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Potentials to Mitigate Climate Change Using Biochar

The Austrian Perspective

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Potentials to mitigate climate change using biochar – the Austrian perspective

Forebiom Country Case Report Austria

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Climate change mitigation strategies, such as carbon capture and storage (CCS) are essential to secure the future of humanity as carbon emissions due to increased human activities are constantly rising. As provision of energy is the largest anthropogenic source of carbon dioxide from combustion of fossil fuels, biomass utilization is seen as one of various promising strategies to reduce additional emissions. A recent project on potentials of biochar to mitigate climate change (FOREBIOM) goes even a step further towards bioenergy in combination of CCS or "BECS" and tries to assess the current potentials, from sustainable biomass availability to biochar amendment in soils, including the identification of potential disadvantages and current research needs. The current report represents an outcome of the 1st FOREBIOM Workshop held in Vienna in April, 2013 and tries to characterize the Austrian perspective of biochar for climate change mitigation. The survey shows that for a wide-spread utilization of biochar in climate change mitigation strategies, still a number of obstacles have to be overcome. There are concerns regarding production and application costs, contamination and health issues for both producers and customers besides a fragmentary knowledge about biochar-soil interactions specifically in terms of long-term behavior, biochar stability and the effects on nutrient cycles. However, there are a number of positive examples showing that biochar indeed has the potential to sequester large amounts of carbon while improving soil properties and subsequently leading to a secondary carbon sink via rising soil productivity. Diversification, cascadic utilization and purpose-designed biochar production are key strategies overcoming initial concerns, especially regarding economic aspects. A theoretical scenario calculation showed that relatively small amounts of biomass that is currently utilized for energy can reduce the gap between Austria's current GHG emissions and the Kyoto target by about 30% if biomass residues are pyrolized and biochar subsequently used as soil amendment. However, by using a more conservative approach that is representing the aims of the underlying FOREBIOM project (assuming that 10% of the annual biomass increment from forests is used for biochar production), each year 0.38 megatons CO_2e could potentially be mitigated in Austria, which is 0.4% of total or 5% of all GHG emissions caused by agriculture in Austria in 2010. In order to produce this amount of biochar annually, about 27 medium-scale or 220 small-scale pyrolysis plants would be required. The economic analysis revealed that biochar yield, carbon sequestration and feedstock costs have the highest influence on GHG abatement costs.

1. Climate change and the carbon cycle

Climate change is a rising threat for the entire world population. It makes future uncertain, especially in terms of provision of food and the usability of natural resources because a greater number and intensity of extreme weather events is expected as a consequence. Besides the direct physical damage such events may create on local scales, moderate, but persistent changes e.g. in temperature and precipitation, have the ability to change the capacities to produce enough food and consequently cause hunger, social inequalities and conflicts for resources. Although it is important to point out that there are both losers and winners in climate change scenarios, there is a good chance that the negative consequences dominate at the end of the day. There is no doubt in the scientific community that anthropogenic greenhouse gas (GHG) emissions are indeed playing a key role in rising global average temperatures during the last decades. Carbon dioxide (CO_2) is put into center stage as it is the most abundant, and therefore most significant anthropogenic GHG despite the fact that there are a number of other common, yet more effective GHG's emitted, e.g. methane (CH_4) or nitrous oxide (N_2O). In terms of global warming potential, methane and nitrous oxide have a 25- and 298-fold warming potential respectively, compared to CO_2 on a 100-year time-horizon (IPCC 2007). Since CO_2 is in terms of quantity the prime GHG emitted when fossil fuels are utilized, it is obvious that atmospheric concentrations are increasing, because fossil fuel deposits are very efficient long-term stores for carbon. On a global basis, the energy industry is the largest emitter of CO_2 (IPCC 2007). The question is, however, how to reduce CO_2 emissions and, in the best case, stabilize or even decrease atmospheric CO_2 concentrations. The relatively simple, yet hard to implement answer is that it needs global joint efforts on multiple scales to reach this goal. Everyone can contribute starting with daily life decisions, e.g. choice of transportation systems, diet and energy efficient lifestyles. However, on industrial scales, scientists and engineers are working on concepts of carbon capture and storage (CCS), where supercritical CO_2 is compressed and deposited in geologically suitable formations. Newer concepts, often referred to as "second generation CO_2 capture methods" include technologies such as dry sorption of CO_2 (carbon looping) or membrane-based methods. Recently, also CO_2 capturing and utilization (CCU) is studied since CO_2 may be used as a valuable feedstock for industrial processes (Markewitz, Kuckshinrichs et al. 2012). However, the focus is usually set at fossil fuelled plants. A step further towards atmospheric carbon management is the promotion of carbon-negative energy systems. Bioenergy in combination with CCS, or "BECS" as indicated by Mathews (2008), may be a potential solution to achieve negative emissions. The current report is the outcome of the project "Potentials for realizing negative carbon emissions using forest biomass and subsequent biochar recycling" (FOREBIOM[1]), trying to assess the potentials for BECS, using woody biomass from forestry as a feedstock material and subsequent biochar amendment.

2. The role of forests in climate change mitigation

The role of forests in global climate change mitigation is significant and manifold. Forests represent the largest terrestrial carbon pool and therefore may act as either sink or source of atmospheric carbon. It is widely recognized that proper forest management is therefore crucial to avoid negative implications on the global carbon cycle. Combating deforestation and improved management practices, e.g. increasing forest productivity, may conserve or sequester significant amounts of carbon (Dixon, Solomon et al. 1994). The authors emphasize that over two third of the total carbon in forest ecosystems is stored in soils. Consequently, forest management has to consider effective soil management in view of climate change mitigation. Human activities have a strong impact on carbon pools in both managed and unmanaged forests and can therefore significantly influence atmospheric carbon concentrations. There are in principle two major pathways of sequestering carbon in forest soils, through litterfall and subsequent degradation, where all aboveground biomass compartments may act as a source. The second pathway originates from belowground sources, such as root and mycorrhizal turnover as well as plant excretions. There is growing evidence in recent years that the latter mechanism may be the most important not only in forest ecosystems but in all vegetated areas (Rasse, Rumpel et al. 2005; Godbold, Hoosbeek et al. 2006).

The role of forests in climate change mitigation is well recognized and a number of recent political decisions reflect the growing critical comments expressed by the international scientific community. As the tropics are the dominant climatic zone in terms of terrestrial-atmospheric carbon exchange (Pan, Birdsey et al. 2011), the Coalition of Rainforest Nations led by Papua New Guinea proposed the United Nations Reducing Emissions from Deforestation and Degradation Program (REDD) in 2005 which was added to the agenda at the 2007 COP13 conference of the UNFCCC[2] in Bali. Basically it represents a market-based mechanism where rich nations pay for reduced deforestation and land degradation in tropical countries. The idea behind this mechanism is that the value of the managed forest (in monetary terms) is higher than if it is clear-cut and the forest will be therefore protected against exploitation with unsound methods leading to further degradation. As industries pay for their emissions, they are allowed to emit carbon dioxide, according to their payment. In terms of implementation, there are so far a number of ongoing activities but those are focused on preparedness in terms of legislation (e.g. access and use rights, sharing of revenue etc.) of the individual countries with leading efforts in Central and South America.

1 FOREBIOM is the acronym for a multinational project titled "Potentials for realizing negative carbon emissions using forest biomass and subsequent biochar recycling". The current report is based on this project which runs from October, 2012 to October 2014. The project consortium consists of partners from South Korea, Turkey and Austria. See http://www.oeaw.ac.at/forebiom for more details.

2 COP13 of the UNFCCC: The 13th session of the Conference of the Parties of the United Nations Framework Convention on Climate Change. The COP 13 took place from 3 to 14 December 2007 in Bali, Indonesia, and respective decisions can be accessed from https://unfccc.int/meetings/bali_dec_2007/session/6265/php/view/decisions.php

The stability or resilience against microbial decomposition of different carbon compartments in the soil is a key factor, setting the tipping points at which forests may become a source of atmospheric carbon. Besides management and guidelines for best practice, set into force by e.g. above mentioned political frameworks, the climate conditions are responsible for the balance between organic matter input and mineralization rates, which are inseparably connected with the emission of GHG's, specifically with carbon dioxide. As it is a direct product of the respiration of plants (autotrophic respiration) and soil microbes (heterotrophic respiration), the latter is strongly influenced by organic matter composition and quality. Mechanisms of stabilizing carbon in the soil may be of climatic origin (freezing, excess moisture or drought), intrinsic recalcitrance (pyrolized carbon, lipid compounds), physical stabilization (organo-mineral compounds) or inhibition of microbial activity (Trumbore 2009). Most mechanisms are given and difficult to influence as a consequence of climate conditions or intrinsic soil properties. However, recalcitrance may be achieved applying industrial processes, such as pyrolysis while typical by-products (volatile compounds separated during the process) may be used as a feedstock for industrial processes or as a source for thermal energy, as proposed in the FOREBIOM project.

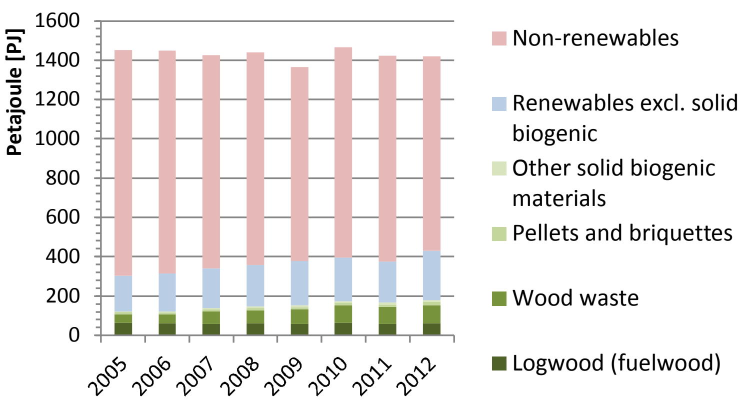

Figure 1: Gross domestic energy consumption in Austria from 2005—2012 (Bittermann 2014). The trend of increasing shares of biomass and other renewables is clearly visible. The lower consumption in 2009 as a consequence of the global financial crisis is relatively small and immediately compensated a year later in 2010.

3. Energy demands and bioenergy provision in Austria in context to European Union policies

The gross domestic energy consumption almost doubled from 797 to 1.421 Petajoule [PJ] between 1970 and 2012 (Bittermann 2014). The share of renewables increased in the same period from 16 to 30%, with a remarkable increase from 21 to 30% from 2005 to 2012 (see Figure 1). With close to 59% in 2009, biomass is by far the most significant contributor to renewable energy in Austria, followed by hydropower (37%) and others sharing the remaining 4% (wind, geothermal and heat pump, solar thermal and photovoltaic) (Austrian Energy Agency 2012). A technical potential[3] of biomass resources of 368 PJ per year is presented in a recent report, published as a result of the 4biomass project (Schilcher and Schmidl 2009). Non-renewable resources, such as crude oil, natural gas and coal have to be imported, since Austria has only a limited amount of domestic fossil resources. As a result, there is a high dependency on foreign markets and associated price fluctuations and the share of renewables should be increased also because of geopolitical reasons. Therefore, the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management commissioned a feasibility study in 2010, aiming at assessing the potential of the shift towards 100% renewables and energy autarky of Austria by 2050. The final report suggests that the transition is possible, but the maneuvering room is relatively small and therefore immediate actions have to be taken in order to reach this goal. Biomass and hydropower will both provide more than half of the total energy demand in all scenarios (Streicher, Schnitzer et al. 2010).

A closer, yet ambitious national aim was implemented in the Austrian Energy Strategy, which resulted from adopting the EU energy and climate package in 2008. According to this

3 The "technical potential" is referring to the potential amount of biomass which can be harvested limited by factors relating to current technology and plant physiology. It is not necessarily the amount of biomass that can be collected from an economic and ecological point of view, which is certainly lower.

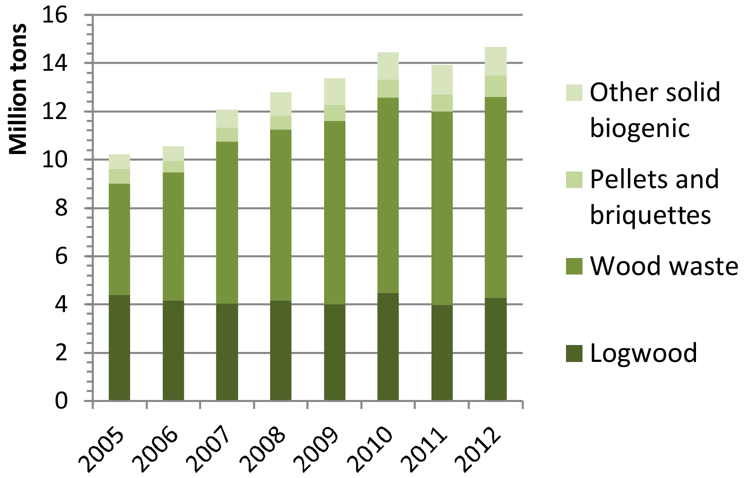

Figure 2: Gross domestic consumption of solid biogenic feedstocks in Austria from 2005—2012 (Bittermann 2014).

regulation, Austria is obliged until 2020 to increase the share of renewables to 34%, reduce the greenhouse gas emissions by 16% (not subject to emission trading) and increase energy efficiency by 20% (BMWFJ and BMLFUW 2010). The Austrian Energy Strategy is not a surrogate for the 2050 aims described above but rather a milestone on the way towards a renewable energy system.

Austria is rich in agricultural land and forests as a consequence of the unique topography with relatively flat areas in the east and the Austrian Alps in the central and western regions. Especially mountainous areas are unsuitable for agriculture, because of shallow soils and steep terrain, leading to soil erosion and land degradation. If well managed, forests provide a permanent vegetation cover which protects shallow soil from erosion and therefore also protects organic matter and ultimately carbon from being permanently lost. According to the latest forest inventory (census 2007–2009), 47.9% of Austria's territory is woodland, with a current annual gain of 4.300ha (Russ 2011).

Austria`s forest industry has a long tradition and even today, it is a very important economical factor for the national economy. Biomass from traditional forestry systems is therefore currently the most important source for bioenergy in Austria. Biomass plantations still do not play an important role in terms of the total amount of biomass produced in such systems. Recent data indicate that only a small area of 2.330 ha is declared as energy wood plantation in 2013 (BMLFUW 2013). The consumption of solid biogenic materials increased remarkably from 10.2 to 14.7 million tons between 2005 and 2012, mainly caused by a higher amount of wood waste consumption, as shown in Figure 2.

4. The limits of biomass production

As mentioned above, biomass is currently the most important source for bioenergy in Austria. The reasons are manifold, from Austria's topography which implies large forested areas at high elevations unsuitable for agriculture, to historical reasons and recent incentives for bioenergy development. However, several research efforts tried to quantify the biomass potentials using different approaches, e.g. Kranzl et al. (2008), Hirschberger (2006) or Splechtna and Glatzel (2005). Although the studies approach the question from different points of view (e.g. GHG emission reduction, biodiversity, soil fertility etc.) there is a common understanding that biomass potentials from forestry are not expected to increase significantly due to a number of reasons. Firstly, biomass production has to be sustainable. The definition of sustainability initially originated from forestry business where it referred to a level of harvests that could be maintained without any negative consequences for future harvests. Basically this is still the essential meaning in context of increasing demands for bioenergy. Soils can be considered as a non-renewable resource as pedogenesis is a process of several centuries or millennia. Improper management and resulting degradation may severely affect the fertility and therefore a sustainable biomass production. In general, the increasing demand for biomass leads to utilization of compounds usually left on site (e.g. twigs, branches, leaves) commonly referred to as slash or harvesting residues. An alternative to produce larger amounts of biomass is a reduction of the rotation period and hence utilizing the fast growing phase of a stand, typically with fast growing species in order to maximize overall biomass production. In both cases, this leads to increased extractions of essential soil nutrients which are concentrated in the bioactive compartments of a tree, i.e. foliage, bark and thin branches. Increased rates of biomass extraction can lead to deficiencies of specific elements, especially in less fertile soils. On the other hand, nutrient extraction rates in conventional forest rotation periods (~80–100 years) in combination with recycling of organic matter and nutrients into the soil may be sustainable even at poor soil conditions as there is sufficient input from bedrock weathering and atmospheric deposition. In any case, soil and environmental conditions are the limiting factor for biomass production and more extensive management options may be possible if soil conditions allow higher rates of nutrient extraction and if there is a sufficient amount of available water. If soils are degraded due to improper management, harvest amounts of subsequent rotations will ultimately decrease as well as the value of the respective land. Biomass for energetic utilization as such has a relative low value per volume unit in monetary terms. Consequently, highly mechanized production systems are required which in turn, cause a loss of biodiversity on such areas in contrast to well managed conventional forestry. Biodiversity conservation approaches might be another obstacle for further developments of large-scale biomass plantations. Even if future market conditions allow substantial biomass imports, especially from Scandinavia, East European countries and Russia, it would be problematic in terms of sustainable production in these countries. Long-distance biomass transports have to be assessed very critically in view of efficiency and reasonability as it may triggers a number of environmental issues. Another potential problem is the competition for the same feedstock material on the market. Streicher et al. (2010) emphasize the bioenergy potentials from forestry in their report about the potential energy autarky in Austria and conclude that there is no significant potential to increase wood production for bioenergy as wood will be increasingly used as a raw material for industrial processes. Recent concerns of the paper industry about wood availability in a period of increasing popularity of wood-fired district and house heating have shown the potential for fierce competition for wood between different user groups. However, there are resources which are currently under-developed. In terms of ownership structure, Austria shows a unique pattern of a large share (~50%) of small-scale private forest ownerships (<200ha), and this is where most of the potential lies. Therefore it is a question of mobilization of smallholders.

According to an assessment of the biomass supply of Austrian forests and its sustainably usable potential until 2020, a total biomass supply between 10 to 11 Mio tons dry matter (dm)[4] is available from Austrian forests considering constraints resulting from the Austrian forestry law, prevailing harvesting methods, aspects of nature conservation and economic profitability (calculated from Gschwantner (2009) using conversion factors from BMLFUW and Austrian Energy Agency (2009)). The majority of the currently unused forestry biomass can be found in the above mentioned small forests where only 73% of the annual growth is used, in contrast to forests owned by federal and large forest companies whose utilization exceeded the annual increment in the reporting periods 2007-2009 (BFW 2011). Therefore, wood mobilization is a substantial challenge to ensure the assumed biomass supply. For facilities utilizing large amounts of biomass, European biomass markets may be considered since trade of biomass and wood products intensified in recent years.

A relatively under-developed source for additional biomass is agriculture. There is potential for additional utilization of waste material, e.g. straw, corn-cobs or chaff, just to name a few. However, the same principals as for forestry apply for agriculture. A certain share of organic matter should be recycled on site (at least roughly the half of above-ground residues), but agricultural soils are usually more fertile as compared to forest soils, facilitating higher rates of sustainable biomass extraction. In addition, nutrient recycling (and biochar amendment) is relatively simple as compared to forest ecosystems.

5. Biochar as a potential solution for climate change mitigation in CCS (BECS) strategies

Wood charcoal is utilized by mankind since millennia, primarily as a renewable and – in comparison to fuelwood – cleaner source of thermal energy as the level of emissions is lower during combustion which has advantages in densely populated areas and when using it indoor.

Despite wood charcoal was beside fuelwood the most important source for thermal energy until the late 18th century, its importance gradually ceased thereafter as a consequence of increasing

4 Whenever we refer to biomass in units of mass in the subsequent manuscript, we refer to dry biomass. Therefore we exclude the notion (dm) in all subsequent numbers.

utilization of fossil fuels, e.g. coal, and later crude oil and natural gas. However, worldwide charcoal production rates are increasing again, particular in less developed and rural areas. 51.3 megatons of charcoal were produced in 2012, where Africa takes the lead with 30.6 megatons followed by South America (10.3 megatons) and Asia (8.6 megatons) (FAO 2013).

Biochar represents pyrolized organic matter, similar to wood charcoal, that is used for barbecue. However, in contrast to BBQ charcoal, it can be produced from any organic matter, regardless of its origin, and the production parameters may be exactly controlled. In the current report, we focus on biochar derived entirely from woody biomass from forests or forest plantations. In a nutshell, pyrolysis is the process of biomass heating in absence of oxygen, while separating the volatile fractions from carbon. From an engineering point of view, the pyrolysis process can be characterized according to the duration which separates slow (in a scale of minutes to hours) from fast (in a scale of seconds) pyrolysis, or the reactor operating characteristics, which could be a continuous or a batch process. Traditional charcoal production refers to slow pyrolysis at a batch setup. The major differences between slow and fast pyrolysis is the duration time of the biomass in the reactor and the heating rate, leading to different char properties and characteristics of the volatile compounds. While slow pyrolysis tends

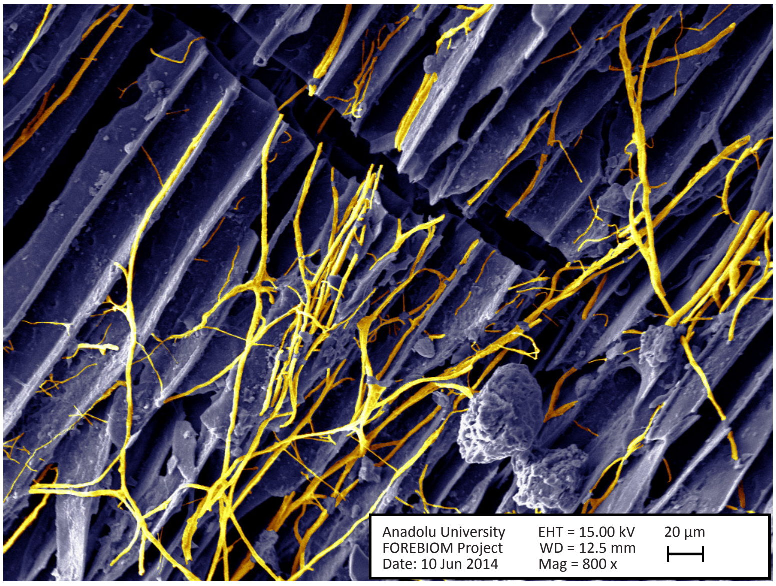

Figure 3: Over time, biochar particles are fully integrated into the soil system and act as a reservoir for nutrients and water as shown here by intensive occurrence of mycorrhizal hyphae. This SEM illustration shows charcoal which was found in a spruce-dominated forest soil in the northern part of Austria and likely origins from the previously common silvicultural practice of slash burning. The estimated age of this charcoal is 110 years, according to a review in historical forest management plans.

to separate them into the gaseous phase, the majority of volatiles are found in the condensable phase in case of fast pyrolysis. The composition of the volatiles is a challenge for further processing, because it is very complex and the conversion e.g. into fuels, is not very efficient with current technologies, both in economical and energetic sense. Bio-oil may be used as an energy carrier or as a feedstock material for further refining. The gaseous compounds are commonly directly used as a source for energy. Although the synthetic gas may be rich in methane, it is quite costly to purify it which is a necessary step if it is fed into the existing natural gas grid or if used as fuel for transportation. The solid product of the pyrolysis process is wood charcoal, with distinct chemical and physical properties. These properties, such as pH-value, surface area, decomposition resilience, cation exchange capacity etc. are highly dependent on the actual pyrolysis settings (especially temperature and reaction time). For instance, it was shown that the pH-value of biochar derived from black locust may range from around 4 to 12, only as a factor of pyrolysis temperature (Lehmann 2007).

As mentioned above, pyrolized organic matter is – depending on the pyrolysis settings – relatively stable against microbial decomposition as a consequence of its intrinsic recalcitrance, mainly due to aromatic carbon ring structures being an obstacle for microbial decomposition (Kumar, Lobo et al. 2005; Schimmelpfennig and Glaser 2012). The formation of organo-mineral compounds, i.e. the bonding between clay minerals and char particles is another mechanism of long-term protection of carbon compounds against microbial decomposition as mentioned above in section two (the role of forests in climate change mitigation). This recently raised attention as biochar may be used in carbon capture and storage (CCS or Bioenergy-CCS "BECS") strategies, if it is used as a soil amendment. In addition, biochar has the ability to positively influence both chemical and physical soil properties (Ennis, Evans et al. 2011). For instance, recent findings suggest that biochar amendment has a profound influence on soil nitrogen cycling in an arable field trial (Prommer, Wanek et al. 2014). As mentioned above, the potentially high pH-value of biochar leads to a liming effect which is often desired in acidic soils. The porous structure of the char itself is capable of raising the cation exchange capacity as a consequence of a high surface area and functional groups at the surface. In addition, pores may increase the soil water retention which is of critical importance on dry and sandy sites. They may also create a suitable habitat for soil microorganisms. Fresh biochar consists of a certain share between labile (5–25%) and stable (75–95%) fractions, mainly controlled by the initial feedstock material and pyrolysis conditions (Cross and Sohi 2013). After incorporation into soil, the labile fraction is oxidized by soil microbes within years and hence no longer acts as a stable carbon pool. It has to be noted here that functions delivered by biochar amendment are subject to temporal changes. For instance, the cation exchange capacity (CEC) is determining the nutrient retention capacity and it changes over time. Fresh biochar has typically a low CEC, which is later increasing as a consequence of oxidation processes and the formation of organo-mineral compounds (Cheng, Lehmann et al. 2006), despite the fact that CEC is also a function of pyrolysis (maximum) temperature. In combination with other functions, such as water retention and habitat for soil microbes it is subsequently traversed by fine roots and mycorrhizal hyphae as shown in Figure 3.

Probably one of the first scientific observations of stable pyrolized carbon occurred in tropical South America where scientists found distinctive patches of soils with unusual high fertility considering the tropical environment. It turned out that biochar is the main reason for the relative large amounts of organic carbon in these soils, coupled with high cation exchange capacities representing a buffer for essential plant nutrients. These soils are known as "Terra Preta" and were initially set-up by the Indios, who mixed organic waste with charcoal and incorporated this mixture in their agricultural soils, leading to a permanent improvement of soil fertility and productivity. Although decomposition processes under tropical environment are usually rapid, these soils are still rich in organic matter, even after centuries of heavy soil weathering. Similar techniques of soil amendment have also been historically deployed in East Asia (China and Japan), West Africa, New Zealand and North Europe.

To illustrate the potentials of biochar in terms of carbon sequestration, the GHG offset potential under a scenario of biochar production from 50% of the total amounts of wood waste and other solid biogenic materials (see Figure 2) was calculated under the assumptions presented in Table 1.

Table1: Assumptions for the biochar GHG offset calculation

Item	Assumption
Feedstock material for pyrolysis	50% of wood waste and other solid biogenic materials (Bittermann 2014) as shown in Figure 2 are pyrolyzed
Feedstock mean carbon content	45%
Carbon yield (pyrolysis)	50% of the initial feedstock carbon remains in charcoal, volatiles contain another 50% (Lehmann 2007).

In the 50% pyrolysis scenario, only the groups "wood waste" and "other solid biogenic materials" of the Statistics Austria energy balances assessment (Bittermann 2014) were considered. It was assumed that only 50% of the respective groups are being pyrolyzed, which represents a moderate utilization of available biomass resources from those groups (50% of 5.2 and 9.3 million tons in 2005 and 2011 respectively). It was further assumed that the resulting biochar is being used as soil amendment and the carbon is therefore captured in a stable pool and does not enter the atmosphere. Initial emissions from the labile pool is not considered under this simple assumption, however, at the same time effects on biomass growth (secondary carbon capture effect) are also not considered which are likely to be positive and therefore neutralizing or even exceeding initial emissions resulting from labile fractions.

The results of this scenario calculation suggest that the production and subsequent amendment of biochar would have been able to annually offset between 9 and 27% of the CO_2 equivalent GHG emissions in the period between 2005 and 2011 (Figure 4), in comparison with the entirely energetic utilization of the feedstock. We would like to emphasize that this calculation is aiming at presenting potentials of climate change mitigation using biochar under optimal conditions and therefore represents a theoretical number.

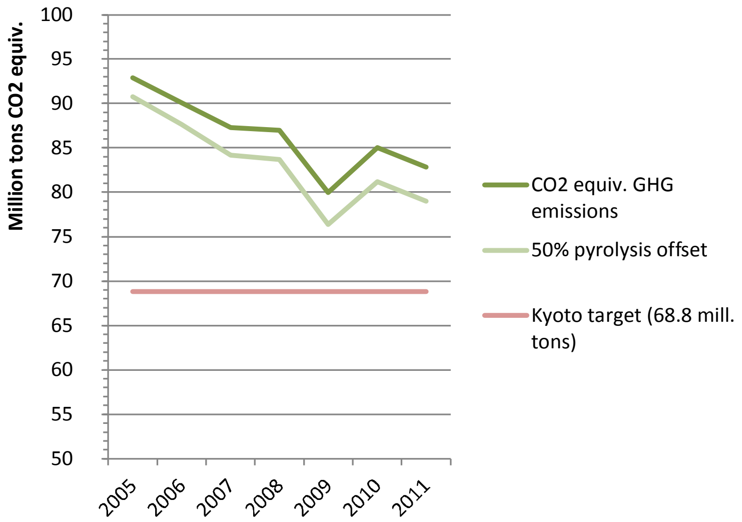

Figure 4: Annual GHG emissions (in million tons CO_2 equivalents) from 2005— 2011. The Kyoto target is shown as red line. In addition, the GHG offset potential (27% in 2011 to reach the Kyoto target) is shown when converting 50% of wood waste and other solid biogenic resources to biochar (see table 1).

We are aware that there are a number of obstacles, limiting the presented range. The projected offset would require a large number of pyrolysis power plants, depending on the overall capacities. Especially financial aspects, such as the costs for biochar production and application, as well as a high degree of uncertainty in monetary quantification of benefits (e.g. increased soil fertility) suggest a more conservative approach, which is used in the following economic consideration. According to the main focus of the FOREBIOM project, we considered only sustainable potentials of biomass from forestry as identified by the last forest inventory (Gschwantner 2009). Considering the increasing competition for forestry biomass from different sectors, we assume 10% of the annual timber growth to be available for biochar production. Based on these assumptions, the biomass supply adds up to a total of 439,500 tons. Pyrolising this feedstock quantity would yield about 153,800 tons of biochar. This would provide biochar for 5,100 hectares of cropland application annually, assuming a moderate application rate of 30 tons per hectare. Biochar is able to off-set between 0.7 to 1.4 tons CO_2 equivalents (CO_2e) per ton of feedstock (Gaunt and Cowie 2009; Woolf, Amonette et al. 2010; Hammond, Shackley et al. 2011). Globally, the GHG mitigation potential is estimated to be maximum 12% of current anthropogenic CO_2e emissions annually, which is about 1,800 million tons CO_2e per year (Woolf, Amonette et al. 2010).

6. Economic aspects

The cost-effectiveness of biochar as GHG mitigation measure is assessed combining feedstock and the technology specific biochar production costs and GHG mitigation potential based on recent research findings. Therefore, we calculate average GHG abatement costs[5] of biochar from forest biomass using slow pyrolysis. Slow pyrolysis in contrast to fast pyrolysis is most suitable for maximising the output of biochar and to improve biochar characteristics for the application in soil. The following costs are included in the analysis: feedstock costs, transportation costs, capital and operation costs of the pyrolysis plant as well as the costs for soil application. Moreover, we include revenues that arise from electricity generation using syngas, a by-product of biochar in the pyrolysis process. For further information on detailed cost estimates and GHG mitigation potential see Table 2.

In order to compare the cost effectiveness of biochar as climate change mitigation strategy with other C removal strategies, average GHG abatement costs are calculated by dividing the total specific costs by the total amount of mitigated CO_2e per applied ton of biochar (see Table 3). GHG abatement costs range from EUR 110 to EUR 200 per ton CO_2e depending on the feedstock price scenario and the respective plant capacity.

5 GHG abatement costs are the costs per ton biochar in relation to the GHG mitigation potential

Table 2: Costs and revenues of biochar production and application and GHG mitigation potential of biochar. Detailed information about calculations are provided in the online-appendix[6]. All mass units refer to dry mass

Feedstock costs — Prices for wood products increased steadily within the last years as a result of a rising demand. In order to reflect different wood prices resulting from different product qualities (for example wood waste compared to wood chips), we consider a wide range of feedstock costs ranging between EUR 60 and EUR 120 per ton of feedstock.

Transportation costs — Transportation costs rise as a function of required feedstock quantities. For distances less than 100 km, trucks with trailers are the cheapest means of transport and specific transportation costs range from EUR 0.20 to EUR 0.60 per kilometer and ton of woodchips including an unloaded return (Kappler 2008).

Capital and operation costs — Pyrolysis technology and plant size (we consider small, medium and large scale pyrolysis) determine the biochar production costs. Due to the lack of data from commercial facilities, cost estimates are highly uncertain. Therefore, we base our calculation on costs of bioenergy plants provided earlier (Shackley, Hammond et al. 2011). According to this study, capital costs contribute about 27 to 31% to total production costs depending on system scale. The operation costs were estimated as a fixed fraction of the investment costs of 5% (Thrän, Bunzel et al. 2010).

Costs for soil application — Biochar application costs are estimated using data for applying agricultural fertilisers to soil (Schindler 2012). We consider variable costs to apply 30 tons of biochar per hectare using a fertilizer spreader including the transport by tractor over a distance of 2 kilometers and required personal costs.

By-product revenues — We assume slow pyrolysis yields of 35% biochar, 30% bio-oil and 35% syngas. When using syngas for electricity generation, this yields in 0.31 MWh per ton feedstock (McCarl, Peacocke et al. 2009). The returns from energy sales are estimated to EUR 18 per ton feedstock assuming costs for electricity generation of EUR 7.89 per ton feedstock and a sale price of EUR 58 per MWh (EXAA 2013). Bio-oil is used to provide process energy for feedstock drying as its use for biofuel production is not feasible at the moment (Shackley, Hammond et al. 2011).

GHG mitigation potential — The potential of biochar to offset GHG emissions is largely dependent on the sequestration of carbon in soil, which amounts to about 2 tons CO_2e per ton biochar applied to soil (assuming a stable carbon content of 55%). Additionally, the following aspects are relevant: effects of biochar on other GHG fluxes from soils such as methane (CH_4) and nitrous oxide (N_2O), GHG emissions resulting from the current biomass use and fossil fuel offsets from energy generation by pyrolysis. However, it is not possible within this analysis to cover all climate-relevant factors and secondary effects (e.g. increased soil fertility leads to higher productivity). For avoided emissions from fossil fuel substitution[7] by energy generation from syngas 0.3 tons CO_2e per ton biochar and for the suppression of N_2O emissions from fertilized soil 0.1 tons CO_2e per ton biochar are assumed. Emissions from feedstock and biochar transport as well as from applying biochar to soil lower the GHG mitigation potential insignificantly[8].

6 The appendix may be derived from http://www.oeaw.ac.at/forebiom/CCRA-appendix.pdf

7 To calculate the reduced CO_2e emissions due to substituted fossil fuel consumption, specific emissions of 340 kg per MWh final energy in Austria were used (Adensam, H., F. Meister et al. 1999).

8 To account for CO_2 released by transportation of feedstocks and biochar 110 g CO_2e per ton and kilometer (IINAS 2013)

Reported values for both costs and the mitigation potential vary considerably depending on the underlying assumptions. To assess the influence of uncertainties within our input data, the effect of changing parameters by 50% on abatement costs of biochar is assessed using a sensitivity analysis as shown in Figure 5[9]. This analysis reveals that the biochar yield from pyrolysis has the strongest influence on GHG abatement costs. A 10%-higher biochar output reduces abatement costs by EUR 20 (from about EUR 210 to EUR 190 per ton CO_2e) but changes in this magnitude are not expectable. Reported biochar yields in recent literature vary only between 35% and 36% for slow pyrolysis, which equals to a deviation of only 3%, compared to the investigated 50% in our analysis. The C sequestration rate of biochar is another important factor showing a change in abatement costs by about EUR 15, if sequestered CO_2 emissions change by 10%.

9 The sensitivity analysis is performed for biochar production via slow pyrolysis of medium scale using woody biomass of assumed costs of EUR 120 per ton feedstock

Table 3: Total costs of biochar production and application, mitigation potential and GHG abatement costs. Note. To convert costs in EUR per ton feedstock to costs in EUR per ton biochar, a biochar yield of 35% is assumed (Bridgwater, Toft et al. 2002; McCarl, Peacocke et al. 2009; Brown, Wright et al. 2011)

Costs in €/ton feedstock	Slow pyrolysis					
	small 2000		medium 16000		large 184800	
price scenario	low	high	low	high	low	high
feedstock costs	60	120	60	120	60	120
transportation costs	4		7		14	
capital costs	39		43		19	
operational costs	16		18		8	
by-product revenues	-10		-10		-10	
costs of soil application	1		1		1	
Specific production and application costs of biochar						
€/ton biochar	**315**	**487**	**342**	**513**	**265**	**436**
Mitigated CO_2-e in ton/ton biochar						
sequested C	2,01		2,01		2,01	
reductionof soil N_2O fluxes	0,14		0,14		0,14	
substitution of fossil fuel	0,30		0,30		0,30	
- transport emission	0,00		0,01		0,03	
sum	**2,45**		**2,44**		**2,42**	
GHG abatement costs						
in €/ton mitigated CO_2e	**129**	**199**	**140**	**210**	**109**	**180**

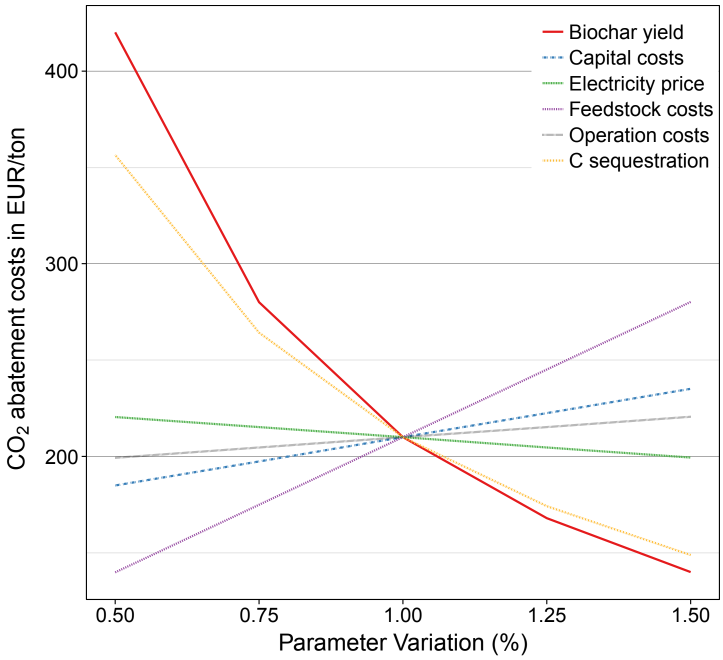

Figure 5: Effect of changing parameters by 50% on average GHG abatement costs of biochar application (sensitivity analysis).

In fact, fluctuating feedstock costs will probably have the greatest influence on GHG abatement costs. A change of 50%, which is within the range of reported feedstock prices, increase abatement costs to EUR 280 or lower them to EUR 140 per ton CO_2e. Therefore, it is essential to use cheap feedstocks such as biomass waste resources (wood waste, sawmill residues, or arboricultural arisings) to make biochar an economically feasible GHG mitigation option. For some waste materials such as sewage sludge even disposal fees could be received. However, before applying biochar from waste materials to soil environmental risks and regulatory questions have to be clarified. GHG abatement costs are also affected by changes in the electricity price achieved for the electricity generated from syngas. In this analysis, an electricity price of EUR 58 per MWh was used. However, prices of up to EUR 150 per MWh could be achieved by assuming feed-in tariffs as provided by Austrian regulatory for renewable energies. In this case, the abatement costs are lowered to about EUR 177 per ton CO_2e. Interestingly, changes in costs for soil application, transport of feedstocks and capital costs show only minor effects on GHG abatement costs. Providing financial incentives such as carbon market offset credits could substantially contribute to support the application of biochar. If carbon prices exceed EUR 110 per ton CO_2e, biochar application to agricultural soils becomes a feasible mitigation option. At present, this seems very unrealistic as carbon prices within the European Trading Scheme (ETS) have varied between EUR 5 to 30 per ton CO_2e since its introduction in 2005 (European Energy Exchange 2013). Currently, prices are at an all-time low of EUR 4 per ton CO_2e. However, the implementation of strong climate policies could reverse this trend. Even if higher prices can be achieved in future, for instance an earlier published market price of EUR 70 per ton CO_2e (Stern 2006), emission trading associated with the application of biochar to soil must be based on economically viable mechanisms to monetize GHG offsets. From an economic point of view, biochar application to agricultural soils for GHG mitigation alone is not feasible under current market conditions. The available biomass feedstocks considered are generally too expensive resulting in high GHG abatement costs, leading to net losses from biochar production despite a rather high mitigation potential, as long as carbon prices do not increase steeply. Compared to biochar, other C sequestration measures such as carbon capture and storage (CCS), reforestation and afforestation or changes in agricultural practices such as grass planting or conservation tillage are cheaper means of climate change mitigation. For example, a global mitigation potential of 1,600 megatons CO_2e per year could be realised by forestry mitigation options at costs of less than EUR 15 per ton CO_2e (Nabuurs and Masera 2007).

The strength of biochar originates obviously from its potential to reduce GHG emissions while generating renewable energy and realizing agronomic and environmental benefits. But a trade-off in the pyrolysis process between energy outputs and the production of biochar and its stability in soil exists. Reported benefits connected to soil-related biochar research are manifold going from biochars potential for improving soil fertility, increasing the water availability, modifying the fate of pesticides to immobilizing pollutants from contaminated soils. Up to date the ability to predict economic returns for these co-benefits is difficult limiting the ability to predict the overall profitability of biochar application. However, only a minor contribution of the agronomic value to total system GHG mitigation and profitability was found for the context of north-central Colorado (Field, Keske et al. 2013), for instance.

The functionality of biochar in soil and the response of soils to biochar inputs are still poorly understood. It remains uncertain how different soil types, environmental conditions, different biochar feedstocks and pyrolysis conditions affect the economic performance of biochar. A profound understanding of the effects of feedstock choice and production conditions is critical in order to develop specifically engineered biocharfor different uses. Confirmation and quantification of proposed benefits for different agricultural settings is required and the site-specific outcome of biochar application must be predictable for farmers planning to apply biochar to their fields. Using the assumed biomass potential from forestry, each year 0.38 megatons CO_2e could potentially be mitigated in Austria, which is 0.4% of total or 5% of all GHG emissions caused by agriculture in Austria in 2010[10]. In order to produce this amount of biochar annually, about 27 medium-scale or 220 small-scale pyrolysis plants would be required. However, if this potential can be utilized depends on actual feedstock costs and hence, on the future development of biomass prices on the Austrian/European biomass market and resulting opportunity costs of biochar.

7. Key areas of research - some outcomes of the 1st FOREBIOM Workshop

The recent FOREBIOM (Potentials for realizing negative carbon emissions using forest biomass and subsequent biochar recycling) workshop held in April 2013 in Vienna tried to bring together experts from forestry and biomass, pyrolysis and biochar soil amendment, to jointly assess the potentials of biochar production in Austria, as well as to identify knowledge gaps and research needs along the whole production and application chain. The two-day workshop was hosted by the Austrian Academy of Sciences and consisted of a plenary lectures and a subsequent discussion block. 50 experts from more than 10 nations participated and shared their experiences and contributed to the success of this event. At the end of the discussion block, participants were asked to discuss the following three questions in detail:

1. What are the premises for biochar production and utilization to help mitigate climate change?
2. What about potential risks and disadvantages for the environment when extending biochar production and utilization globally?
3. Where do we need more research and what are currently the main obstacles to put biochar on the market?

The discussion confirmed that the questions brought forward imply highly interdisciplinary approaches as certain aspects are interlinked with each other. In addition, the questions themselves are linked and several key aspects were independently mentioned in different workgroups. Although the focus of the workshop was set on the Austrian perspective, input from international experience was also considered in the following section. Table 4 provides an overview of some of the key challenges and associated potential solution pathways.

As for the preconditions for large scale biochar utilization for climate change mitigation in CCS strategies, one of the most stressed arguments is the need for guidelines for production, trade and amendment. It was mentioned that ways have to be found to reduce costs of biochar production. Currently, it seems that alternative uses of biochar may be more promising, e.g. as additive for composting or as a substitute for peat in the production of specific soil qualities or growth substrates (e.g. in combination with compost). A potential attempt to deal with the costs and enhance the development for a biochar market is the quality diversification, which would lead to specific properties depending on the anticipated utilization (soil amendment is just one potential utilization. It was also mentioned that the technology has to be developed in a way to be locally feasible, which includes the local biomass availability, as well as regional soil properties in the target areas of biochar application. In contrast to the need for locally adapted small scale production units is the argument of scales of economy and therefore costs of production and the associated level of technology, including sophisticated filter technologies and healthy working conditions. Air pollution and associated health risks, especially for plant operators, were reported from rural areas of emerging and developing countries. In this context, a major obstacle is lack of knowledge, especially in the field of biomass pyrolysis technology and in biochar application, rendering the need for guidelines as mentioned above. In general, prior to any soil amendment, detailed soil

10 Assuming total GHG emissions of 84.6 million tons from which 7.4 million tons resulting from agriculture in Austria Umweltbundesamt (2012). Austria's National Inventory Report 2012. Vienna, Austria: 497.

analysis is highly recommended but spatial soil information is usually not or just rudimentary available. It was stressed that important stakeholders, such as policy makers, farmers, but also the general public has to be informed about biochar and its abilities, and this starts already at transparent research. The positive – especially in monetary terms – functions of biochar in the soil should be highlighted, such as increased fertilizer efficiency because of decreased nutrient losses, leading to lower total amounts required per unit of area, lower nitrate losses towards groundwater, increased water retention under conditions of drought and consequently a higher productivity. A potential way to create more public awareness could be branded carbon, where designated carbon-neutral agricultural products may be sold from farms using biochar as soil amendment. A similar approach of eco-branding is currently being successfully tested in Japan (McGreevy and Shibata 2010). It was commonly agreed that the highest potential of large-scale biochar utilization lies in the tropical and subtropical region as a consequence of high biomass availability in combination with suitable soils (poor, heavily weathered soils profit most from positive effects of biochar amendment). However, it was also mentioned that increased biochar production may trigger direct and indirect land use change, especially via increased biomass combustion which can, in turn lead to higher carbon emissions. Therefore, it is necessary to ensure sustainable and clean production and assessment of the entire life cycle (LCA).

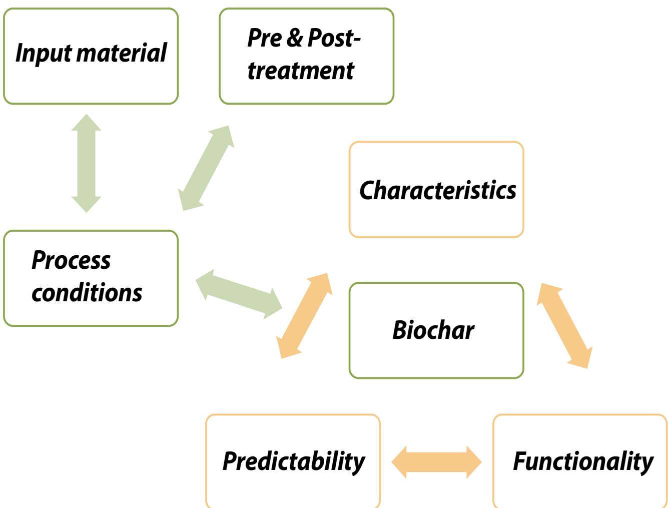

Figure 6: Key areas of knowledge deficits in view of biochar production and application.

Concerning potential risks and drawbacks, as addressed by the second question, the feedstock production was one of the most stressed aspects, besides contamination of biochar with heavy metals and health risks associated with production and application. It was mentioned that an over-exploitation of biomass resources such as consequent utilization of all harvesting residues may cause soil degradation as they are necessary for recycling of soil organic matter, especially on less fertile soils and this applies for both forestry and agriculture. It was also mentioned that recent developments on the bioenergy market and certain commodities, such as pellets and woodchips, for instance, may be based on the same feedstock. Therefore creating a potential competition for biomass unless there are waste materials used which (currently) have no market. In case additional bioenergy plantations are set up to produce feedstock for pyrolysis, there may be competition for land under certain circumstances. In view of biochar amendment, there are several issues which are not entirely understood, resulting in potential negative consequences. The long-term behavior of biochar in soils is not well understood, especially under changing soil and climate conditions. In addition, in the first year a biochar amendment likely affects albedo which in turn increases soil temperatures, especially in agricultural environments with lower vegetation cover but this effect is only transient. Elevated temperatures may cause higher microbial activities and therefore respiration and carbon loss from the soil. A similar, climate forcing effect can originate from black carbon emitted into the atmosphere as particulate carbon compounds during the production and application process. A large number of small biochar production facilities may increase the chance of using untested biochar with unknown and potentially harmful properties. A sudden rise in soil pH-values may decrease nutrient availability in acidic ecosystems. However, availability of toxic aluminum may decrease in turn. From the producer's point of view, there is currently a high risk as a consequence of lacking legal regulations for biochar amendment. A more technical problem is the storage of biochar as self-ignition is a common problem when storing large amounts of char.

The third and final question tried to conclude the former issues and provide areas of key interest for further research. The experts agreed that production is too expensive to consider biochar amendment as a climate change mitigation strategy at larger scales under current market conditions. In order to overcome these obstacles, they suggested that the pyrolysis technology has to be further developed and producers may receive governmental incentives or subsidies, at least in the initial phase until the technology is well established. Likewise, the feedstock, as well as the application technology was mentioned to be a factor of high costs and therefore currently questioning economic feasibility, as justified by our own investigation above. Consequently, biochar application in soils is currently also not feasible in REDD projects as the current price for carbon emissions is too low. In addition, it needs standards and guidelines for sustainable biomass production, pyrolysis and biochar application. Sustainability criteria have to be developed for the whole biochar life cycle. The Swiss biochar research network (SBFN) released the certification of biochar, which includes criteria of biomass, pyrolysis, properties and application of biochar (Schmidt 2010). It is currently the most detailed certification scheme and is according to their website based on the following principals: Independent on-site control, unified analytical methods (accredited labs), annual revision of standard by the scientific board of the EBC, legal back-up, economic viability and understandable guidelines and thresholds which are close to practice. The current version of the European biochar guideline can be downloaded at the website of the European Biochar Foundation[11]. The International Biochar Initiative (IBI) issues IBI biochar standards[12] (currently version 1.1 is available). Compared to the European biochar guidelines, the IBI guideline is based on much less onbligation. A detailed comparison can be obtained from the website of the European Biochar Foundation. The UK biochar research centre published the Biochar Quality Mandate (current version: 1.0) in 2013, which is currently available online[13]. It is a part of the results of the "Biochar Risk Assessment Framework" (BRAF) project and represents mainly the UK interpretation of an efficient use of biochar and includes issues such as sustainable feedstocks, production and application.

Nevertheless, workshop participants agreed that it needs more *in-situ* experiments under real conditions, with a focus on application methods, long-term effects, behavior of "charged biochar[14]" and there need to be more experiments with tailored designer biochar[15] with distinct desired functions that addresses specific soil properties. From an engineering point of view, the introduction of mobile small scale pyrolysis units seems to be a feasible business model and has to be further investigated, especially in view of efficient, low-tech and affordable solutions. Corrosive volatile organic compounds as well as the formation of slag under certain circumstances were mentioned as a further challenge for the durability and efficiency of reactor systems. It was also mentioned that there seems to be a lack of interdisciplinary discourse, combining views from feedstock providers, engineers, plant operators and biochar customers. The same argument was brought forward in view of a wider application or cascading use of biochar. For instance, it can be used in livestock production as an absorbent material for urea and ammonia and in general to be mixed with manure or slurry to reduce odors and facilitate decomposition. In addition, soil amendment may also focus on absorbing reactive nitrogen compounds from deposition and/or reduce emission of nitrous compounds from the soil. In general, the aspects of biochar characterization, the functionality and therefore predictability and the respective interrelationships are key areas of interest (Figure 6). Another potential utilization might be realized in filter technologies where both exhaust air or waste water may be treated and the filter material (modified biochar) can be subsequently used for soil amendment. In this case, however, it is essential to standardize char properties in terms of contents of potential contaminations, especially heavy metals and polycyclic aromatic hydrocarbons (PAH's). Social sciences should be involved to assess the impact

11 The European biochar guideline may be available here: http://www.european-biochar.org/

12 The current version of the IBI biochar standards is available online: http://www.biochar-international.org/characterizationstandard

13 The UK Biochar Quality Mandate is available here: http://www.geos.ed.ac.uk/homes/sshackle/BQM.pdf

14 The term "charged biochar" commonly refers to a modification of biochar, e.g. by treatment with compost, manure or other biogenic waste high in nutrients. The idea is to charge the biochar with nutrients which are slowly released in the soil according to actual requirements of the vegetation

15 Tailored biochar or designer biochar refers to biochar which was designed (different input material, processing conditions, pre-/post-treatment) with specific characteristics and functions to enhance a specific soil, e.g. biochar with elevated pH-values for acidic soils in order to benefit from the liming effect and increase the soil pH

of developing new markets and income opportunities especially in under-developed and rural areas. In terms of climate change mitigation, it was concluded that it needs systematic investigation about carbon credentials, i.e. how biochar amendment increases total soil carbon and the impacts on ambient soil organic carbon. Finally, it needs much more public awareness and the clear benefits (but also risks) of biochar amendment have to be communicated.

Table 4: Key challenges and potential solution pathways of large scale biochar application

Callenge	**Potential solution pathways**
High costs of biochar production	• Quality diversification • Development of market • Governmental incentives (reduced taxes) • Subsidies in the initiating phase • Wider and if possible cascaded utilization including provision of energy during biochar production • Upscaling of production • Production and marketing of by-products, such as bio-oil and wood vinegar
Impacts on soil properties	• Soil and biochar characterization before amendment • Consideration of existing biochar standards and qualities • Best practice soil application methods • Potential impact of changing albedo • Production of tailored biochar with specific functions desired at the site of amendment
Proof of climate change mitigation potential	• Assessment of long-term stability, including potential changes in environmental conditions • Buffering of reactive nitrogen depositions and biochar capability to reduce GHG emissions from the soil, • Interaction of biochar with ambient organic matter (priming effect) • Secondary carbon sequestration potential (via increased growth rates as a consequence of increased soil fertility) • Reduced (black carbon) emissions via improved production and application methods
Sustainability	• Application of sustainability criteria and binding guidelines, based on life cycle assessment (LCA) • Long-term stability is a key factor in terms of climate change mitigation potential • Investigations on positive effects on increased fertilizer efficiency have to be conducted *in-situ*
Health risks	• Of special concern at small scale biochar production units in rural areas and/or developing and emerging countries. Those units are typically not equipped with adequate exhaust air filter systems – improved technology is needed also for small-scale units • Excess dust emissions during biochar handling and application to be reduced by best practice methods, e.g. wetting of biochar
Development of a biochar market	• Consideration of more specific utilizations to address specific soil parameters using “tailored biochar” • Cascaded utilization where possible • Wider application, e.g. as a substitute for peat, as a designated growth medium • Development of biochar-based filter systems • Eco-branding may be used to raise awareness for GHG neutral agricultural products • Understanding market mechanisms • Legal basis for biochar production and application; EU-wide regulations to create legal certainty

8. Biochar research from global to local scales

The biochar research community in Austria is relatively small, there are working groups or individual researchers in a number of academic institutions (Table 5), usually with an agricultural or forestry background. Despite the fact that research efforts are partly fragmented, there is active collaboration among the scientific stakeholders in Austria as shown during the 1st FOREBIOM Workshop and in recent publications (Kloss, Zehetner et al. 2014; Kloss, Zehetner et al. 2014; Prommer, Wanek et al. 2014; Watzinger, Feichtmair et al. 2014).

Figure 7: *In-situ* biochar trials in Traismauer, Lower Austria managed by the Austrian Institute of Technology (AIT). Photo provided by Gerhard Soja.

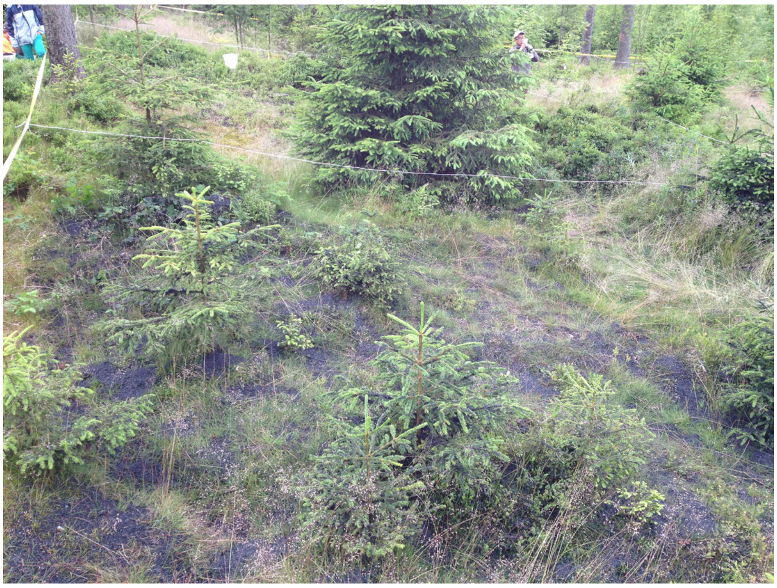

Figure 8: Experimental plots were set up for *in-situ* experiments in Lower Austria as an activity of the FOREBIOM project. 10 tons/hectare of untreated biochar derived from spruce woodchips were distributed on the surface of the experimental plots.

On international level, biochar research is conducted in many institutions worldwide, with a focus in tropical and subtropical regions as a consequence of the potential improvements of these highly weathered soils. The International Biochar Initiative[16] (IBI) is an internationally well-known biochar research network. Its board of directors consists of internationally recognized specialists in biochar research, such as Johannes Lehmann (USA), Saran Sohi (UK), Andreas Hornung (Germany), Marta Camps (New Zealand) and others. Besides being a platform for international collaboration and exchange of ideas, IBI is currently working on several knowledge gaps mentioned above. For instance, biochar standards are available online and based on them, they developed a biochar certification program targeted at biochar producers to meet minimum requirements. But also other topics, such as sustainability, biochar markets, industry and policy are addressed.

On European level, the European Biochar Research Network[17], supported by COST Action TD1107[18], coordinates biochar research activities and cooperation and is probably of higher relevance for European biochar producers, consumers and policy makers. Currently the website offers contacts to ongoing projects as well as an interactive map of biochar projects in Europe. In terms of certification, the European Biochar Certificate (EBC) was developed to become a volunteer standard in Europe as mentioned above. Several European biochar producers are certified according to this standard. The Austrian Standards Institute currently prepares standards for biochar with a very strong link to EBC. Committee No. 199 prepares standards for feedstock requirements, quality requirements and test methods as well as application guidelines. The draft standard publicatuion is scheduled for May, 2015.

According to information on the EBC website, the main difference between the EBC and the IBI standard mentioned above is that EBC includes obligatory on-site checks and analyses of product

16 See http://www.biochar-international.org/ for more information

17 See http://cost.european-biochar.org/en for more information

18 COST is an intergovernmental framework for European Cooperation in Science and Technology, allowing the coordination of nationally-funded research on a European level. Projects funded under COST are called "actions" and the current biochar COST action runs from 2012–2016

quality and sustainable production, while IBI is based on voluntary testing of any produced biochar[19].

9. Biochar producers, developers and consultants in Austria and Europe

Biochar production is mostly limited to laboratory scales, aiming at studying the effect of pyrolysis conditions and/or different feedstock materials or production of small qualities for lab-scale experiments. However, on national level there is currently only a single unit producing larger quantities for field-scale experiments in Burgenland, Austria, with a second one to be installed this year in Vorarlberg. The company "Sonnenerde" operates an industrial-scale PYREG reactor and sells the char mixed with compost and soil as a superior growth substrate for home gardens.

There are currently a limited number of biochar suppliers in Europe. The European Biochar Research Network lists a few companies which are engaged in biomass production as developers, consultants or producers[20].

19 For detailed differences between IBI and EBC, please consult http://www.european-biochar.org/en/ebc-ibi.

20 The list can be found here: http://cost.european-biochar.org/en/ct/16-Biochar-Producers

Table 5: Biochar research contacts in Austria[21]

Research Institution	City	Focus	Contact
BOKU University, Institute of Soil Research, Institute of Agronomy, Institute for Sustainable Economic Development	Vienna	Biochar and soil interaction, soil biology, economics	http://www.wabo.boku.ac.at/en/soil-research-ibf/, Franz Zehetner, Sophie Zechmeister-Boltenstern http://www.dnw.boku.ac.at/en/pb/, Peter Liebhard, Roland Kariger http://www.wiso.boku.ac.at/en/inwe/ Michaela Klinglmüller
University of Vienna	Vienna	Biochar and nitrogen	http://131.130.57.230/ cms/index.php?id=125, Wolfgang Wanek, Judith Prommer
Austrian Institute of Technology (AIT)	Tulln	Agricultural application of biochar	http://www.ait.ac.at/research-services/soil-remediation-and-isotope-applications/biochar, Gerhard Soja, Rebecca Hood-Nowotny
Federal Research and Training Centre for Forests, Natural Hazards and Landscape (BFW)	Vienna	Biochar and GHG emissions	http://bfw.ac.at/db /bfwcms.web?dok=4232, Barbara Kitzler
Austrian Academy of Sciences	Vienna	Carbon sequestration, life cycle	http://www.oeaw.ac.at/forebiom, Viktor Bruckman
Sonnenerde	Reidlingsdorf	Production of growth media	http://www.sonnenerde.at/ Gerald Dunst

21 The contents of this table were carefully reviewed and represent the outcome of a questionnaire distributed during the 1st FOREBIOM Workshop in Vienna. The aim is to provide an overview and facilitate communication with national/international biochar experts; however some institutions/contacts may not listed here

10. Acknowledgements

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Appendix

a. Information on prices of wood biomass

Wittkopf et al. (2003) compared the performance and costs of different woodchip production systems. According to that, the costs for roadside delivery ranged from EUR 80 to 113 per ton woodchips. In its monthly publication of wood prices the Austrian Agricultural Chamber has been observing steadily increasing prices due to the rising demand within the last years. For 2011, prices for woodchips including delivery ranged from EUR 80 to 90 per ton (Tretter, 2011). Biermayr et al. (2011) also observed increasing prices of woodchips from EUR 48 in 2005 to EUR 110 per ton feedstock in 2011. Lauer (2012) assumed even higher prices of EUR 120 to 150 per ton for forestry woodchips, but he also mentioned industrial waste wood as a cheaper option with costs of about EUR 60 to 90 per ton feedstock.

Table I: Supply region area, resulting transportation distances and costs

	Ref.	Unit	Woodchips		
Biomass supply	Q	t dm	2.000	16.000	184.800
Yield	y	t dm / km²	338	338	338
Area share	a	%	0,50	0,50	0,50
Availability	b	%	0,15	0,15	0,15
Supply area	A	km²	79	631	7290
Radius	x	km	5,01	14,17	48,17
Tortuosity	t		1,33	1,33	1,33
Average distance	x'	km	4,44	12,57	42,71
Specific transp. costs	c'	€ t^{-1} dm km^{-1}	0,93	0,58	0,33
Transportation costs	c	€ t^{-1}	4,13	7,30	14,26
Total transp. costs	C	€	8.258	116.746	2.634.859

Table II: Supply region area, resulting transportation distances and costs

Pyrolysis technology	Capacity	Investment costs	Specific Investment costs	Specific annual capital costs	Ref.
	t dm y^{-1}	€	€ t^{-1} dm	€ t^{-1} dm y^{-1}	
slow	2.000	656.934	328	38,58	[1]
slow	16.000	5.839.416	365	42,87	[1]
slow	184.800	30.109.489	163	19,14	[1]
slow	70.080	10.802.920	154	18,11	[2]
slow	1.060	400.000	377	44,32	[3]
fast	2.000	2.381.975	1.191	139,89	[4]
fast	16.000	9.594.170	600	70,43	[4]
fast	814.800	49.423.937	267	31,41	[4]
fast	70.080	17.299.270	247	28,99	[2]

[1] Shackely et al. (2011)
[2] McCarl et al. (2009)
[3] Lauer (2011)
[4] Bridgwater (2009)

b. Transportation distance

The transportation distance was estimated assuming a circular supply region: A=Q/Y*a*b, where Q is the total biomass required for the pyrolysis plant (ton), Y is the feedstock yield (ton per kilometer), a defines the fraction of useful forest area within the supply region and b stands for the percentage of biomass that is available under consideration of current competing biomass uses. The share of forest area within the supply region (a) was assumed to be 50%, since the average forest area in Austria is nearly 50%. The factor for the available forest biomass (b) was 15%, which equals the unused annual timber growth (BFW, 2011). The radius (x) of the supply area was calculated by: $x=\sqrt{(A/\pi)}$. The mean transportation distance (x') to the pyrolysis plant can be calculated based on the radius (x) and an estimated tortuosity factor (t): x'=2/3*x*t. The tortuosity factor describes the ratio of the actual road distance to sight distance. Walla & Schneeberger (2008) suggested a tortuosity factor of 1.33 for Austria. The transportation costs (y, in EUR per ton) are dependent on the transportation distance (x, in km) and were calculated based on data from Kappler (2008) using the following formula: $y=1.8246*x^{-0.4524}$. Supply region area, resulting mean transportation distances and transportation costs for woodchips are shown in Table I.

c. Estimation of capital costs

In order to harmonize the annual capital cost estimates, an interest rate of 10% and a plant lifetime of 20 years were used for the calculation (annuity factor of 0.1175). For a comparison of different capital costs published in recent literature see Table II.

d. Carbon sequestration

The amount of sequestered carbon in ton CO_2 per ton biochar can be calculated based on the carbon content and the ratio of CO_2 per metric ton carbon (C), which is 44 tons of CO_2 per 12 tons of C (Hiraishi & Minxing, 2000). The carbon content is estimated to 73% as a mean value of C contents found in slowly pyrolysed biochars from popular wood and spruce wood depending on feedstock and pyrolysis temperatures (Kloss et al., 2012). How long biochar C is inert in soil is still uncertain. Therefore, some assessments use conservative estimates of only 68 to 80% of the C content to be stable in soil (Roberts et al., 2010; Shackley et al., 2011) for more than 100 years. For this assessment, the stable C content was reduced by 25%, corresponding to a stable C content of 55%. Based on these assumptions, the sequestered CO_2 per ton biochar is estimated to 2.01 tons. Galinato et al. (2011) estimated that annually approximately 2.2 to 2.93 tons CO_2 or 0.61 to 0.80 tons C are sequestered per ton biochar applied to soil.

e. Suppression of nitrous oxide fluxes from agricultural soils

Biochar application was reported to reduce soil-N_2O fluxes from different types of soil (Rondon et al., 2005, Singh et al., 2010, Van Zwieten et al., 2010, Case et al., 2012, Cayuela et al., 2013). A for arable land mean N application rate of 147 kilograms N per hectare (Schönhart et al., 2011) is multiplied with the emission factor of 1.25 tons N_2O-N per ton N for direct N_2O emissions from agricultural soils (Hiraishi & Minxing, 2000) and converted to N_2O emissions by the multiplication with 44/28. Based on that, N_2O emissions of 2.89 kilograms per hectare and year are emitted from cropland with mean fertilisation. Finally, it was assumed that by applying biochar, N_2O could be halved to 1.44 kilograms N_2O or 429 kilograms CO_2e per hectare and year. Assuming an application rate of 30 tons biochar per hectare and a constant suppression effect over at least 10 years, this amounts to about 0.14 tons mitigated CO_2e due to N_2O reduction.

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