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Potential Analysis of Biochar-Systems for Improved Soil and Nutrient Management in Ethiopian Agriculture

REPORT 1

State of the Art of Biochar-Systems in the Tropics, with a Focus on Sub-Saharan Africa

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Summary

The population of Ethiopia is growing rapidly, increasing the food demand and the pressure on soils and other natural ressources. In the highlands of Ethiopia, relatively fertile soils of volcanic origin (Nitisols) predominate. However, many of them are affected by several fertility constraints, such as erosion, nutrient depletion, acidity or waterlogging. On behalf of the German Government, the Federal Institute for Geoscience and Natural Resources (BGR) is working with the Ethiopian Ministry of Agriculture and Natural Ressources and international partners to assess the potential of biochar as a new strategy for Ethiopia to counteract its soil degradation. Recent research around the globe has shown that using biochar as a soil conditioner can amend these issues, when not applied purely to the soil but in combination with other organic amendments, such as compost, urine or manure. However, more research on a local level is necessary to predict the long-term effects of biochar on crops, soils, climate, humans and the whole environment. Key factors of these effects are the technology and the feedstock sources used for the production of biochar. Production technologies are available from small-scale cook stoves up to sophisticated large-scale pyrolysis plants. Whereas feedstocks should be carefully selected from nutrient-poor organic waste, in order to avoid nutrient losses and biomass competition. However, not only technical factors are vital for the implementation of biochar into cropping systems, but also social and political ones. The cultural compatibility and political conditions need to be taken into consideration as well.

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1 Introduction

Ethiopia is the thirteenst most populated country in the world and the second in Africa. In 2015, the total population accounted for more than 99 million, and by 2050 it is expected to be almost double with 188 million citizens (United Nations 2015). Consequently its population density is going to raise from approx. 90 km^{-1} to 170 km^{-1}, but the area of fertile arable will probably not grow in the same way (Teshome 2014). This number illustrates the future challenge of Ethiopia to use its natural resources sustainably and to retain their productivity. The most important natural resource in this aspect, are Ethiopian soils, which are the foundation of the nation's food-security, but in the same way highly vulnerable to misdirected soil management. Rather fertile soils of volcanic origin are found across the highlands and they are used intensively (Fritzsche et al. 2007). However, this intensive land-use has led to severe deforestation and unbalanced crop and livestock production and thus is accompanied by land degradation (Gashaw et al. 2014, Nyssen et al. 2015).

To cope with land degradation, many plans and programs have been established by the government and international organizations (Haregeweyn et al. 2015). Recently, the Agricultural Transformation Agency (ATA) has published a "5-year Strategy for the Transformation of Soil Health and Fertility in Ethiopia" (ATA, 2013). In this paper, twelve key soil-level constraints that compromise soil fertility were identified:

› Organic matter depletion
› Nutrient depletion
› Soil erosion
› Soil acidity
› Low moisture availability
› Soil structural deterioration
› Soil pollution
› Soil fauna and flora depletion
› Biomass coverage removal
› Salinity and sodicity
› Waterlogging
› Physical land degradation

In order to counteract these constraints, several interventions have been identified, each of them cross-linked to more than one other. These interventions are achieved by different actions, such as composting, intercropping, bio-fertilizer production and dissemination, agroforestry, and other land management practices.

However, the technology of applying biochar for counteracting these issues has remained unconsidered in official action plans so far; even though it has been proven that biochar affects most of the them in a positive way (Glaser et al. 2002, Sohi et al. 2010, Lehmann et al. 2011). Therefore, the German government has commissioned BGR to support its partner in gaining knowledge in biochar-systems for improved soil and nutrient mangement in Ethiopian agriculture. As a first step, this report will provide an overview of the state of the art of biochar research with a focus on Africa and assess the basic prerequisites for the implementation of biochar systems in Ethiopia.

2 Definition of biochar, biochar substrates, and biochar systems

2.1 Physical and chemical properties of biochar

Biochar is a carbonous and porous material obtained by thermochemical conversion (pyrolysis, gasification) of biomass waste (Demirbas 2004) with the primary goal of soil improvement (Lehmann et al. 2006). From a physico-chemical point of view, biochar cannot be distinguished from char(coal) (Glaser et al. 2002) but the latter is used primarily for energy production.

Although biochar has a legal status in some countries such as Switzerland, Austria, and Italy, there is no legally accepted definition of biochar apart from the preliminary biochar definition in Annex A of the new European Fertilizer Directive (see also Meyer et al. in press). Besides, there are a few voluntary biochar regulations available such as the International Biochar Initiative guidelines (IBI), the European Biochar Certificate (EBC) and the British (biochar) Quality Mandate (BQM). Most striking features are thresholds for organic carbon content and the H/C ratio resembling the polycondensed aromatic carbon structure of biochar. Thresholds for inorganic and organic contaminants comply with national soil protection regulations. More comparative details of IBI, EBC and BQM regulations are given in appendix A.

From a physical point of view, biochar has a low bulk density due to its porous structure leading to a high specific surface area ranging from 50 – 900 m^2 g^{-1} (Schimmelpfennig and Glaser 2012), and a high water holding capacity (Glaser et al. 2002; Liu et al. 2012).

From a chemical point of view, the most striking feature of biochar is its polycondensed aromatic structure (Glaser et al. 1998) caused by dehydration during thermochemical conversion (Schimmelpfennig and Glaser 2012) leading to its black color and the low molar H/C_{org} ratio. This structure is also responsible for its relative recalcitrance compared to other organic matter in the environment. In addition, basic ash compartments lead to a high pH value.

2.2 Combination of biochar with organic amendments

It is important to stress that although biochar alone can improve poor tropical soils, due to its ash content (Glaser et al. 2002), it should never be applied purely, but at least together with other nutrient-rich organic waste such as compost or organic manure (Fig. 1; Fischer and Glaser 2012; Glaser et al. 2012). Long-term proof of this concept is the occurrence of Anthrosols around the world, especially the famous Terra Preta soils in Amazonia (Glaser et al.

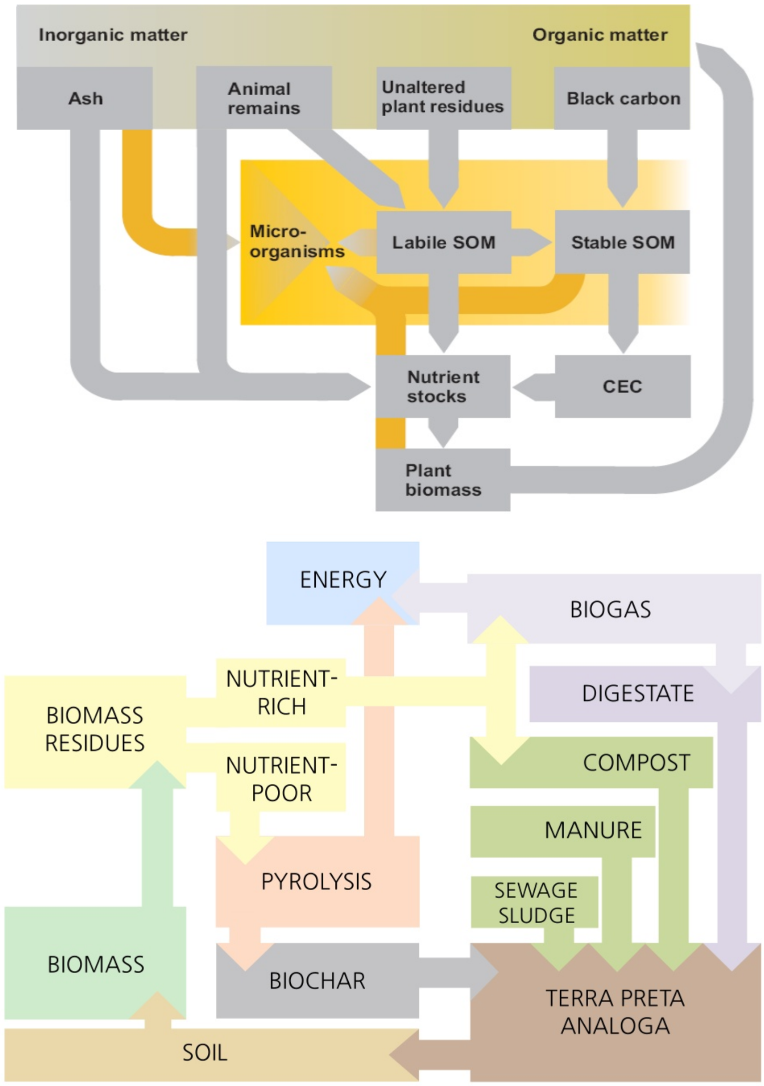

Figure 1: Bio-based circular economy principle of ancient anthrosols (top) and modern society (bottom) (Glaser 2015, modified).

2001; Glaser 2007; Glaser and Birk 2012) but also the African Dark Earths (Frausin et al. 2014, Solomon et al. 2016) and Nordic Dark Earths (Wiedner et al. 2015). To create such sustainably fertile soils, not only biochar but also tremendous amounts of nutrients derived from organic (kitchen) wastes and excrements are necessary, which are turned over and stabilized by native soil (micro) organisms over a long period of time, creating large stocks of stable soil organic matter (Fig. 1; Glaser and Birk 2012). In this content, biochar has always to be considered as additional additive of an adequate soil and fertilizer management. Thus, for the production of high quality organic fertilizers or soil activators additional amendment, e.g. rock flour, could be of advantage.

2.3 Biochar in a systemic point of view

The use of biochar for soil improvement according to the Terra Preta principle has created a new world of biochar systems such as cascade uses or the hygienisation of excrements, sewage or animal bones. Sustainable biochar systems consider not only ecological aspects but also the economic use of excess energy and the produced biochar products as well as the socioeconomic consequences including health issues. A general overview of such biochar systems is given in Fig. 2.

3 Production technologies for biochar and their suitability in an African context

Biochar can be produced via pyrolysis and gasification processes. Pyrolysis technologies carbonize biomass in the absence of oxygen, whereas gasification processes are carried out under oxygen deficiency conditions. Char yields obtained by pyrolysis processes are generally higher (in the range of 30%) as compared to gasification processes (with typical char yields of about 10%) (Table 1), which are mostly focused on the production of a high caloric gas, which can be used for energy provision. In the past decades, carbonization facilities have been developed covering a broad range of application purposes from household level gasifiers up to industry scale pyrolysis retort systems. However, recent research in the tropics focuses on small-scale, easy-to-handle and cheap batch systems, such as kitchen stoves (Johnson et al. 2009, Whitman and Lehmann 2009, Torres-Rojas et al. 2011), Kon-Tiki technology (Schmidt et al. 2015) or traditional earth pits or mounds (Bayabil et al. 2015, Agegnehu et al. 2016), that enable farmers and/or farmers associations to improve there own production conditions without a need for large capital investment. Large scale biochar production facilities need concentrated biomass feedstocks (e.g. processing residues) to ensure an adequate degree of capacity utilization. It is the advantage of small scale production units that dispersed biomass sources can be used as well. It should be noted that the presented technologies have different demands on the minimum and maximum size of the feedstock fractions. For example, it is difficult to carbonize very fine biomass particles in automatically fed pyrolysis plants due to clogging of the combustion chamber, when they are not mixed with coarser particles. A minimum amount of coarse biomass pieces is also needed to run flame curtain kilns. For all presented technologies, the water content of biomass limits the applicable biomass feedstock fractions. Special care has to be taken to avoid the pyrolysis of biomass feedstock with high chlorine contents due to the threat of dioxin formation (Wiedner et al. 2013).

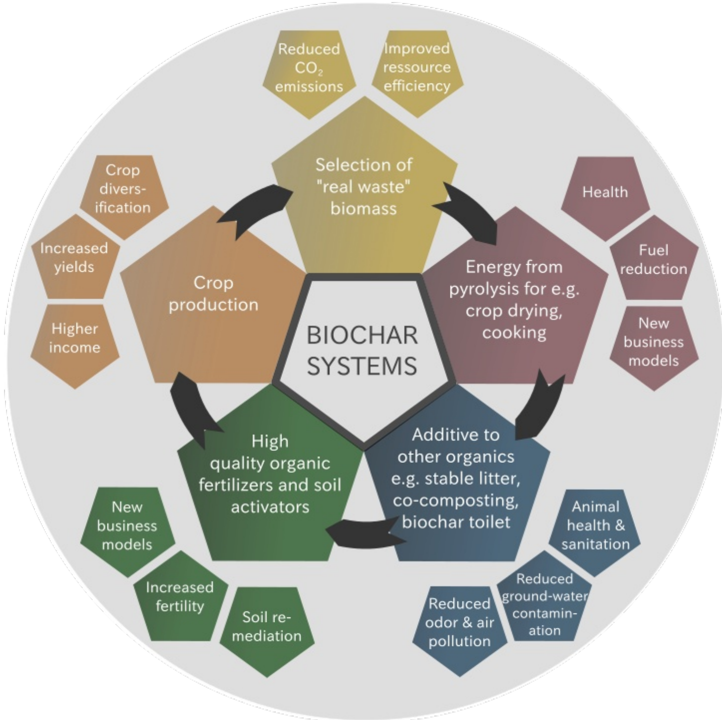

Figure 2: Schematic diagram of biochar systems

Table 1: Comparison of slow pyrolysis and gasification. SPY: solid product yields, SPCC: solid product carbon content, CY: carbon yield. All yields and contents are on a gravimetric basis. SPY is derived from a dry wood feedstock. (Meyer et al. 2011)

Process type	Process temperature	Residence time	SPY	SPCC [%]	CY
Slow pyrolysis	~ 400 °C	minutes to days	≈ 30	95	≈ 0.58
Gasification	~ 800 °C	~ 10 to 20 seconds	≈ 10	35	≈ 0.04

In the following subsection, we describe and evaluate a broad selection of carbonization technologies, which are available on the market today and might be suitable to produce biochar in Ethiopia.

3.1 Small-scale pyrolysis units

The conical shaped flame curtain or "Kon-Tiki" kilns (Fig. 3) have been designed in Switzerland in 2014 and are currently being used in more than 50 countries due to open source technology transfer (Cornelisson et al. 2016). Due to the flame curtain, which oxidizes the largest parts of the pyrolysis gases, these kilns allow for a relatively clean and rapid (within several hours) carbonization of biomass at comparably low investment costs (from 30 € for a soil pit shield up to 5.000 € for a large metal kiln). If a mere conically shaped soil pit is used for biochar production with a flame curtain, the investment costs are close to zero. Biochar yields are around 22% on average for production batches in the several 100 kg range (Cornelisson et al. 2016). It has been proved that the biochars produced in Kon-Tiki kilns comply with the quality criteria of the European Biochar Certificate (Cornelisson et al. 2016).

A reasonable concept to use the heat of the biochar production has still to be developed to increase the energy efficiency of this process, since the largest part of the produced heat is currently not used at all. However, a modification of this technology, in order to use it for cooking, similar to traditional practices, should be easy. Due to the biomass scarcity in Ethiopia, this issue has to be solved before a field application of flame curtain kilns can be recommended. Further on, these kilns require continuous attention by the operator and independent research on this technology in developing countries is missing.

Traditional earth pits and mounds are mainly preferred due to their simple technology and its local adaptivity (Duku et al. 2011, Bayabil et al. 2015). However, process energy remains unused, pyrolysis gas and vapors are released to the atmosphere and the biochar yield is low (Duku et al. 2011). Small-scale modern charcoal retort systems with an internal combustion of pyrolysis gases are generally

Figure 3: A metal flame curtain biochar kiln (left) and a soil pit flame curtain biochar kiln (right). (left: fingerlakesbiochar.com 2016, right: the biocharrevolution.com 2016). These kilns can be produced in various sizes and layouts.

less problematic in this respect (Cornelisson et al. 2016). The so-called ANILA stoves developed by the University of Mysore in India allow for using the pyrolysis gases for cooking. Due to their design features, it is unlikely that the produced chars are contaminated with polycyclic aromatic hydrocarbons.

Figure 4: PYREG pyrolysis plant P500 which is suitable for the carbonization of 500 kW of biomass feedstock input (www.pyreg.de).

Figure 5: BIOMACO$_2$N pyrolysis plant (www.biomacon.com)

Figure 6: CarboChar pyrolysis plant of PRO-NATURA (www.pronatura.org)

3.2 Medium and large-scale pyrolisis units

In this subchapter, three producers of medium and large-scale pyrolysis units are presented: The container-sized pyrolysis plant of the German company PYREG is a good example for a modern, medium to large scale industrial biochar production facility (Fig. 4). The biomass is transported into the system, pre-heated (and pre-dried) by the - comparably clean - combustion gases and finally carbonized in the pyrolysis unit. The resulting annual biochar production is approx. 300 tonnes (PYREG 2016).Typical biochar yields are in the range of 30% and comply with the criteria of the EBC. The pyrolysis plant offers several options to use the process heat (150 kW$_{th}$, e.g. for drying purposes). To run the plant, an electricity grid connection is needed. The pyrolyzer is cooled by air, thus a water supply is not necessary. The maximum feedstock water content is 50%. Investments costs for PYREG plants are in the range of 300.000 € – 400.000 €.

Pyrolysis plants of the German company BIOMACO$_2$N (Fig. 5) are available with annual production capacities between 40 and 200 tonnes (BIOMACO$_2$N 2016). The process heat (between 25 kW$_{th}$ and 250 kW$_{th}$) is taken up by a water-flushed heat exchanger and can be used for industrial heating applications. To run the plant, an electricity grid, internet connection and a reliable fresh water supply for emergency cooling in case of electricity supply failures are needed. Prices for the smallest BIOMACO$_2$N units are around 75.000 €. A certification of the produced biochar according to the EBC-criteria is not yet available.

The international nature protection organization PRO-NATURA has developed different pyrolysis units (CarboChar 1-3, fig. 6) for an annual biochar production of 300 – 1,200 tonnes. It is possible to use the excess process energy (120 kW_{th} - 1.000 kW_{th}, depending on the pyrolisis unit size) for heating purposes. Electricity supply and emergency water supply is needed to run the pyrolysis units. The maximum feedstock humidity is 15%. The smallest unit is available for about 70.000 € and can be mounted on a trailer to be moved from site to site. A certification of the produced biochar according to the EBC-criteria is not yet available.

Scientific research with large-scale, sophisticated pyrolysis plants are rare in Sub-Saharan Africa, even though some technologies may be well suited. Duku et al. (2011) stressed the potential of screw type pyrolysers from PRO-NATURA, due to their relatively small-scale use, their feedstock flexibility and high yields. However, most authors point out the higher expense and complexity of these technologies (Brown 2009, Duku et al. 2011, Gwenzi et al. 2015), which hamper their implementation in developing countries. Also, the installation preconditions for medium to large scale modern pyrolysis units (e.g. electricity supply, partly also internet access and continous water supply) and an as-easy-as-possible maintenance of the plants have to be ensured.

3.3 Small-scale gasifiers

Gasifier-stoves made from steel (e.g. the so-called Elsa microgasifier stoves developed by the university of Udine) or clay are another option to produce biochar (Fig. 7). In general, cook stoves are attributed with the benefits of being more efficient, causing less pollution, burning different biomasses and combining biochar production with energy use for cooking (Carter and Shackley 2011, Torres-Rojas et al. 2011), but they were negatively rated by local women in India, especially in terms of

Figure 7: Pro Lehm Clay gasifiers stoves (left) and Elsa metal gasifier stoves with different pot raiser (Venkata et al. 2016)

required attention to the stove and its socio-cultural fit (Carter and Shackley 2011). Though detailed evaluations of local acceptance of biochar producing stoves are missing for Sub-Saharan Africa, conclusions might be drawn from other improved cook stoves (ICS) evaluations. Most of the key issue areas for ICS could be relevant for small scale gasifiers as well. These are: time savings, fit with cooking preferences and convenience, durability, safety and stability, aesthetic appeal and aspirational status (World Bank 2014). According to the German company Pro Lehm (Bierig 2016), biochar yields of 10%-20% can be obtained with clay gasifier stoves. Biochar production rates of 1 kg per day and household can be expected if clay gasifier-stoves are used for cooking. Fuelwood consumption can be reduced by 50% with clay gasifier-stoves if compared to three stone stoves. A certification of the gasification char according to the quality criteria of the EBC has not been carried out yet.

3.4 Medium and large-scale gasifiers

There are reliable medium to large-scale gasifiers for electricity and heat production available in Europe (e.g. Spanner Re², Burkhardt, Advanced Gasification Technology S.r.l.). Gasifiers were constructed to produce electric energy and due to this, they generally have a low biochar yield (about 10%). In addition, they often produce biochars with high PAH content, especially if co-current flow gasifiers are used (Schimmelpfennig and Glaser 2012; Wiedner et al. 2013).

3.5 Use of process energy

In the case of Ethiopia, it is very important to efficiently use biomass, since the agricultural soils in the country have partly very low carbon contents (Agegnehu et al. 2016). Any unit of lost process bioenergy not only reduces the recycling of organic carbon to the soil, but will also add additional pressure on other scarce and precious biomass stocks as source for fuelwood or charcoal production. Seen from this perspective, the use of biochar cook stoves and large-scale pyrolyis systems currently have a clear advantage over the use of flame-curtain kilns or traditional earth pits, with the latter still lacking the option to make efficient use of the process heat. In the case of medium and large-scale pyrolysis plants, it is also vital to substitute other fuels with the process energy, in order to make them economically feasible. The use of process energy for electricity production is generally subject to substantial investments and technical challenges. For that reason, it will be more economical to provide electricity from solar energy and wind energy sources in most cases and to use the energy from pyrolysis for heating purposes, such as cooking, crop drying, boiling water, etc..

4 The role of feedstock

4.1 Feedstock availability and biomass competition

The implementation of biochar into cropping systems generally requires a feedstock source that has been "real waste" so far and that does not have a competitive use. Otherwise, biochar systems may be in danger to put additional pressure on the fragile food supply of the Ethiopian people and could eventually trigger land-grabbing and promote deforestation, as discussed by Leach et al. (2011), with negative effects on biodiversity and climate change. It seems to be no coincidence that the interest in biochar systems in Europe in the last years rose in parallel to the collapse of the popularity of biofuel production. A better understanding of the interactions between biofuel use, energy crop provision, direct and indirect land use change (Panichelli and Gnansounou 2008), food production and the resulting environmental impacts drastically changed the public opinion on biofuels as well as the support policy for biofuels in the European Union, in recent years.

The availability of "real waste" feedstock depends highly on local conditions, such as predominant crops or distance to bio-waste producing industries. Konz et al. (2015) stated that "one of the key factors that needs to be taken into account [for feedstock selection] is the likelihood of

Table 2: Overview on recent biochar studies in Ethiopia

Feedstock	Application rate t ha^{-1}	Combination	Content	Reference
Wood (Charcoal)	4, 8, 12	min. fertilizer	soil properties, crop yield	Abewa et al. 2013
	10 (estim.)	pure	soil properties	Bayabil et al. 2015
	10	min. fertilizer, compost	crop yield, NUE	Agegnehu et al. 2016
Coffee husks	0, 5, 10, 15	pure	biochar properties, soil properties	Dume et al. 2015
Rice husks	11.4, 45.6, 114.0, 228.0	pure	soil properties	Tesfamichael and Gesesse unpubl.
Maize				
cobs	see above	see above	see above	Dume et al. 2015
stems	0, 5, 10	pure	soil properties, nutrient uptake	Nigussie et al. 2012
	see above	see above	see above	Tesfamichael and Gesesse unpubl.
Prosopis juliflora	2, 4, 7	min. fertilizer, compost	soil properties, crop yield	Gebremedhin et al. 2015
Animal bones	-	-	bonechar properties	Simons et al. 2014

feedstock procurement". In their recent feasibility study from South Africa, for example, they have identified alien invasive plants and sawmill wastes as the two most promising feedstock sources for biochar production, out of a wide range of potential feedstocks, based on a multi-layered analysis.

In Ethiopia, different feedstocks have been used in recent studies (Table 2). Apart from charcoal, most of these feedstocks are well suited for biochar production. Especially coffee husks, *Prosopis juliflora* and animal bones do not have a competitive use in most areas. Charcoal, however, could easily promote further deforestation and, therefore, most woods should be used very cautiously for biochar production not only in Ethiopia. Still, the potential of charcoal fines left after charring being used as biochar needs to be investigated.

4.2 Nutrient content of feedstocks

Various feedstock sources have been proposed for biochar production in Sub-Saharan Africa (Konz et al. 2015). Despite this variety, the majority of biochar research is conducted with wood or crop residues (Zhang et al. 2016). This practice is also recommendable, since wood and crop residues have a high C:N ratio and contain few nutrients. Thus, less nutrients get lost through pyrolysis compared to high quality feedstocks, such as slurry or sewage sludge. These nutrient-rich feedstocks will undergo a critical loss of available nutrients, when processed to biochar, above all N and P (Fischer and Glaser 2012; Glaser 2014; Ippolito et al. 2015). More than any other nutrient, available N will suffer from pyrolysis. Its plant-available amount in biochar is almost negligible (Kloss et al. 2012, Ippolito et al. 2015). Additionally, the amount of available P ranges between 0.4% and 34% of total P only, even though P gets concentrated through pyrolysis (Cantrell et al. 2012, Ippolito et al. 2015). As a consequence, nutrient-poor feedstocks with a high C:N ratio should be preferred for the production of biochar as a soil amendment (Glaser 2014). Whereas nutrient-rich materials should be used to upgrade pure biochar in terms of CEC and nutrient load, e.g. by co-composting with biochar as proposed by Glaser et al. (2015) or Agegnehu et al. (2015).

4.3 Biochar quality as a result of feedstock source and pyrolysis conditions

The quality of biochar is generally related to its physical and chemical properties and depends mainly on both, pyrolysis conditions and feedstock source (Chia et al. 2015). Therefore, also from a material properties point of view, the source of feedstock should be carefully selected, since not every biomass is appropriate for the production of biochar and the properties of the final product are highly dependent on its feedstock (Joseph et al. 2009, Enders et al. 2012, Jindo et al. 2014, Chia et al. 2015). In this section, we mainly compare the difference in using woody biomass or crop residues as feedstock, since other, nutrient-rich feedstocks are not recommendable for the production of biochar (see section 4.2). Instead, they should be used for co-composting of biochar (Fischer and Glaser 2012).

Regarding physical properties of biochar, it is most important to look at its surface area, which is a result of its pore size distribution. Generally it can be stated that highest surface areas are observed at pyrolysis temperatures between 500 °C and 700 °C (Schimmelpfennig and Glaser 2012, Gai et al. 2014, Chia et al., 2015) and that lower heating rates increase surface area (Ronsse et al. 2013, Chia et al. 2015). Regarding the influence of the feedstock, most studies observe higher surface areas for ligneous material, such as trees, than for grasses or other lignin-poor residues (Mukome et al. 2013, Ronsse et al. 2013, Jindo et al. 2014, Chia et al. 2015). But particle sizes of the feedstock surely also play a role.

Chemical properties are critical for the quality of biochar. Especially pH and electrical conductivity (EC), which are closely connected to each other, due to the concentration of alkaline elements, are strongly affected by both feedstock source and pyrolysis conditions (temperature and residence time). Both are higher for biochars derived from non-wood materials, which is related to a higher content of alkaline elements (Mukome et al. 2013, Ronsse et al. 2013) and it increases with higher pyrolysis temperatures and residence time, due to a higher ash content (Ronsse et al. 2013, Gai et al. 2014, Jindo et al. 2014, Dume et al. 2015, Ippolito et al. 2015). The most determining factors for CEC are the pyrolysis temperature and the oxygen content/availability, both being negatively correlated with CEC (Kloss et al. 2012, Gai et al. 2014, Ippolito et al. 2015). However, CEC is related to the amount of functional groups of the biochar and can be increased by biological aging (see section 5.1). A distinct classification of feedstock sources with respect to the CEC of the biochar can not be made (Mukome et al. 2013). Further important for biochar quality is its content of polycyclic aromatic hydrocarbons (PAH). A recent study, that compared woody material to straw concluded that the formation of PAHs is up to 5.8 times higher for straw feedstock than for woody feedstock and that PAH formation (Buss et al. 2016). This classification can be supported by other studies, such as Keiluweit et al. (2012) and Kloss et al. (2012). However, there is no clear correlation of PAHs and pyrolysis temperature (Buss et al. 2016), even if single PAHs, such as Naphtalene clearly correlate positively to higher temperatures (Kloss et al. 2012). It rather seems to be a matter of production technology, to which extent PAHs are formed (Schimmelpfennig and Glaser 2012, Buss et al. 2016).

5 Agronomical impacts of biochar

The world-wide occurrence of biochar-containing, sustainably fertile Anthrosols proves that it is, in principle, possible to convert infertile soils into sustainably fertile soils even under intensive agriculture. Therefore, those Anthrosols are a general model for a sustainable improvement of soil fertility and ecosystem services while storing large amounts of C in the soil for a long period of time (Glaser et al. 2001; Glaser 2007; Glaser and Birk 2012). Essential for this improvement are increased levels of soil organic matter and nutrient stocks by using a circular economy with all kinds of biogenic “wastes” as natural resources (Fig. 1), including food leftovers and excrements. The key factor of ancient and modern bio-based circular economies is the combination of biochar and in-situ recycling of organic wastes, in the course of which, turnover and stabilization of organic matter is carried out by native soil (micro) organisms (Fig. 8). From these concepts, it is clear that it makes no sense to apply pure biochar to mimic Terra Preta effects or to create sustainably fertile soils. Instead, it has to be combined with recycling of nutrient-rich organic wastes.

Nevertheless, biochar has various effects on soil properties and agronomic performance. It is important to stress that biochar itself is mostly polycondensed aromatic (stable) carbon with a variable ash

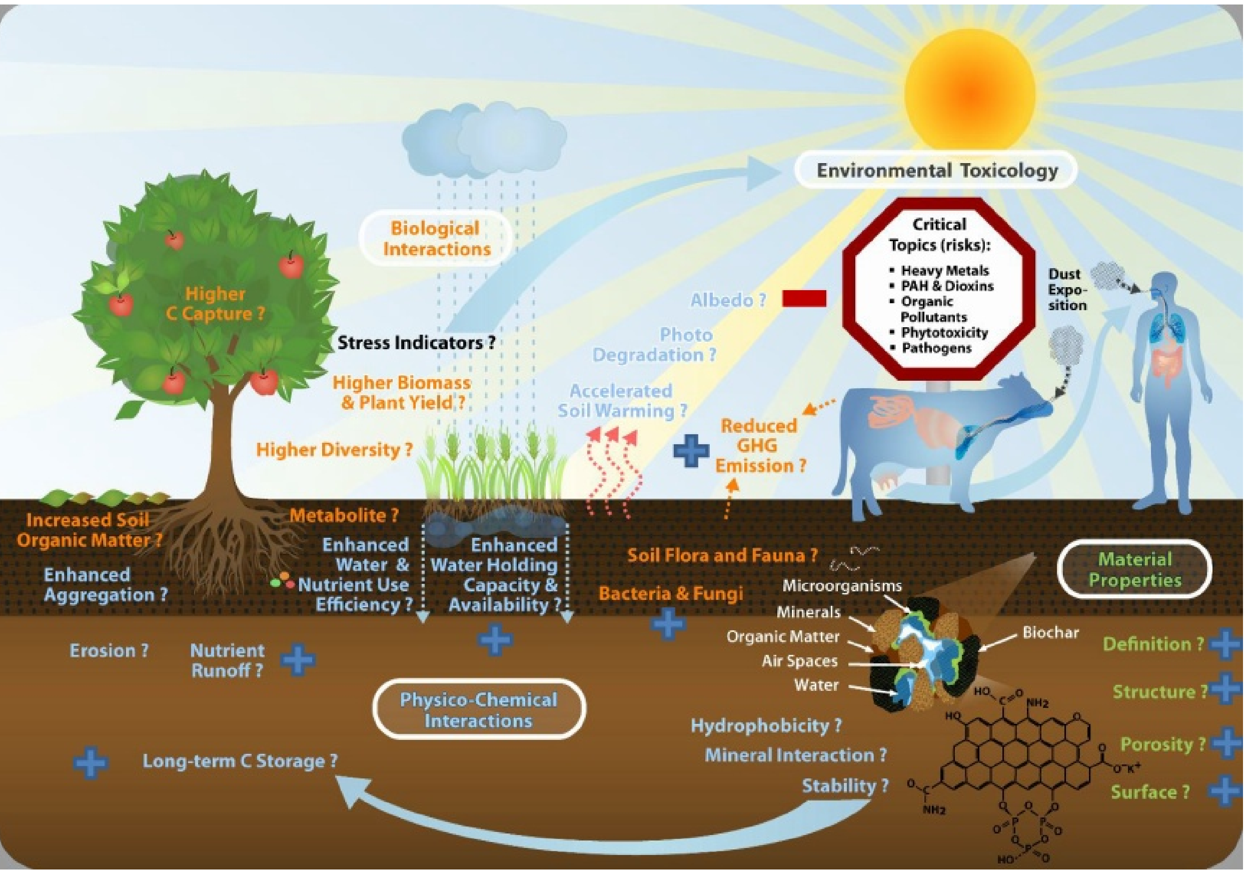

Figure 8: General effects of biochar on soil physico-chemical and (micro) biological processes (from Glaser 2015 with permission).

content which can act predominantly as soil conditioner rather than as fertilizer, at least in the longer term. Only the ash content serves as liming medium and immediate fertilizer, while biochar interacts with soil physico-chemical and (micro) biological processes as outlined in fig. 8. Apart from a clearly negative effect on soil albedo (Meyer et al. 2012), most soil processes are affected positively by the addition of biochar (Fig. 8). Best effects on agronomic performance and thus on overall soil improvement have been achieved when biochar was combined with organic fertilizers (Fischer and Glaser 2012, Glaser et al. 2015). Generally, it can be stated that the poorer the soil conditions, with respect to SOC-content, pH and texture, the higher is the positive biochar effect (Glaser et al. 2002).

5.1 Impacts on soil fertility

Although biochar quality depends on feedstock and production technology (see section 4.3) (Schimmelpfennig and Glaser 2012, Wiedner et al. 2013), it is more important to look at matter fluxes (Fig. 1). Organic waste streams should not be mixed up, but rather concatenated reasonably. Biochar should only be made out of nutrient-poor organic matter. Then biochar should be biologically activated by co-composting together with nutrient-rich organic wastes, called "biological aging". Biochar in Terra Preta was exposed to, on average, 2000 years of biological aging, significantly increasing its surface reactivity (Wiedner et al. 2015).

5.1.1 Effect on CEC and nutrient retention

The process of biological aging can increase the cation exchange capacity (CEC) of biochar and thus its nutrient holding capacity (Prost et al. 2013). The principal nutrient retention mechanisms, such as pores, surface adsorption, cationic and anionic interaction, are determined by the physical and chemical structure of biochar. Although fresh biochar has only a low number of functional groups, such as carboxylic acid, higher cation retention was observed when mixing soil with biochar (Glaser et al. 2002). The higher cation exchange capacity of Terra Preta is partly a "simple" pH effect, as it is known that variable (pH-dependent) cation exchange sites increase with increasing pH, and Terra Preta has a higher pH compared to surrounding soils. However, the potential CEC is also increased in Terra Preta, corroborating the fact that CEC of soil organic matter (SOM) can be increased when biochar is present.

It is anticipated that biochar reduces nutrient leaching and, thus, improves fertilizer use efficiency (Glaser et al. 2002). For Africa, only little literature is available on this subject. Sika and Hardie (2014) demonstrated in a South African context, that biochar can decrease nitrogen leaching by up to 96% with excessive and not recommendable amounts of biochar, but simultaneously it reduced its plant availability. In the case of Ethiopia, Agegnehu et al. (2016) outlined the potential of biochar to recover nitrogen from organic and inorganic sources, especially on soils with low fertility. In a study from Germany, biochar addition did not reduce ammonium, nitrate, and phosphate leaching compared with mineral and organic fertilizers, but it reduced nitrification (Schulz and Glaser 2012). However, a meta-analysis of biochar systems across the tropics and subtropics showed an improved crop productivity only in combination with mineral fertilizer (Jeffery et al. 2011). On the other hand, Schulz and Glaser (2012) and Glaser et al. (2015) showed that crop production could be significantly increased when biochar was combined with organic fertilizers (compost, biogas digestate) compared with pure biochar, pure mineral fertilizer, and biochar combined with mineral fertilizer.

5.1.2 Effect on water retention

Biochar has a porous physical structure, which can absorb and retain water, although its chemical structure, being dominated by condensed aromatic moieties, suggesting hydrophobicity. The water retention of Terra Preta was 18% higher compared with adjacent soils (Glaser et al. 2002). Addition of 20 Mg ha^{-1} biochar to a sandy soil in northeast Germany increased water-holding capacity by 100% (Liu et al. 2012). Major et al. (2010) suggested that, due to the physical characteristics of biochar, there will be changes in soil pore size distribution, and this could alter percolation patterns, residence time, and flow paths of the soil solution. Cornelisson et al. (2013) found a significant increase of plant-available water in Zambian soils already at biochar application rates as low as 4 Mg ha^{-1}. In parts of the Ethiopian highland, soil degradation has led to hydrological issues causing waterlogging, runoff and accelerated erosion (Bayabil et al. 2015), some of them being key soil constraints defined by ATA (see section 1). A study in northern Ethiopia found that biochar from wood can increase the infiltration rate of heavy soils and thus counteract these issues (Bayabil et al. 2015). In a field trial on a sandy soil in northeast Germany, application of 20 Mg ha^{-1} biochar together with 30 Mg ha^{-1} compost significantly increased plant-available water content during dry conditions, when compared with the pure compost treatment or the control site without any amendment. This result was quite surprising, as it was anticipated that the fine pores of biochar would retain water being not plant-available, which obviously was not the case (Glaser et al. 2015).

5.2 Crop productivity

Biochar application to soil can increase crop yields (Glaser et al. 2002; Jeffrey et al. 2011; Glaser et al. 2015, Agegnehu et al. 2016). Tremendous yield increases were observed in degraded or low-fertility soils rather than in already fertile soils (Glaser et al. 2002). All over the world, a mean crop production increase of about 10% was observed when using 10–100 Mg ha^{-1} biochar alone in agricultural systems (Jeffery et al. 2011). Crop yield increases were higher when additional nutrients were added (Agegnehu et al. 2016) or when biochar was made from nutrient-rich material such as poultry litter (Jeffery et al. 2011). However, nutrient supply, pH and other soil properties alone were not always sufficient to fully explain the observed positive or negative effects of biochar on yields. It is interesting to note that no single biochar application rate exhibited a statistically significant negative effect on the crops (Jeffery et al. 2011).

5.3 Carbon Sequestration

Biochar is assumed to be stable in the environment. The stability of biochar carbon in soils makes it a highly promising tool for climate change mitigation. However, mean residence times varying from centennial to millennial timescales have been reported (Fig. 9). This discrepancy might be due to the facts that (i) different technologies produce biochars with different stability and (ii) individual biochars are not homogeneous with respect to degradation but contain both labile and stable carbon. Carbon sequestration potential could be calculated as the amount of biochar carbon that is expected to remain stable after 100 years (BC+100). As this is very difficult to determine experimentally for individual biochars, more simple methods to estimate biochar stability (BC+100) are necessary. As shown in fig. 6, the molar ratio of H/C_{org} significantly correlated negatively with the relative stability of biochar. Therefore, by means of the molar H/C_{org} ratio of a given biochar, the amount of stable biochar C can be estimated, which can contribute to potential business models as C offset payments (Glaser 2015).

5.4 Other uses of biochar

Charcoal is predominantly used as energy source for cooking in Ethiopia. The total charcoal production and consumption in Ethiopia was around 6 million tonnes in

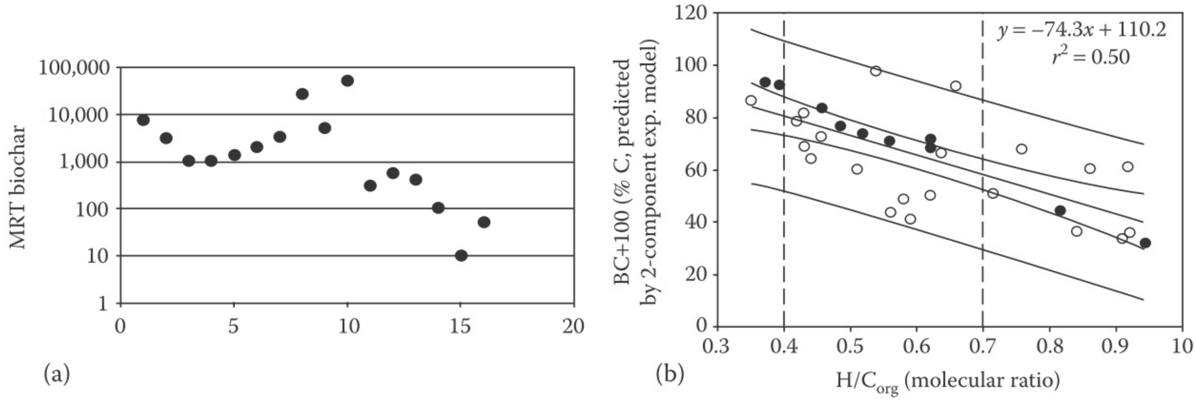

Figure 6: (a) Mean residence time (MRT) of various biochars, x-coordinate as number of reports, (b) correlation between the molar H/C_{org} ratio and the fraction of biochar being more stable than 100 years (Glaser 2015).

2014 (African Development Bank, 2016). Based on this number, there should be a considerable amount of charcoal fines available which are not usable for energy production, but can be used as biochar. Since using these fines would result in additional income to the charcoal producers, only charcoal fines from sustainable charcoal production should be used for biochar systems. About 80 million tonnes of firewood were cut in Ethiopia in the same year. According to Bierig (2016), the price for charcoal in Ethiopia is approx. 500 € per tonne. This is a large incentive for biochar producers to sell their products to the energy market. Considerable amount of charred biomass will probably only be used as biochar if the soil application returns a value which is comparable to energy applications to the user. Besides energy and soil application, biochar can be used as fodder supplement to increase cattle health, as stable litter component to reduce ammonia gas emissions and increase nitrogen fixation and as manure supplement to decrease nitrogen losses and reduce odor contamination (Gerlach and Schmidt 2008). This will be most valuable in areas of intensive livestock production in Ethiopia. In rural areas with small flock sizes on pastures, maintaining cattle health and managing manure will generally be less important. All of these usage options allow for a biochar use cascade, since the biochar is used in the stable or applied to manure, it may later be transported to agricultural soils and help to improve soil properties. Biochar can also be used as filtering agent in water and air filtration systems, which might be an interesting added value application in Ethiopia.

5.5 Risks and challenges of biochar use

The biggest risk that derives from biochar production is its potential to compete with other biomass uses, if no "real wastes" are used (see section 4.1). Thus, it could increase the pressure on cropping systems, promote deforestation and raise the prices for energy and food supply. Also the selection of feedstock is critical for a sustainable use of biochar. If nutrient-rich biomass is being used, large amounts of nutrients get lost during pyrolysis (see section 4.2). To minimize soil pollution risks, it is necessary to restrict biochar production to clean feedstocks with low heavy metal contents and take care that no organic pollutants (e.g. dioxins, PAHs) are formed during the carbonization processes (McKay 2002, Meyer et al. 2014). The pyrolysis of biomass fractions which contain chlorine is especially critical with respect to dioxin formation. Polycyclic aromatic hydrocarbons are often found in biochars from co-current flow gasifiers and sometimes also in kiln-derived charcoals (Schimmelpfennig and Glaser 2012).

Biochars should preferrably be used in agricultural production systems with continuous vegetation or mulch cover to reduce the climate impact of the albedo reduction caused by biochar application. Under European condition, a reduction of the climate mitigation benefit of biochar systems of about 20% due to the albedo impact has been calculated in agricultural production systems without continuous vegetation and mulch cover (Meyer et al. 2012).

Even though biochar has the potential to sequester carbon for a long time in soils (see section 5.3) and, thus, mitigate climate change, there are controversial reports about its effect on green house gases (GHG) fluxes from soils (Ameloot et al. 2013, Gurwick et al. 2013, Lorenz und Lal 2014, Song et al. 2016). In their review, Lorenz and Lal (2014) emphasize that the scientific state of knowledge is inconclusive with respect to GHG fluxes after biochar application. However, the meta-analysis of Song et al. (2016) demonstrates how this inconclusive-ness, is related to several experimental conditions. Especially, the duration of the experiments and the setting in the field or laboratory have a critical influence on the outcomes, but of course, also soil and environmental conditions. The authors stress the need for more long-term field trials to gain a better understanding of that matter.

In the case of CO_2, Lorenz and Lal (2014) conclude that biochar might cause a short-term increase in soil CO_2 emissions, after biochar addition but the long-term effects may be different (Lorenz and Lal 2014). Song et al. (2016) found a decrease in CO_2 emissions in field trials only for application rates <10 t ha^{-1} and for pyrolysis temperatures between 500°C and 600°C.

Even though, interactions between biochar application to soils and CH_4 fluxes are not well understood (Lorenz and Lal 2014), special attention should be paid to this aspect, because the results in literature are contradictory (Song et al., 2016; Jeffery et al. 2016). Biochar had only had a CH_4 source-decreasing or sink-increasing effect in soils fertilized at rates <120 kg N ha^{-1}. At higher N application rates, the CH_4-oxidising activity of an agricultural soil decreases with a risk of CH_4 release (Jeffery et al. 2016).

The key mechanisms of how biochar affects N_2O fluxes are not well understood and long-term field trials are missing (Lorenz and Lal 2014). Libra et al. (2011) found a reduction of N_2O release after biochar addition, in seven out of nine studies. Cayuela et al. (2013) demonstrated the significant impact of biochar on denitrification, with a consistent decrease in N_2O emissions by 10–90% in 14 different agricultural soils. A meta-analysis by Cayuela et al. (2014) found an overall reduction of N_2O emissions by 54%. By means of an innovative stable isotope approach, Cayuela et al. (2013) demonstrated that biochar facilitates the transfer of electrons to soil denitrifying microorganisms, which together with its liming effect promotes the reduction of N_2O to N_2.

6 Biochar as a development feature

Implementing biochar into cropping systems of developing countries has been proposed as a climate-smart and soil-improving technology for sustainable development (Scholz et al. 2014). The question however is, if biochar might be a "Western" technology and to which extent and in which way it is adoptable to societies in the global south? So far biochar is still an unfamiliar technology for most small-holder farmers and implementing new biochar projects in rural areas will require a highly location-specific understanding of people and their needs, values, and expectations (Scholz et al. 2014). Therefore, the same authors argue conclusively, that there is a need for education and demonstration projects to show farmers that making and using biochar would be worth their time (Scholz et al. 2014). But not only farmers need to be trained in the management of biochar. Many small-scale projects work with biochar cook stoves as production units (see section 3.4), which are mostly handled by women. Thus, there must be a benefit for local women to use new stoves, instead of their traditional ones. To enhance the chance of success of a new biochar development project, it should aim at the contribution and participation of local stakeholders as early as possible. A field guide from the Ethiopian Ministry of Agriculture describes a participatory learning approach that iteratively uses a learning cycle of four phases "that move from initial community engagement to one of action planning, implementation and on to assessment and learning, which assist in setting new technologies and innovations in place" (SLMP 2016). These principles are also recommendable for new biochar activities on a local level in Ethiopia.

However, local knowledge and capacity building is only one piece of the puzzle. As emphasized in section 2.3, biochar needs to be considered as a system and many criteria have to be met that the system works. Several of these criteria have been mentioned above, such as: availability of "real waste" biomass, appropriate production technology, effective use of process energy, combination of biochar with other organic amendments (cascade use) and infertile soils with a high potential to upgrade. But to ensure that a biochar system is also viable in the long term, they also have to be economically feasible. Business models with biochar have to be developed, which take all costs and returns into account and are adapted to local markets. Yet, there neither is a demand nor a supply for biochar in Ethiopia. Both has to be established and well connected to each other. By means of these criteria, existing biochar activities in Ethiopia will be compiled and evaluated in a second report.

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Appendix A

Table A1: Tresholds for biochar according to the International Biochar Initiative guidelines (IBI), the European Biochar Certificate (EBC), and the British Quality Mandate (BQM). SOC: soil organic carbon, PAH: Polycyclic aromatic hydrocarbons, PCB: Polychlorinated Biphenols

Element(ratio)	Unit	IBI	EBC (basic)	EBC (premium)	BQM (standard)	BQM (high grade)
SOC	[%]	Class 1: > 60 Class 2: 30-60 Class 3: 10-30	> 50	> 50	> 10	>10
$H:C_{org}$	[-]	< 0.7	< 0.7	< 0.7	< 0.7	< 0.7
Dioxin/Furan	[ng kg^{-1} I-TEQ]	< 17	< 20	< 20	< 20	< 20
PAHs	[mg kg^{-1}]	< 6 – 300	< 12	< 4	< 20	< 20
PCBs	[mg kg^{-1}]	< 0.2 – 1	< 0.2	< 0.2	< 0.5	< 0.5
As	[mg kg^{-1}]	< 13 – 100	-	-	< 100	< 10
Cd	[mg kg^{-1}]	< 1.4 - 39	< 1.5	< 1.0	< 39	< 3
Cr	[mg kg^{-1}]	< 93 - 1200	< 90	< 80	< 100	< 15
Cu	[mg kg^{-1}]	< 143 - 6000	< 100	< 100	< 1500	< 40
Pb	[mg kg^{-1}]	< 121 - 300	< 150	< 120	< 500	< 60
Hg	[mg kg^{-1}]	< 1 – 17	< 1	< 1	< 17	< 1
Mo	[mg kg^{-1}]	< 5 - 75	-	-	< 75	< 10
Ni	[mg kg^{-1}]	< 47 - 420	< 50	< 30	< 600	< 10
Se	[mg kg^{-1}]	< 2 - 200	-	-	< 100	< 5
Zn	[mg kg^{-1}]	< 416 - 7400	< 400	< 400	< 2800	< 150