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

CUMULATIVE REPORT

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cover (farmer ploughing field in Amharan highlands)
p. 3: unfiltered compost
p. 20: farmer in Amharan highlands
p. 48: young wheat plants

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Abbreviations

ADLI - Agricultural Development-led Industrialization
AEZ - Agro-ecological zone
ARARI - Amhara Regional Agriculture Research Institute
ARE - Apparent recovery efficiency
ATA - Agriculture Transformation Agency
BD - Bulk density
BGR - Bundesanstalt für Geowissenschaften und Rohstoffe
BQM - British Quality Mandate
CEC – Cation exchange capacity
CSA – Central Statistical Agency
DAP – Diammonium phosphate
DM - Dry matter
EBC - European Biochar Certificate
EC - Electrical conductivity
ECX – Ethiopian Commodity Exchange
EnDev – Energising Development Partnership Programme
EthioSIS – Ethiopian Soil Information System
GHG - Greenhouse gas
GIZ - Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
HoA-REC&N – Horn of Africa Regional Environment Centre and Network
IBI - International Biochar Initiative
ICS – Improved cookstoves
IRDP - Integrated rural development project
ISFM^{+} - Integrated Soil Fertility Management Project
LIFT – Land Investment for Transformation
LZ – Livelihood zone
MfM – Menschen für Menschen
MoANR – Ministry of Agriculture and Natural Ressources
MSME – Micro, small and medium enterprise
MWS - Micro-watershed
NGO – Non-government organization
PAHs - Polycyclic aromatic hydrocarbons
PASDEP - Plan for Accelerated and Sustainable Development to End Poverty
PIF - The Agriculture Sector Policy and Investment Framework
Qt - Quintal (100 kg)
RARI - Regional Agricultural Research Institute
SDPRP - Sustainable Development and Poverty Reduction Program
SLM – Sustainable Land Management Programme

SME – Small- and medium-scale enterprise
SNNPR – Southern Nations, Nationalities and Peoples' Region
SOC – Soil organic carbon
SOM - Soil organic matter
TERI - The Energy and Ressource Insitute
TLUD – Top Lit Up Draft
UNEP - United Nations Environment Programme
USFS – United States Forest Service
WIYA - Women Innovators of the Year Award

Executive summary

The German government has commissioned the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) to support its partner, the Ethiopian Ministry of Agriculture and Natural Resources (MoANR), in gaining knowledge in biochar-systems for improved soil and nutrient mangement in Ethiopian agriculture. Therefore, the aim of this report is to provide basic information about the principles of biochar systems and the prerequisites for a succesful implementation in Ethiopia. The fundamental questions this report deals with and tries to answer are:

i) In which way and from which feedstock can biochar be produced in Ethiopia?

ii) Which positive and negative effects does the application of biochar substrates have on the soils, the environment, the climate and on the livelihoods?

iii) Which experiences have been made in Ethiopia with biochar systems?

iv) Who could partner a prospective pilot project and where are the best conditions?

v) Which policies and legal frameworks will affect the implementation of biochar systems?

The outcomes of this feasibility study are based on literature reviews, expert interviews, workshops and field trips. An initial review of current literature on biochar research and state-of-the-art production technologies has demonstrated that there are feasible options to produce biochar on small, medium and large scales. Considerung the use of biochar as a whole system that includes cascade-uses of biochar and combinations with other soil amendments, reveals the huge potential to tackle soil degradation issues and to improve livelihoods. The effective enhancement of important soil properties, such as pH, CEC, SOC content, water and nutrient retention, through the application of biochar substrates has also been proved in various research projects in Ethiopia. Apart from its soil improving effect, biochar is a very stable form of organic carbon, which can be stored in the soil, being an option for climate change mitigation.

In Ethiopia, Jimma University has implemented the major share of biochar research in cooperation with Cornell University (USA); but also other universities and institutes have been envolved and are going to launch new activities. Espacially, Injibara University, Haramaya University, Awassa University and Dilla University will play an important role in further biochar research. The main questions they have to address are:

- Which feedstocks are locally available?
- Which production technologies are affordable and fit the needs of either rural households or small- and medium-scale enterprises?
- What are farmers perceptions of this new technology and what kind of social, cultural, gender-based or politcal barriers are related to it?

Practical experience and projects on the ground with farmers are rare in Ethiopia. Most activities are carried out by non-governmental organizations or private entrepreneurs. Public projects with biochar have not been established so far. Up to now, there are no long-term biochar

projects in Ethiopia.. Those pioneers who try to establish biochar systems face numerous barriers in their activities. The most important ones are:

- Lack of awareness and knowledge of farmers about biochar
- Inappropriate production technologies
- Limited capital and high investment costs
- Low demand for biochar on the market
- Missing support from public institutions
- Lack of guidelines and standards

Other actors that are interested in biochar systems and might serve as potential partners have been evaluated. Among the most important public stakeholders are the Ministry of Agriculture and Natural Resources, the Ethiopian Agricultural Transformation Agency, the Ministry of Environment, Forestry and Climate Change, the Ministry of Water, Irrigation and Energy, the Ethiopian Standard Agency and public research institutions, such as universities and regional agricultural research institutes.

The total amounts of biomass residues from different sources and processes that are potentially available for the production of biochar in Ethiopia have been estimated. Among the most promising biomass resources are coffee husks, rose rootstocks, *P. juliflora*, animal bones and farm and household waste. While the selection does not reflect a detailed survey, it rather indicates the order of magnitude of feedstock availability according to the limited information available from primary and secondary sources.

Based on these feedstock sources and the scale of the different production technologies, three schemes of potential biochar systems can be drawn:

i) small-scale biochar systems, based on the production in pyrolysis cookstoves by local households, using coffee residues or farm and household waste as feedstock.

ii) medium-scale biochar systems based on the use of institutional gasifier cookstoves or small pyrolysis plants in small- and medium-scale enterprises, such as bakeries, community kitchens, hotels or coffee roasteries.

iii) large-scale biochar systems using pyrolysis plants for industrial purposes, such as cooling stores, dyeing or boiling processes, based on feedstocks like rose or sugarcane residues.

On the basis of these options, two priority areas have been identified that are best suited for the implementation of biochar systems. Priority area I is located within the target area of the ISFM$^+$ project by GIZ and aims at the introduction of a biochar system based on small-scale production units. It suggests the use of coffee residues as feedstock and the combination of biochar with other soil improvement measures from the ISFM$^+$ project, such as manure or compost. A suitability map indicates that the soils in the project areas in Oromia and Amhara have a higher potential to be improved by biochar application than those in Tigray.

Priority area II is located within the rose farming clusters South and South-West of Addis Abeba and deals with the implementation of a large-scale pyrolysis plant. The model suggests the use of rose rootstocks as feedstock combined with composting of green residues from roses,

according to a business model of *Soil and More Ethiopia.* The excess heat from pyrolysis could be transformed into cooling energy by using so-called absorption chiller systems. Thus the current energy supply for rose cooling stores can be substituted by the excess heat of a pyrolysis plant.

Finally, a risk assessment on the negative impacts of biochar on soils emphasizes the importance of clean feedstocks and reliable cookstoves, in order to avoid the formation of polycyclic aromatic hydrocarbons (PAHs), dioxines and other pollutants. To assess the climate impact of biochar systems, it is necessary to take the emissions and removals of greenhouse gases, as well as the changes in the soil albedo and the emission of ultrafine carbon aerosols into account. The main negative impacts are caused by the provision of the feedstock and the albedo impact. However, the major CO_2- savings (i.e. carbon sequestration, replacement of fossil fuels and the reduction of soil greenhouse gas emissions) can outweigh the negative effects and dominate the overall climate impact, when managed appropriately.

1 Introduction

Ethiopia is the thirteenth 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 by 188 million citizens (United Nations 2015). Consequently, its population density is going to raise from approx. 90 km^{-2} to 170 km^{-2}, but the area of fertile arable land will probably not grow in the same way (Teshome 2014). These numbers illustrate 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 basis 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:

> Soil 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 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.

The aim of this report is to provide basic information about the principles of biochar systems and the prerequisites for a succesful implementation in Ethiopia. The fundamental

questions this report deals with and tries to answer are:

> In which way and from which feedstock can biochar be produced in Ethiopia?

>Which positive and negative effects does the application of biochar substrates have on the environment, the climate and on the livelihoods?

> Which experiences have been made in Ethiopia with biochar systems?

> Who could partner a prospective pilot project and where are the best conditions?

> Which policies and legal frameworks will affect the implementation of biochar systems?

To respond to these questions a feasibility study has been conducted, including a review of primary and secondary literature, expert interviews, workshops and field trips. First (part I), the state of the art of current biochar research and technology with a focus on Sub-Saharan Africa has been evaluated. Second (part II), a synopsis of past, current and future biochar activities in Ethiopia has been compiled; including scientific, as well as practical projects. Third, the overall amounts of the best-suited feedstocks for biochar production have been estimated. Fourth, based on the scale of the production units, different schemes for the implementation of biochar systems in Ethiopia have been drawn. Finally (part III), two priority areas have been identified, that provide the best conditions for biochar systems pilot projects and a risk assessment has been undertaken for these areas.

This report will create an understanding of the opportunities and challenges that are connected to the production and the application of biochar in Ethiopian agriculture. Since there are numerous different approaches to introduce biochar systems, the report does not reflect the full range of opportunities that exist in Ethiopia. However, it provides the best information available. Thus, it offers different strategies for the implementation of a prospective bilateral cooperation and indicates where promising, local collaborations are likely to be found.

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

PART I

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. 2017). 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 I.

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

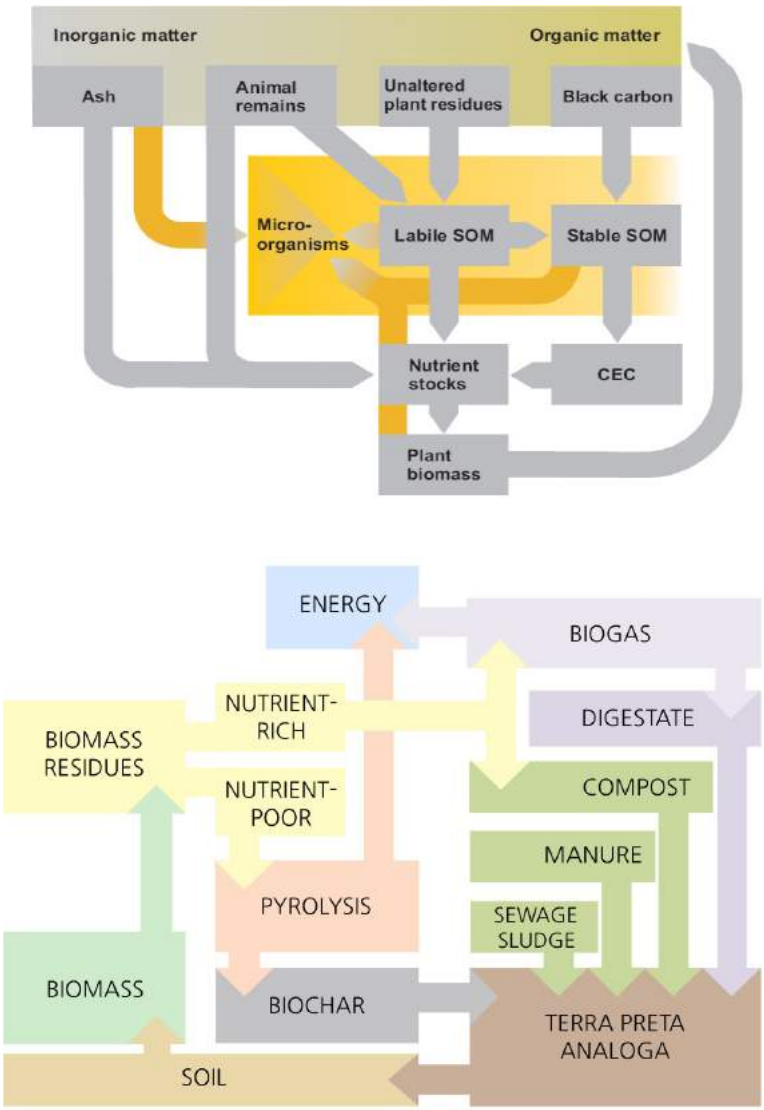

Figure 1: Biochar-based circular economy principle of ancient anthrosols (top) and modern society (bottom) (Glaser 2015, modified).

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). The variety of blends that can be created from biochar and other organic or inorganic materials are subsumed under the term "biochar substrates" in this report.

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. 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

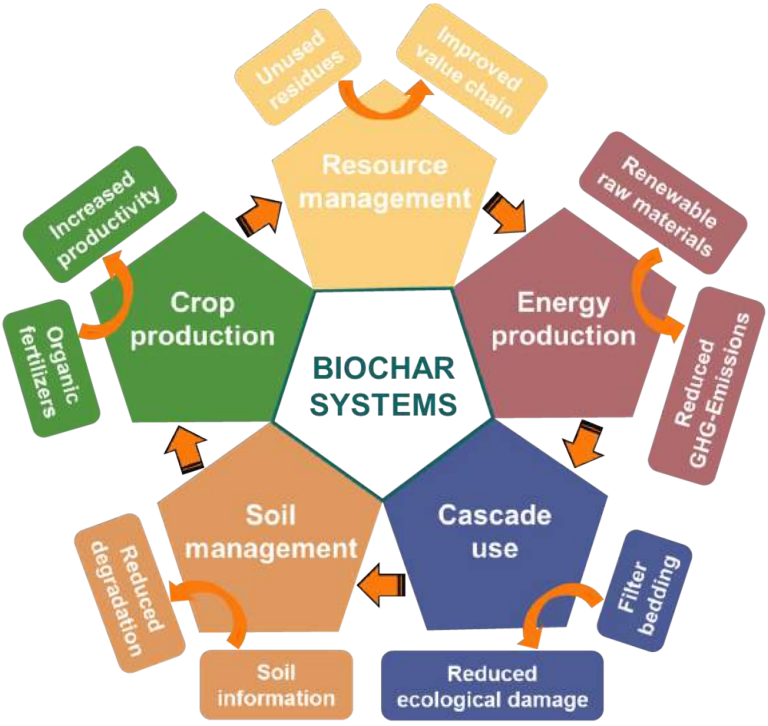

Figure 2: Schematic diagram of biochar systems (copyright: Andreas Möller)

additional amendment, e.g. rock flour, could be of advantage.

2.3 Biochar from 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 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 sub-Sahara African contexts

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, that 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 required 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).

In the following subsections, 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.

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

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 range of several 100 kg (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 still needs 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 the use 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 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 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.

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 around 400.000 €.

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

Pyrolysis plants of the German company $BIOMACO_2N$ (fig. 5) are available with annual production capacities between 40 and 200 tonnes ($BIOMACO_2N$ 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 required. The smallest $BIOMACO_2N$ units cost around 75.000 €. A certification of the produced biochar according to the EBC-criteria is not available yet.

Figure 5: $BIOMACO_2N$ pyrolysis plant (www.biomacon.com)

The international nature conservation 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.

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

Electricity supply and emergency water supply is required 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 available yet.

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 expenses 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, internet access and continous water supply) and an as-easy-as-possible maintenance of the plants should 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 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 (ICSs) 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

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

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 Re^2, 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 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 is 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 Role of feedstock

4.1 Feedstock availability and biomass competition

The implementation of biochar into cropping systems generally requires a feedstock source that is not used for any other purposes so far. Otherwise, biochar systems may be in danger to put additional pressure on the fragile food and biomass 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 non-competitive feedstock depends highly on local conditions, such as predominant crops or distance to bio-residues 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 feedstock procurement". In their recent feasibility study from South Africa, for example, they have identified alien invasive

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

plants and sawmill residues 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 (section 7.2), *Prosopis juliflora* (section 7.6) and animal bones (section 7.3) 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 use of charcoal fines left after charring as biochar needs to be investigated (section 6.3.4).

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 nutrient-rich 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. (2016a).

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 (Joseph et al. 2009, Enders et al. 2012, Schimmelpfennig and Glaser 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 (see section 4.2).

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 an important 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 factor for CEC is the pyrolysis temperature, whichis 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 (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).

Box 1 - Essentials about feedstock

A sustainable feedstock needs to be:
> non-competitive
> nutrient-poor
> ligneous
> easily procurable
> abundantly available
> heavy metal- and chloride-poor

Besides pyrolysis conditions, the physical and chemical properties of the feedstock are critical for the quality of biochar.

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 residues 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 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

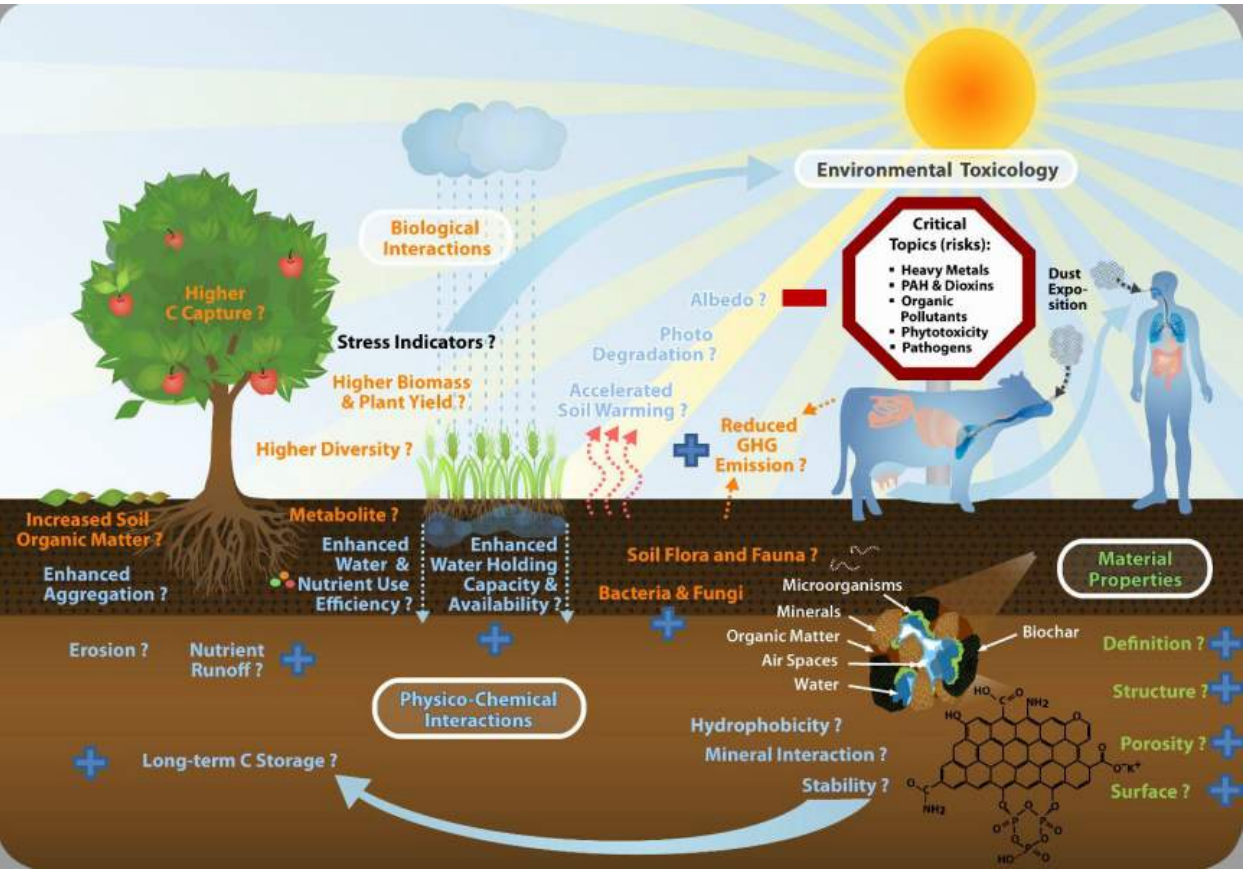

Figure 8: General effects of biochar on soil physico-chemical and (micro) biological processes (from Glaser 2015 with permission).

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 effect of biochar (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). 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. (2016b) 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 t 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 t 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 t ha^{-1} biochar together with 30 t 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. 2016b). 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 t ha^{-1} pure biochar in agricultural systems (Jeffery et al. 2011). Crop yield increases were higher when additional nutrients were added (Agegnehu et al. 2016b) 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 more stable than natural soil organic matter. 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. 9, 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 Risks and challenges of biochar use

Apart from several constraints related to biochar production and use already mentioned in preceding sections (competion with other biomass, loss of nutrients, PAH and dioxin formation, heavy metal contents), there are some more important points to mention:

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

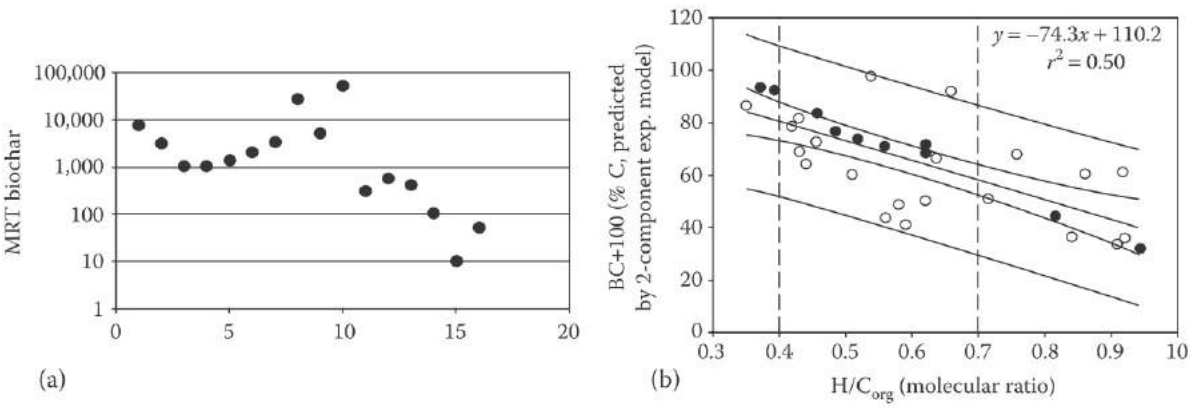

Figure 9: (a) Mean residence time (MRT) of various biochars, x-coordinate as number of reports, (b) correlation between the molar H/C_{org} ratio and the fraction of biochar being more stable than 100 years (Glaser 2015).

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.

Synopsis and Evaluation of Biochar Activities in Ethiopia - Schemes for Potential Biochar Systems

PART II

6 Synopsis of biochar activities and evaluation of obtained results

This section compiles and evaluates all available information on scientific and practical biochar activities in Ethiopia (figure 10), and draws conclusions for further implementations of biochar systems. The compilation of these activities will elucidate the opportunities and challenges, that biochar systems are facing or might face in the future. An overview of recent biochar research in Ethiopia is given in table 2. In the following, obtained results of available scientific biochar projects in Ethiopia are evaluated.

6.1. Scientific perspective

6.1.1 Jimma-cornell-group

In recent years, Jimma University has collaborated intensively with Cornell University (USA), and has gained a leading role in Ethiopian biochar research. Their joint program called ''Indigenous Bio-Fertilizer Development for Agro-Ecological Intensification of Sustainable Enset Legume Cereal Production in South and Southwestern Ethiopian Smallholder Farming System'' has included many activities on different subjects around biochar, addressing the following objectives:

1. Identify opportunities to restock soils with nutrients and carbon from non-competitive residues and wastes from agricultural and agro-industrial sources.
2. Develop indigenous and low-cost alternative fertilizers and soil conditioners targeting specific production constraints.
3. Provide a proof-of-concept for a recapitalization of soil fertility using local

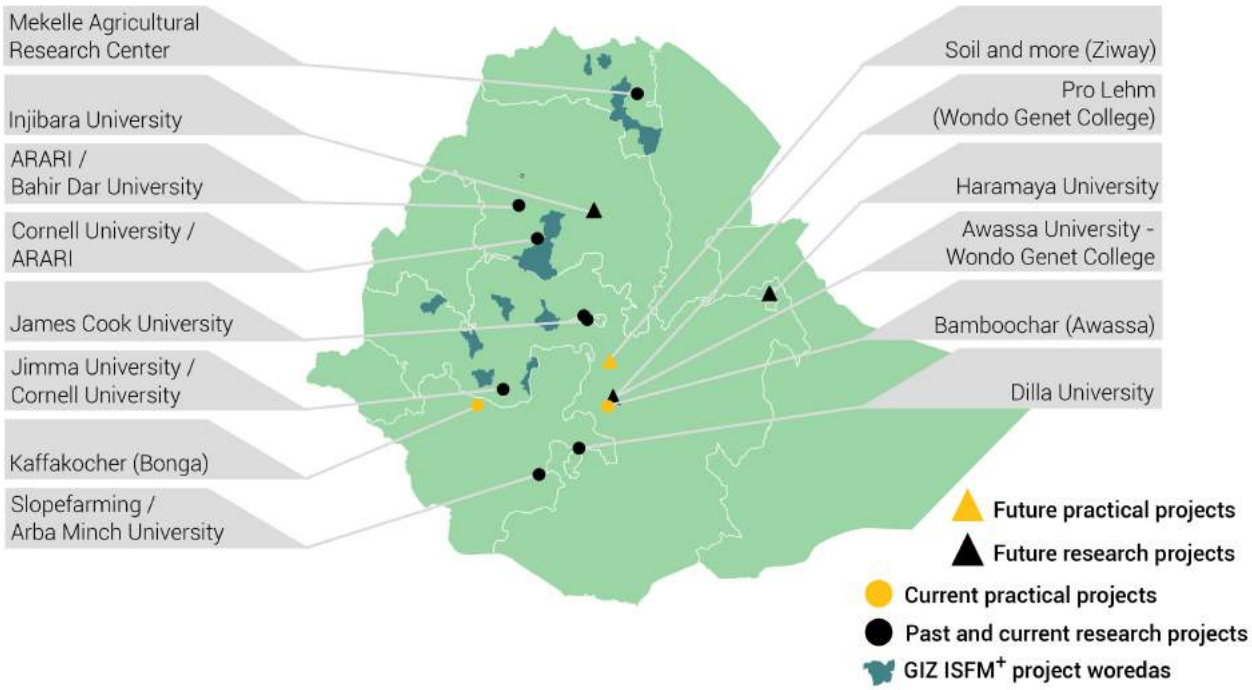

Figure 10. Outline map with compilation of biochar activities in Ethiopia

Table 3. Total N and available nutrient (Mehlich III extractable) contents of biochar and biochar-based indigenous fertilizers from Jimma-Cornell Group (derived from internal report)

Indigenous Bio-fertilizer	N	P	K	Ca	Mg	S
	mg kg^{-1}					
Coffee husk biochar	14.6	497.5	10549.5	1485.9	603.7	835.1
P. juliflora biochar	13.7	228.6	6218.7	1482.7	124.6	254.2
Bone char	14.7	5088.8	389.9	23683.1	2363.0	102.7
Coffee husk biochar-compost mix[1]	21.7	3408.6	5296.2	7197.8	1636.1	138.0
Sawdust biochar-bone char mix[2]	13.2	4268.7	5109.5	18624.9	2078.5	24.9
P. juliflora biochar-compost mix[3]	16.1	9349.3	3884.7	11428.8	2545.8	350.9
Jimma-biochar-based indigenous fertilizer mix[4]	19.2	2519.0	5085.9	7768.9	1841.7	225.0
Awassa-biochar-based indigenous fertilizer mix[5]	14.6	3167.9	3916.3	10568.9	2455.6	485.8

[1]Coffe husk biochar mixed and cocomposted with coffee husk, farm yard and chicken manure. [2]Sawdust biochar co-pyrolyzed and composted with bone char. [3] *P. juliflora* biochar mixed and co-composted with sugarcane, farm yard and chicken manure. [4] Coffee husk biochar, coffee husk, farm yard and chicken manure compost, ash and bone meal co-composted. [5] *P. juliflora* biochar, sugarcane, farm yard and chicken manure compost, ash and bone meal co-composted

nutrient sources.

4. Develop an appropriate technology for the production, packaging and delivery of indigenous fertilizers for small-scale farmers.

A central activity of the group, in the early stage, was to detect the most promising feedstock sources in the region for biochar production. This was done by a review of secondary data and a socio-economic household and agro-industry waste streams survey. The survey included detailed questionnaires to assess the locally available biomass resources and their competitive uses, the farmer's perception towards these resources and their willingness to pay for so-called indigenous fertilizers, that are based on biochar and bone char. Initially, the group's activities were directed to establish a biochar system. But their biomass-assessment found a huge potential for animal bones as feedstock. However, the char obtained from bones must not be called biochar, but "bone char", since it consists mainly of tricalcium phosphate and not carbon. Apart from animal bones, their assessment mainly stressed the potential of coffee husks, but also sawdust, *Prosopis juliflora* and sugar cane residues as feedstock. Further details on biomass availability from this study are given in section 7.1.

Their survey also revealed that for Jimma area only 13% of farmers were not willing to pay for any fertilizer. Among those who are willing to pay for fertilizers 62% would prefer a combination of inorganic and organic fertilizers. For Awassa area the willingness to pay for a combined fertilization is even higher (70%). They also observed that most farmers used only one third of the recommended amount of mineral fertilizers, if they used fertilizers at all.

From this assessment the group developed several so called “indigenous bio-fertilizers” and characterized them by their nutrient content (table 3). Substrates that contained bone char or bone meal had an outstanding P content, compared to the others. Having the idea of a bone char based P-fertilizer, the group calculated that the average livestock herd kept in Ethiopia between 2008 and 2011, could provide between 17,291 and 36,272 tonnes of phosphorus for

plant uptake per year (table 6), by converting their bones into char. This could substitute up to 58% of the Ethiopian P fertilizer consumption every year, if every single bone from slaughtered animals in Ethiopia is used for bone char production.

In on-farm field trials, their biochar-based indigenous fertilizers, which was made out of biochar from *P. juliflora*, compost, bone meal, ash and additional NPK fertilizer, was the only treatment that significantly increased crop yields compared to conventional fertilizer use (figure 11). This underlines the need to combine biochar with other soil amendments to achieve clear yield improvements. The biochar used in their experiments had been produced by a research-grade pyrolysis unit manufactured at Cornell University. The merits of their activities was a series of commercial indigenous bio-fertilizers called *Abyssinia Phosphorous* (figure 12), which they plan to distribute commercially.

Within the groups efforts for local capacity building was also the plan to design, produce, test and distribute improved fuel-efficient cookstoves for clean cooking and for the production of biochar, which could be used for home-made indigenous fertilizer. Several types of cookstoves have been developed at Jimma

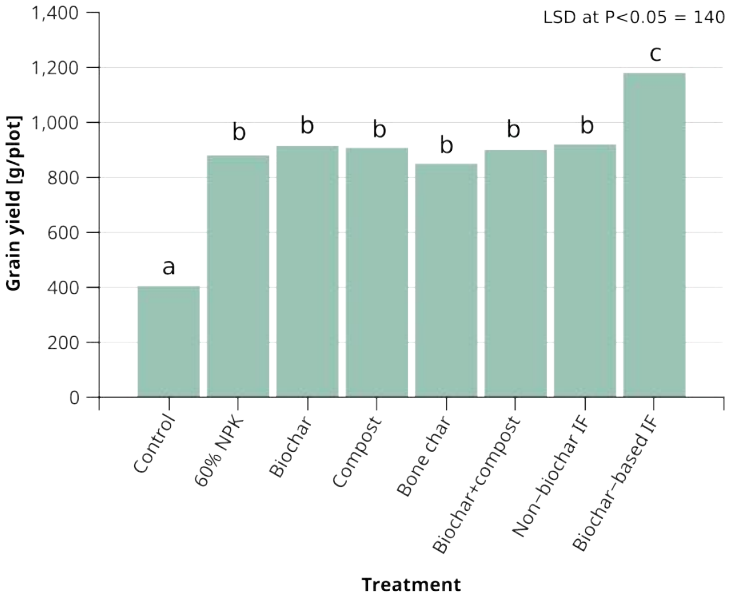

Figure 11. Maize yield of on- farm field plot trials of Jimma-Cornell Group (taken from internal report)

University (section 3.3), however, on a field demonstration during a biochar workshop at Jimma University in June 2016, local cookers failed to use the cookstoves as intended by the researchers. For local cookers it seems to be a bigger challenge to shift their cooking habits according to the new stove's requirements, than most researchers and designers have expected. Therefore, the adoption of improved cookstoves is a common problem of such projects around the globe (Global Alliance for Clean Cookstoves 2011, Jeuland et al. 2013, GIZ 2014a, Palit and Bhattacharyya 2014, Thacker, Barger and Mattson, 2014, Dickinson et al. 2015) and conclusively Prof. Johannes Lehmann from the

Figure 12. Commercial indigenous bio-fertilizer products called "Abyssinia Phosphorous" from Jimma-Cornell Group (Copyright: Berhanu Belay)

Jimma-Cornell-Group stated on the workshop at Jimma that the stove design remains a key-challenge for their project.

Cornell did not only collaborate with Jimma, but also with the University of Bahir Dar and Amhara Regional Agriculture Research Institute (ARARI). In a joint study, they observed the effect of different biochars on water retention and hydraulic conductivity of very clayey soils in the Anjeni watershed, that are affected by waterlogging (Bayabil et al. 2015). The biochars were obtained from Acacia (*Acacia abyssinica*), Croton (*Croton macrostachyus*), Eucalyptus (*Eucalyptus camaladulensis*), Oak (*Quercus*) and Maize (Zea mays) by charring them in the local way or in a research pyrolyser at 450 °C. The only relevant observations were that wood biochars significantly decreased soil moisture content at low pF-values (pF 2 and 2.4) (low water potentials) and that the same increased hydraulic conductivity, due to coarser particle sizes. The use of these woods as feedstock is not recommendable in Ethiopia for ecological reasons, nor is it to produce biochar in the same way as charcoal is being produced.

Also Jimma published some studies on their own. Dume et al. (2015) compared biochars made from coffee husks and corn cobs at two different pyrolysis temperatures (350 °C and 500 °C) with a research pyrolysis unit. Both feedstocks can be a sustainable source for biochar production in the area. Their results regarding soil amendment effects are:

- Every biochar treatment increased soil pH, SOC and total N at every application rate (5 t, 10 t and 15 t ha^{-1}) compared to the control. The highest increases for pH (from 5.2 to 6.1) and SOC (from 3.70% to 6.69%) were achieved with an application rate of 15 t ha^{-1}
- Available P was mainly increased by biochars derived from higher pyrolysis temperatures.
- Coffee husks biochar tended to have a bigger effect on soil properties than corn cob biochar.

Most of these findings concur with an earlier study from Jimma, which observed that pH, SOC, total N and available P was significantly increased by applying 10 t ha^{-1} of maize stalk biochar pyrolysed at 500 °C with the same research unit (Nigussie et al. 2012). In most cases, also 5 t ha^{-1} led to significant improvements of the same soil properties. Further on, they found that biochar can significantly improve the plant uptake of N, P and K and reduce the uptake of harmful Cr in a pot experiment with soil from a Nitisol.

6.1.2 James cook university (australia)

Other universities and institutes have also been working on biochar, however, not within such a large scale project as Jimma and Cornell. A research group from James Cook University (Queensland, Australia) has been working on organic fertilizers, including biochar and their effect on soil properties of an Eutric Nitisol and the performance of barley in Ethiopia (Agegnehu et al. 2016a, Agegnehu et al. 2016b). The group used biochar that has been produced as ordinary charcoal from Acacia, in traditional earth kilns, which does neither represent a sustainable feedstock, nor a sustainable way of production. Fortunately, Agegnehu et al. (2016a, b) did not

only compare pure biochar and compost with inorganic fertilizers but also tested a mix of biochar and compost and co-composted biochar, with a gravimetric biochar content of 17%. In this study, all inorganic and organic amendments increased yields significantly and organic amendments were sometimes even higher. But the highest yields were achieved when organic and inorganic fertilizers were combined with each other (figure 13). Regarding the impact on soil conditions, organic amendments had a clear advantage over inorganic ones. Almost all organic amendments increased soil pH significantly, whereas inorganic ones did not. The biggest changes were achieved by the highest application rate of 10 t ha^{-1} of pure biochar (from pH 4.85 to 5.37). The same was found for SOC content, which was even decreased by some inorganic fertilizers (Agegnehu et al. 2016a). Another remarkably positive effect of organic amendments were their effect on soil water content after harvest, which remained unaltered by inorganic soil amendments. The highest value was achieved by 10 t ha^{-1} of pure biochar with 49%, compared to the control with 38% (Agegnehu et al. 2016a). This property is of special interest in a country like Ethiopia, where water is rare after the rain season, since it will promote the germination of new seeds. Regarding nitrogen use efficiency, the group's results demonstrate a clear advantage of biochar. Pure biochar treatments achieved an apparent recovery efficiency (increase in N uptake per unit of N applied, ARE) of 50% at a fertilizer rate of 69 kg N ha^{-1}, whereas all other treatments have an ARE below 40%.

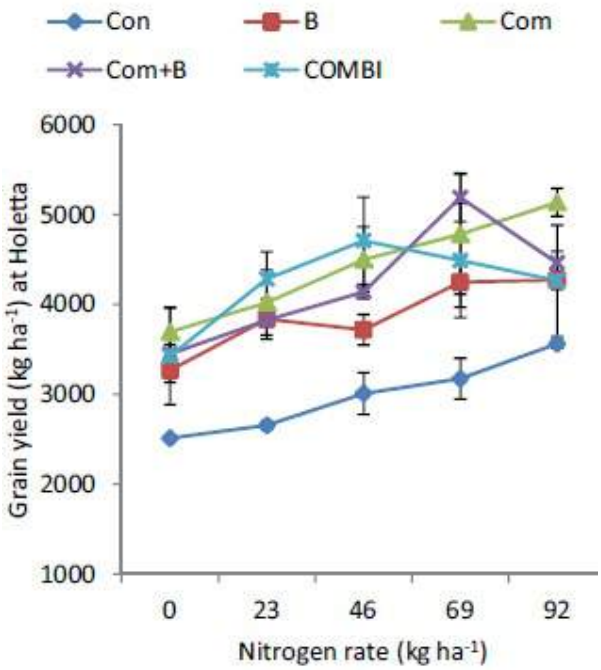

Figure 13. Barley grain yield as influenced by the interaction of organic amendment and N fertilizer rate at Holetta (taken from Agegnehu et al. 2016a). Con: control, B: biochar, Com: compost, Com+B: compost mixed with biochar, COMBI: co-composted biochar.

Also the agronomic efficiency (yield increase per unit of N applied) significantly increased by biochar treatments, especially at low fertilizer rates (Agegnehu et al. 2016b). These findings underpin the potential of biochar to improve the efficiency of inorganic fertilizers and to contribute to the success of large-scale fertilizer projects such as EthioSIS[1].

6.1.3 Mekelle agricultural research centre

A pilot pot experiment, which observed the effect of biochar, compost, and their mixture combined with mineral fertilizers on soil properties and the yield of wheat was conducted at the Mekelle Agricultural Research Centre, Tigray (Gebremedhin et al. 2015). The feedstock for the biochar was *P. juliflora*, which is very suitable, since it is an invasive tree in the Eastern

[1]The Ethiopian Soil Information System (EthioSIS) project gathers and analyzes soil samples from each of the country's 18,000 agricultural kebeles to develop soil fertility maps and fertilizer recommendations for each region.

part of the country. However, the biochar has been produced in the local way as charcoal, which is not recommendable. Since the test soil was already alkaline (pH 8.1), it is no surprise that biochar did not have a liming effect. But very puzzling is the observation that neither biochar (4 t ha^{-1}), nor compost (7 t ha^{-1}), nor their combination (2t biochar + 3.5 t compost ha^{-1}) could increase the SOC and the CEC compared to the mineral fertilizer treatment (100 kg urea + 100 kg DAP). However, grain yield was significantly increased (+16%) by the combination of biochar and mineral fertilizers. Even though the researchers infringed basic scientific principles, this outcome concurs with other findings mentioned above.

6.1.4 Dilla university

According to a paper by Berihun et al. (2017), farmers around Dilla recently started to use biochar as a cheap and readily available lime supplement. A small survey among 50 farmers revealed, that they were using various kinds of feedstock to produce biochar: maize cobs, barley straw, wheat straw, pea straw, bean straw, *Lantana camara*, *Eucalyptus globulus* and Bamboo. Mostly, however, they used *E. globulus*, *L. camara* and maize cobs, in descending order. Unfortunately, no information is available about the agronomic impacts of these biochars and how the farmers got aware of this technology. The study itself investigated the effect of biochar from *E. globulus, L. camara* and maize cobs on physical and chemical soil properties of an acidic Nitisol. All biochars significantly decreased bulk density and increased porosity at every application rate (6, 12, 16 t ha^{-1}). Moreover, every biochar treatment significantly increased pH, SOC and available P. Total N and K were only increased by application rates of 12 and 16 t ha^{-1}, and exchangeable acidity only by 16 t ha^{-1} independent of the type of feedstock. The researchers, and presumably also the farmers, produced their biochar in traditional earth mounds, which restricts the efficiency and sustainability of this biochar production.

Box 2 - Findings and open issues of biochar research in Ethiopia

Findings:
> biochar, in combination with other organic and inorganic fertilizers, has the potential to substitute mineral fertilizers and to overcome serious soil constraints
> even application rates of <10 t ha^{-1} significantly reduce soil acidity and increase SOC content
> biochar substrates are an excellent nutrient carrier that increase the availability of nutrients and reduce nutrient losses
> several non-competitive feedstock sources that can improve biomass use efficiency are available, such as animal bones, *Prosopis juliflora*, or coffee husks

Open issues:
> lack of an appropriate production technology, that is affordable and fits the needs of either rural households or small- and medium-scale enterprises (SMEs)
> potential barriers related to this new technology and farmers perceptions have not been investigated

6.1.5 Amhara regional agriculture research institute

The Amhara Regional Agriculture Research Institute (ARARI) has published a paper on the effects of biochar on soil conditions and the yield of teff (*Eragrostis teff*), Ethiopias most important crop (Abewa et al. 2013). In their study, ordinary charcoal from eucalyptus (*E. globulus*) produced in traditional earth kilns served as biochar, which does neither represent a sustainable feedstock, nor a sustainable way of production. The group observed the highest yields for each biochar rate (4, 8 and 12 t ha^{-1}) when it was combined with 60 kg N ha^{-1}.

6.1.6 Addis abeba university

Recently also Addis Ababa University has launched research on biochar and soil fertility. They investigated the carbon sequestration potential and the effect on soil conditions of two different feedstock types (rice husks and maize straw) and different pyrolysis temperatures (Tesfamichael and Gesesse, unpubl.). However, the results are not available, yet.

6.2 Practical perspective

6.2.1 Kaffakocher

At Kafa area around Bonga (SNNPR) a project called *Kaffakocher* has been established by a Swiss consortium of two companies, called *Kaskad-e GmbH* and *bonnepomme* (kaffakocher.ch). Their aim is to improve livelihoods and health of local people and to reduce deforestation and CO_2 emissions by using clean and fuel-efficient gasifier cookstoves.

Figure 14. Burning Prototype 1 from Kaffakocher (Copyright: Nadine Guthapfel)

These stoves are fed with coffee husks from dry processing units in the area. The project cooperates with the Kafa Forest Coffee Farmers Cooperatives Union, which represents 30 coffee cooperatives in the area and runs a dry processing unit on its own. Within the project, a pyrolysis cookstove has been developed for the use of loose sun-dried coffee husks as fuel and for baking injera (figure 14). They have been developed based on the gasifier “PyroCook” developed by *Kaskad-e GmbH* and are based on a Top Lit Up Draft (TLUD) principle. However, it is still under development. These clean burning and fuel-efficient stoves decrease the amount of fuel and also indoor air pollution, compared to traditional three stone stoves (Roth 2011, Martin et al. 2013). In workshops the project wants to train local craftsmen to manufacture these stoves and to distribute them independently. The biochar is intended to be co-composted and subsequently applied to the farmers fields.

The first phase of the project has been completed and the project has faced several barriers for the implementation of their biochar system. The biggest issue is the stove

technology. For more than 3 years, the group around Stephan Gutzwiller has been working with support from international gasifier experts, such as Christa Roth, to develop a proper stove model. However, technology adaptation remained challenging and results remained unsatisfactory until the end. Loose coffee husks turned out to be very variable depending on the climate and the time of the year, therefore a fan for forced draft was necessary. Furthermore, the cookstove could not completely fulfill all the expected requirements of a proper stove so far. In addition, user acceptance is lacking, e.g. due to complicated handling or shorter burning duration. Currently, a stove model for injera baking exists, using a traditional *Mirt* stove as outer cylinder of the stove and a fan for forced draft. Further adaptations might be possible. For additional simplifications, using a stove model with natural draft, pelleting of the coffee husk is required.

Apart from technical challenges, the coffee farmers in the project area do not have SOC depleted soils. The traditional forest coffee and semi-forest coffee cropping systems are quite sustainable agroforestry systems that retain a lot of organic matter to the soils and conserve their fertility (Gole 2015). Consequently, the soils have little potential to be improved by biochar, and farmers are not interested in it. For these reasons, the project has not conducted any agronomic pilot trials to demonstrate their biochar-compost-concept to farmers, yet. But a follow-up project is being prepared that intends to intensify their agronomic activities.

6.2.2 Pro lehm - marius bierig

Another private entrepreneur is Marius Bierig who runs the company *Pro Lehm* (Germany) and has been developing different gasifier stoves from clay and recycled materials in Ethiopia for more than four years. He has been working in Addis Abeba and, since 2014, also in Barhir Dar. His recent activities are embedded in a project of *Welthungerhilfe*. They have established a workshop to train locals in manufacturing different types of clay gasifiers, and they have supervised ten test households in using them and producing biochar. A *Wot*-gasifier has been developed for cooking and a *Mirt*-gasifier for baking Injera. The latter, however, still needs modifications. Unfortunately, a detailed evaluation of these activities and biochar quality test results are not available, yet. According to Marius Bierig, clay stoves are cheap, easy and fast to produce, very fuel-efficient and clean-burning. Moreover, they have calculated all expenses and revenues of their stoves and have developed a profitable business model. So far, the project has been working with eucalyptus wood as feedstock, which should be reconsidered, since one great advantage of gasifier technologies is their ability to burn different types of organic materials. The clay gasifier stoves of *Pro Lehm* seem to be one of the most promising technologies for a houshold-scale production of biochar. And the inventors are eager to continue their work in the longer term and to move the development of well-working stoves forward. Agronomic pilot trials with biochar were not included in their activities,

Figure 15. Furnace for biochar production from bamboo (Copyright: Tarikayehu Gebresilassie)

but will be conducted within the cooperation with the Awassa University (section 6.3.3).

6.2.3 Bamboochar - tarikayehu gebresilassie

At Awassa, one biochar project already runs a medium-scale pyrolysis unit and produces biochar. It is a private entrepreneur called Tarikayehu Gebresilassie, who has launched her own enterprise with biofertilizers, and who won the Women Innovators of the Year Award (WIYA) 2015. She produces approx. 100 kg of biochar per day from bamboo in a furnace that she has built on her own (figure 15), and also bamboo vinegar for soap production. Her products are sold at several bio-fertilizer hubs in the country, which have been financed and installed by LIFT[2] (Land Investment for Transformation) Ethiopia. Apart from that, she sells her products privately and plans to cooperate with the Agricultural Regional Bureau of Awassa. However, the biggest challenges she faces are limited funds, lack of people's awareness of the topic and trained manpower. So far, she did not have the capacities to assess the agricultural potential of her biochar in pilot field trials.

6.2.4 African briquet factory plc

Since 2011, the African Briquet Factory PLC produces briquettes from different agricultural residues, such as coffee husks, maize stalks, bagasse, peanut pods, etc. These briquettes are a sustainable and environmentally friendly energy source that is being used in different industries, such as textile, leather, soap production, cement, paper and others. Earlier activities of the company were directed to gasifier stoves for households and small- and medium-scale enterprises (SMEs). They have developed their own stove models for that purpose, which are still running in approx. ten SMEs. This business, however, was not profitable and the company stopped their activities. There is no information available on the use of the resulting biochar.

6.2.5 Slopefarming

In 2015, the Hamburg University of Technology (Germany) in cooperation with the Arba Minch University (Ethiopia) has set up the *Slopefarming* project. They will develop a holistic approach regarding the restoration of degraded soils and ecosystems. Different measures will be set into practice in order to tackle the

[2] Land Investment for Transformation (LIFT) is a project being implemented under the Ministry of Agriculture of the Government of Ethiopia by DAI Europe and Nathan Associates. LIFT aims to improve the incomes of the rural poor and to enhance economic growth through second level land certification (SLLC), improved rural land administration and the development of the rural land market system following the M4P approach. LIFT will distribute 14 million second level land certificates to small rural landholders in 5.5 years.

deterioration of arable land by soil erosion and degradation, which is caused by non-adapted conventional agricultural practice and the destruction of natural vegetation. Among these measures are rain water harvesting, agroforestry and silvopastoral systems, but also gasifier cookstoves and a Terra Preta Sanitation system, that combines composting of faeces, biochar and other organic wastes. The feedstock for biochar production in the stoves is sawdust from nearby sawmills. Still, their stove model is under development and results from agronomic trials are not available, yet.

Box 3 - Practical activities and their constraints in Ethiopia

Little experience has been gained in the practical application of biochar in Ethiopia, yet. Most activities are carried out by non-governmental organizations or private entrepreneurs. Public projects with biochar have not been established, so far. There are no projects that have been running continuously for a long period of time. Those pioneers who try to establish biochar systems face numerous barriers in their activities. The most important ones are:

> Lack of awareness and knowledge of farmers about biochar
> Inappropriate production technologies
> Limited capital and high investment costs
> Low demand for biochar on the market
> Missing support from public institutions
> Lack of guidelines and standards

6.3 Other suitable institutions and opportunities

In Ethiopia, many present activities are dealing with soil protection, climate-smart and sustainable agriculture, efficient use of natural ressources, and rural development in general. Since biochar can be a promising complement for such projects, some of them are already planning to establish biochar systems. Others, that provide good preconditions for this technology, have indicated their interest.

6.3.1. German gesellschaft für internationale zusammenarbeit (GIZ)

The German 'Gesellschaft für internationale Zusammenarbeit' (GIZ) is an important player in agricultural development projects in Ethiopia. The Integrated Soil Fertility Management (ISFM^{+}) project is a component of the GIZ contribution to the joint Sustainable Land Management (SLM) program of the Ethiopian Ministry of Agriculture and Natural Ressources (MoANR). It promotes integrated soil fertility management approaches and practices in rural areas in Tigray, Amhara and Oromia on 57,000 ha. Yet, biochar is not a tool within its basket of soil fertility enhancing techniques, but it may become in the future, provided following prerequisites are met:

1) Proof-of-concept that biochar increases yields and income.
2) Possibility of on-farm production of biochar, based on locally available and non-competitive feedstock.
3) No or only little extra labour and costs connected to biochar for farmers and rural

households, e.g. through the use of cookstoves that produce biochar as a by-product.

Not only that biochar systems fit the objectives of ISFM+ perfectly, but also other reasons make the project a potential collaborator for the establishment of biochar systems. Its large action radius gives the possibility to identify those farmers who have the most depleted soils, that have the highest potential to be improved by biochar. Its suite of soil-enhancing techniques allows to combine biochar with different practices, such as compost, urine collection or minimum tillage. The project is closely connected to the MoANR, Regional Agricultural Research Institutes (RARIs) and, most importantly, to the country's extension system, which can promote the use of biochar among farming communities all over the country. The operational plan of the project is based on a participatory learning cycle, and underlines the importance of knowledge and capacity building with methods, including model farmers, field demonstrations, training manuals and awareness creation materials.

Apart from the SLM program, there is another program from GIZ that might be beneficial for the implementation of biochar systems. The Energising Development (EnDev) program includes the dissemination of improved cookstoves (ICSs) to reduce fuel consumption by raising awareness and establishing a network of stove producers. In several regions, the program trains around 500 artisans in producing different types of ICSs. If an appropriate biochar producing gasifier stove is available, their network could contribute to a broad dissemination of these stoves.

6.3.2 Soil and more ethiopia

Soil and More Ethiopia is a for profit private company engaged in environmentally and socially sound business. Their focus is on the establishment of large scale composting sites and technology transfer. It is a social entrepreneur company that strives to promote sustainable and climate-smart agriculture from grass root level through addressing the issue of input and knowledge gap. The company runs a commercial compost production site at Ziway. The feedstock for compost production are flower residues from nearby flower farms. Around 20% of the flower residues they receive are hard-to-compost rootstocks and they accumulate on their compound. A rough estimation, based on internal intake-data from March to September 2016, accounts for a weekly average of 150 tonnes of non-compostable biomass (fresh matter). The company plans to use this biomass for biochar production and to combine it with their compost, to create a commercial organic fertilizer substrate. Yet, they lack appropriate partners, qualified staff and fundings for the production of biochar. The constant stream of non-competitive residues from flower farms would allow for a large-scale pyrolysis unit. A feasible option to use the process energy of a pyrolysis plant has not been identified, yet.

Appart from their activities at Ziway, they have signed a contract with LIFT to establish 30 compost hubs within 15 months that will produce and distribute compost products in the

Figure 16. Left: Mound of acacia stems for charcoal production. Right: Smoke emissions during traditional charcoal production. (Copyright: Berhanu Belay)

four project regions (Oromia, Amhara, Tigray and SNNPR). Their activities include trainings of hub owners and demonstrations for farmers. *Soil and More International* has a compost management license that allows to use the following feedstocks for composting: woodchips, shredded cardboard / paper, straw, leaves, grasses, harvest residuals, waste fruit, peels, pulps, cow, chicken and other manure, but no municipal waste or slurry, nor pig and hog manure (Soil and More 2016). As potential suppliers for biomass the organization has identified farms, agricultural and animal husbandry industries, processing industries and municipalities, private and public organizations. Due to this network and their focus on tailor-made business plans, *Soil and More Ethiopia* can be an excellent partner for the establishment of a medium or large-scale biochar system.

6.3.3 Awassa university

In march 2017, the *Forschungszentrum Jülich* (Germany), in collaboration with the Awassa University (Ethiopia), has approved a 4-years project that aims at building capacities in climate-smart agriculture and ecological sanitation of human faecals by the use of compost and biochar. The project will establish an experimental farm at Wondo Genet College of Forestry and Natural Resources, that serves as both, research site and training center for local farmers. The project will evaluate suitable feedstock sources and options to combine biochar with compost. The biochar will be produced in clay cookstoves, in cooperation with *Pro Lehm* (see section 6.2.2).

6.3.4 Injibara university

The newly founded Injibara University in the Amhara regional state plans to establish a biochar research program connected to the local production of charcoal and the cultivation of acacia trees. The president of the university, Prof. Berhanu Belay, has been a main promoter of the biochar programme at Jimma University, before. In the area of Injibara, the production of charcoal and the supply to the central market at Addis Abeba is a common practice. The fines and leftovers of the charring are applied to the soil and farmers are aware of the positive impact

that the char has on soil fertility and crop productivity. Acacia, which is the preferred species for charcoal making, is cultivated in nurseries, transplanted to fields and cut at the age of 4-5 years for charcoal production (figure 13). The focus for biochar application to soils will be on high value crops such as vegetables and fruits. The university wants to conduct a systematic value chain analysis of charcoal from seed collection to charcoal selling at the central market in Addis Ababa, and investigate the role of charcoal fines as soil amendment and crop productivity enhancement. Further on, they want to assess the complementary and competitive aspects of charcoal being used as fuel or as soil amendment. Since these charcoal fines are a non-competitive byproduct, and there is no deforestation caused by the charcoal production, this biochar source seems to be sustainable. However, efforts should be made to combine the biochar application with other soil amendments and to develop an appropriate pyrolysis technology, in order to prevent the environmental pollution of traditional charcoal production with earth kilns (figure 16).

6.3.5 Haramaya university

Haramaya University has been working on vermicompost and plans to establish a new biochar technology center on their main campus. The biochar research group wants to address following objectives:

1) Produce various types of biochar from different organic waste streams and materials. Several biomass sources, including bones, maize cobs, animal manures, khat residues, *Lanthana camara*, paper wastes and *Parthenium* are found close to the campus and can be used for biochar production.
2) Provide biochar in quantities and qualities required for research purposes and the amendment of degraded soils, in order to serve as one of the most important component inputs for climate smart agriculture.
3) Contribute to environmental health and reduce emission of green house gases by converting organic wastes and materials into economically and environmentally useful materials.

Research activities are supposed to start in mid-2017. However, their work plan does not reveal which production technology they are going to install and which options there are to use the process energy.

6.3.6 Menschen für menschen

The German N*GO Menschen für Menschen* (MfM) has been working in Ethiopia since 1981 and strives to trigger a permanent and sustainable improvement of people's living conditions by using the principle of integrated rural development projects (IRDPs). These projects are initiated as long-term projects on Kebele or Woreda level, that run up to 17 years and that have five key areas: agriculture, water, health, education and income. The key areas are interlinked with each other and most measures within the project are connected to more than one area. Yet, biochar is not within their agricultural measures, but the organisation

indicated that they are open to implement a biochar pilot project in one of their IRDPs. In general, MfM is a promising partner for the implementation of biochar pilot projects, since the principles if IRDPs guarantee a long-term and professional support of farmers. Other measures that are already applied in their projects, such as composting or improved cookstoves are important for potential biochar systems.

6.3.7 The climate foundation

The Climate Foundation is a non-profit organization based in the United States which has developed and tested a pyrolysis reactor for the production of biochar from human faeces in the USA and India. The reactor works independently from the electricity grid and can process faeces of about 2,000 persons per day. While the reactor was originally developed to overcome sanitation problems in urban areas in developing countries, the co-produced biochar could be used for energy and/or soil improvement applications. Although *The Climate Foundation* has not been working in Ethiopia yet, the organization is interested in testing its reactors in urban areas of Ethiopia.

It should be kept in mind that a large part of macronutrients (e.g. nitrogen and phosphorus) contained in human faeces is lost during pyrolysis (Fischer and Glaser 2012; Glaser 2015; Ippolito et al. 2015). For this reason, the use of composting or the hydrothermal carbonization [HTC] technology should be preferred, if nutrient losses during faeces management shall be minimized. However, composting faeces is challenging in a mega-city like Addis Abeba and the HTC technology has still to be adapted to the local infrastructure conditions. Besides that, the current status of human faeces management in Addis Abeba offers a huge potential for improvements in terms of mitigation pollution risks and improving resource use efficiency.

7 Estimated amounts of the best-suited feedstock sources

In the following sections, we estimate the total amounts of biomass residues from different sources and processes that are potentially available for the production of biochar in Ethiopia. The calculations are based on data from primary and secondary sources. Consequently, it is not a detailed survey, but rather an estimation of the order of magnitude of the potential of available biomass for biochar production. Obviously, there are numerous other feedstock sources that could be used for biochar production, but the selection below represents those, which are most promising from our point of view, and to the best of our current knowledge. The term "feedstock potential" is used as the total amount of biomass residues from one or more feedstock sources that can potentially be used for biochar production, no matter which other competitive uses this biomass might have at present. An overview of all feedstocks and their feedstock potentials is given in table 4.

7.1 Smallholder farms residues

Only few data are available to estimate reliably the feedstock potential of waste from rural households and smallholder farmers. In 2013, the Jimma-Cornell research group has conducted a survey, in order to quantify the average amount of crop residues and to identify their uses on farms. They have collected data from a total of 350 households around Jimma and Awassa. Since the amount of crop residues was not assessed directly but was calculated by crop residue ratios (CRRs) from literature, table 5 shows only a rough estimation of average crop residue production. The total amount of crop residues accounts for 6.7 t ha^{-1} and 6.5 t ha^{-1} annually for Jimma and Awassa area, respectively, with maize residues representing almost half of it. However, no crop residues are left as non-competitive waste. They are mainly used for feeding own animals (either collecting crop residues, or grazing animals on the fields after harvest), kitchen or household fuel, and soil

Table 4. Selected feedstock potentials for Ethiopia on an annual basis ([1] *P. juliflora* reflects the feedstock potential of a total eradication)

Feedstock source	Feedstock potential [kilotonnes per year]
Houshold waste	**high variation**
Coffee husks	**403**
Flower waste	**140**
Sugar cane	**3,148 – 4,206**
P. juliflora [1]	**9,198 – 9,975**
Sesame	**236**
Animal bones	**192 – 330**
Human feaces	**75 (only Addis Abeba)**

Table 5. Mean annual crop residues production [Qt] using crop residue ratios in 2012/13 (taken Jimma Cornell Group, internal report)

Type of crop residue	Jimma (n=150)		Awassa (n=200)	
	Mean	SD	Mean	SD
Coffee	0.7	0.4		
Maize	32.4	17.8	30.8	13.6
Chat	1.3	0.4	1.4	0.6
Fruits	7.5	3.8	7.4	3.7
Sugar cane	4.7	1.2	5.4	2.7
Tubers	14.6	4.6	15.1	4.3
Enset	4.9	1.3	5.0	1.5
Total	**67.1**	**19.3**	**65.2**	**15.3**

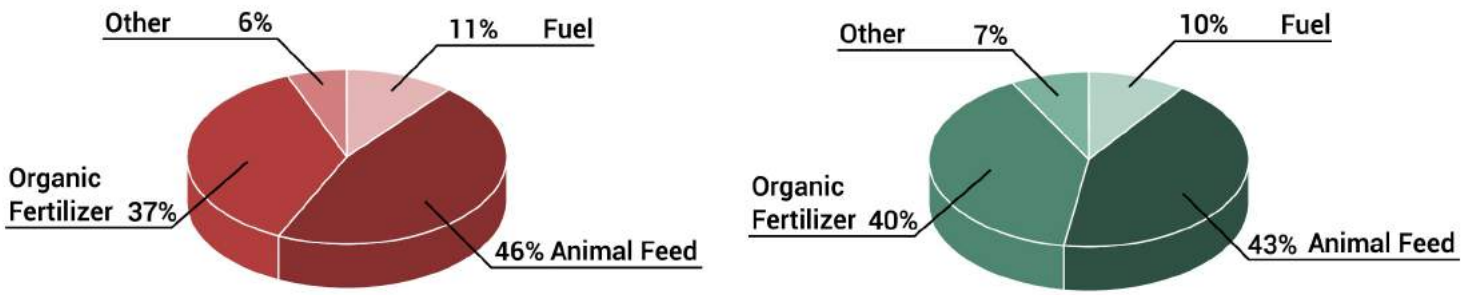

Figure 17. General uses of crop residues in Jimma area (left) and Awassa area (right) from Jimma-Cornell Group (derived from internal report)

fertility management (leaving crop residues in the fields as fertilizer, mulching or collecting biomass to apply as organic soil amendments). Figure 17 shows that in both areas more than 80% of crop residues are already being used for animal feed and organic fertilizer. Only few crop residues serve as fuel for cooking.

However, there are indications that the availability of this resource might differ considerably, depending on the region. Peter Renner, a member of the executive committee of the German NGO *Menschen für Menschen* approved that within their IRDP communities, sufficient farm residues are available to launch a pilot project with pyrolysis cookstoves (Peter Renner, personal communication). Moreover, the survey of Berihun et al. (2017) showed that the straw of wheat, barley, peas and beans have other uses for rural households, but maize cobs were non-competitive in their study area.

7.2 Coffee residues

Generally, coffee residues, including pulp, mucilage and hull, are regarded as one of the most promising biomass sources. Box 4 shows common advantages that are related to the use of coffee residues as feedstock.

To estimate the total amount of coffee residues being produced in Ethiopia and, thus, its overall biochar feedstock potential, we used the official coffee yield from the Central Statistical Agency (CSA) of Ethiopia, that is assessed by farmers surveys. The total amount of dry coffee beans produced in Ethiopia on private peasant holdings accounted for 419,980 tonnes, and on commercial farms 79,971 tonnes, in the cropping season 2014/2015, which corresponds to an average yield of 7.4 Qt ha^{-1} on both farm types (CSA 2015a, CSA 2015b). The total amount of coffee production we obtained from the Ethiopia Commodity Exchange (ECX) was much lower. Therefore, we decided to use the data from CSA, in order to get the full picture and not just the legally traded share of it (ECX). To estimate the amount of coffee residues we assumed that beans constitute 55.6% of the coffee berry's weight (on DM basis), and the rest are residues (Brahan and Bressani 1987). Consequently, the overall feedstock potential of

Box 4 - Advantages of coffee residues as feedstock for biochar production

> Available in large parts of the country
> Centralized accumulation at coffee processing units
> Few competitive uses
> Constantly available
> Nutrient poor material

coffee residues in Ethiopia accounts for 402,488 tonnes or 5.9 Qt ha^{-1}. Detailed feedstock potentials for each region are given in appendix II and III. A big advantage of coffee husks is, that they are available in large parts of the country and that they are being produced throughout the year (at least for most dry processing units). Generally, there are few other uses for this biomass source, and many times, mounds of coffee husks decompose spontaneously and start to burn (figure 18). Recently, more actors became aware of it and some entrepreneurs started to tap this resource. The African Briquette Factory PLC, for example, produces briquettes from coffee husks, that can be used for industrial furnaces (see section 6.2.4). Since 2012, the Dilla Briquette Factory, that has been established by the *Horn of Africa Regional Environment Center and Network* (HoA-REC&N), produces between 1,800 and 5,400 tonnes of coffee husks briquettes per year (HoA-REC&N 2013).

Figure 18. Spontaneous composting and ignition of discarded coffee husks (Copyright: Nadine Guthapfel)

7.3 Animal bones

Ethiopian slaughterhouses produce huge amounts of animal bones that have no other use, than being dumped as waste. Also, small, local butchers would only discard these bones, making them a reliable biomass source being scattered all over the country and easily available. According to an article in *ensia* magazine, this biomass source could become a reliable income for young unemployed, who collect the bones and sell them to local producers of bone char fertilizers (Gewin 2016). The total potential of animal bones as feedstock for bone char production has been assessed by Simons et al. (2014) and is estimated between 192,118 and 329,744 tonnes per year (table 6). Around 80% of these bones derive from cattle, and the rest from sheep and goats with almost equal shares. As outlined in section 6.1.1, char produced from bones is very well suited as a phosphorous fertilizer supplement.

Table 6. Annual total phosphorus in animal bone residues from slaughtered animals in Ethiopia (taken from Simons et al. 2014)

	Total no. of animals	Bone mass [kg per animal]	% of animals slaughtered [per year]	Bone residues [tonnes per year]	Total Phoshphorous [tonnes per year]
Cattle	50,283,000	20 - 30	16 - 17	160,908 – 256,447	
Sheep	23,642,000	4 - 5	19 - 34	17,968 – 40,192	
Goats	22,070,000	4 - 5	15 - 30	13,242 – 33,106	
Total	95,995,000			192,118 – 329,744	17,279 – 36,272

7.4 Flower residues

Almost all Ethiopian flower farms are located in Oromia, where they are classified into different clusters, according to the altitude of their location. The amount of stems produced, as well as the amount of stems rejected vary significantly with respect to these clusters (appendix IV). It seems likely that the total amount of residues also varies for each cluster, however, there is no data or information available to verify. The residues consist of rejected stems and flowers, but also uprooted rootstocks (figure 19). We received some production and reject data from the Ethiopian Horticulture Development Agency (EHDA) from 2013/14 and calculated the overall feedstock potential (appendix V). According to their data, the total amount of residues from flower production accounted for 6,415 tonnes, representing only rejected stems, but not rootstocks. Hence, discussing our results with experts from *Soil and More Ethiopia* revealed that the actual flower residues production must be much higher than our estimation. Therefore, we used the waste intake data from March to September 2016 from *Soil and More Ethiopia* and calculated the total amount of biomass they received on a weekly basis. Assuming that one truck load is around 10 tonnes, they received 856 tonnes of fresh flower residues every week. Consequently, the annual amount the company received accounted for 44,532 tonnes. Given that the flower farms that supplied *Soil and More Ethiopia* had 428 ha under cultivation, the average feedstock potential for flower residues per hectare and year is 104 tonnes. Ethiopian flower farms cultivated a total of 1,348 ha in the cropping season 2013/14 (EHDA data). Finally, the overall feedstock potential for flower residues accounts for 140,000 tonnes per year. It is important to emphasize that this is a rough estimation on basis of several generalizations.

Figure 19. Branches and rootstocks from rose flowers

7.5 Sugar cane residues

The amount of sugar cane grown on medium and large scale commercial farms is much bigger than sugar cane grown on smallholder farms. The commercial farms are directly connected to one of the six sugar factories in Ethiopia. On average, three of these factories produced 279,000 tonnes of sugar per year between 2003/04 to 2012/13 (Bayrau et al. 2014), the other three launched production after 2012/13. The total amount of sugar cane accounted for 6,748,000 tonnes in the cropping season 2011/12, with a share of 85% by commercial farms (Bayrau et al. 2014). Meanwhile, the production should be much higher, since three new sugar factories have started to work, but detailed data is not available.

The amount of bagasse produced per tonne of cane stalks processed can vary significantly, and depends on many factors, such as variety, growing area or pressing techniques (Hassuani et al. 2005, Valk 2014). Reliable crop residue ratios (CRR) for sugar cane in Ethiopia are missing. Therefore, we draw on an average proportion of bagasse of 29%, that is frequently found in literature (Hassuani et al. 2005, Valk 2014, Gebre et al. 2015) and is in line with a case study at *Metehara Sugar Factory* (Berhane, 2007). Consequently, the annual feedstock potential of bagasse accounted for 1.2 million tonnes in 2011/12, but is much higher today, due to the expansion of sugar cane production. However, the proportion of bagasse that is available can not be estimated easily, since it is used in sugar factories for co-generation of heat and electricity.

Another by-product of sugar cane that may serve as feedstock, are cane tops that get chopped in the field during the harvest. In most cases they do not have a competitive use and get burned. Detailed information on the amount of cane tops is not available for Ethiopia. On average, cane tops represent 15-25% of the cane's above ground biomass (Heuzé et al. 2016). Consequently, the feedstock potential of cane tops accounted for 1.2 - 2.2 million tonnes in 2011/12.

Combining the feedstock potentials of bagasse and cane tops, the overall feedstock potential of sugar cane accounted for 3.1 – 4.2 million tonnes in 2011/12. At present, the feedstock potential is probably much higher, but it is not clear, which amount might be available for biochar production, due to the co-generation of heat, as mentioned before.

7.6 Prosopis juliflora

The invasive species *P. juliflora* has spread to many areas of the Afar region. Yet, reliable reports are missing about the exact area covered by the tree, since it is a dynamic state, driven by fast expansion of the species and controlling measures against it. However, an estimation that has been adopted by several reports recently (e.g. GIZ 2014b), accounted for 700,000 ha in the Afar region (USFS 2006). The total amount of biochar that can be produced potentially from this area can not be predicted accurately. However, two different studies from USFS and Farm Africa calculated that from one hectare of *P. juliflora*, it is possible to yield 438 - 475 bags of charcoal, with each bag weighing around 30 kg (Admasu 2008, Wakie et al. 2012). According to these figures, the current stand of *P. juliflora* has the potential to produce between 9,198,000 and 9,975,000 tonnes of charcoal or biochar. However, it needs to be stressed that a total eradication of *P. juliflora* is neither possible, nor sustainable. A recent impact assessment by an Ethiopian-German research team emphasizes the need for a participatory management strategy that integrates local and national institutions and that takes traditional knowledge and pastoral practices into account (Ilukor et al. 2016). Since charcoal production from *P. juliflora* threatens indigenous trees, which are (illegally) similarly cut, causes air pollution and brings benefit to only 18% of local households (Ilukor et al. 2016) (Appendix D), the authors advocate

Figure 20. General uses of sesame straw at Metema area (left) and Humera area (right) (derived from Aregawi et al. 2013)

charcoal production only in selected areas. The same restrictions are probably valid for biochar production. The main uses of *P. juliflora* among Afar pastoral households are given in appendix VI.

7.7 Sesame

Sesame (*Sesamum indicum*) is mainly grown in Oromia, Amhara and Tigray regions, in descending order, regarding the cultivation area. For Ethiopia, a total of 420,491 ha are cropped with sesame. A recent study has conducted a household survey to investigate the amount of sesame straw and its competitive uses in two disctricts in Tigray and Amhara (Aregawi et al. 2013). According to their results, the straw yield was 5.6 Qt ha^{-1} in both districts and thus, much lower than an estimation by Gebresas et al. (2015), who assumed a straw yield of 20 Qt ha^{-1} in the same district, without elucidating the origin of that figure. Therefore, it is recommendable to draw on the conservative estimation of 5.6 Qt ha^{-1} by Aregawi et al. (2013). Using this amount, the overall feedstock potential of sesame in Ethiopia accounts for 235,475 tonnes per year. Apart from the amount of sesame straw, Aregawi et al. (2013) also found that 67.7 % and 75.3 % of these residues are not of any use to the farmers in both areas and get burned. Other uses of sesame straw are given in figure 20.

7.8 Human faeces

The availability of biomass feedstock for biochar production in the mega-city of Addis Abeba is limited. However, the inhabitants of the capital (about 3.3 million people in 2016) produce about 75,000 tonnes (DM) of faeces every year (calculation based on data from *Geselllschaft für ökologische Technolgie und Systemanalyse e.V.* 2010). A large part of the faeces is currently being dumped in an open landfill. Since this existing waste management problem has to be solved for health and environmental reasons anyway, biochar production based on pyrolysis processes or hydrothermal carbonization might be a solution for this challenge, independent from the subsequent use of the produced pyrochar or hydrochar.

8 Policies and regulations

8.1 Regulatory frameworks

In the early 1990s, the Ethiopian Government has introduced the strategy of an Agricultural Development-led Industrialization (ADLI), which emphasizes the importance of the Ethiopian agricultural sector for the country's economic development. It is an evolving strategy that included subsequent development policies and strategies, such as the Sustainable Development and Poverty Reduction Program (SDPRP) and the Plan for Accelerated and Sustainable Development to End Poverty (PASDEP 2005–2010). It forms the strategic basis for the country's development goals in the two Growth and Transformational Plans (GTP I 2010/11 – 2014/15 and GTP II 2015/16 – 2019/20) that aim to make Ethiopia a middle income country by 2020.

The Agriculture Sector Policy and Investment Framework (PIF 2010 – 2020) provides a strategic framework for the prioritization and planning of investment that will serve as an engine for driving Ethiopia's agricultural development. The PIF is a 10-year road map for development that identifies priority areas for investment and estimates the financing needs to be provided by Government and its development partners. Regarding the thematic areas and strategic objectives (SOs) of the PIF (table 7), one can clearly see that biochar systems may contribute essentially to their achievement. It has been demonstrated (section 5.2) that biochar systems can increase crop yields and thus agricultural productivity (SO1). Large-scale pyrolysis plants may support the energy demand of agricultural processing industries (SO2). The clearly positive effects of biochar systems on several soil properties (section 5.1) can counteract the critical soil degradation in Ethiopia (SO3). The combined effect of these improvements will thus result in a better food security (SO4). However, the introduction of biochar systems will require detailed strategies that specify environmental and technological standards for the production of biochar. Moreover, regional guidelines need to be composed, in order to address specific regional issues, especially in terms of feedstock acquisition.

Table 7. The Agriculture Sector Policy and Investment Framework, thematic areas and strategic objectives

Thematic Area	Strategic Objectives (SOs)	
Productivity and Production	SO1	To achieve a sustainable increase in agricultural productivity and production
Rural Commercialisation	SO2	To accelerate agricultural commercialisation and agroindustrial development
Natural Resource Management	SO3	To reduce degradation and improve productivity
Disaster Risk Management and Food Security	SO4	To achieve universal food security and protect vulnerable households from natural disasters

8.2. Public stakeholders

There are numerous public stakeholders that can be involved in the successful implementation of biochar systems in Ethiopia. In the following, we will list those, who are most important in terms of political decision-making, governance and assistance for the introduction of biochar to national agricultural policies.

► Ministriy of Agriculture and Natural Resources (MoANR) is responsible for developing policies and strategies, in order to enhance the agricultural productivity and to conserve, develop and sustainably use natural resources. It supervises the regional agricultural bureaus and the national extension system, which can have a key role in overseeing and guiding the dissemination of biochar systems.

► Ethiopian Agriculture Transformation Agency (ATA) strives to introduce new technologies and approaches that can address systemic bottlenecks & catalyze transformation of the sector and to play a catalytic role to support partners to effectively execute agreed upon solutions in a coordinated manner. Therefore, it should be one of the main actors for the implementation of biochar systems.

► Ministry of Environment, Forestry and Climate Change is in charge of an environmentally friendly and climate-neutral development of the economy. It can promote biochar as a climate-smart technology in national policies and strategies.

► Ministry of Water, Irrigation and Energy is responsible for the sustainable energy supply of household and the industrial sector. The introduction of new cookstoves or industrial energy technologies is within its competence.

► Research institutions, such as universities and regional agricultural research institutes have to prove the concepts of biochar from a scientific point of view with respect to regional requirements.

► The Ethiopian Standard Agency (ESA) can develop national quality standards for biochar, in accordance with the quality standards we presented in section 2.1.

9 Schemes for biochar systems in Ethiopia

A variety of biochar systems can potentially be established in Ethiopia. Several opportunities and challenges are connected to each biochar system. The most determining factor that distinguishes one biochar system from another is, from our point of view, the scale of production. Therefore, we classified all biochar systems according to their scale of production and identified their most important characteristics (table 8).

9.1 Small-scale biochar systems

9.1.1 Technology, feedstock and biochar management

On a household level or for individual peasants, the only production unit that is feasible, is a pyrolysis or gasifier cookstove, with an annual production of up to 1 tonne per unit (section 3.3). Yet, a suitable cookstove technology is missing, but promising models are

Table 8. Synopsis of potential biochar systems according to their production scale

Project Scale	Household Level	Small and Medium Enterprises Level	Large Scale Industrial Level
Production volume Per year and unit	< 1 tonne	< 100 tonnes	> 100 tonnes
Potential operators	Private households	Community kitchens, hotels, Bakeries, coffee roasteries	Sugar industry, municipal waste management companies, textile industry, breweries
Suitable biomass feedstock	Crop residues, household waste, coffee residues, Sesame straw	Crop residues (commercial farms), coffee residues, sesame straw, *P. juliflora*	Crop residues (commercial farms), processing residues, feaces, *P. juliflora*
Suitable process technology	Pyrolysis or gasification cookstoves	Medium scale pyrolysis units (e.g. Kontiki, Biomacon), medium scale gasifiers (e.g. Spanner Re²)	Large scale pyrolysis units (e.g. PYREG, Biomacon, PRO-Natura)
Heat usage options	Cooking	Cooking, drying, boiling, roasting	Boiling, fermentation, Pre-drying of faeces, bleaching
Biochar usage options	Soil improvement in gardens and smallholder farms	Soil improvement on smallholder farms, commercial bio-fertilizer, inoculant carrier	Soil improvement on large commercial farms, commercial bio-fertilizers, fertilizer blending
Advantages	Low investment, fuel and heat efficiency, health improvement	Efficient heat use	Efficient heat use, large Environmental impact
Disadvantages	Low impact in initial phase	Inefficient heat use (Kontiki), long transportation distances	long transportation distances
Challenges	Appropriate technology, farmers and cookers awareness and acceptance	Resource use efficiency (Kontiki), combination with other Organic amendments	High investement costs, infrastructure demands, technology adoption, maintenance, combination with other organic amendments, feedstock supply
Risks	Organic pollutants in Gasifier biochars	Organic pollutants in gasifier biochars	Unsustainable feedstock use
Potential Project Partners	Kaffakocher, Menschen für Menschen, GIZ, Pro Lehm	Soil and More, TERI, Moyee C offee, Tarikayehu Gebresilassie	Sugar corporate, Soil & More, Climate Foundation

being developed by Jimma University, Marius Bierig (*Pro Lehm*) or Stephan Gutzwiller (*Kaffakocher*), and it is likely that in the near future a well-working model is available. Several household and farm residues are suitable as feedstock for the stoves: coffee husks, maize stalks and cobs, rice husks, sesame straw, peanut pods, etc.. Low investment costs, fuel savings and the combined use for cooking and biochar production, will lead to a fast amortization of the stove, depending on the prize of the stove. The biochar obtained can be mixed up or co-composted with other organic household waste or it can be used as litter in stables and applied with the manure to the field. Both will charge the biochar with nutrients and promote soil improvement and nutrient recycling.

9.1.2 Challenges

The biggest challenge in these biochar systems is the adoption of pyrolysis or gasifier cookstoves, which are not easy to introduce to rural communities (section 6.1.1 and 6.2.1). Moreover, the quality of the biochar is likely to vary and the risk of organic pollutants in the biochar can not be eliminated. Due to the capacity of the stove, the production of home-made biochar substrate is limited and the impact on a farmers' fields is weak, in early years, but the biochar will accumulate on the fields, year by year.

9.1.3 Potential partners

Many activities mentioned in section 6 aim at small-scale biochar systems. Consequently, there are a number of potential partners for these biochar systems: GIZ (ISFM^{+}), Jimma University, *Pro Lehm*, Awassa University, *Kaffakocher* and *Menschen für Menschen*. All of them can contribute essentially to the success of a biochar project on small-scale production.

9.2 Medium-scale biochar systems

9.2.1 Production technology and identification of operators

Several technologies are available to produce biochar on a medium scale (up to 100 tonnes per year and unit). These technologies are mainly used in micro, small and medium enterprises (MSMEs) and the type of pyrolysis or gasification unit to be used is mainly dependent on the purpose of the process energy in the MSMEs. A very common purpose is the use of bigger gasification cookstoves for restaurants or community kitchens at universities, hospitals, prisons or other institutions. These bigger units are so-called institutional gasifier cookstoves. Jimma University has introduced several units of improved institutional cookstoves to their community kitchen, in order to reduce the air-pollution (figure 21). However, these were not gasifiers. The African Briquette Factory PLC has developed an institutional gasifier cookstove, that is currently used in 10 MSMEs. But evaluations of this model are not available.

Besides cooking, there are several other options to use the heat of medium-scale pyrolysis or gasification units in Ethiopia. The biggest potential is probably given in bakeries, coffee roasteries, textile or leather industries (dying processes) and hotels (hot water,

Figure 21. Indoor air-pollution by traditional stoves in the community kitchen of Jimma University and replacement by clean institutional cookstoves (Copyright: Ancha Venkata Ramayya)

swimming pool). These MSMEs could use e.g. a small pyrolysis unit from *Biomacon*.

The Energy and Resource Insitute (TERI) (India) in cooperation with the Swiss Agency for Development and Cooperation has set up a program that aims to establish knowledge transfer with the private/public sector in target regions and to enable local manufacturing of biomass gasifiers for thermal applications in MSMEs (TERI 2014). On a stakeholder consultation workshop at Addis Abeba, an expert of TERI has stressed the experiences of the organization in using gasifiers for textile dying, rubber industries and foundries across India. And they have classified the MSME sector in Ethiopia into six clusters (TERI 2014), out of which only the Kirkos textile and leather cluster in Kirkos sub-city in Addis Abeba has a high potential for the introduction of gasifier technology, from our point of view. The other clusters mainly contain industries with little heat demand. However, TERI has not been engaged in biochar production and use, yet.

Kontiki kilns are also suitable for medium-scale production, but not within MSMEs. The lack of options to use the process energy prevents its application for (semi)industrial purposes. However, its mobility, low price and easy handling make it a convenient alternative in remote areas where large amounts of biomass accumulate without any options for thermal use nearby. This could be one component of fighting the *P. juliflora* invasion in the Afar region, for example. Also flower farms or coffee processing units could use Kontiki kilns to get rid of their residues. But still, the low resource use efficiency of Kontiki kilns should be improved to make this technology suitable in a country that suffers from deforestation and drought.

9.2.2 Potential feedstocks

Several feedstocks come into consideration for medium-scale production units. Institutional gasifier stoves can be fed with coffe husks, e.g. as briquettes, or other woody crop residues. Even if wood, as the traditional fuel, is kept on being used, this will be an improvement in terms of efficiency and CO_2 balance. Other pyrolysis or gasification units may draw on invasive species, like *P. juliflora*, woody crop residues, e.g. flower root stocks, or briquettes made from other crop residues, e.g. coffee husks.

9.2.3 Challenges

A big challenge of medium-scale biochar systems is the supply of feedstock. Most enterprises are located in urban areas, where most of the feedstock mentioned above is not available. Hence, feedstocks need to be transported from the site of creation to the individual MSME. On our request, some single enterprises estimated that transport costs for one truck are in the range of 2,000 to 4,000 ETB (83 – 166 €) per 100 km. Transportation costs even increase, since the biochar obtained needs to be transported to rural areas where biochar is being used. Another challenge are high investment costs for pyrolysis technologies, which can not be born by most Ethiopian MSMEs.

9.2.4 End-user analysis

The biochar obtained from these enterprises is a well suited resource for commercial products, such as bio-fertilizers, that can be purchased by farmers or private gardeners. A business-model like that is being established within the frame of the LIFT programme that cooperates with Tarikayehu Gebresilassie and *Soil and More Ethiopia*. The biochar can also be used as one component of an indigenous bio-fertilizer, as developed by the Jimma-Cornell group. Another option might be the use as inoculant carrier, as proposed by Vanek et al. (2016). Dr. Assefaw Hailemariam, a representative of the *Menagesha Biotech Industry PLC*, which produces inoculants, has already indicated his interest in that technology. Also *Soil and More Ethiopia* uses inoculants for their compost systems and is interested in biochar as a carrier.

9.3 Large-scale biochar systems

The highest output can be achieved by industrial pyrolysis plants that produce more than 100 tonnes per year (section 3.2). All of them provide a steady stream of heat for industrial purposes. However, they also require a steady stream of feedstock, in order to keep the plant running constantly and to pay off the huge investment costs as fast as possible. Several feedstocks can be considered for large-scale biochar systems.

9.3.1 Briquettes

Processing different biomasses to briquettes will increase the bulk and energy density of the material (Seboka et al. 2009), and thus increase their efficiency. Briquetting factories should be located closely to their biomass supply, such as coffee processing units, in order to keep the transport costs low. Also other feedstocks can be used for briquetting, such as cotton stalks, saw dust, bamboo or *P. juliflora* (Seboka et al. 2009). A recent study by the *United Nations Environment Programme* (UNEP) emphasizes the potential of biomass briquettes as fuel for Ethiopian cement factories (Seboka et al. 2009). But they also could be used for other heat demanding industries, such as dyeing factories or foundries. Theoretically, all of the large-scale pyrolysis units can be integrated to the heat supply of these industries. The biochar they obtain can be sold to enterprises that use it for the production of organic fertilizers, such as indigenous biofertilizers, developed by the Jimma-Cornell group. Or it could become a component of fertilizer blending, as promoted by the EthioSIS

project by the Agricultural Transformation Agency (ATA), in order to improve carbon-depleted soils.

9.3.2 Sugar cane system

Another feedstock for large-scale production could be bagasse from sugar cane factories (section 7.5). Most factories in Ethiopia already use this resource as fuel for their own heat demand and occasionally even shortages of bagasse occurred (Assefa and Omprakash 2013). But the Ethiopian Government has launched large sugar development programmes to boost the sugar industry, to become one of the world's top 10 sugar producers by 2023 (USDA 2015). Hence, it is expected that the production of bagasse will increase drastically and a huge surplus of biomass will be available (GIZ 2009). Several sugar factories are under construction and new pyrolysis plants could be integrated to these factories or replace old furnaces in old factories. The biochar obtained from these factories can be used for commercial purposes, as described above, or sugar factories could give it to their suppliers, in order to increase soil fertility on sugar cane fields. However, for the latter option possibilities need to be found how to combine the biochar with other amendments, such as manure, urine or compost.

9.3.3 Flower system

Huge amounts of biomass is being produced by flower farms (section 7.4). A big share of it consists of woody rootstocks that are hard to compost and that do not have a competitive use. Therefore, flower residues are an ideal feedstock for biochar. Besides, pyrolysis can degrade pesticide contamination of flowers, as long as they do not contain too much chloride, since this may lead to dioxine formation. *Soil and More Ethiopia* is about to develop a business model for large-scale production of biochar, that allows to combine biochar with their compost activities. The resulting substrate can be distributed within their network of smallholder farmer communities and the projects of LIFT Ethiopia or sold to flower farms. One opportunity to use the heat from pyrolysis units, might be cooling of cold stores at flower farms. A feasible option for this purpose are so-called absorption chiller systems, which are run by thermal energy and are very environmentally friendly (see section 10.3.4).

9.3.4 Other

Also breweries have a big potential for large-scale biochar production. The factories produce huge amounts of sludge, that have no other use than being dumped. It is likely that this sludge can serve as feedstock, and that breweries can use pyrolysis plants for their own heat demands. But we lack further information to estimate opportunities and challenges of such a biochar system.

As mentioned in section 7.8, also human faeces can be a feasible option for large-scale biochar production. Though this system might have a huge potential for the waste management in Addis Abeba, technical and regulatory challenges could not be evaluated conclusively.

Identification and Characterization of Two Priority Areas for a Biochar System Pilot Project in Ethiopia

PART III

10 Identification and characterization of two priority areas

10.1 Decision making

In a final step, the obtained results will be filtered and aggregated, in order to identify two areas in Ethiopia that offer the best opportunities for a biochar system pilot project. The selection of these "priority areas" has been based on various meetings and interviews with experts from governmental institutions, universities, NGOs and the private sector. These priority areas are characterized in detail and the positive and negative effects that biochar systems might have in these areas will be evaluated. Priority area I aims at the introduction of a biochar system based on small-scale production units, whereas priority area II deals with large-scale pyrolysis plants. Thus, this section offers small- and large-scale approaches for future activities.

Several criteria are important for the choice of a priority area. From our point of view, the most significant ones are:

- other rural development projects
- availability of feedstock
- process heat usage options
- depleted soils with a high potential of improvement
- available infrastructure

Regarding priority area I, “other rural development projects” is considered as the most striking criterion, since biochar systems can only be one part of a successful and sustainable soil management, especially in smallholder farming systems. Other soil improvement practices should already be established in areas where biochar systems are introduced: Farmers should be aware of re-using agricultural residues and they should be trained in composting techniques. Cookers should be adapted to improved cookstoves (ICSs). Rural communities should be experienced in participating in trainings and demonstrations. Biochar systems are not a technique, that is suitable for primary development projects. It can rather enhance existing soil management measures, such as manuring or composting. Furthermore, the “availability of feedstock” and the “presence of depleted soils with a high potential of improvement” are crucial for the successful implementation of a small-scale biochar system.

The choice of priority area II has mainly been based on the criterion “availability of feedstock”. A large-scale pyrolysis plant needs a continuous feedstock source, in order to run the plant efficiently. Moreover, heat usage options should be nearby to ensure the profitability. Since large amounts of biomass and biochar need to be transported to and from the pyrolysis plant, a well-developed infrastructure is indispensable as well.

10.2 Priority area I – ISFM+ project area

10.2.1 Specification of the priority area

Priority area I aligns with the project area of ISFM$^+$ from GIZ. The targeted area for soil fertility improvement technologies comprises a total of

31,802 ha of arable land in 18 woredas[1] in the regional states of Amhara, Oromia and Tigray (table 9) (GIZ-ISFM+ Baseline report I 2015). Altogether, 72 microwatersheds have been selected as target area. Regarding the agro-ecological zones (AEZ), the ISFM+ woredas in Amhara are mainly classified as highland (2,000-2,500 masl) or midland (1,500-2,000 masl), whereas the woredas in Oromia and Tigray predominantly are classified as midland and lowland (<1,500 masl). The total number of households targeted by ISFM+ is 25,388: in Amhara 7,739 households, in Oromia 5,672 households and in Tigray 11,977 households. In each of the microwatersheds there have already been measures against soil erosion, but few measures against soil degradation. Thus, the potential to improve soil fertility is very high and farmers are already used to other agricultural interventions.

10.2.2 Implementation strategies

10.2.2.1 Livelihood

To estimate the chances of a successful implementation of a biochar system, it is reasonable to take a look at the livelihood conditions in the priority area. Biochar systems have a significant effect on several factors that characterize a livelihood zone and, simultaneously, are affected by these factors, themselves. Which crop predominates in an

Table 9. Project woredas and targeted micro watershed (MWS) areas (ISFM+ Baseline report I 2015)

Woreda	Total area (ha)	Arable area (ha)	Proportion of irrigated area (%)	Targeted MWS area (ha)	Targeted MWS arable area (ha)
Amhara					
Hulet Eju Enebse	151,563	62,866	26	2,584	1,932
Bibugn	30,972	21,157	26	2,225	756
Sinan	41,372	24,178	31	1,686	1,224
Machakel	79,556	51,480	13	1,715	1,155
Gozamin	119,580	49,152	32	2,610	1,958
Baso Liben	113,284	46,599	14	2,584	1,647
Oromia					
Ambo	83,599	62,167	6	3,940	1,855
Gudeya Bila	84,275	44,666	7	2,894	1,992
Boji Dirmaji	65,662	38,142	3	2,923	1,369
Bedele	114,057	18,090	20	2,503	1,064
Gummay	44,225	14,176	7	2,616	1,393
Sokoru	92,744	33,858	18	2,362	1,369
Tigray					
Adwa	65,531	13,714	na	5,703	3,375
Tahtay Maichew	57,468	17,696	na	4,894	2,844
Raya Azebo	176,308	47,215	10	6,517	1,199
Emba Alaje	76,773	24,677	34	3,820	1,615
Seharti Samre	171,650	45,022	20	4,707	2,491
Dogua Tembien	112,500	19,473	na	5,715	2,565

[1] "Woreda" is an administrative division in Ethiopia (managed by a local government), equivalent to a district with an average population of 100,000. woredas are composed of a number of Kebele, or neighborhood associations, which are the smallest unit of local government in Ethiopia. Woredas are typically collected together into zones, which form a Kilil (Regional government administration) (woredaNet).

area, or how much livestock one family owns, influences the amount of organic residues considerably. Moreover, families with higher income or families that own more land can try more easily to adopt a new soil improvement strategy than poor families that face insufficient food supply. According to An Atlas of Ethiopian Livelihoods (USAID 2011), the wealthiest[2] farmers live in the target woredas in Oromia, followed by the woredas in Amhara, and the poorest households live in Tigray. This aligns with the observation that in Oromia most farmers grow cash crops (mainly coffee) or crops for sale. Whereas, farmers in Tigray mainly grow crops for their own consumption. Thus, the project woredas in West-Oromia may provide enough residues for biochar production. In higher altitudes in Amhara with more precipitation, farmers mainly grow barley and wheat, whereas in medium altitudes they also grow teff, maize and also pulses, which leads to a higher income, and thus, to more household investments. A list of the livelihood zones in the project areas is given in appendix VII.

10.2.2.2 Technology

A central issue for the implementation of a small-scale biochar system is an appropriate stove technology, that is adopted by local cookers. As outlined in sections 6.2.1 and 6.2.2, the most promising gasification cookstoves are currently developed by *Pro Lehm* in cooperation with Awassa University and by *Kaffakocher*. Both should be considered as potential partners for the introduction of gasification cookstoves. Both projects have pointed out a high potential for injera-baking gasification cookstoves. A single stovemodel can not be recommended at this point.

10.2.2.3 Feedstock

According to the ISFM+ project manager Steffen Schulz (personal communication) the availability of non-competitive biomass is a key bottleneck in every project area. Therefore, the availability of uncompetitive feedstock is likely to be the limiting factor for the efficiency of a biochar system. Most likely, cookers have to continue to use wood as fuel source and, hence, also as feedstock for biochar production. Using gasification cookstoves, will increase fuel efficiency, and automatically produce biochar as a by-product. This will reduce the amount of fuel wood per household and save labour for collecting wood. The situation might be different in woredas in Oromia, where coffee is grown and coffee processing units are nearby. Farmers can take coffee residues as sustainable fuel and feedstock source for biochar production (see section 7.2).

10.2.2.4 Integration into ISFM+ technologies

The ISFM+ project has demonstrated and applied several soil improving technologies within their project area. Especially liming strategies can be substituted by or supplemented with biochar. In every project area compost technologies have been introduced. It has been observed that co-composting with biochar will increase the stability of the resulting substrate (Fischer and Glaser 2012) and, thus,

[2] Wealth is related to the total income of a household. Total income is defined as the sum of a household's annual food income and cash income, converted to calorie equivalents, and expressed in relation to the household's annual calorie requirement (USAID 2011).

the sustainability of the technology. In the ISFM Fieldguide Technical Implementation - Integrated Soil Fertility Management (MoANR 2016), farmers can learn how to make compost and which resources they can use. The bottom left picture in figure 22 indicates that farmers should use the ash residues from cooking, which is the basic step for an integration of biochar into composting strategies. Given the conditions mentioned in section 6.3.1 are met, the ISFM project manager considers biochar as a feasible soil improvement tool for selected target areas.

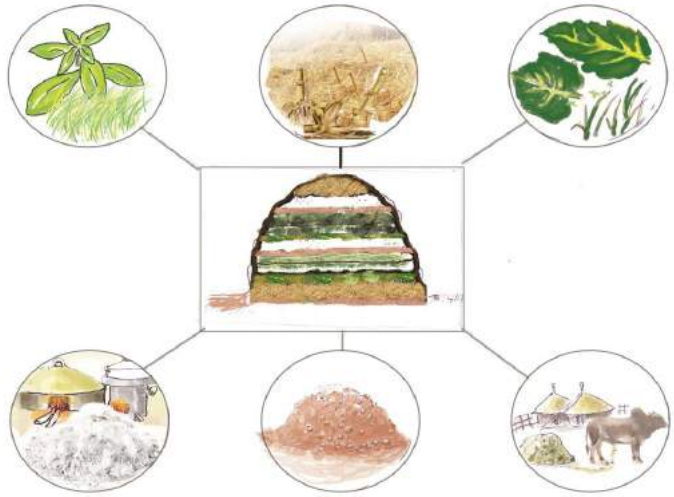

Figure 22. Ingredients to make compost (taken from MoANR 2016)

10.2.3 Expected soil improving effects

Only limited information is available about the soil conditions in these areas. In the woreda Gozamin in Amhara, there seem to be some Acrisols, that would benefit from the liming effect of biochar (table 10). Other soil types that are found within the project area and that could be improved by biochar substrates are mainly Vertisols and Lixisols. The former mainly occurs in the woredas Ambo and Sokoru in Oromia, the latter mainly in Boji Dirmaji and Bedele, also in Oromia. For Tigray region only soil texture is available. Very sandy soils are found in the woreda Seharti Samre, and very clayey soils occur in the woredas Tahtay Maichew, Raya Azebo, Emba Alaje and Dogua Tembien (GIZ-ISFM⁺ Baselinestudy I 2015). Sandy soils can be improved in terms of water holding capacity and CEC, whereas clayey soils are improved in terms of drainage, aeration and workability.

Regarding soil acidity, one can clearly see that most acid soils are found in Oromia (appendix VIII); whereas soils in Tigray have mostly a pH >6. In Amhara they are rather acidic. Since the use of lime is associated with high costs and difficulties in transportation (Abate et al. 2016), most Ethiopian farmers apply only insufficient amounts of lime to counteract soil acidity (Lemma 2011, Abate et al. 2016). Biochar

Table 10. Relative distribution of soil types in some ISFM⁺ project woredas (ISFM⁺ Baseline report I 2015)

Woreda	Nitisol	Cambisol	Acrisol	Vertisol	Andosol	Lixisol	Luvisol	Nitisol high clay
Amhara								
Gozamin	40	50	10	0	0	0	0	0
Oromia								
Ambo	36	0	0	34	29	0	0	0
Gudeya Bila	100	0	0	0	0	0	0	0
Boji Dirmaji	5	0	0	0	0	80	15	0
Bedele	39	0	0	0	0	28	33	0
Gummay	0	0	0	5	0	0	60	35
Sokoru	60	0	0	30	0	0	10	0

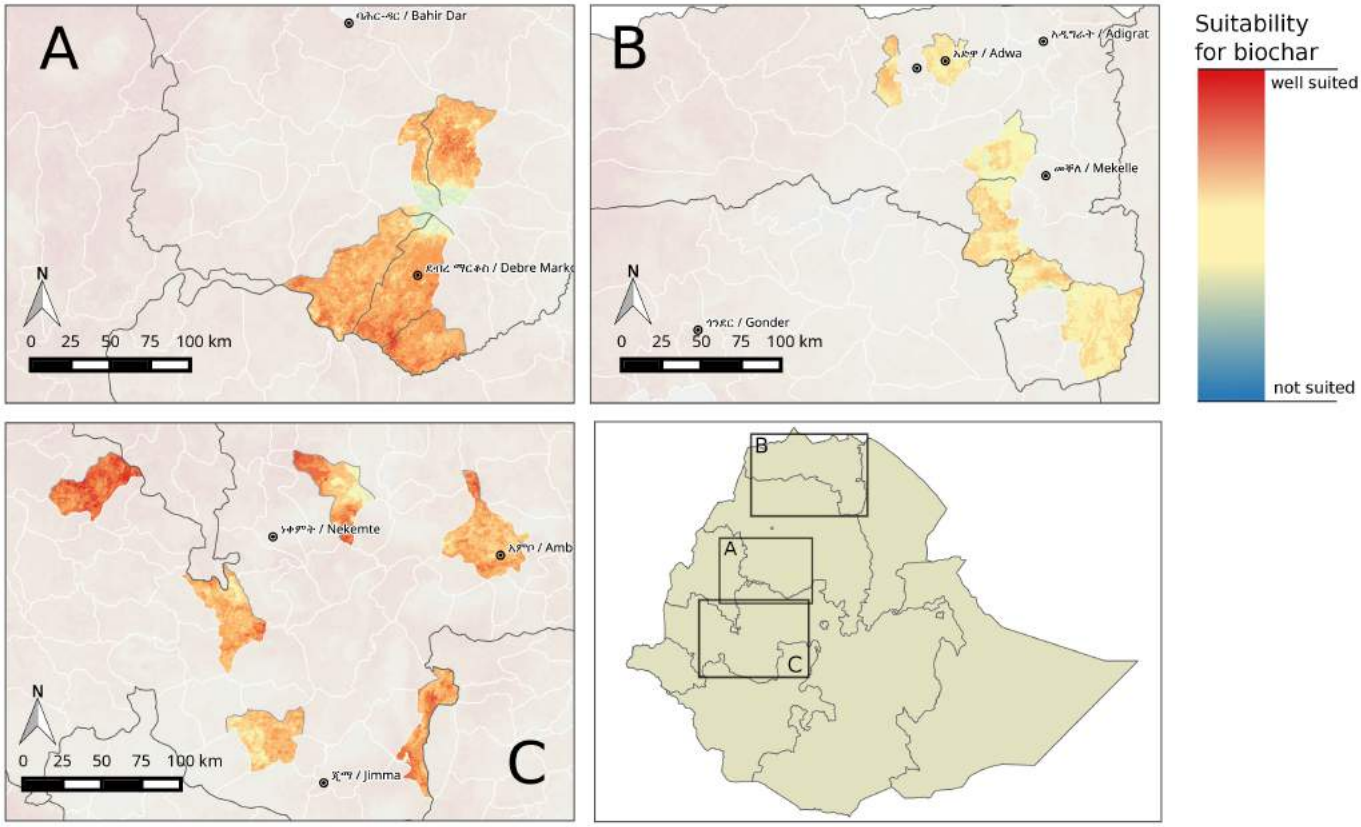

Figure 23. Suitability map for biochar substrate application within ISFM+ project woredas, based on soil pH and SOC. A: Amhara, B: Tigray, C: Oromia (methodology is given in appendix X)

can be a cheap and easily available alternative to lime. It increases the soil pH effectively, as described by Berihun et al. (2017) for farmers around Dilly area (SNNPR). However, acid soils in Oromia are also those soils with the highest organic carbon content (appendix IX) and production rate (section 10.2.2.1) and, thus, they offer little incentive for farmers to invest in soil improving technologies (see section 6.2.1). Therefore, we created a suitability map that combines high soil acidity with low SOC, and, thus, shows those areas that are best suited for the application of biochar substrates (figure 23). The map indicates that the project woredas in Tigray are less suited for biochar substrate application than the project woredas in Amhara and Oromia. Especially Boji woreda in Western Oromia seems to provide good conditions for the implementation of biochar systems. However, the map only focuses on two soil properties, whereas the success of the implentation of biochar systems is dependent on many more conditions.

10.2.4 Model of a biochar system in priority area I

The single elements of a small-scale biochar system that were discussed above can be put into one model of a circular economy (figure 24). The model uses coffee residues as feedstock, as it can be the case in project woredas in Oromia: The coffee residues are taken from coffee processing units and used as fuel in a pyrolysis or gasification cookstove (previous pelletizing might be required). Biochar is produced as a by-product of cooking. Subsequently, it should be

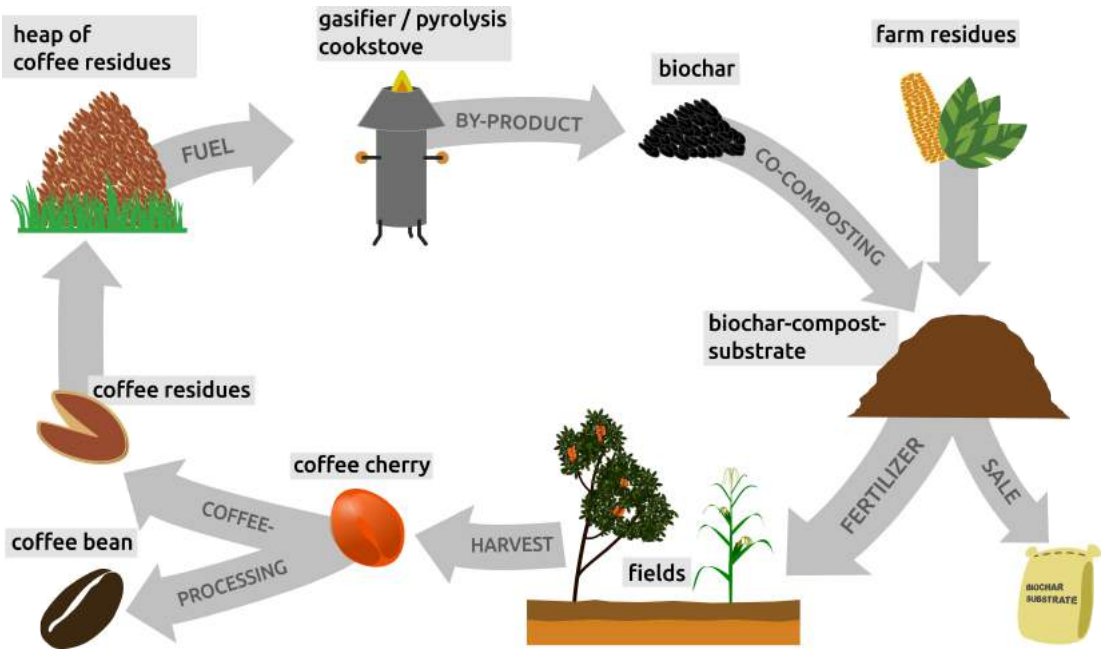

Figure 24. Model of a small-scale biochar system based on coffee residues as feedstock

co-composted with organic household waste and farm residues. The resulting biochar-compost-substrate can be applied as fertilizer or lime supplement to the field or sold as soil conditioner. The application of fertile biochar-compost-substrate will increase the crop yields and thus also the amount of coffee and farm residues.

10.3 Priority area II – Flower production area of central Oromia

10.3.1 Specification of the priority area

The second priority area for a prospective biochar project is located in central Oromia. It comprises the flower growing areas South and West of Addis Abeba (figure 25), including the major flower growing towns: Holeta, Sebeta, Addis Alem, Menagesha, Debre Zeyit, Koka and Ziway. We mainly focus on rose production farms, since we have no information about the amount of residues from other ornamental flowers, such as *Gypsophila paniculata* or *Hypericum*. However, their residues may be suited for biochar production, too. In total, the area under production in these towns comprises about 1000 ha of rose cultivation (internal data from Ethiopian Horticulture Development Agency). A detailed description of the allocation of rose farms in the priority area is given in appendix XI.

The flower sector in Ethiopia is dominated by international companies from several countries, such as The Netherlands, Israel, England, Belgium, India, Germany, and others. The major share of the sector is held by Dutch companies, which have settled their businesses mainly in Ziway. Many Ethiopian farms are found at Sebeta, whereas many Indian farms are at Holeta.

As outlined in section 7.4, the annual residue production per ha of rose cultivation accounts for at least 100 t, with approx. 20% of

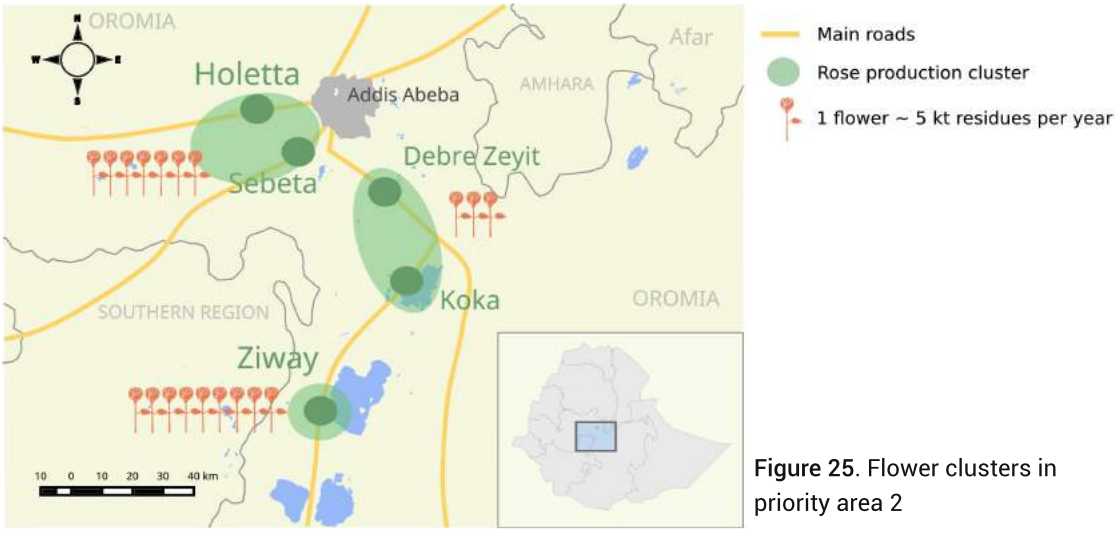

Figure 25. Flower clusters in priority area 2

woody rootstocks (estimated numbers). This results in an estimated total annual residue production of 100,000 t in the priority area. However, it is recommendable to consider only woody rootstocks as biochar feedstock, since green biomass is nutrient-rich and should rather be composted in order to restore the nutrients contained. Consequently, there are approx. 20,000 t of woody residues available for biochar production, which can be transformed into about 6,000 t of biochar. This amount allows for a large-scale pyrolysis plant as presented in section 3.2.

Since there are no data available, which amounts and ratios of biochar, organic nutrient sources and compost are best suited for rose cultivation, a prospective biochar project needs to be backed by continuous scientific evaluation.

Another factor that gives reason to select the flower sector as priority area is the well developed infrastructure in the area and the good connection to the capital Addis Abeba. Thus, it is possible to draw on the capital's market to distribute biochar for other purposes such as a carrier agent for inoculants or as a prepacked potting soil substrate for homegardens.

10.3.2 Creation of fertile biochar substrate from rose residues

Ideally, biochar from root stocks should be co-composted with the remaining 80% of green residues, in order to create a fertile biochar substrate that can be used on flower farms or sold to farmers (figure 26). Depending on the nutrient content of the compost, additional nutrient sources might be necessary, in order to create nutrient-rich bio-fertilizer substrate. During composting, a mass loss of more than 50% of the fresh green material occurs, when applying an aerobic windrow composting method with regular turning (Tiquia et al. 2002, Tirado and Michel 2010, Verma et al. 2014). Agegnehu et al. (2015) recommend a ratio of 1:5 biochar: compost on a dry matter (DM) basis, to create a fertile biochar-compost-mix. In their study they applied 12 t per ha of biochar-compost substrate to barley. Consequently, 6,000 t of biochar can be mixed with 30,000 t (DM) of compost which would suffice for 3,000 ha

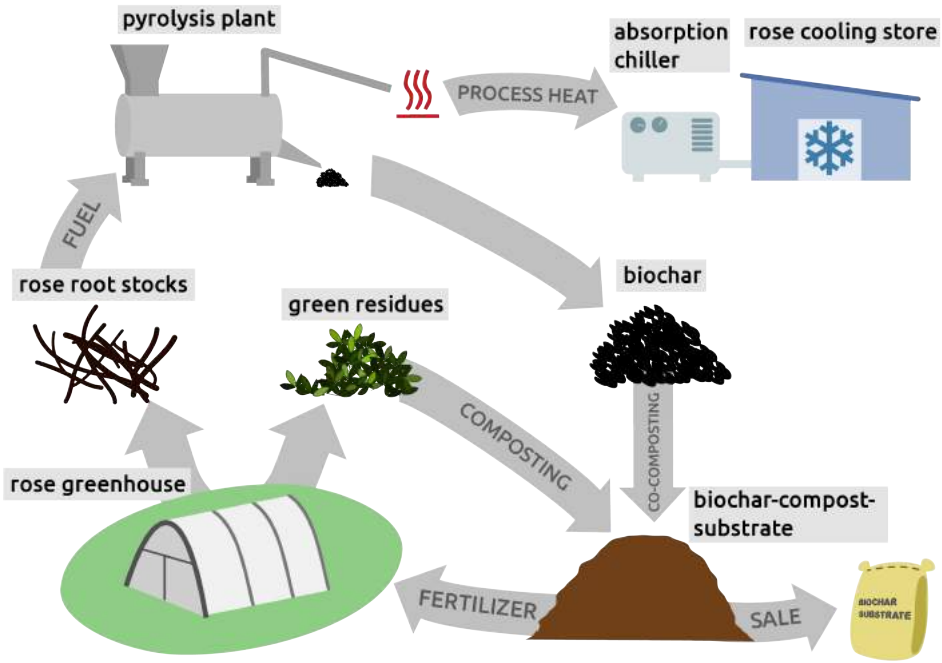

Figure 26. Model of a large-scale biochar system based on flower residues.

of cropping land. For rose production in greenhouses, however, it is recommendable to apply much more substrate, since the optimum soil organic matter content is about 10% (Handbook for Modern Greenhouse Rose Cultivation 2001).

10.3.3 Effects of biochar on soil quality

There are several reasons why the use of biochar substrates is very recommendable within rose farms. Apart from the possibility of using it as a growing media for hydroponic systems (Dumroese et al. 2011, Tian et al. 2012, Northup 2013, Steiner und Harttung 2014, Fascella 2015, Dispenza et al. 2016), biochar substrates can improve the soil quality for rose cultivation and decrease negative environmental impacts. Even though roses can grow in a variety of different soils, there are some characteristics that are preferred for rose cultivation (Handbook for Greenhouse Rose Production in Ethiopia, 2011):

1) homogeneous, stable structure
2) high permeability
3) no disturbing layers in soil profile
4) good drainage and constant groundwater level

As outlined in section 5, biochar can have positive effects according to these preferences. An important factor for high permeability is a low bulk density of the soil. The bulk density of biochar substrates depends highly on the feedstock and the pyrolysis conditions (Downie et al. 2009). Byrne and Nagle (1997) have shown that there is a linear relationship between the bulk density of wood biochars (BD_{BC}) and the bulk densities of their feedstock (BD_{FS}):

$BD_{BC} = 0.8176\ BD_{FS}$

Accordingly, the biochar investigated by Dispenza et al. (2016), which derived from several different wood residues (*Abies alba*, *Larix decidua*, *Picea excelsa*, *Pinus nigra*, *Pinus sylvestris*) had a bulk density of 0.64 g cm^{-3} and,

thus, it is averagely lower than the bulk density of most soils but higher than the bulk density of peat substrate (0.32 g cm^{-3}), which is the common growing media for hydroponic rose cultivation. However, the bulk density of biochar would decrease considerably when it is crushed.

Another important characteristic of biochar is its ability to avoid the release of pesticides to the environment. According to Moncada (2001), flower growers around lake Naivasha (Kenya) averagely use 69 kg per ha and year of active ingredients from pesticides; for comparison, vegetable growers only used 19 kg. In the cropping season 1999 – 2000, Kenyan Rose farmers used a total of 36 different pesticides (appendix XII). Even if secure data are missing for Ethiopia, one can assume that the amounts are comparable to that in Kenya. For that reason Kassa (2017) stresses the hazardous effect that excessive pesticide use can have on soils, ground and surface water, fauna and flora in Ethiopia. Especially insecticides are intensively used in rose cultivation and are very toxic for humans and aquatic organisms (Hengsdijk and Jansen 2006).

Biochar is a well known tool to immobilize hazardous chemicals in soils and thus prevent them from contaminating the environment. The review of Khorram et al. (2016) outlines that the high organic carbon content, the high specific surface area (SSA) and its porous structure are the main determinants of the adsorption capacity of most biochars. Alongside a higher adsorption capacity compared to un-amended soils, biochar-amended soils reduce the amount of leached chemicals and their bioavailability to soil organisms considerably (Khorram et al. 2016). This is of special interest in regions where roses are cultivated next to sensitive water bodies that are also used by local inhabitants for washing and recreational purposes, e.g. in Ziway.

10.3.4 Heat usage for cooling stores

Large scale pyrolysis systems co-produce significant amounts of thermal energy during the carbonization process. As described in section 3.2, between 100 kWth and 1.000 kWth of excess heat power are provided by commercial pyrolysis units. Although energy is in general a precious resource in Ethiopia, it is not easy to find consumers for thermal heat in the flower clusters of the country. The flower cluster have intentionally been established in regions of the country with very warm and stable climate. There is however a high cooling demand in the flower sector to store the roses close to the production site before transport (Reggentin 2016). For this reason, options to convert heat energy to cooling energy are described below.

The heat of pyrolysis systems can be used in either adsorption (1) or absorption (2) cooling systems to provide cooling energy:

1) In adsorption cooling system, the refrigerant (e.g. water) is adsorbed to the surface of solid adsorbers such as silica gel or zeolite (Kim and Ferreira 2008).

2) In absorption cooling system, the refrigerant (e.g. water) is absorbed (taken up) by liquids such as a lithium bromide salt solution (Srikhirin et. al. 2001). The operation principle of absorption cooling cycle of lithium bromide

refrigerators is illustrated in Box 5.

The following preconditions have to be met to convert heat energy from a pyrolysis unit into cooling energy for a rose storage:

► Minimum temperature level of the heat source: Absorption cooling system need a higher heat temperature level to power the process (above 85 °C) than adsorption cooling systems (above 60 °C). For comparison: The exhaust gas temperature of pyrolysis systems has several hundred degrees and thus is high enough to power both types of cooling systems.

► Temperature level demand of the rose storage: For the storage of roses close to the production site, temperature of about 5 °C are required (Reggentin 2016). Since the cooling water provided by adsorption cooling systems typically cannot reach temperatures below 6 °C, only absorption cooling systems are suitable for this task (Schwarz 2013). Absorption cooling systems use a lithium bromide salt solution as absorber and can thus provide cooling temperature of about 5 °C. To provide even lower cooling temperature, (diffusion) absorption cooling systems using e.g. ammonia as refrigerant are needed.

► Cooling power supply for the rose storage: Adsorption cooling system units typically provide less cooling power (1 kW to 250 kW) than absorption cooling system units (10 kW to more than 1000 kW) (Schwarz 2013). The energy demand of the indicated cooling unit can be met by pyrolysis units of appropriate size.

One example of an absorption refrigerator manufacturer is the Austrian Company Pink GmbH that provides ammonia and lithium bromide absorption cooling systems with max. 100 kW cooling power (and even larger refrigerator systems together with cooperation partners) (Pink GmbH 2017).

10.3.5 Current state of biochar systems in priority area II

Yet, there is no operation running that produces biochar from flower residues. However, *Soil and More Ethiopia* already uses rose residues as source for commercial compost production and plans to establish a biochar system on the basis of non-compostable root stocks (section 6.3.2). In collaboration with the British company

Box 5. The absorption cooling cycle of lithium bromide refrigerators (Srikhirin et. al. 2001)

1. **Evaporation:** A liquid refrigerant (water) evaporates in a low partial pressure environment in a first chamber of the refrigerator. Because of the low partial pressure, the temperature needed for this evaporation is low. For the evaporation process, energy is needed. Thus, energy (heat) from a second, separate cooling water cycle is extracted. Thereby, the water in this second cooling water cycle is chilled down. This chilled water is used to cool down a rose storage.
2. **Absorption:** The water vapor is absorbed by a concentrated lithium bromide salt solution within the first chamber of the refrigerator.
3. **Regeneration:** The water-saturated lithium bromide salt solution is heated (with the heat of the pyrolysis unit) in the second chamber of the refrigerator, causing the water to evaporate out of the water-diluted lithium bromide solution. The hot water vapor passes through a heat exchanger, transferring its heat outside the system (such as to surrounding ambient-temperature air), and condenses. The condensed water and the concentrated lithium bromide salt solution are recycled to the first chamber of the refrigerator.

Carbon Gold, they plan to set up a test-pyrolysis plant and to make first trials on their demonstration farm. Another important actor close to the priority area is the Wondo Genet College of Forestry and Natural Resources, where a project was launched in March 2017 to establish biochar and compost systems from different feedstocks. Therefore, the College might be a suitable institution to evaluate biochar activities in the flower sector from a scientific point of view.

11 Risk assessment for the implementation of biochar systems

11.1 Soil protection

Biochar pollution prevention starts with the feedstock selection. Only feedstock with low heavy metal contents and preferably with low organic pollutants levels should be used for biochar production, even if large pyrolysis plants are able to eliminate organic pollutants in the feedstock (see below). Special care has to be taken if co-current flow gasifiers shall be used for biochar production (Schimmelpfennig and Glaser 2012; Wiedner et al. 2013) (section 3.4). To check whether the described conditions have been fulfilled, a representative sample of the final biochar product should be analyzed and compared to the stringent quality criteria of the European Biochar Certificate (EBC).

The following soil protections risks have to be addressed in the priority areas:

Priority area I: In case the selected biochar cook-stoves are based on a gasification process (such as the *Pro Lehm* gasifier stove (section 3.3) or the gasifier stoves developed by *Kaskad-E GmbH* (Guthapfel and Gutzwiller 2016)), the technology should only be applied if the biochar samples fulfill the conditions of the EBC biochar standard (especially regarding the PAH limit).

Priority area II: Based on an internal analysis report by *Soil and More Ethiopia*, the chloride content in the dry rose residue compost is in the range of 520-820 mg kg^{-1}. The chloride content in the root stocks has to be analyzed to determine whether this feedstock can be pyrolysed without the risk of dioxine formation.

Due to the high temperatures in the combustion chamber of large pyrolysis plants, organic pollutants potentially contained in the biomass feedstock (e.g. pesticide residues) are generally broken down and combusted. This safeguard misses in small-scale cookstoves. For that reason, the content of organic pollutants of local feedstock sources that may serve as fuel in gasifier cookstoves, such as coffee residues, should be analyzed.

11.2 Climate mitigation

To assess the climate impact of biochar systems, it is necessary to take into account the emissions and removal of greenhouse gases, as well as the changes in the soil albedo and the emission of ultrafine carbon aerosols. A general

overview of the effects of biochar on different GHGs is given in section 5.5, within the priority areas we focus on CO_2, CH_4 and N_2O. The climate impact of the introduction of biochar systems cannot be determined without assessing the status quo with regard to biomass feedstock use, energy supply and agricultural production.

The following climate protection risks have to be addressed in the priority areas:

Priority area I: Not utilized coffee production residues are mostly stored on heaps outdoors. The aerobic and anaerobic decomposition of the coffee residue heaps and resulting CO_2- and CH_4-emissions represent the current status quo of this feedstock use.

The positive and negative impacts of a biochar system based on small scale gasifier cookstoves using coffee residues as feedstock are shown in box 6.

Priority area II: In the composting facility of the company *Soil and More Ethiopia* at Ziway, rose root stocks are sorted out of the rose residues before composting. The root stocks are stored on heaps and are currently not utilized (see section 7.4). A slow (mainly aerobic) decomposition of the rose stock heap and resulting CO_2-emissions represent the current status quo of this feedstock use. It should also be noted that the majority of the roses produced in Ethiopia is being exported. Due to a long range transport and cooling demand, cut flowers cause average emissions of 11,5 kg CO_2 kg^{-1} (Grabolle et

Box 6. Positive (green) and negative (red) climate impacts of a small-scale biochar system in priority area 1 and strategies to counteract the negative impacts (grey)

+	1) Reduction of the CO_2 - and CH_4 emissions of the outdoor residue storage 2) Replacement of fuel-wood use for cooking (reduction of connected GHG emissions) 3) Sequestration of carbon contained in the biochar produced from the coffee residues after biochar application to the soil 4) Reduction of the GHG emissions caused by the production of nitrogen fertilizer (since biochar can increase the nitrogen usage efficiency (Agegnehu et. al. 2016b)) 5) Reduction of the soil N_2O emissions (see Kammann et al 2012)
–	1) GHG emissions caused by the feedstock provision 2) GHG emissions caused by the manufacturing of the cook-stoves 3) GHG emissions caused by the biochar production 4) GHG emission caused by the biochar transport to the field and the biochar application 5) Albedo impact of biochar application (Meyer et. al. 2012) 6) Emission of ultrafine carbon aerosols (Maienza et al. 2017)
~	1) Usage of modern cook-stoves that burn the majority of the pyrolysis / gasification gases (they contain inter alia CH_4) 2) Local usage of the biochar, usage of low-energy intensive transport and application means 3) Continuous vegetation cover on the biochar-amended plots (to reduce the albedo impact) 4) Co-composting, pelletizing, moistening or mixing of biochar with moist substrates before application to minimize aerosol emissions 5) Incorporation into the soil

al. 2007).

The positive and negative effects of a large scale pyrolysis plant using rose root stocks as feedstock are shown in box 7.

The calculation of comprehensive climate impact balances (CIBs) for the two recommended biochars systems in Ethiopia is out of the scope of this report. However, the CIB for a large-scale biochar system based on wheat straw as feedstock, presented in Meyer et al. (2012) (figure 27), gives a first indication for the order of magnitude of the climate impact of biochar systems as specified for priority area II.

The ordinate of the figure shows the amount of CO_2-equivalent-emissions (positive values) and savings (negative values) per tonne of feedstock (dry mass). The biomass provision causes the most emissions , followed by the albedo impact of biochar applied to the field. The GHG emissions caused by the manufacturing of the pyrolysis plant and the GHG emissions caused by the biochar transport to the farm and the biochar application have a marginal impact on the climate. The major CO_2- savings of this biochar system is the balance of the biogenic CO_2-emissions (during pyrolysis) and the CO_2-

Box 7. Positive (green) and negative (red) climate impacts of a large-scale biochar system in priority area 2 and strategies to counteract the negative impacts (grey)

+	1) Reduction of the CO_2 - (and CH_4-)emissions of the current outdoor root stock storage 2) Replacement of the status quo energy supply for cooling purposes. The reduction of GHG emissions depends on the type of status quo energy supply: large reductions, if the energy is provided by diesel generators, whereas the replacement of hydro-power will result in marginal (or no) emission savings. 3) Sequestration of carbon contained in the biochar produced from the root stocks after biochar application to the soil 4) Reduction of the GHG emissions caused by the production of nitrogen fertilizer (since biochar can increase the nitrogen usage efficiency (Agegnehu et. al. 2016b)) 5) Reduction of the soil N_2O emissions (see Kammann et al 2012)
−	1) GHG emissions caused by the feedstock provision 2) GHG emissions caused by the manufacturing of the pyrolysis plant 3) GHG emissions caused by the biochar production 4) GHG emission caused by the biochar transport to the farms and the biochar application 5) Albedo impact of biochar application (Meyer et. al. 2012) 6) Emission of ultrafine carbon aerosols (Maienza et al. 2017)
~	1) Usage of modern large scale pyrolysis systems that burn all pyrolysis gases (they contain inter alia CH_4) 2) Local usage of the biochar, usage of low-energy intensive transport and application means 3) Continuous vegetation cover on the biochar-amended plots (to reduce the albedo impact) 4) Co-composting, pelletizing, moistening or mixing of biochar with moist substrates before application to minimize aerosol emissions 5) Incorporation into the soil

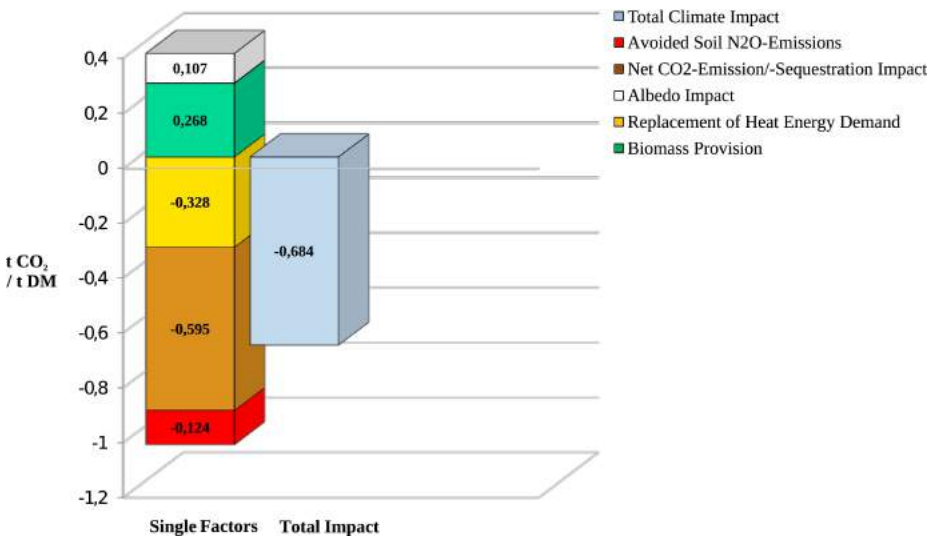

Figure 27. Climate impact (CO_2 emissions and savings) of a large-scale biochar system per tonne of wheat straw (DM) as annual feedstock (Meyer et al. 2012). The balance on the right side of the figure already includes the following minor climate impacts: Emissions: biomass transport (0,001 t CO_2 / t DM), production of the pyrolysis plant (0,02 t CO_2e / t DM) and the biochar transport to the field (0,001 t CO_2 / t DM). Savings: reduction in fertilizer production (- 0,034 t CO_2e / t DM).

sequestration via biochar. In this context, it should be noted that biomass produced with short rotation periods (e.g. wheat straw, coffee husks or rose residues) generally has a more favorable impact on the climate than biomass produced with long rotation periods (e.g. wood). The replacement of the status quo energy use (natural gas based heat provision in the example by Meyer et al. 2012) by the excess heat of the pyrolysis process constitutes the next major CO_2-saving. Additionally, the assumed reduction in soil N_2O-emissions has an important cooling effect on the climate. The reduction of the GHG emissions caused by the production of nitrogen fertilizer has a minor impact. The reduction of the CO_2- and CH_4-emissions of an outdoor storage of the feedstock has not been assessed.

As illustrated on the right side of the figure, the net climate impact of the straw-based pyrolysis biochar system examined by Meyer et al. 2012 is positive. There is no reason to assume that the climate impact of a rose residues based biochar system in Ethiopia will deviate drastically from the illustrated result.

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Appendix I

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		< 0.2 – 1	< 0.2	< 0.2	< 0.5	< 0.5
As		< 13 – 100	-	-	< 100	< 10
Cd		< 1.4 - 39	< 1.5	< 1.0	< 39	< 3
Cr		< 93 - 1200	< 90	< 80	< 100	< 15
Cu		< 143 - 6000	< 100	< 100	< 1500	< 40
Pb		< 121 - 300	< 150	< 120	< 500	< 60
Hg		< 1 – 17	< 1	< 1	< 17	< 1
Mo		< 5 - 75	-	-	< 75	< 10
Ni		< 47 - 420	< 50	< 30	< 600	< 10
Se		< 2 - 200	-	-	< 100	< 5
Zn		< 416 - 7400	< 400	< 400	< 2800	< 150

Appendix II

Coffee and coffee residues production on regions and zones level for private peasants holdings (CSA 2015a)

Region	Zones	Total production [Qt]	Area [ha]	No. of Farmers	Production [Qt/ha]	Total residues [Qt]	Residues [Qt/ha]
Amhara		**33,837**	**8,009**	**412,639**	**4.2**	**27,240**	**3.4**
	North Wolo	3,310	582	48,293	5.7	2,665	4.6
	South Wolo	10,580	1,786	79,387	5.9	8,517	4.8
	North Shewa	2,129	551	52,280	3.9	1,714	3.1
	East Gojjam	905	374	29,478	2.4	728	1.9
	West Gojjam	9,569		91,665		7,703	
	Awi	2,849	987	65,932	2.9	2,294	2.3
	Argoba Special	8	2	398	4.5	6	3.6
Oromia		**2,865,350**	**381,515**	**1,790,042**	**7.5**	**2,306,762**	**6.0**
	West Welega	572,011	75,631	237,924	7.6	460,500	6.1
	East Welega	96,766	11,031	82,318	8.8	77,902	7.1
	Illubabor	426,631	66,597	200,970	6.4	343,461	5.2
	Jimma	803,224	97,155	444,216	8.3	646,639	6.7
	Arsi	65,775	7,564	53,806	8.7	52,952	7.0
	West harerge	124,306	15,154	134,458	8.2	100,073	6.6
	East Harerge	41,038	6,553	132,899	6.3	33,038	5.0
	Bale	113,956	15,467	46,976	7.4	91,740	5.9
	Bolena	79,348	9,342	65,126	8.5	63,879	6.8
	South West Shewa	1,491	258	39,984	5.8	1,200	4.6
	Guji	176,453	17,456	98,073	10.1	142,054	8.1
	Kelem Wellega	279,270	47,018	145,694	5.9	224,827	4.8
Benishangul – Gumuz		**4,011**	**1,126**	**27,889**	**3.6**	**3,229**	**2.9**
	Asoa	1,398	233	16,827	6.0	1,126	4.8
	Moa Komo	1,673	426	3,653	3.9	1,347	3.2
SNNPR		**1,296,098**	**163,874**	**2,470,309**	**7.9**	**1,043,429**	**6.4**
	Hadiya	37,189	6,416	148,103	5.8	29,939	4.7
	Gurage	7,207	2,222	77,955	3.2	5,802	2.6
	Kembata Tembaro	13,019	3,242	79,641	4.0	10,481	3.2
	Sidama	471,732	60,359	863,460	7.8	379,770	6.3
	Gedio	238,685	29,669	196,544	8.0	192,155	6.5
	Wolayita	62,687	9,198	359,953	6.8	50,466	5.5
	South omo	12,522	2,021	37,497	6.2	10,080	5.0
	Sheka	154,899	15,218	47,044	10.2	124,702	8.2
	Keffa	102,377	12,198	150,969	8.4	82,419	6.8
	Gamo Gofa	20,974	3,704	174,679	5.7	16,885	4.6
	Bench Majo	121,850	13,276	104,405	9.2	98,096	7.4
	Yem Special Wereda	1,819	327	13,960	5.6	1,464	4.5
	Dawro	8,978	1,520	73,717	5.9	7,228	4.8
	Basketo Special Wereda	4,620	615	14,303	7.5	3,719	6.1
	Konta Special Wereda	2,585	508	20,713	5.1	2,081	4.1
	Silitie	1,644	293	39,931	5.6	1,324	4.5
	Alaba Special Wereda	1,812	210	14,362	8.6	1,459	7.0
	Segan Peoles Zone	31,499	2,878	53,074	10.9	25,358	8.8
Dire Dawa		**393**	**149**	**5,138**	**2.6**	**316**	**2.1**
Ethiopia		**4,199,802**	**568,740**	**4,723,483**	**7.4**	**3,381,068**	**5.9**

Appendix III

Coffee and coffee residues production on regions level for large and medium scale commercial farms (CSA 2015b)

Region	Production [Qt]	Area [ha]	Waste [Qt]	Waste [Qt/ha]
Amhara	4524.5	455.2	3642.5	8.0
Oromia	393697.5	46562.8	316947.8	6.8
Benishang	140.1	25.7	112.8	4.4
SNNPR	401335.1	60961.3	323096.4	5.3
Ethiopia	799714.0	108007.0	643813.1	6.0

Appendix IV

Flower growing clusters in Ethiopia

Major Clusters	Number of stems in 1 Kg	Average Reject %	Altitude (*m* a.s.l.)
Unknown Cluster (estimated)	20	15	
Holeta	22	15	>2391
Sebeta	24	12	>2100
Debre Zeyit	38	5	> 1800
Ziway	45	8	> 1643

Appendix V

Flower production data according to clusters (ethiopian horticulture development agency)

Cluster	Quantity [mio stems]	Stems per kg	Biomass [t]	Rejected stems average [%]	Reject stems [mio. Stems]	Reject stems biomass[t]	Production area [ha]	Average waste [t ha^{-1}]
Unknown Cluster (estimated)	53.8	20	2689	15	9.5	474	80	5.9
Holeta Cluster	154.7	22	7034	15	27.3	1241	213	5.8
Sebeta Cluster	158.1	24	6588	12	21.6	898	183	4.9
Debre Zeyit Cluster	173.3	38	4560	5	9.1	240	219	1.1
Ziway Cluster	1,842.6	45	40948	8	160.2	3561	573	6.2
Grand Total	**2,382.5**		**61818**		**227.7**	**6415**	**1268**	**5.1**

Appendix VI

Main uses of Prosopis juliflora among Afar pastoral households (taken from Ilukor et al. 2016)

Environmental good	Harvest/year	Value/year (ETB)	Proportion due to *P. juliflora*	% of HH benefitting	*P. juliflora* income per HH
Fuelwood, home consumption	119	2,983	65	96	1,939
Fuelwood, sale	153	5,648	76	3	4,292
Charcoal, home consumption (bags)	35	1,712	86	18	1,472
Charcoal, sale (bags)	1043	57,631	90	18	51,868
Poles for house construction	69	1,664	54	52	899
Poles for house repair	26	210	68	47	143
Fencing (home farm, kraal)	34	699	71	74	496
Farm implements	14	261	43	21	112
Household furniture	77	1,636	17	4	278
Honey (litres)	48	5,760	5	0.2	288
Wild fruits	65	530	4	3	21
Bush meat	12	2,550	23	1	587
Medicinal use	49	1,294	6	10	78
Leaves for livestock feed	175	3,995	30	12	1,199
Pods for livestock feed	136	3,374	87	39	2,935
Total		95,890	46		69,248

Source: Field Survey Data (January 2014 and December 2013): The harvest per year, value per year, proportion and the proportion of households earning a given income are generated from household survey data. Income due to *P. juliflora* is computed from value per year based on proportion income associated to *P. juliflora*

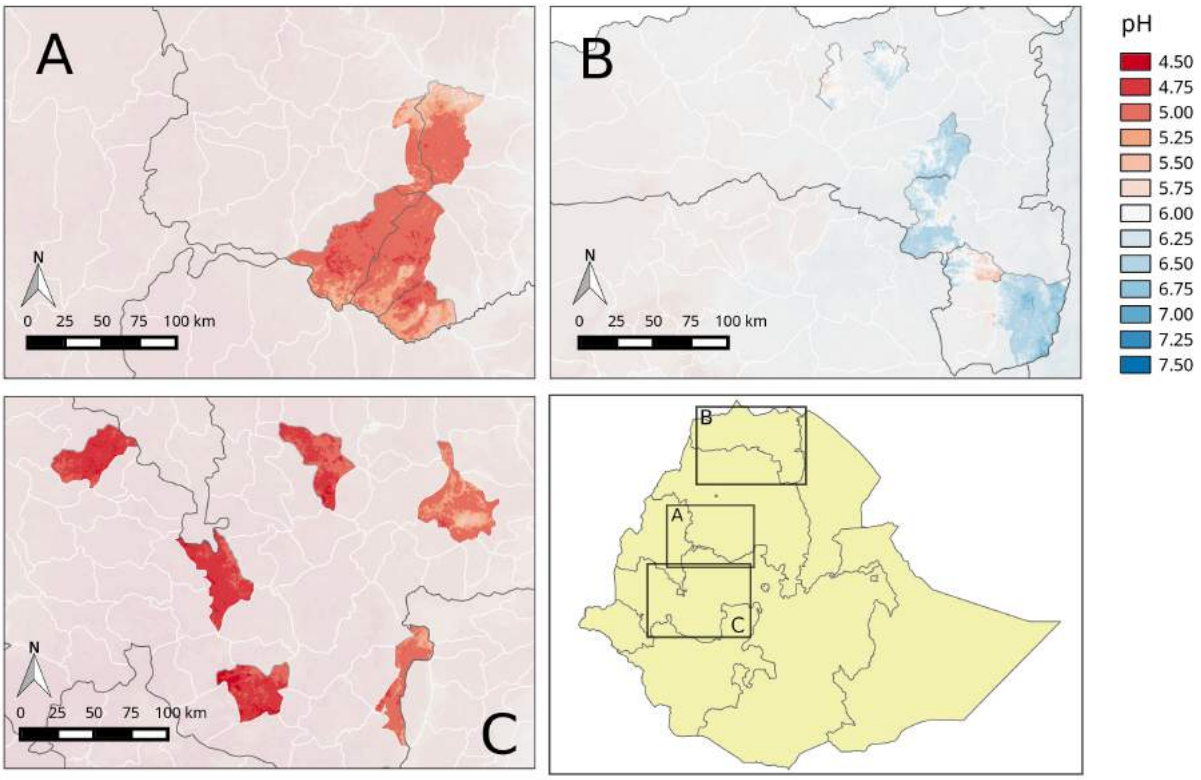
Appendix VII

Livelihood zones within the ISFM+ project woredas, according to An Atlas of Ethiopian Livelihoods (USAID, 2011)

Region	Livelihood Zone
Amhara	
	Abay Beshilo River Basin
	Central Highland Barley and Potato
	South-West Woyna Dega Wheat
	South-East Woyna Dega Teff
Tigray	
	Alaje Ofla Highland
	Central Mixed Crop
	Middle Tekeze
	Enderta Dry Midland
	Raya Valley
	West Central Teff
Oromia	
	Chebo-Inchini Enset, Barley & Cattle
	Didessa-Gibe-Wama Valley Sorghum, Maize & Oilcrops
	Nadda-Gilgel Gibe Maize, Teff and Sorghum
	Nole-Meko-Diga Teff & Cattle
	Wellega Coffee, Maize & Sorghum
	Muger-Abay-Jema Sorghum & Teff Belt
	Jimma-Illubabur Coffee, Cereals & Chat

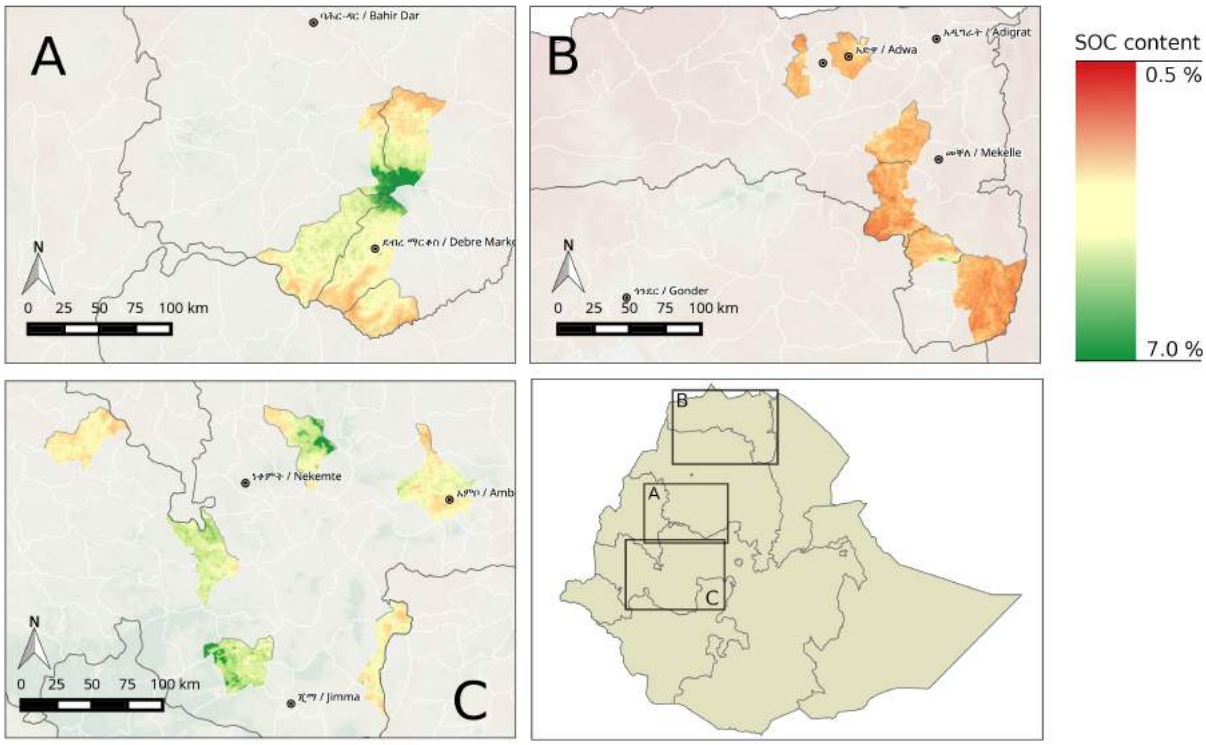
Appendix VIII

pH in ISFM+ project woredas (based on data from ISRIC - soilgrids.org)



Appendix IX

SOC content in ISFM+ project woredas (based on data from ISRIC - soilgrids.org)



Appendix X

Methodolgy of spatial suitability analysis (based on an approach by Geographical Information Technology Traning Alliance (GITTA); http://www.gitta.info/Suitability/en/text/Suitability.pdf)

Criteria	weighted intervals									
	lower boundary									upper boundary
standardized value	10	9	8	7	6	5	4	3	2	1
SOC [%]	<1	1 – 1.5	1.5 – 2	2 – 2.5	2.5 – 3	3 – 3.5	3.5 – 4	4 – 4.5	4.5 – 5	>5
pH	<4.5	4.5 – 4.75	4.75 – 5.0	5.0 – 5.25	5.25 – 5.5	5.5 – 5.75	5.75 – 6.0	6.0 – 6.25	6.25 – 6.5	>6.5

The sum of standardized criteria at one point on the map reflects its suitability

20 = well suited

2 = not suited

Example:

SOC content = 1.8, pH = 5.6

standardized SOC value = 8, standardized pH = 5

sum (suitability) = 13

Appendix XI

Clusters, towns, flower production area and waste production in priority area 2 (based on internal data from Ethiopian Horticulture Development Agency)

Parts of the priority area	Towns	ha	Waste production per year [t]
Central Oromia /West Addis		355.53	36,975
	Sebeta	120.13	
	Tefki	2.4	
	Holeta	102.1	
	Woliso	27.5	
	Menagesha	26.4	
	Addis Alem	77	
Central Oromia /South Addis		152	15,808
	Debre zeyit	132	
	koka	20	
South Oromia		428.5	44,564
	Ziway	428.5	

Appendix XII

List of pesticides used in Kenyan rose production (period 1999-2000) (taken from Moncada 2001)

Alliette	Lannate	Rafast
Apollo	Meltatox	Rovral
Bavistin	Milraz	Rubigan
Bravocarb	Mitac	Saprol
Bulldock	Nemacur	Scala
Cascade	Nimrod	Spare-kill
Daconil	Nomolt	Stroby
Dimilin	Nustar	Tedion
Dithane M45	Oscar	Temik/Furadan
Dynamec	Previcur	Thiodan
Equation PRO	Pride	Thiovit
		Vydate