil. Since this question can not be fully answered yet, it would at least be possible to establish a classification system based on simple production parameters, like feedstock, maximum pyrolysis temperature, fixed carbon content, ash content, and particle size.

The application to soils can be quite an effort in large scale systems. Biochar can be added manually to planting holes, or it can be spread superficially on the top soil. In the latter case, there is a high risk of erosion, especially by wind. The dustiness of biochar poses also a health risk, and there is still the small risk of self combustion. When the biochar particles have the right size, then it is possible to apply it with machinery in bands directly into the soil, which is also used for sowing. The dust problem at the application site can be eliminated, when biochar is incorporated with compost, manures, or digested residues. (Lehmann, Joseph 2009) This approach could be very promising, because there is not only the, already stated, positive influence of biochar to the composting process. Biochar additions can also promote biogas yields from anaerobic digestion (Kumar, Jain & Chhonkar 1987).

The stability of biochar in soils is relevant for GHG mitigation policies. So could the application to soils not only raise the income of farmers by increasing crop yields, but also by carbon trade. To make this possible, easy test methods for the biochar content in soils have to be developed. Of course, biochar had to be fully integrated into the carbon trade market, which is not only a scientific, but also a political effort.

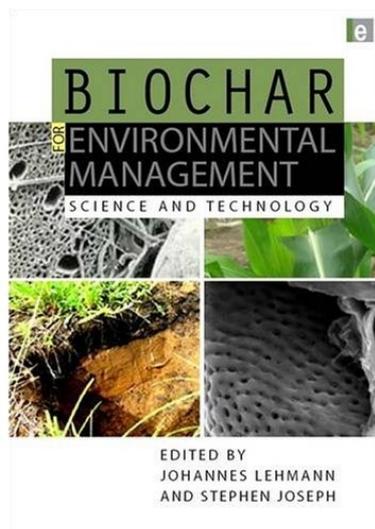
6.1 Biochar initiatives and working groups

The most important source for information about biochar and for further links to other sources is the International Biochar Initiative (IBI) (<http://www.biochar-international.org>). IBI is a registered non-profit organization, which supports researchers, commercial entities, policy makers, development agents, farmers and gardeners. Its purpose is to promote research, development, demonstration, deployment and commercialization of the promising technology of biochar. There are already some regional IBI groups and

people are encouraged to share their biochar projects with the community.

Another interesting address is “BioEnergy Lists: Biochar (Terra Preta)” (<http://terrapreta.bioenergylists.org/>). It is a site with regular postings from members, who discuss the use of biochar as soil amendment and carbon storage. Postings come from scientists, as well as from interested people, around the world.

The greater part of all important resources about biochar can be found through these two addresses. The first book about biochar as soil amendment, as shown in Figure 17, was published in Spring 2009. “Biochar – Environmental Management – Science and Technology” gives very detailed insights into many different aspects of biochar. More information to this book can be found at the IBI website.



*Figure 17: The first book on biochar
(www.earthscan.co.uk)*

7 Appendix

7.1 Biochar necessary for individual CO₂ emission offset

The average Finn emitted 11 Mg CO₂ in 2005 (UNSD 2008b). The molecular weight of CO₂ (44.010), divided through the molecular weight of C (12.011), results in a mass conversion factor of approximately 3.664. Therefore, 11 Mg CO₂ equals an amount of pure C of around 3 Mg. Assumed that the biochar had a fixed carbon rate of 80%, which is common for wood biochar, then 3.75 Mg biochar would be necessary to offset the emitted amount of CO₂. Although biochar is the most recalcitrant organic carbon known, it is not invulnerable. Assumed that the chemical and or biological oxidation of biochar would reach 25% in several hundred years, then the necessary amount would increase to 5 Mg.

It is to mention that this calculation is only appropriate, when the biochar feedstock comes from a sustainable cultivation. That means that on a long term, the extracted biomass must not be higher than the biomass growth. One could even consider CO₂ emissions associated with the cultivation, e.g. from fertilizer, or machinery.

Bibliography

- Antal, M.J., Jr. & Gronli, M. 2003, "The Art, Science, and Technology of Charcoal Production", *Industrial & Engineering Chemistry Research*, vol. 42, no. 8, pp. 1619-1640.
- Archer, D. & Brovkin, V. 2008, "The millennial atmospheric lifetime of anthropogenic CO₂", *Climatic Change*, vol. 90, no. 3.
- BBC, *The Secret of El Dorado* 2002, DOX Productions
- Buchanan, B.J. 2006, *Gunpowder, explosives and the state : a technological history*, Ashgate, Aldershot, England ; Burlington, VT.
- Bush, M. 2007, "Amazonian exploitation revisited: ecological asymmetry and the policy pendulum", *FRONTIERS IN ECOLOGY AND THE ENVIRONMENT*, vol. 5, no. 9, pp. 457-465.
- Day, D. 2005, "Economical CO₂, SO_x, and NO_x capture from fossil-fuel utilization with combined renewable hydrogen production and large-scale carbon sequestration", *Energy*, vol. 30, no. 14, pp. 2558-79.
- Döhler, H., Pradt, D., Ebenhöch, J., Röhling, S., Gransee, A., Stilgenbauer, H., Hesse, A., Zorn, W. & Küsters, J. 2007, "Rohstoffverfügbarkeit für Mineraldünger - Perspektiven unter hohen Energiekosten und begrenzten Ressourcen", ed. Bundesarbeitskreis Düngung (BAD), .
- Doney, S.C. 2009, "Ocean Acidification: The Other CO₂ Problem; Ocean Acidification: The Other CO₂ Problem", *Annual Review of Marine Science*, vol. 1, no. 1, pp. 169.
- EIA 2008, *International Energy Annual 2006*, Energy Information Administration, U.S. Department of Energy.
- FAO Forestry Department (ed) 1987, *Simple technologies for charcoal making*, 2nd edn, FAO, Rome.
- FAOSTAT , *Food and Agriculture Organization of the United Nations - Statistics*.
- Freese-Green, D. 2008, *Biochar and SCAD*, Bristol, UK.
- Glaser, B., Haumaier, L., Guggenberger, G. & Zech, W. 2001, "The 'Terra Preta' phenomenon: a model for sustainable agriculture in the humid tropics", *Die Naturwissenschaften*, vol. 88, no. 1, pp. 37-41.

- Gundale, M.J. & DeLuca, T.H. 2007, "Charcoal effects on soil solution chemistry and growth of *Koeleria macrantha* in the ponderosa pine/Douglas-fir ecosystem", *Biology and Fertility of Soils*, vol. 43, no. 3.
- Haefele, S.M., Konboon, Y., Knoblauch, C., Koyama, S., Gummert, M. & Ladha, J.K. 2008, "Black carbon from rice residues as soil amendment and for carbon sequestration"
- Harris, P. 1999, "On charcoal", *Interdisciplinary Science Reviews*, vol. 24, no. 4, pp. 301-306.
- Hermann, W.A. 2006, "Quantifying global exergy resources", *Energy*, vol. 31, no. 12, pp. 1685-1702.
- Horio, M. 2009, "Development of biomass charcoal combustion heater for household utilization", *Industrial and Engineering Chemistry Research*, vol. 48, no. 1, pp. 361-372.
- Hsieh, M. 2007, "Application of bamboo charcoal particles in blood purification: Cytotoxicity and absorption capability assessments", *Journal of Medical and Biological Engineering*, vol. 27, no. 1, pp. 47-51.
- IFA 2009, *International Fertilizer Industry Association - Database*. Available: <http://www.fertilizer.org> [2009]
- Janzen, H.H., 2004, "Carbon cycling in earth systems-a soil science perspective", .
- Jenssen, T.K. & Kongshaug, G. 2003, "Energy consumption and greenhouse gas emissions in fertiliser production", *Proceedings No. 509*, ed. The International Fertiliser Society
- Kim, J., Sparovek, G., Longo, R.M., De Melo, W.J. & Crowley, D. 2007, "Bacterial diversity of terra preta and pristine forest soil from the Western Amazon", *Soil Biology and Biochemistry*, vol. 39, no. 2, pp. 684-690.
- Kumar, S., Jain, M.C. & Chhonkar, P.K. 1987, "A note on stimulation of biogas production from cattle dung by addition of charcoal", *BIOL. WASTES. Vol.20*, vol. 20, no. 3, pp. 209-215.
- Lehmann, J. 2007, "A handful of carbon", *Nature*, vol. 447, no. 7141, pp. 143-144.
- Lehmann, J., Joseph, S., 2009, *Biochar for environmental management : science and technology*, Earthscan, London.
- Lehmann, J., Gaunt, J. & Rondon, M. 2006, "Bio-char Sequestration in Terrestrial Ecosystems – A Review", *Mitigation and Adaptation Strategies for Global Change*, vol. 11, no. 2.
- Lehmann, J., Kern, D., Glaser, B. & Wodos, W. *Amazonian Dark Earths*, Springer Netherlands.

- Lehmann, J., Sohi, S., 2008, "Comment on "Fire-Derived Charcoal Causes Loss of Forest Humus", *Science*, vol. 321, pp. 1295.
- Lima, H.N., Schaefer, C.E.R., Mello, J.W.V., Gilkes, R.J. & Ker, J.C. 2002, "Pedogenesis and pre-Colombian land use of "Terra Preta Anthrosols" ("Indian black earth") of Western Amazonia", *Geoderma*, vol. 110, no. 1-2, pp. 1-17.
- Lin, J.C.M., 2006, "Development of a high yield and low cycle time biomass char production system"
- Mann, C.C. 2008, "Ancient Earthmovers of the Amazon", *Science*, vol. 321, no. 5893, pp. 1148.
- Mann, C.C. 2002, "The Real Dirt on Rainforest Fertility", *Science*, vol. 297, no. 5583, pp. 920.
- Marris, E. 2006, "Putting the carbon back Black is the new green", *Nature*, vol. 442, pp. 624-626.
- Mwampamba, T.H., 2007, "Has the woodfuel crisis returned? Urban charcoal consumption in Tanzania and its implications to present and future."
- Rogers, R.W. 1977, "Monograph on Carbon: Activated Charcoal", *Available from the National Technical Information Service*
- Rondon, M.A., Lehmann, J., Juan Ramírez & Hurtado, M. 2007, "Biological nitrogen fixation by common beans (*Phaseolus vulgaris* L.) increases with bio-char additions", *Biology and Fertility of Soils*, vol. 43, no. 6.
- Schroeder, D. 1992, *Bodenkunde in Stichworten*, Hirt Verlag, Berlin, Stuttgart.
- U.S. Department of Commerce 2008, *Trends in Atmospheric Carbon Dioxide - Mauna Loa*. Available: <http://www.esrl.noaa.gov/gmd/ccgg/trends/> [2008, 11/2008] .
- UNSD 2008a, 12. Dec 2008-last update, *UN data - Commodity Trade Statistics Database*. Available: <http://data.un.org/Default.aspx> [10. May 2009]
- UNSD 2008b, 12. Dec 2008-last update, *UN data - Energy statistics database*. Available: <http://data.un.org/Default.aspx> [07. May 2009]
- US Energy Information Administration 2007, 18.09.2007-last update, *World Carbon Dioxide Emissions from the Consumption and Flaring of Fossil Fuels, 1980-2005*. Available: <http://www.eia.doe.gov/environment.html> [2008, 11/2008] .
- Wardle, D.A., Marie-Charlotte Nilsson & and Olle Zackrisson 2008, "Fire-Derived Charcoal Causes Loss of Forest Humus", *Science*, vol. 320, pp. 629.
- Yoshizawa, S., Tanaka, S. & Ohata, M. 2007, "Proliferation effect of aerobic microorganisms during composting of rice bran by addition of biomass charcoal", *Proceedings of the International Agrichar Conference*.

Zhou, A. 2008, "Effect of charcoal media for the treatment of wastewater in a biological filter", *2nd International Conference on Bioinformatics and Biomedical Engineering, iCBBE 2008*, , pp. 3527-3530.

Zhu, X., Long, S.P. & Ort, D.R. 2008, "What is the maximum efficiency with which photosynthesis can convert solar energy into biomass?", *Current Opinion in Biotechnology*, vol. 19, no. 2, pp. 153-159.