Climate Protection Through Biochar in German Agriculture: Potentials and Costs

by Isabel Teichmann

In recent years, there has been much discussion about biochar—a carbonaceous product made of biomass—as a promising technique for mitigating climate change. In particular, this method has the potential to remove carbon dioxide from the atmosphere for the long term by incorporating biochar into the soil while enhancing soil fertility at the same time.

A research project conducted by DIW Berlin calculated the greenhouse gas mitigation potential and possible costs of using biochar in German agriculture. According to this study, approximately one percent of the greenhouse gas reduction target for 2030 could be met using biochar, but largely at a cost of over 100 euros per tonne of CO_2. Ultimately, however, biochar's potential for reducing greenhouse gas emissions is limited by the availability of biomass. The possible agricultural benefits of biochar in the form of enhanced soil fertility could improve the greenhouse gas reduction potential and costs. This may be of particular relevance in tropical and subtropical regions.

The German government aims to reduce annual greenhouse gas emissions in Germany by 55 percent (compared to 1990 levels) by 2030 and by 80 to 95 percent by 2050.[1] In this context, biomass has been used so far in various forms as a regenerative source of energy for the production of electricity, heat, and fuels. Currently, it is discussed how biomass-derived biochar can contribute to climate protection in the future.

Biochar, also called black carbon,[2] is created by heating biomass in the near absence of oxygen (incomplete combustion). During this process, part of the biomass is decomposed into gaseous and liquid components. The remaining solid residue, which consists largely of stable carbon, is referred to as biochar. In very simple terms, biochar is charcoal, which can be produced not only from wood, but from any type of biomass, such as straw, green waste, biogenic household waste, liquid manure, digestates, or sewage sludge.

Like the original biomass, biochar can be used energetically and replace fossil fuels. Unlike the original biomass, it can also contribute to the long-term removal of carbon dioxide (CO2) from the atmosphere (carbon sequestration) by incorporating biochar into soils (see Figure 1).[3] The carbon in biochar is characterized by high

---

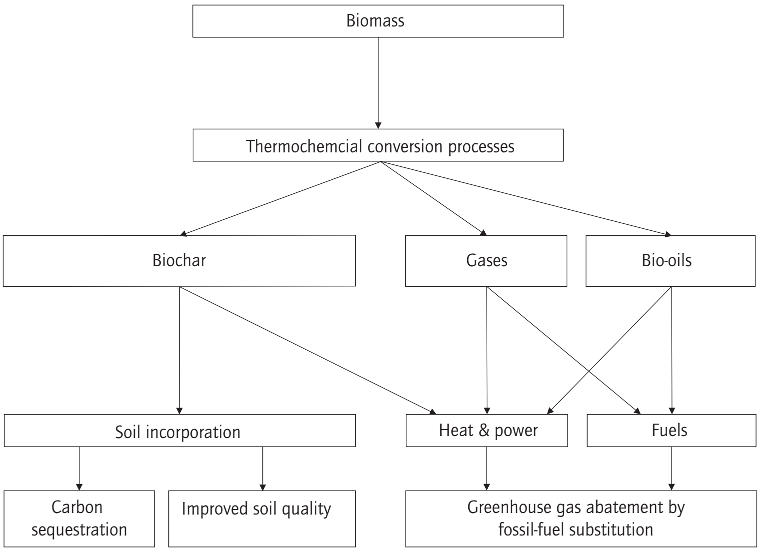
[1] BMWi and BMU, eds., Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung, Federal Ministry of Economics and Technology (BMWi), Federal Ministry for Environment, Nature Conservation and Nuclear Safety (BMU) (2010).

[2] Some authors use the term biochar only when referring to applications in agriculture and reserve the term charcoal for energy applications. See J. Lehmann and S. Joseph, "Biochar for Environmental Management: An Introduction, " in "Biochar for Environmental Management: Science and Technology," eds. J. Lehmann and S. Joseph, Earthscan (London, UK and Sterling, VA, United States: 2009): 1–12. This report follows a broader definition of biochar which includes energy use.

[3] In this context, biochar is also discussed as a so-called climate-engineering measure, that is, as a targeted technical intervention in the climate system. See W. Rickels, G. Klepper, J. Dovern, G. Betz, N. Brachatzek, S. Cacean, K. Güssow, J. Heintzenberg, S. Hiller, C. Hoose, T. Leisner, A. Oschlies, U. Platt, A. Proelß, O. Renn, S. Schäfer, and M. Zürn, Large-scale intentional interventions into the climate system? Assessing the climate engineering debate, Scoping report

Figure 1

Biochar Flowchart[1]



1 The use of biochar to generate energy was not examined in this study.
Source: diagram by DIW Berlin.

© DIW Berlin 2014

The application of biochar in agriculture can abate greenhouse gas emissions and improve soil quality.

stability; chemical and biological processes take significantly more time to convert it back to CO2 than the carbon in the original biomass.[4] In addition, biochar can improve the nutrient-retention and water-holding capacities of the soil.[5] Accordingly, its incorporation into the soil could contribute to improving soil quality and, thus, to increasing agricultural productivity. This is of great importance due to the rising global demand for food and energy crops, whereby soil quality is becoming an ever greater constraint, also in Europe and Germany.[6]

A well-known example of the lasting effect of biochar is the so-called Terra Preta do Indio, a particularly fertile dark earth occurring in spots throughout the Amazon Basin. Terra Preta is significantly different from the usual soils in the humid tropics because of its high levels of carbon and nutrients, such as nitrogen, phosphorus, and potassium, as well as its better nutrient-retention capacity. The Terra Preta soils date back to human activity in pre-Columbian times. In addition to animal and human excrements, bones, fish bones and turtle backs, Terra Preta contains a high percentage of biochar.[7] While most of the nutrients were probably introduced through organic waste,[8] the biochar is largely responsible for the high stability and persistent fertility of Terra Preta.

A research project conducted at DIW Berlin calculated the potentials and costs of carbon sequestration and greenhouse gas abatement based on the agricultural use of biochar from domestic biomass.[9]

Different Conversion Processes and Feedstocks

The yield of biochar and its specific properties are largely determined by the conversion processes and feedstocks used in its production.

Biochar Can Be Produced in Different Ways

Biochar is naturally occurring, for example, as a by-product of vegetation fires where oxygen supply is limited. For the industrial production of biochar, various thermochemical conversion processes are suitable (see Figure 2).[10] They range from the dry processes of pyrolysis and gasification to the wet process of hydrothermal car-

---

conducted on behalf of the German Federal Ministry of Education and Research (BMBF), Kiel Earth Institute, Kiel, 2011.

[4] For example, J. Lehmann, C. Czimczik, D. Laird, and S. Sohi, "Stability of Biochar in the Soil," in "Biochar for Environmental Management: Science and Technology," eds. J. Lehmann and S. Joseph, Earthscan (London, UK and Sterling, VA, USA: 2009): 183–205. „

[5] J. Lehmann, "Bio-Energy in the Black," Frontiers in Ecology and the Environment 5, no. 7 (2007): 381–387.

[6] A. Jones, P. Panagos, S. Barcelo, F. Bouraoui, C. Bosco, O. Dewitte, C. Gardi, M. Erhard, J. Hervás, R. Hiederer, S. Jeffrey, A. Lükewille, L. Marmo, L. Montanarella, C. Olazábal, J.-E. Petersen, V. Penizek, T. Strassburger, G. Tóth, M. Van Den Eeckhaut, M. Van Liedekerke, F. Verheijen, E. Viestova , and Y. Yigini, The State of Soil in Europe: A Contribution of the JRC to the European Environment Agency's Environment State and Outlook Report – SOER 2010, JRC Reference Reports, EUR 25186 EN (Luxembourg: European Commission, 2012).

[7] For example, B. Glaser, L. Haumeier, G. Guggenberger, and W. Zech, "The ‚Terra Preta' Phenomenon: A Model for Sustainable Agriculture in the Humid Tropics," Naturwissenschaften 88, no. 1 (2001): 37-41.

[8] B. Glaser, "Prehistorically Modified Soils of Central Amazonia: A Model for Sustainable Agriculture in the Twenty-First Century," Philosophical Transactions of the Royal Society B 362, no. 1478 (2007): 187–196.

[9] The analysis was carried out as part of the project "Biochar in Agriculture – Perspectives for Germany and Malaysia" funded by the Leibniz Association, www2.atb-potsdam.de/biochar/biochar_start.htm. The detailed assumptions and calculations will be published shortly in a DIW Discussion Paper.

[10] Biochar can be produced in traditional ways in small, simple kilns. However, the following focuses on more sophisticated industrial technologies.

bonization (HTC).[11] While the biomass is heated without oxygen in the pyrolysis process, a small amount of oxygen is added in the gasification process. HTC differs fundamentally from these two processes in that water is added. Biochar produced by the HTC method is also called HTC char or hydrochar.

The biochar yield is determined by the conversion process as well as the specific reaction conditions, most importantly, the highest heating temperature and residence time. In particular, the average biochar yield decreases with an increase in the reaction temperature from slow pyrolysis to gasification. The highest biochar yields are obtained by the HTC method.

At the same time, the conversion process and reaction conditions determine the properties of the biochar. While the biochar yield decreases as the reaction temperature increases, the carbon content of the biochar increases in the reaction temperature.[12] Of the dry processes, the slow pyrolysis method transfers the most carbon from the biomass to the biochar.[13] Biochar from the dry processes is more stable than HTC char.[14]

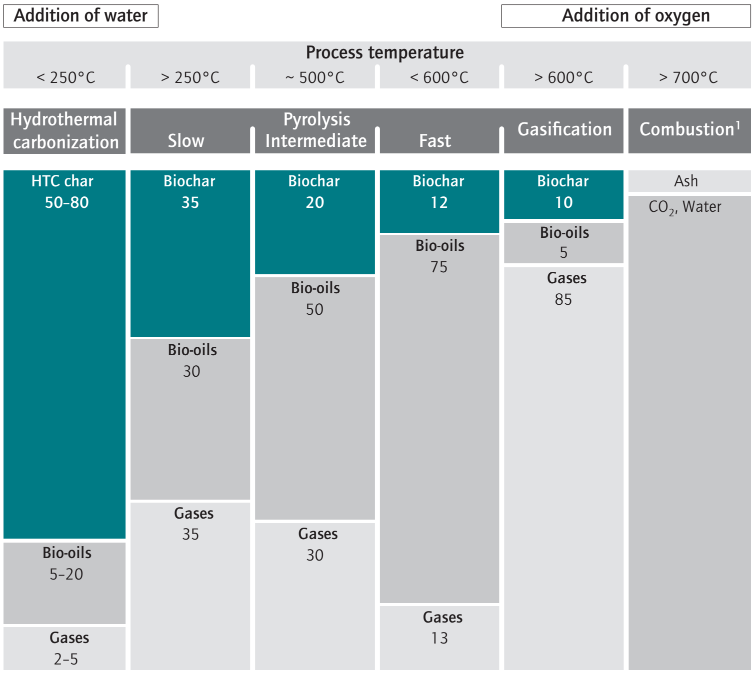
Therefore, biochar obtained from the (slow) pyrolysis process tends to be particularly suited for soil carbon sequestration, while the less stable HTC chars tend to be more advantageous for energetic uses. The gasification process is primarily aimed at extracting gases for energy purposes; however, if sufficient capacities were established, biochar from this process would also be suitable for carbon sequestration despite the lower biochar yield.[15]

From an economic perspective, HTC as a wet process seems advantageous for converting biomass with a high moisture content. In contrast to pyrolysis or gasification, the biomass does not have to be pre-dried at great expense in the HTC process.[16]

Figure 2

Thermochemical Conversion Processes for the Production of Biochar

Weight distribution in percent



1 No biochar is created during complete combustion It is only shown for comparison.

Sources: Quicker, "Thermochemische Verfahren," ORBIT, Weimar, (2012), 21-33; Libra et al., "Hydrothermal carbonization of biomass residuals," Biofuels 2(1), (2011): 89–124; DIW Berlin.

Biochar yields depend mainly on the process temperature.

Biochar Properties Depend Significantly on the Type of Feedstock

In the trade-off between conversion process, yield, properties and intended use of biochar, the initial biomass also plays an important role. In particular, the yield and the carbon content of biochar are highly dependent on the chemical composition of the biomass. For a given conversion process, for example, higher biochar yields can frequently be achieved from feedstocks with a high ash content.[17] This means, however, that the cor-

---

[11] J. A. Libra, K. S. Ro, C. Kammann, A. Funke, N. D. Berge, Y. Neubauer, M.-M. Titirici, C. Fühner, O. Bens, J. Kern, and K.-H. Emmerich, "Hydrothermal Carbonization of Biomass Residuals: A Comparative Review of the Chemistry, Processes and Applications of Wet and Dry Pyrolysis," Biofuels 2, no. 1 (2011): 89–124.

[12] For example, O. Mašek, P. Brownsort, A. Cross, and S. Sohi, "Influence of Production Conditions on the Yield and Environmental Stability of Biochar," Fuel 103 (2013): 151-155.

[13] For example, K. B. Cantrell, P. G. Hunt, M. Uchimiya, J. M. Novak, and K. S. Ro, "Impact of Pyrolysis Temperature and Manure Source on Physicochemical Characteristics of Biochar," Bioresource Technology 107 (2012): 419–428.

[14] For example, C. Kammann, S. Ratering, C. Eckhard, and C. Müller, "Biochar and Hydrochar Effects on Greenhouse Gas (Carbon Dioxide, Nitrous Oxide, and Methane) Fluxes from Soils," Journal of Environmental Quality 41, no.4 (2012): 1052–1066; S. Steinbeiss, G. Gleixner, and M. Antonietti, "Effect of Biochar Amendment on Soil Carbon Balance and Soil Microbial Activity," Soil Biology & Biochemistry 41, no. 6 (2009): 1301–1310; Y. Kuzyakov, I. Subbotina, H. Chen, I. Bogomolova, and X. Xu, "Black Carbon Decomposition and Incorporation into Soil Microbial Biomass Estimated by ^{14}C Labeling," Soil Biology & Biochemistry 41, no. 2 (2009): 210–219.

[15] Libra et al., "Hydrothermal Carbonization of Biomass Residuals," 89–124.

[16] Libra et al., "Hydrothermal Carbonization of Biomass Residuals," 89–124.

[17] Cantrell et al., "Impact of Pyrolysis Temperature," 419–428.

responding biochar has a lower carbon content. At the same time, a higher ash content, as in liquid and solid manure, leads to a higher nutrient content of the biochar, which, in turn, is important for use in agriculture.

Multiple Benefits of Adding Biochar to Soils

If biochar is not used energetically, but added to soil, this might not only lead to a permanent sequestration of carbon, but also improve the quality of the soil. In addition, the conversion of biomass into biochar enables valuable recycling of biomass residues, such as liquid manure, which sometimes occur in such large quantities that a use in agriculture becomes difficult.[18] Moreover, biochar production results in both liquid and gaseous by-products, which can be used in renewable energy generation (see Figure 1).

Carbon Sequestration through Biochar

The soil incorporation of biochar can serve as a near-surface carbon sink due to the high content of stable carbon in the biochar.[19] As a rough estimate, about half of the carbon removed from the atmosphere through photosynthesis remains in the biomass; thereof, in turn, about half is recovered in biochar during pyrolysis.[20] Up to 80 percent of that carbon might remain stable in the soil long-term. Consequently, converting biomass into biochar, up to 20 percent of the carbon that was originally taken up by the plants through photosynthesis might be removed from the atmosphere for the medium to long term. Without transforming the biomass into biochar, the biomass carbon would be fully released over the life cycle of a plant—either through natural decomposition processes or through the energetic use of the biomass.[21]

However, it has not yet been possible to quantify the long-term stability of biochar in soil exactly. The stability depends on many factors, such as the biomass the biochar is made of, the specific conversion process, the soil the biochar is added to, and the climatic and environmental influences the biochar is exposed to. In general, soil processes are very complex and difficult to quantify.[22] In addition, the effect of carbon sequestration might be eliminated, for example, as soon as there is a fire on the site where the biochar was added to the soil. For an overview of the current options for determining the stability of biochar, see the box.

Agricultural Benefits Possible, But Not Certain

The introduction of carbon into the soil and biochar's capability to store nutrients and water particularly well could help improve the quality of the soil and, thereby, increase agricultural productivity. In this way, the addition of biochar could increase plant growth. Likewise, it could reduce the use of synthetic fertilizers. However, it has not yet been completely understood how biochar affects plant growth exactly, especially in the long term. A recent metastudy on the short- to medium-term effects of biochar shows an average yield increase of 10 percent, whereby the results range from -28 percent to +39 percent.[23] Thus, negative effects on plant growth cannot be ruled out. Ultimately, the effects depend on many factors, in particular, the plant species, the type and quantity of biochar added, the type of soil, and other environmental conditions. Generally, smaller growth impulses are expected in the temperate zone than in tropical or subtropical regions, which usually have less fertile soils.

Biochar and the Other Conversion Products Can Be Used Energetically

As an alternative to soil incorporation, biochar can also be used to produce energy.[24] This can be particularly useful if the transport or the direct energetic use of the original biomass are not practicable. For example, biochar can be co-combusted in conventional coal-fired power plants. The calorific values of biochar depend on the feedstock and the chosen conversion process. The conversion of wood into biochar in the pyrolysis process, for example, can result in calorific values of up to 30 megajoules per kilogram (MJ/kg), which corresponds

---

[18] Libra et al., "Hydrothermal Carbonization of Biomass Residuals," 89–124.

[19] In contrast, carbon capture, transport and storage (CCS or CCTS), whose practicability has been much discussed lately, involves sequestering CO_2 in geological depths. See C. von Hirschhausen, J. Herold, P.-Y. Oei, and C. Haftendorn, "CCTS-Technologie ein Fehlschlag: Umdenken in der Energiewende notwendig," Wochenbericht des DIW Berlin, no. 6 (2012).

[20] J. Lehmann, "A Handful of Carbon," Nature 447 (2007): 143–144.

[21] However, this comparison abstracts from a possible stabilization of biomass carbon through soil processes when biomass is introduced into the soil.

[22] M. W. I. Schmidt, M. S. Torn, S. Abiven, T. Dittmar, G. Guggenberger, I. A. Janssens, M. Kleber, I. Kögel-Knabner, J. Lehmann, D. A. C. Manning, P. Nannipieri, D. P. Rasse, S. Weiner, and S. E. Trumbore, "Persistence of Soil Organic Matter As an Ecosystem Property," Nature 478 (2011): 49–56.

[23] S. Jeffrey, F. G. A. Verheijen, M. van der Velde, and A. C. Bastos, "A Quantitative Review of the Effects of Biochar Application to Soils on Crop Productivity Using Meta-Analysis," Agriculture, Ecosystems and Environment 144, no. 1 (2011): 175–187.

[24] In addition, biochar may be used as a material, for example, as a feed additive, as a reductant in metallurgical processes, or as a raw material for carbon fibers and plastic.

Box

Determining the Stability of Biochar

The proportion of biochar carbon that remains stable in the soil for the long-term is not precisely quantifiable. However, there are a number of methods for measuring the stability of biochar that provide estimates for possible orders of magnitude.

Some methods are based on the properties of the biochar itself. For example, there are various indicators of the content of stable carbon in the biochar. These include, among others, the share of fixed carbon, the ratio of oxygen to carbon,[1] or a combination of the volatile-matter content of the biochar with the ratio of oxygen or hydrogen to organic carbon.[2] In addition, a so-called recalcitrance index was developed to indicate the thermal stability of biochar compared to that of graphite.[3] The higher this index, the higher the carbon sequestration potential of the biochar. Another indicator is measuring the share of aromatic carbon.[4] Common to these indicators, however, is that they cannot reflect the decomposition processes the biochar is exposed to in the soil.

The methods that attempt to mimic these decomposition processes include incubation studies in which laboratory-produced biochar is mixed with soil samples and then subjected to certain thermal, chemical, or other treatments. Based on the incubation studies, which are usually of only short duration, conclusions can then be drawn for the long-term stability of biochar. The results of these studies point to the longevity of biochar. For example, mean residence times of at least 200 to 2,000 years were inferred for biochar in soils in temperate latitudes.[5]

Another approach is to measure the stability of historical biochar in its natural environment. The results for such naturally occurring biochar vary significantly. For instance, mean residence times between 718 and 9,259 years were calculated for biochar from vegetation fires in Australian soils.[6] In contrast, naturally occurring biochar in soils in Zimbabwe appears to survive only for decades to centuries,[7] while biochar in Kenya was found to have a mean residence time of only 8.3 years.[8] These mixed results indicate that the stability of biochar depends on many factors, not least on climatic conditions and other environmental influences. In addition, there are considerable difficulties and differences in determining the quantities of natural biochar present in soils.

Finally, the findings derived from Terra Preta studies suggest that biochar can be stored in the soil over a period of thousands of years. Radio carbon dating of biochar in certain European soils has produced similar results, with biochar ages ranging from 1,160 to 5,040 years.[9] In the case of these measurements, however, the amount of biochar that was originally added to the soil is unknown.

---

[1] K.A. Spokas, “Review of the Stability of Biochar in Soils: Predictability of O:C Molar Ratios,” Carbon Management 1, no.2 (2010): 289–303.

[2] Enders et al., “Characterization of Biochars,” 644–653.

[3] O.R. Harvey, L. J. Kuo, A.R. Zimmerman, P. Louchouarn, J.E. Amonette, and B.E. Herbert, “An Index-Based Approach to Assessing Recalcitrance and Soil Carbon Sequestration Potential of Engineered Black Carbons (Biochars),” Environmental Science & Technology 46, no.3 (2012): 1415–1421.

[4] For example K. Hammes, R.J. Smernik, J.O. Skjemstad, A. Herzog, U. F. Vogt, and M.W.I. Schmidt, “Synthesis and Characterisation of Laboratory-Charred Grass Straw (Oryza Sativa) and Chestnut Wood (Castanea Sativa) As Reference Materials for Black Carbon Quantification,” Organic Geochemistry 37, no. 11 (2006): 1629–1633.

[5] Kuzyakov et al. “Black Carbon Decomposition,” 210–219.

[6] J. Lehmann, J. Skjemstad, S. Sohi, J. Carter, M. Barson, P. Falloon, K. Coleman, P. Woodbury, and E. Krull, “Australian Climate-Carbon Cycle Feedback Reduced by Soil Black Carbon,” Nature Geoscience 1 (2008): 832–835.

[7] M.I. Bird, C. Moyo, E.M. Veenendaal, J. Lloyd, and P. Frost, “Stability of Elemental Carbon in a Savannah Soil,” Global Biogeochemical Cycles 13, no.4 (1999): 923–932.

[8] B. T. Nguyen J. Lehmann, J. Kinyangi, R. Smernik, S.J. Riha, and M.H. Engelhard, “Long-Term Black Carbon Dynamics in Cultivated Soil,” Biogeochemistry 89, no.3 (2008): 295–308.

[9] M.W.I. Schmidt, J.O. Skjemstad, and C. Jäger, “Carbon Isotope Geochemistry and Nanomorphlogy of Soil Black Carbon: Black Chernozemic Soils in Central Europe Originate From Ancient Biomass Burning,” Global Biogeochemical Cycles 16, no.4 (2002): 70-1-70-8.

Table 1

Biomass and Biochar Potentials in Germany in 2030

	Feedstocks[2]	Biomass potentials		Biochar		
		For energetic use	*Thereof: assumed use for biochar*	Yield	Carbon content	Mass
		Thousand tonnes of dry matter per year		Percent		Thousand tonnes of dry matter per year
Solid biomass	Cereal straw	2,971	1,040	34	70	354
	Forestry residues	9,534	3,337	30	81	1,001
	Open-country biomass residues	1,264	442	31	69	137
	Industrial wood waste	3,098	1,084	29	82	314
	Wood in municipal solid waste[3]	1,225	429	30	81	129
	Green waste: Compensation areas	570	200	32	63	64
	Biomass: Habitat-connectivity areas	1,100	385	31	69	119
	Green waste: Extensive grassland	1,630	571	31	69	177
	Poplars and willows: Erosion areas	5,500	1,925	25	72	481
Digestable biomass	Sewage sludge	965	338	49	35	166
	Cattle manure	4,753	1,664	47	51	782
	Swine manure	1,276	447	47	49	210
	Poultry manure	814	285	44	46	125
	Liquid manure (cattle and swine)	8,967	3,138	45	44	1,412
	Crop residues (potato haulm and sugar-beet leaf)	884	309	45[1]	51[1]	139
	Commercial and industrial waste	595	208	37	66	77
	Organic municipal solid waste	2,296	804	45[1]	63	362
	Digestates from energy crops (corn)	3,589	2,692	49	42	1,319
	Total	**51,031**	**19,296**	–	–	**7,369**

1 Calculated as the average of the corresponding values for digestable biomass.
2 Selection according to J. Nitsch, et al. and U. R. Fritsche, et al.
3 Wood content collected separately.
Sources: Nitsch et al., "Ökologisch optimierter Ausbau"; Fritsche et al., "Stoffstromanalyse"; calculations by DIW Berlin.

The greatest biochar potentials are from liquid manure, digestates, and forestry residues.

approximately to the calorific value of hard coal.[25] Typical calorific values for HTC char are to be found between 20 MJ/kg and below 30 MJ/kg, but well above the calorific value of lignite.[26] However, also significantly lower calorific values are possible in general.

Irrespective of the intended use of the biochar itself, the bio-oils and gases generated as by-products of the biochar production process can also be used for energy generation. The bio-oils can be used as a valuable transport fuel after they have been converted to bio-diesel, for example.[27] Depending on the chosen conversion process, the gases consist primarily of carbon monoxide, carbon dioxide, hydrogen, methane, and other hydrocarbons. A mixture of carbon monoxide and hydrogen (synthesis gas), for example, can be used to generate heat and electricity or be converted into transport fuels.[28]

Potentials for the Use of Biochar in Agriculture as a Carbon Sink in Germany

Against the background of the German government's climate goals, it is important to determine biochar's potential contribution to climate protection. At DIW Berlin, the greenhouse gas mitigation potentials and costs of biochar in German agriculture have been calculated, taking account of the energetic use of the bio-oils and gases generated during biochar production.

---

[25] P. Quicker, "Thermochemische Verfahren zur Erzeugung von Biokohle," in "Biokohle im Blick – Herstellung, Einsatz und Bewertung," eds. K. Fricke, C.-G. Bergs, C. Kammann, P. Quicker, and R. Wallmann, ORBIT (Weimar: 2012): 21–33.

[26] Quicker, "Thermochemische Verfahren," 21-33.

[27] R. Slade, R. Saunders, R. Gross, and A. Bauen, Energy From Biomass: The Size of the Global Resource, Imperial College Centre for Energy Policy and Technology and UK Energy Research Centre (London: 2011).

[28] Slade et al., Energy From Biomass.

Due to the importance of the initial biomass for the yield and properties of the biochar, the abatement opportunities and costs were differentiated according to the type of feedstock. The study considered only biochars produced in the slow pyrolysis process since they tend to be very stable in soil and since the carbon transfer from the biomass to the biochar is especially high.

Exemplifying the analysis, the following provides the results from a chosen scenario for 2030.[29] The reference is provided by a so-called baseline scenario, i.e. by assumptions about the conventional feedstock management if the biomass is not converted to biochar. Although the costs of carbon sequestration through biochar might be reduced by possible co-benefits in agriculture, these effects are not taken into account here.

Climate Protection Potential of Biochar Depends Largely on Availability of Biomass

Besides the choice of the baseline scenario and other assumptions, the greenhouse gas abatement potential of biochar depends largely on the assumed biomass potential available for biochar. In order to obtain a reasonably realistic estimate of the biomass potential for future biochar production in Germany, first, the calculations were based on the biomass potentials considered available for energy generation in the literature.[30] Then, assumptions were made as to how much of this potential could be used for biochar. Thereby, the focus was primarily on biomass residues. Digestates from biogas production were explicitly included in the analysis to take account of so-called cascade utilization in which a raw biomass material is first used to produce energy and then to produce biochar.[31]

Table 1 shows the biomass potentials the calculations for 2030 are based on. The chosen scenario assumes that there will be a relatively high availability of biomass for the production of biochar—35 percent of the energetic potential of solid and digestable biomass and 75 percent of the potentially available digestates from energy crops.[32] The table also shows the quantities of biochar that can be produced from this biomass. The largest quantities of biochar can be generated from liquid manure and digestates from energy crops, followed by forestry residues. In total, approximately 19 million tonnes of biomass (dry mass) are available in the chosen scenario. They can be turned into more than 7 million tonnes of biochar.

Based on assumptions in the literature, 68 percent[33] of the carbon in biochar made from solid biomass and 34 percent[34] of the carbon in biochar made from digestable biomass and digestates are considered to remain stable in the long term, that is, for at least 100 years. In addition to the carbon sequestration from adding biochar to the soil, the analysis also covers the avoided emissions of CO2, methane (CH4) and nitrous oxide (N2O) caused by the shift from conventional feedstock management to biochar production. These include, for example, emissions from the conventional manure management or composting. The emissions avoided by substituting fossil fuels by the pyrolysis oils and gases are also taken into account. These vary depending on whether lignite, hard coal, or natural gas are replaced, and whether they are used for the production of heat or electricity.[35]

The production and use of biochar, however, also leads to some emissions, for example, caused by transporting the biomass and biochar between the pyrolysis plants and fields, by adding the biochar to the soil, and by soil processes. In addition, energy is required for drying the biomass and for the pyrolysis process itself. Since the demand for this energy is only generated by the biochar production, the study assumes that fossil energy sources will be used to cover this demand, thereby, causing greenhouse gas emissions.[36]

---

[29] In the specific scenario, it is assumed that biochar is produced in medium-sized pyrolysis plants with an annual biomass capacity of 16,000 tonnes of dry matter. An upcoming DIW Discussion Paper includes a number of other scenarios up to 2050. The scenarios differ, in particular, according to the possible feedstock-specific biomass potential, the size of the pyrolysis plants, and the amount of biochar that is incorporated into the soil.

[30] J. Nitsch, W. Krewitt, M. Nast, P. Viebahn, S. Gärtner, M. Pehnt, G. Reinhardt, R. Schmidt, A. Uihlein, K. Scheurlen, C. Barthel, M. Fischedick, and F. Merten, Ökologisch optimierter Ausbau der Nutzung erneuerbarer Energien in Deutschland, Research Project on behalf of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, FKZ 901 41 803, long version (Stuttgart, Heidelberg, Wuppertal: 2004); and U. R. Fritsche, G. Dehoust, W. Jenseit, K. Hünecke, L. Rausch, D. Schüler, K. Wiegemann, A. Heinz, M. Hiebel, M. Ising, S. Kabasci, C. Unger, D. Thrän, N. Fröhlich, F. Scholwin, G. Reinhardt, S. Gärtner, A. Patyk, F. Baur, U. Bemmann, B. Groß, M. Heib, C. Ziegler, M. Flake, M. Schmehl, and S. Simon, Stoffstromanalyse zur nachhaltigen energetischen Nutzung von Biomasse, Joint Project supported by the BMU as part of ZIP, promoter: FZ Jülich, final report (Darmstadt, Berlin, Oberhausen, Leipzig, Heidelberg, Saarbrücken, Braunschweig, Munich: 2004).

[31] Cp. J. Mumme, "HTC, Biogas und Landwirtschaft – das APECS-Konzept," in "Biokohle im Blick – Herstellung, Einsatz und Bewertung," eds. K. Fricke, C.-G. Bergs, C. Kammann, P. Quicker, and R. Wallmann, ORBIT (Weimar: 2012): 135.

[32] An alternative scenario, not discussed in more detail here, is to first use the digestable biomass residues for biogas production and then to use the resulting digestate to make biochar.

[33] S. Shackley, J. Hammond, J. Gaunt, and R. Ibarrola, "The Feasibility and Costs of Biochar Deployment in the UK," Carbon Management 2, no.3 (2011): 335–356.

[34] Author's own assumptions based on the reduced stability of biochar with high ash content. Cp. A. Enders, K. Hanley, T. Whitman, S. Joseph, and J. Lehmann, "Characterization of Biochars to Evaluate Recalcitrance and Agronomic Performance," Bioresource Technology 114 (2012): 644–653.

[35] For the case outlined here, it is assumed that the pyrolysis oils and gases replace hard coal in power generation.

[36] It is assumed here that the heat required for the pyrolysis process (including drying the biomass) is derived from natural gas.

Table 2

Greenhouse Gas Mitigation Potentials and Costs of Biochar in Germany in 2030

	Feedstocks[2]	Baseline scenario	Mitigation potential		Mitigation costs
			Tonnes of CO_2 equivalents per tonne of biomass (dry mass)	Thousand tonnes of CO_2 equivalents	Euros per tonne of CO_2 equivalent
Solid biomass	Cereal straw	Decomposition in field	0.86	893	187
	Forestry residues	Decomposition in forest	0.93	3,088	256
	Open-country biomass residues	Composting, land spread	1.24	547	76
	Industrial wood waste	Energetic use	−0.19	−206	–
	Wood in municipal solid waste[3]	Composting, land spread	1.34	575	68
	Green waste: Compensation areas	Decomposition on site	0.76	152	367
	Biomass: Habitat-connectivity areas	Composting, land spread	1.24	476	76
	Green waste: Extensive grassland	Composting, land spread	1.24	707	76
	Poplars and willows: Erosion areas	Energetic use	−0.29	−566	–
Digestable biomass	Sewage sludge	Composting, land spread	0.04	12	4,044
	Cattle manure	Solid storage, land spread	0.54	897	220
	Swine manure	Solid storage, land spread	0.90	404	148
	Poultry manure	Solid storage, land spread	0.68	194	151
	Liquid manure (cattle and swine)	Liquid storage, land spread	−0.62	−1,960	–
	Crop residues (potato haulm and sugar-beet leaf)	Decomposition in field	−0.46	−143	–
	Commercial and industrial waste	Composting, land spread	0.92	192	119
	Organic municipal solid waste	Composting, land spread	0.46	371	277
	Digestates from energy crops (corn)	Composting, land spread	0.05	141	2,979
	Total	–	–	8,648[1]	–

1 Includes only positive abatement potentials.
2 Selection according to J. Nitsch, et al. and U. R. Fritsche, et al.
3 Wood content collected separately.
Source: calculations by DIW Berlin.

Greenhouse gas mitigation potentials and costs for the individual feedstocks vary widely.

Table 2 summarizes the greenhouse gas emissions that are sequestered or avoided by the use of biochar and of the pyrolysis oils and gases. In the example chosen here, they amount to approximately 8.6 million tonnes of CO2 equivalents in 2030. This potential corresponds to approximately 1.3 percent of the reduction target for 2030 of 678 million tonnes of CO2.[37] Thereby, the greatest greenhouse gas abatement potential is associated with biochar made from forestry residues, that is, from a relatively dry feedstock occurring in relatively large quantities.

The 8.6 million tonnes of CO2 do not include biochar produced from industrial wood waste, poplars and willows from erosion areas, liquid manure (cattle and swine) and crop residues (potato haulm and sugar-beet leaves), which result in positive greenhouse gas emissions. The reasons for the additional greenhouse gas emissions when using industrial wood waste as well as poplars and willows can be found in the chosen baseline scenario, which assumes that both feedstocks are used energetically. Replacing hard coal, the conventional feedstock management reduces greenhouse gas emissions considerably. If, instead, biochar is produced from these feedstocks, the emission reductions are comparatively low. For liquid manure and crop residues, in turn, the high emissions from drying these very wet feedstocks are crucial for the negative greenhouse gas balance.

Costs of Biochar Carbon Sequestration Vary Widely and Are Sometimes Substantial

Table 2 also contains the specific costs associated with the production of biochar and its addition to soil, as compared to the baseline scenario. The costs mainly consist of the investment and operating costs for the pyrolysis plants, the feedstock and transport costs for the biomass as well as the costs of transporting and storing the biochar and adding it to the soil. The items that have to be deducted from the costs include the revenues from providing the pyrolysis oils and gases for energy generation as well as the avoided costs associated with conventional feedstock management in the baseline scenario.

---

[37] The 678 million tonnes of CO_2 are calculated based on the base year emissions in Germany of 1,232.4 million tonnes of CO_2 and the reduction target of 55 percent. See UNFCCC, Report of the Review of the Initial Report of Germany (2007).

Given the applied assumptions, the costs of greenhouse gas abatement in 2030 range from 68 euros per tonne of CO2 for wood in municipal solid waste to over 4,000 euros per tonne of CO2 for sewage sludge. The very high specific costs for sewage sludge and digestates from energy crops (corn) are caused by the very high water contents of these substrates.

Figure 3 summarizes the potentials and costs of carbon sequestration and greenhouse gas abatement from biochar in a so-called marginal abatement cost curve. Thereby, the possible measures for greenhouse gas abatement—based on the feedstocks used for the biochar—are first ordered by cost (lowest first). Then, the abatement potential (in millions of tonnes of CO2 equivalents) for each measure is plotted on the horizontal axis and the associated costs (in euros per tonne of avoided CO2 equivalent) are shown on the vertical axis. For a given level of greenhouse gas abatement, the curve shows the costs that would be incurred by an additional unit of greenhouse gas abatement—known as the marginal abatement costs. Consequently, the curve indicates which measures can most efficiently achieve a given greenhouse gas reduction target. At the same time, the curve shows the amount of greenhouse gas emissions that can be mitigated at a given carbon price—such as in an emissions trading system—when only taking into account greenhouse gas abatement measures with costs at or below the carbon price.

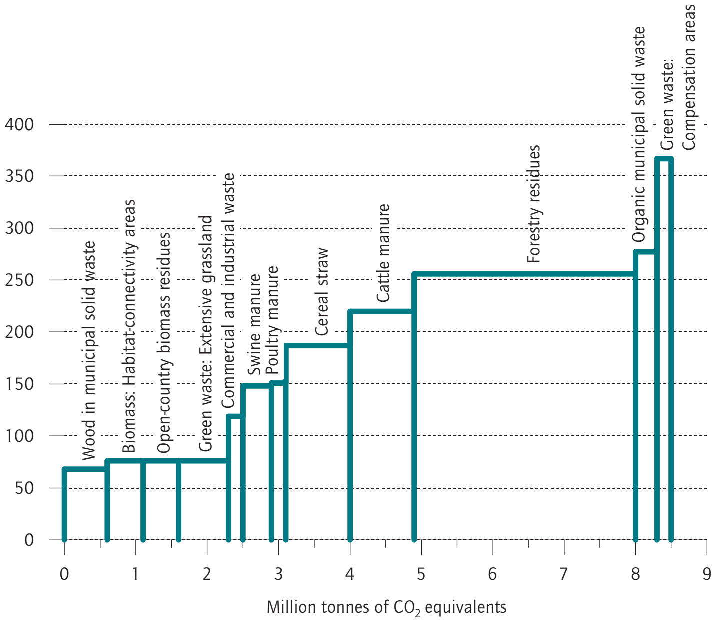
As shown in Figure 3, only approximately 2.3 million tonnes of greenhouse gases can be mitigated with the help of biochar in 2030 at a cost below 100 euros per tonne of CO2 equivalent, i.e. only about 0.3 percent of the reduction target for 2030. This refers to biochar made of the following feedstocks: wood in municipal solid waste, biomass from habitat-connectivity areas, open-country biomass residues, and green waste from extensive grassland.

The calculated values are comparable to the results obtained from a similar study for the UK.[38] The study finds that – depending on the assumed biomass potential – approximately one to six million tonnes of CO2 can be mitigated annually by using biochar in British agriculture; however, at a price of just 29 US dollars per tonne of CO2 (based on 2007 prices) or approximately 21 euros per tonne of CO2.[39]

Figure 3

Marginal Abatement Cost Curve[1] of Possible Biochar Options in Germany in 2030

Euros per tonne of CO_2 equivalent



1 Only options with abatement costs of less than 400 euros per tonne of CO_2 equivalent are shown. Thus, biochars from sewage sludge and from digestates from energy crops (corn) are not shown. In addition, options resulting in negative emission abatement are not included (industrial wood waste, poplars and willows, liquid manure, and crop residues).

Source: calculations by DIW Berlin.

About 2.3 million tonnes of CO_2 can be mitigated at a cost of less than 100 euros per tonne of CO_2 equivalent.

A comparison of biochar with other greenhouse gas abatement measures does not permit any general conclusions. Compared to the broad-scale implementation of CCS in the energy sector—which is, however, unrealistic from today's perspective[40]—the greenhouse gas abatement potential of biochar appears low and its costs seem high. For 2030, McKinsey & Co. arrived at a mitigation potential of 66 million tonnes of CO2 through CCS, at a cost of 30 to 90 euros per tonne of CO2.[41] In the same study, an abatement potential of nine million tonnes of CO2 was assumed for the energetic use of biomass—for 2020, however—whereby the cost was generally less than 30 euros per tonne of CO2. Finally, for certain biofuels, the costs of greenhouse gas abatement were estimated to reach 190 to 240 euros per tonne of

---

38 Shackley et al., "The Feasibility and Costs of Biochar," 335–356.

39 The conversion was based on the average 2007 exchange rate of 1.3705 US dollars to 1 euro. See Deutsche Bundesbank, Euro Reference Exchange Rates of the European Central Bank: End-of-Year Rates and Annual Averages, exchange rate statistics as of Dec 31, 2012.

40 See von Hirschhausen et al. "CCTS-Technologie ein Fehlschlag."

41 McKinsey & Company, Costs and Potentials of Greenhouse Gas Abatement in Germany, a report by McKinsey & Company, Inc., on behalf of "BDI initiativ – Business for Climate."

CO_2 by 2020, with a low abatement potential of approximately one million tonnes of CO_2.

The greenhouse gas abatement potential and costs of biochar strongly depend on the assumptions made about future developments. These include, in particular, the chosen baseline scenario, the fossil fuels used for biomass drying and pyrolysis, the fossil fuels replaced by the pyrolysis oils and gases, as well as the size and distribution of the pyrolysis plants. Following a change in the set of assumptions, further cost reductions and/or increases in the greenhouse gas abatement potential may be possible.

Conclusion

Biochar is produced by heating biomass in the near absence of oxygen. It is characterized by a high and stable carbon content as well as large nutrient-retention and water-holding capacities. These properties render biochar very attractive for an application in agriculture. By incorporating biochar into soils, carbon dioxide can be removed from the atmosphere for long time scales. At the same time, soil fertility can be increased.

Given it will be possible in the future to precisely quantify how much carbon can be stored long-term in soil using biochar, the use of biochar in German agriculture seems a possible option for climate protection, which could complement other greenhouse gas mitigation measures. Based on the sample calculation presented in this report, approximately 1.3 percent of the German greenhouse gas reduction target for 2030 could be achieved through the use of biochar in agriculture, approximately 0.3 percent at costs below 100 euros per tonne of CO_2.

The specific greenhouse gas abatement potentials and associated costs depend on the chosen scenario assumptions, in particular on the biomass potential considered available for biochar. Thereby, competition with food production and energy generation for the use of biomass must also be taken into account, but cannot be studied in more detail in a scenario-based analysis like this. In addition, future research will reveal to what extent possible agricultural co-benefits of biochar in the form of enhanced soil fertility will improve biochar's greenhouse abatement potential and costs.

In other climate regions, the assessment of biochar might differ from that in Germany. Particularly in the tropics and subtropics, which typically have severely degraded soils, biochar might significantly improve soil quality. This is also supported by the example of Terra Preta.

While the present analysis has focused on the soil incorporation of biochar, its use in generating energy should be studied in more detail. In particular, the use of wet biomass residues in the HTC process to produce biochar for generating energy may prove to be an efficient alternative. Optimized combinations of feedstock types, biochar production processes and biochar use can be expected to increase the areas of biochar application and to reduce its costs.

Isabel Teichmann is a Research Associate in the Energy, Transportation, Environment Department at DIW Berlin

JEL: Q15, Q24, Q54
Keywords: Biochar, soil carbon sequestration, climate change, agriculture

DIW Berlin—Deutsches Institut
für Wirtschaftsforschung e. V.
Mohrenstraße 58, 10117 Berlin
T +49 30 897 89 -0
F +49 30 897 89 -200

Volume 4, No 4
11 April, 2014
ISSN 2192-7219

Translation
HLTW Übersetzungen GbR
team@hltw.de

Press office
Renate Bogdanovic
Tel. +49-30-89789-249
presse@diw.de

Sales and distribution
DIW Berlin