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Biochar as a strategy for sustainable land management, poverty reduction and climate change mitigation/adaptation? Thermolysis of lignin for value-added products

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Biochar as a Strategy for Sustainable Land Management, Poverty Reduction and Climate Change Mitigation/Adaptation?

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This work is dedicated to Mother Earth.

Abstract

In the context of current concerns about food security, energy security and environmental degradation, the characteristics of biochar are analyzed to determine if biochar systems are a possible solution to these interlinked global issues. With this purpose, the mechanisms by which biochar can affect global biogeochemical cycles are revised. Feasibility of biochar production and application to soil, among other options, is then examined under the criteria of energy, greenhouse gas emissions and financial performance. This is carried out by using life-cycle assessments (LCA) from the literature and by performing a cost-benefit analysis, in the context of a developing country.

It is determined that, under certain conditions detailed in the body of the work, biochar can be well suited as a strategy for promoting sustainable land management, climate change mitigation and adaptation, and subsequently, poverty reduction. Among the relevant variables that determine the feasibility of biochar systems are: feedstock; production conditions; geographic context; and current management of biomass.

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List of Abbreviations

CH_4:	Methane
CO_2:	Carbon dioxide
FAO:	Food and Agriculture Organization of the United Nations
GHG:	Greenhouse gas(es)
HTT:	Highest-treatment temperature
IEA:	International Energy Agency
IFAD:	International Fund for Agricultural Development
ILO:	International Labor Organization
IPCC:	Intergovernmental Panel on Climate Change
MEA:	Millennium Ecosystem Assessment
N_2O:	Nitrous oxide
UNDP:	United Nations Development Program
UNEP:	United Nations Environment Program
UNFPA:	United Nations Population Fund
UNU:	United Nations University
US EIA:	U.S. Energy Information Administration
US EPA:	U.S. Environmental Protection Agency
WB:	World Bank
WHO:	World Health Organization

CHAPTER 1

Introduction

The food, energy and environmental crises justifiably dominate the headlines in the world today. They are primarily caused by the demand of ever-increasing global population under a high-carbon economic model. Land degradation and climate change are relevant associated processes requiring change in order to solve these crises. The consequences of these processes are felt throughout the globe, disproportionally affecting the livelihoods of more than one billion people living in poverty (UNDP, 2006). In this context, for natural resource-abundant developing countries, land degradation and climate change tend to aggravate poverty. Thus, this thesis discusses the opportunities for production of biochar with sustainably managed natural resources to combat land degradation and climate change while simultaneously alleviating poverty. Biochar is charred biomass that results from thermo-chemical treatment; it is produced specifically for application to soil as part of agronomic or environmental management (Brown, 2009) and its properties are described in detail in Chapter 2.

Land degradation

Land degradation is a long-term loss of ecosystem function and services, caused by disturbances from which the system cannot recover unaided (UNEP, 2007). Land-use change and excessive pressure on agricultural lands are responsible for land degradation, resulting in soil productivity loss and roughly one third of global greenhouse gas (GHG) emissions (IPCC, 2007). In the context of agriculture, as global demand for food increases, current agricultural lands are over-fertilized in the attempt to raise soil productivity, while the expansion of the agricultural frontier signifies more pasture lands and forests converted into new cultivation areas, soon to be over-fertilized. Additionally, the production of synthetic fertilizers requires large amounts of fossil fuel energy (natural gas). A higher-than-optimal application to soil leads to losses of reactive nitrogen into the environment, causing pollution to soil, water and land (Erisman et al, 2009). This represents a very inefficient energetic process, while causing damage to the environment. On top of this, land degradation often means loss of terrestrial C sinks and loss of biodiversity, e.g. through deforestation. Biodiversity is important partly because it promotes ecosystem stability: the more diverse an ecosystem, the greater its ability to withstand shocks and stresses (Kahn, 2004).

Climate Change

The emission of GHG due to human activities increases their concentration in the atmosphere and leads to a change in the energy balance of the Earth System. As a consequence, changes in climate occur. The main drivers of change are carbon dioxide (CO_2) emissions – 77%, primarily from fossil fuel use and land-use change; methane (CH_4) emissions – 14% – attributed to agriculture and fossil fuel use; and nitrous oxide (N_2O) emissions – 9%, mainly from agriculture (IPCC, 2007). Some results of increased concentration of GHG include: changes in global biogeochemical cycles that regulate conditions for life on Earth; changes in the hydrological cycle, such as sea level rise and Polar ice cap melting, which affect water availability and precipitation patterns; increased tendency for soil erosion and biodiversity and ecosystems function loss, which reduce the terrestrial C pool and productive and adaptive capacity of terrestrial ecosystems; and the risk of reaching tipping points, crossing thresholds that could provoke sudden self-reinforcing climatic events difficult to reverse, among many.

As can be evidenced, land degradation results from a disturbance, which in reality often is climate change-derived. At the same time, land degradation is a cause of climate change, which increases the tendency for land degradation. They mutually reinforce each other and thus can be represented by a vicious cycle.

Effects of climate change, land degradation and their interaction on poverty

Despite some progress in poverty reduction in the last decades, the process has been accompanied by rising inequality (UNDP, 2007): half of the world population owns barely 1% of global wealth (UNU, 2008). Table 1 lists some facts about poverty, climate change, land degradation and their interactions.

On the other hand, there is a relatively small group of industrialized countries that have propelled their economies since the industrial revolution with the use of fossil fuels. Changes in climate have occurred as a consequence. The adverse impacts of climate change will affect poor nations disproportionally, because of their geographical and climatic conditions, their high dependence on natural resources, and their limited capacity to adapt (UNDP, 2003).

Steady global population growth, which increases pressure on land for productive purposes, has led to increased rate of land degradation. As a consequence, in recent years, food prices have increased rapidly, giving rise to major concerns over the food security of the world's most vulnerable people (FAO, 2008). At the same time, almost half of the world population lacks access to modern energy (UNDP/WHO, 2009) while developed countries and, more recently, emerging economies continue to affect fragile environmental balances.

It is clear that fast-growing world population, increased demand for natural resources, increased environmental degradation and high inequality result in an increasing proportion of people in the world living in degraded environments and thus under impoverished conditions. It seems needless to say that other external shocks, like the financial crisis of 2007-2008, only aggravate the situation.

Even though poverty is not a major cause of land degradation and climate change, it is affected by both in a mutually reinforcing cycle, thus completing the multiple vicious cycle, shown in figure 1.1.

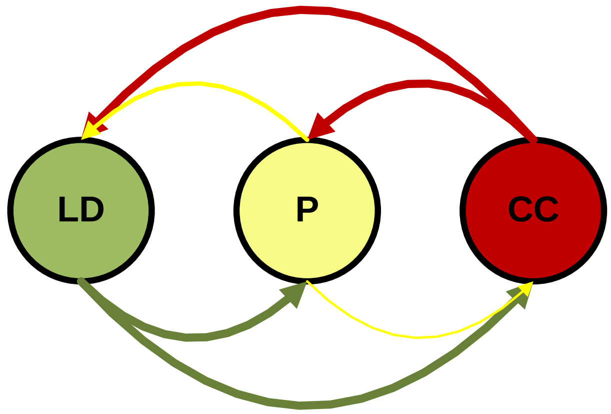


Figure 1.1 Schematic cause-effect relationships between land degradation (LD), poverty (P) and climate change (CC). Width of arrows indicates the strength of relationship

It is important to recognize that all human activities, and more precisely economic activities, are embedded in the greater Earth System. As they are transformed, natural resources flow as inputs and outputs of the economy. Limits to economic activity and economic growth coincide with limits to the absolute availability of, and accessibility to, natural resources, despite technological progress achieved [i.e. growth in land productivity is expected to continue, although at a declining rate (Smith et al, 2007)]. The voracious appetite of the dominant global economic model is leading, on one hand, to ever-increasing environmental degradation, which affects the own economy's productive capacity; and on the other, to increased societal inequalities, as people living in poverty, and who are highly dependent on natural resources for subsistence, feel the impact of reduced access to resources and reduced income more profoundly. In opposition, a sustainable model of economic growth is one that regards the environment as a valuable input for economic activity production (Kahn, 2004), thus promoting environmental preservation.

Table 1.1 Relevance of land degradation, poverty and climate change, and interactions between them

	Relevance	**Affects…**
Land degradation **(Agriculture)**	- Agriculture accounts for 24% of world economic output (1) - Agricultural lands occupy about 40-50% of the Earth's surface (2) - LD caused the decline in net primary productivity of 25% of agricultural lands between 1981-2003 (3) - The rate at which arable land is being lost is increasing and is currently 30-35 times the historical rate (3) - Food production provides the nutrients necessary for sustaining life of 100% of humanity	❖ *Poverty:* - One third of the world's population is employed in agriculture, mostly people from developing countries (3 and 4) - Dryland and desert areas have the highest number of poor people (7) ❖ *Climate Change:* - Agriculture contributes to 14% of global GHG emissions; land use change, accounts for another 17% (2) - LD increases the loss of soil organic matter and nutrients, increasing the impact of climate change (3)
Poverty **(&Inequality)**	- 1,4 billion people live in extreme poverty (5) - Approx. 3,7 billion people suffer of malnourishment (6) - The bottom half of the world population owns 1% of global wealth (9) - 1,2 billion people have inadequate access to water and 2,6 lack basic sanitation (11) - 3 billion people continue to lack access to sustainable and affordable modern energy (12) - Roughly 1 billion of the world's poorest people live in rural areas as subsistence farmers (10)	❖ *Land degradation:* - People living in poverty tend to over-harvest in order to cover basic nutrition needs, facilitating LD - Land fragmentation leads to intensive agriculture, driver of LD ❖ *Climate Change:* - Developing countries have not contributed substantially to climate change; nevertheless, they are the most vulnerable to its effects - The carbon footprint of the poorest 1 billion people is about 3% of the world's total footprint (8)

Climate Change	- Atmospheric concentrations of GHG in 2005 exceed by far the natural range over the last several thousand years (2) - Impacts of increased GHG concentrations in the atmosphere (depend on region) include: - Biodiversity loss, ecosystem services loss, ice cap melting, sea level rise, change in precipitation patterns, water shortages, flooding, accelerated desertification, risk of tipping points, among others (2)	❖ *Land degradation:* - Rising global temperatures increase desertification and LD (2) - Causes and effects of LD and CC (e.g. loss of soil organic matter and nutrient mining) are intertwined (3) ❖ *Poverty:* - Agriculture-based developing countries are more vulnerable to changes in climatic patterns, including extreme weather events, rainfall patterns, and the availability of water resources, temperatures and the length of cropping seasons, and ultimately food production (6)

1 FAO (2003)
2 IPCC (2007)
3 UNEP (2007)
4 ILO (2007)
5 WB (2008)
6 Pimentel and Pimentel (2006)
7 MEA (2005)
8 UNFPA (2009)
9 UNU (2008)
10 UNDP (2003)
11 UNDP (2006)
12 UNDP/WHO (2009)

The driving forces that exacerbate the interactions between land degradation, climate change and poverty in a multiple vicious cycle can be reversed to bring benefits for society. The quest for strategies able to efficiently address these interrelated global issues represents the underlying motivation of this thesis dissertation.

The main objective of the present work is to analyze the benefits of biochar as a strategy that can address the problems of land degradation, poverty and climate change simultaneously. For this, an overview of the most up-to-date state of the science supporting biochar is presented in chapter 2; in chapter 3, the mechanisms by which biochar can affect global biogeochemical cycles, regulating conditions for life on Earth, are explored; a Life Cycle Assessment-based study and a cost-benefit analysis are presented in chapter 4, showing the energy, GHG emissions and financial performance for different management options of biomass residues, including biochar production and use. To finalize, follow a short discussion and closing remarks, including recommendations.

The explicit research question of this dissertation is presented as follows:

Research question

Can the production of biochar for environmental management be considered a suitable strategy for combating increasing climate change, poverty and land degradation?

Supporting questions

What are the main benefits of biochar production and application to soil?

Which conditions are necessary for biochar systems to fulfill their potential?

How can global biogeochemical cycles, which are relevant to climate change and land degradation processes, be affected by biochar production and application to soil?

What is the life-cycle energy balance of biochar systems in comparison with current biomass management options in agriculture?

What does the life-cycle greenhouse gas balance evidence?

Which are the parameters, conditions, barriers, trade-offs and risks that determine feasibility of a biochar system?

Can biochar systems improve the livelihoods of, specially, people living in poverty?

CHAPTER 2

Characteristics of Biochar

In this chapter are presented the general characteristics of biochar. They are subdivided into: physical, chemical, nutrient and biological. But first, the global role of bioenergy production is discussed in the context of the current energy system.

Bioenergy in context

"The climate problem is mostly an energy problem"

- David MacKay. Sustainable energy - Without the hot air (2009)

Currently, fossil fuels represent more than 80% of the world primary energy supply; biomass and waste, although contributing more than double the share of all other renewables combined, account for nearly 10% (IEA, 2007). Many studies have assessed the global potential of energy from biomass (Yamamoto et al, 2001; Fischer and Schratenholzer, 2001; Hoogwijk, 2004; Field et al, 2007; Erisman et al, 2009) and consensus exists on bioenergy playing an important role in achieving a carbon-free economic growth model (Muradov and Veziroglu, 2008). In this context, it is important to enhance the potential of bioenergy avoiding conflicts with food security and land use change, among others. To simplify the discussion, the present work focuses on the production of bioenergy using biomass residues from agriculture.

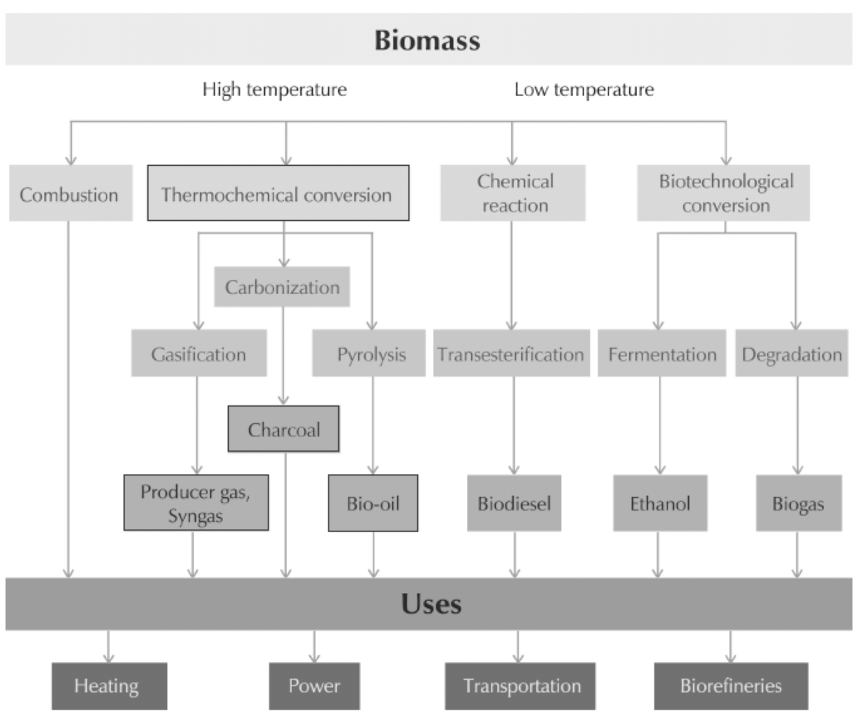


Figure 2.1 Technological routes for bioenergy production. Source: ISPRE (2009)

There are several technological routes to produce energy from biomass (Figure 2.1), which can be categorized into combustion, thermochemical conversion, chemical reaction and biotechnological conversion (ISPRE, 2009). This thesis focuses on thermochemical routes, characterized by environments with limited oxygen supply, by which biomass is transformed into liquid (bio-oil), solid (biochar) and gas (syngas) phases in different proportions, discussed later in this chapter.

Biochar characteristics

Biochar is charcoal produced from the thermal decomposition of biomass in a low- or zero-oxygen environment, at relatively low temperatures (<700°C) (Lehmann and Joseph, 2009a). During this process (pyrolysis), energy-rich gases are released, which are then used to produce liquid fuels or directly for power generation (Shackley et al, 2009). Biochar is a carbonaceous material produced specifically for application to soil as part of agronomic or environmental management (Brown, 2009). It is often regarded as a by-product of other thermochemical routes, e.g. gasification, used to produce energy from biomass.

Land application of biochar is not a new concept. Patches of black soil found in the Amazon Basin (so-called Amazonian Dark Earths or "*terra preta*") seem to have been covered with large amounts of residues from biomass burning (Sombroek et al, 2003). These applications were most likely a result of both habitation activities and deliberate soil application by Amerindian populations before the arrival of Europeans (Lehmann et al, 2006). Large amounts of biochar-derived C stocks remain in these soils today, hundreds of years after they were abandoned. The total C storage is more than twice as high compared to Amazonian soils without biochar (Glaser et al, 2001). Such C storage in soils far exceeds the potential C sequestration in plant biomass even if bare soil were, theoretically, restocked to primary forest (Sombroek et al, 2003).

Reasons that motivate biochar use for environmental management, as shown in figure 2.2, are: soil improvement; waste management; climate change mitigation; and energy production.

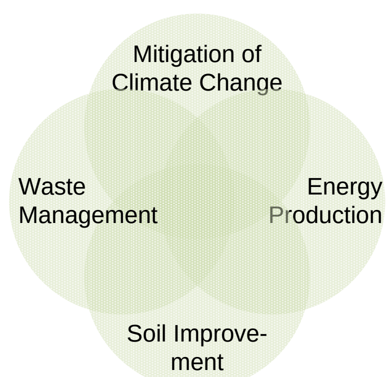


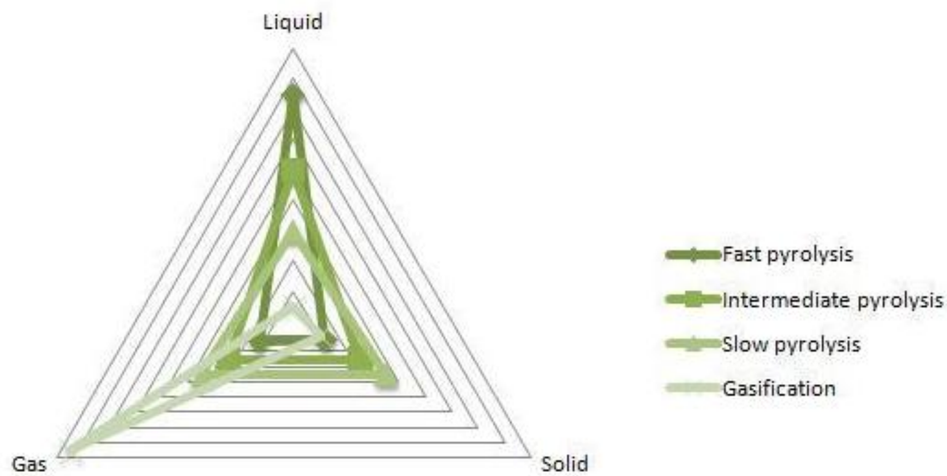
Figure 2.2 Motivation for biochar-to-soil systems. Source: Lehmann and Joseph (2009a)

Some basic characteristics of biochar are presented as follows, starting with how it is obtained. The information in the following sections has been extracted mainly from Lehmann and Joseph (2009), Verheijen et al (2010) and Sohi et al (2009). More light will be shed on biochar characteristics when exploring the biogeochemical cycles in chapter 3 and in the life-cycle assessment of chapter 4.

Biochar production

Biochar is produced through thermochemical routes, with yields varying for each (see figure 2.3). Production parameters will determine the physical characteristics and properties of biochar. These are covered in detail in the following sections.

Potential feedstocks for biochar production include all materials of biological origin, such as manures, rendering wastes, and lignocellulosic biomass. In the last subcategory, the use of agricultural residues for biochar and bioenergy production presents advantages over dedicated crops, as production inputs for the latter affect energy, GHG and financial performance. Waste biomass such as yard wastes or animal manure may even prove better since they pose disposal issues and may even generate tipping fees (Gaunt and Lehmann, 2008).



Process	Liquid	Solid	Gas
Fast pyrolysis	75%	12%	13%
Intermediate pyrolysis	50%	25%	25%
Slow pyrolysis	30%	35%	35%
Gasification	5%	10%	85%

Figure 2.3 Products and yields of thermochemical routes for bioenergy production. Modified from Bridgewater (2007)

In general, lower HTT, slower heating rate, higher pressure and greater concentration of lignin in the substrate result in larger yields of biochar.

Biochar production systems are possible at different scales, ranging from decentralized rural farms to large commercial facilities. There are a number of case studies of current biochar systems in developed and developing countries, included in the Appendix, although many of them are only at pilot scale.

Application to soil

The maximum amount of biochar that can be applied to soil has been assessed by Lehmann et al (2006) stating that even with very high application rates of biochar (up to 140 ton C/ha), crop yield improvements can be achieved with no registered negative impacts. This high capacity of soil to store pyrolysis-derived C combined with high stability of biochar results in the ability to realize long-term C sequestration.

Physical properties

Biochar consists mainly of four phases: stable carbon; labile carbon and other volatile compounds; mineral ash material; and moisture (table 2.1). Proportions vary according to original biomass, pyrolysis conditions, highest treatment temperature, heating rate, pressure, and pre- and post-handling conditions, among others. Physical characteristics of biochar depend mainly upon feedstock and pyrolysis conditions (Downie et al, 2009).

Table 2.1 Biochar components as a percentage of total weight. Source: Verheijen et al (2010)

Component	Proportion (%)
Fixed carbon	50-90
Volatile matter	0-40
Moisture	1-15
Ash (mineral matter)	0.5-5

During pyrolysis, at low temperatures, cellulose and hemicellulose are lost in the form of volatile organics leading to mass loss and shrinkage. The mineral and C skeleton formed retains the structure of the original material. The molecular structure of biochar is of high porosity and a large surface area, from which derive chemical properties similar to those of activated carbon. Micropores contribute most to surface area and are responsible for the high absorptive capacity; mesopores are important for liquid-solid adsorption processes; and macropores are important for aeration, hydrology, movement of roots and bulk soil structure. Application of biochar to soil also changes the physical nature of soil, causing a net increase in the total soil-specific surface, improving soil structure and aeration (Kolb, 2007).

As final temperature increases, more structured regular spacing between the planes in the molecular structure of biochar result. Interplanar distances decrease as ordering of molecules becomes dominant, leading to larger surface areas per volume. After a threshold of operating temperature (<900°C), however, deformation occurs, micropores widen due to destruction of the walls between adjacent pores and a decrease in surface area results.

Also with increasing temperature, due to loss of volatile matter, particles of produced biochar decrease in size. This, in turn, leads to a higher ordering of graphene layers, increasing solid density and therefore increased mechanical strength of biochar in soil. When applied to soil, particle fragmentation will tend to increase surface area and facilitate the movement of biochar particles in soil by wind and water erosion, allowing it to penetrate and collaborate to formation of dissolved organic carbon (Hammes and Schmidt, 2009).

The physical structure of biochar can also be categorized into (see also figure 2.X):

i. Conducting phase – crystalline aromatic compounds stacked as flat graphene sheets
ii. Non-conducting phase – aromatic-aliphatic organic compounds of complex structure (including residual volatiles) and inorganic ash

Chemical properties

Biochars, being derived from a variety of biological feedstocks that have been thermally degraded under a range of variable conditions, exhibit a correspondingly large range in composition and chemistry (Amonette and Joseph, 2009). Chemical properties of biochar are determined mainly by feedstock and pyrolysis conditions. The processes and products resulting from pyrolysis under different parameters for usual biomass feedstocks are described in table 2.2. Correspondingly, figure 2.4 shows the evolution of biochar characteristics during pyrolysis.

Table 2.2 Pyrolysis products and characteristics. Modified from Amonette and Joseph (2009) and Sohi (2009)

Temperature (°C)	Process	Products	Biochar characteristics
>300	- Little mass loss - C concentration begins to increase (150°C), with loss of H and O. N concentration maximum	Mostly biochar and biogas + Water, CO, CO_2	- Amorphous C matrix - C content 40-50%
300-600	- Loss of amorphous C phase to aromatic C structure - Increase in mass loss - Decrease in biochar production - Increase in porosity	Mostly liquids and tars	- Graphene sheets increasingly present and ordered - C content 70-80% - High porosity
<600	- Production of biochar, tars and liquids at minimum - Carbonization (removal of non-carbonaceous elements O, H, N, S)	Mostly biogas	- Higher porosity, surface area, mechanical strength - C content ca. 90% - Low nutrient availability

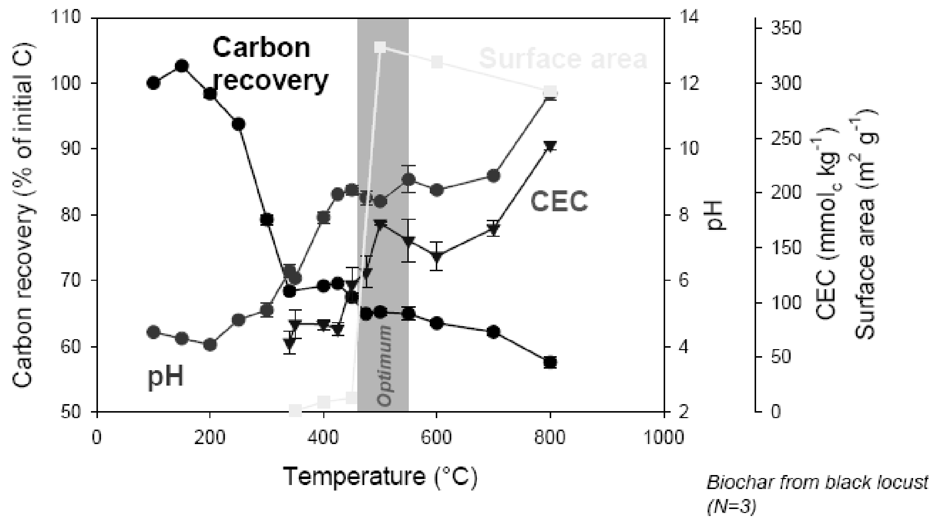


Figure 2.4 Evolution of biochar characteristics during pyrolysis. Source: Lehmann (2007)

H and O are lost initially as water, later as hydrocarbons, tarry vapors, H2, CO and CO_2 (Antal and Gronli, 2003). N is volatilized, and K and Cl, highly mobile, vaporize at relatively low temperatures. Ca and Si are released at higher temperatures. Mg is even more stable, while Fe and Mn are largely retained in biochar. P and S are relatively stable at low temperatures only. A part of the inorganic compounds is volatilized during thermal degradation and the majority is retained as part of the structure of the carbonaceous residue.

Of particular chemical importance is the formation of graphene, starting at 250°C until 550°C. Graphene is a polyaromatic structure: a flat monolayer of carbon atoms that presents high indices of stability, breaking strength and electrical conductivity (Geim and Novoselov, 2007). The fact that its entire volume is exposed to its surrounding makes it very efficient to adsorb molecules. As temperature increases in this range, ordering of graphene sheets occurs. Biochars produced above 350°C are dominated by aromatic C groups.

A range of different functional groups exist in the surfaces of the graphene sheets. H, N, O, P and S are incorporated in the aromatic rings and determine the electronegativity of the biochar product, influencing the cation exchange capacity (CEC). CEC is a measure of the surface charge in soil or biochar, and increases as the biochar ages. Surface charge determines the nature of the interaction between biochar and, among others, soil particles, dissolved organic matter, gases, microorganisms, and water (Joseph et al, 2009).

With time, biochar becomes deactivated as its pores become clogged and its sorption ability decreases. Inner pores become inaccessible (Warnock et al, 2007) causing a decrease in surface area. Reactivation is possible when over time bacteria, fungi and certain nematodes enter into the pores and colonize biochar particles (see Biological Properties).

H/C and O/C ratios are used to measure the degree of aromaticity and maturation (Hammes et al, 2006). Unburned biomass present average ratios of 1.5, graphite-like materials, e.g. lignite and soot, show values of 0.1, while biochar values fall in the range between 0.4 and 0.6, closer to those of graphite, most likely due to the presence of graphene sheets. Values decrease with increasing temperatures and residence time, as C content increases, as shown in figure 2.5. High-ash mineral content biochars show a lower C content (Krull et al, 2009).

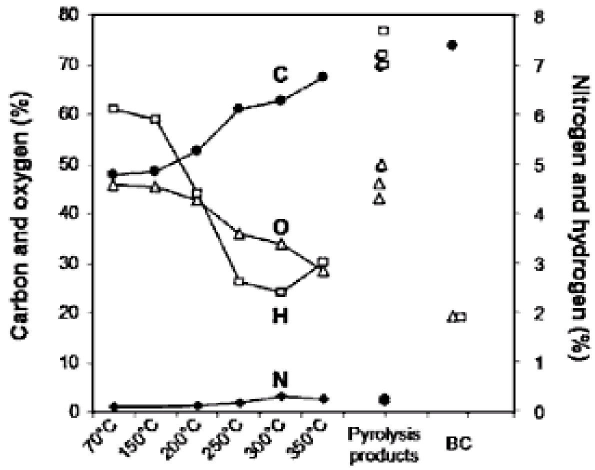


Figure 2.5 Changes in elements in biochar with increasing temperature. Source: Krull et al (2009)

The stability against decomposition is attributed to the transformation of labile compounds into environmentally recalcitrant forms. This occurs as a consequence of the transformation of the three main building blocks of biomass: a decline in cellulose and hemicellulose structures with a simultaneous relative increase of lignin. These chemical conversions occur concurrently with mass loss, with reported values of 3 to 81%, with temperature increase from 150 to 300°C (Baldock and Smernik, 2002). The half-life of biochar C in soil is in excess of 1000 years (Laird, 2008). As shown in figure 2.6, conversion of biomass C to biochar C leads to sequestration of about 50% of the initial C compared to the low amounts retained after burning (3%) and biological decomposition (<10–20% after 5–10 years) (Lehmann et al, 2006). The global potential for terrestrial C sequestration through biochar application in soil is large, and will be detailed later.

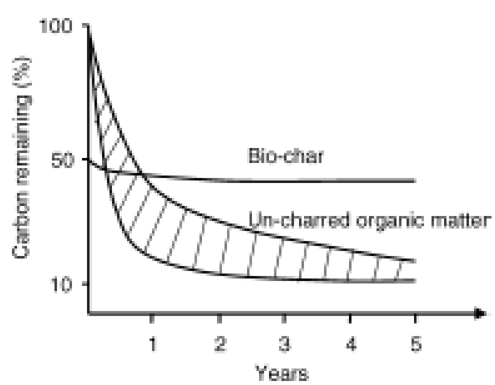


Figure 2.6 Simplified stability of biochar C and biomass C in soil. Source: Lehmann et al (2006)

Nutrient properties

Often biochar is regarded as a by-product to be upgraded to activated carbon and used in purification processes (Horne and Williams, 1996). However, a positive attribute of biochar is its nutrient value when used for soil application. Although biochar does not usually contain high levels of available N, indirect nutrient value is attributed to its ability to retain nutrients in soil and reduce leaching losses, resulting in increased nutrient uptake by plants and higher crop yields (Chan and Xu, 2009). Concentrations of the basic elements in biochar are listed in table 2.3. Chan and Xu (2009) report a wider range of pH values collected from different studies.

Table 2.3 Summary of total elemental composition and pH range of biochar from a variety of feedstocks and pyrolysis conditions. Source: Verheijen (2009)

		pH	C	N	N (NO^{-3}, NH_4^+)	P	Pa	K
			(g/kg)	(g/kg)	(mg/kg)	(g/kg)	(g/kg)	(g/kg)
Range	From	6.2	172	1.7	0.0	0.2	0.015	1.0
	To	9.6	905	78.2	2.0	73.0	11.6	58
Mean		8.1	543	22.3	-	23.7	-	24.3

The occurrence of graphene means a reduction in mineralization of organic C, leading to a reduction in the availability of nutrients in biochar. Nitrogen (N) starts volatizing at low temperatures and, in general, mineral N results present in small concentrations. This is not the case for potassium (K), which has been reported to be highly available in biochars. Phosphorus (P) concentrations are usually high, more for biochars produced from animal manure than those from plant biomass. In an experiment with sewage sludge biochar by Shinogi (2004), although total P increased with increasing temperature, available P concentrations decreased. With the purpose of maintaining high nutrient contents and availability in biochar it is preferable to keep process temperature low (<500°C).

It becomes evident that the elemental composition of biochar is complex and highly variable. It is suggested that feedstock and pyrolysis parameters are the controlling variables of nutrient composition in biochars. Ranges of basic elements in biochars are wider than those of commonly used organic fertilizers. This high variability may indicate potential benefits for biochar systems, but at the same time increases uncertainty on the interaction of different biochars and soils. The optimal conditions for biochar production and application most likely need to be determined on a case-by-case basis (Glaser et al, 2002).

A meta-analysis of observed effects of biochar application to soil by Verheijen et al (2009) (Figure 2.7) shows overall positive crop responses: an average of 12% increase in plant productivity. The main reasons offered are enhanced ability to retain applied fertilizer; increased water-holding capacity; increased cation exchange capacity; and reduced soil strength. In addition, environmental benefits from biochar application to soils include reduced nitrogen loss into water bodies and air, and reduced need for fertilizer.

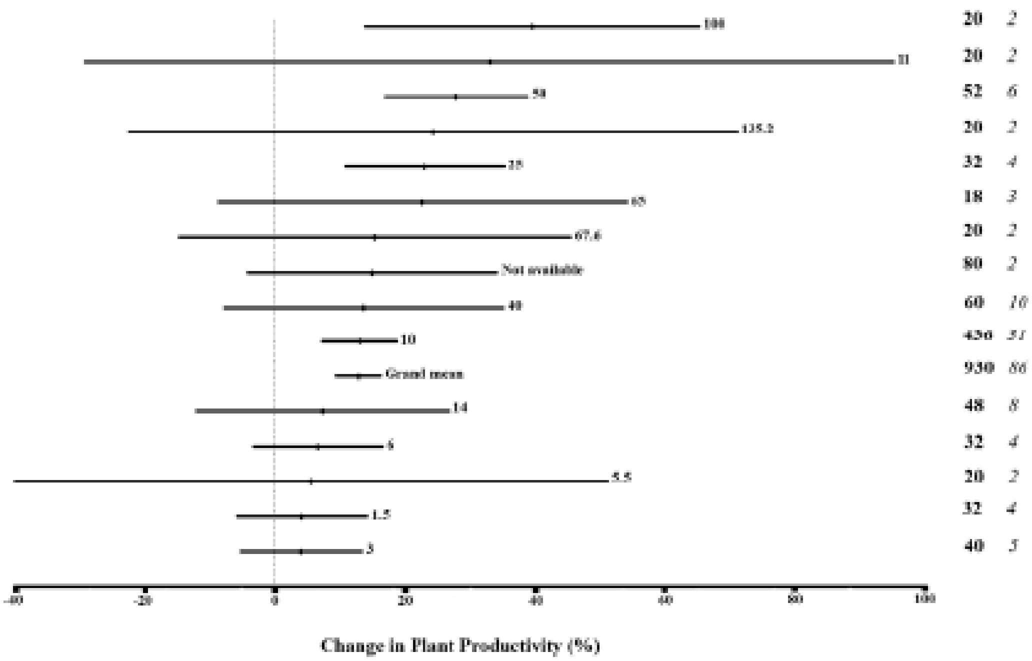


Figure 2.7 Meta-analysis of change in crop productivity due to biochar application to soil. Source: Verheijen et al (2009)

Some biochars have shown fairly high concentrations of carbonates, which can be valuable as a liming material for overcoming soil acidity (Van Zweiten et al, 2007)

On the negative side, few data is available on the content of trace elements in biochars. This is an area that deserves attention, as heavy metals entering the food chain can pose potential human health risks.

Biological properties

Biochar is not an inert material (figure 2.8). Unlike other types of organic amendments to soil, biochar changes the physical and chemical environment of the soil, which will, in turn, affect the characteristics and behavior of the soil biota. Soil biological communities are complex assemblages of bacteria, archaea, fungi, algae, protozoa, nematodes, arthropods and a diversity of invertebrates (Thies and Rillig, 2009). Interactions among the members of these populations and soil chemical and physical properties affected by biochar will determine overall ecosystem function and productivity, e.g. crop growth and yield.

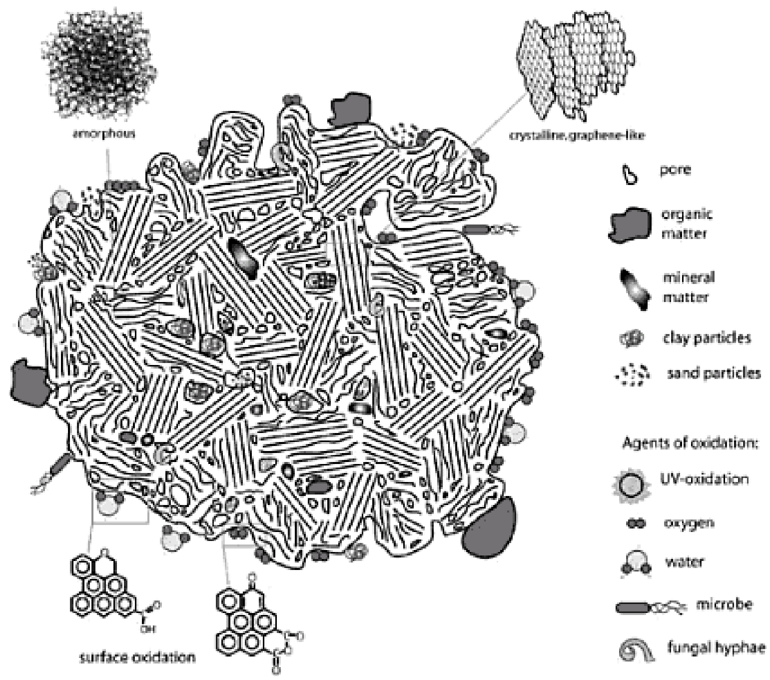


Figure 2.8 Basic model of a complex biochar particle. Source: Hammes and Schmidt (2009)

The high internal surface area and ability to absorb soluble organic matter, gases and inorganic nutrients are likely to provide a highly suitable habitat for microbes to colonize, grow and reproduce. Also, the high C content and stability of biochar increases levels of SOC, which plays a pivotal role in nutrient cycling and in improving plant-available water reserves, soil buffering capacity and soil structure.

The chemical and physical characteristics of different biochars will add another layer of complexity to soil food web interactions by altering the availability of soluble organic matter, mineral nutrients, pH, soil aggregation and the activity of extracellular enzymes. Thus, biochar will affect diversity, abundance and distribution of associated microbial communities. The environmental factors that most strongly influence bacterial abundance, diversity and activity are moisture, temperature and pH, all of which can be affected by biochar. Changes in soil properties derived from biochar application are summarized in figure 2.9.

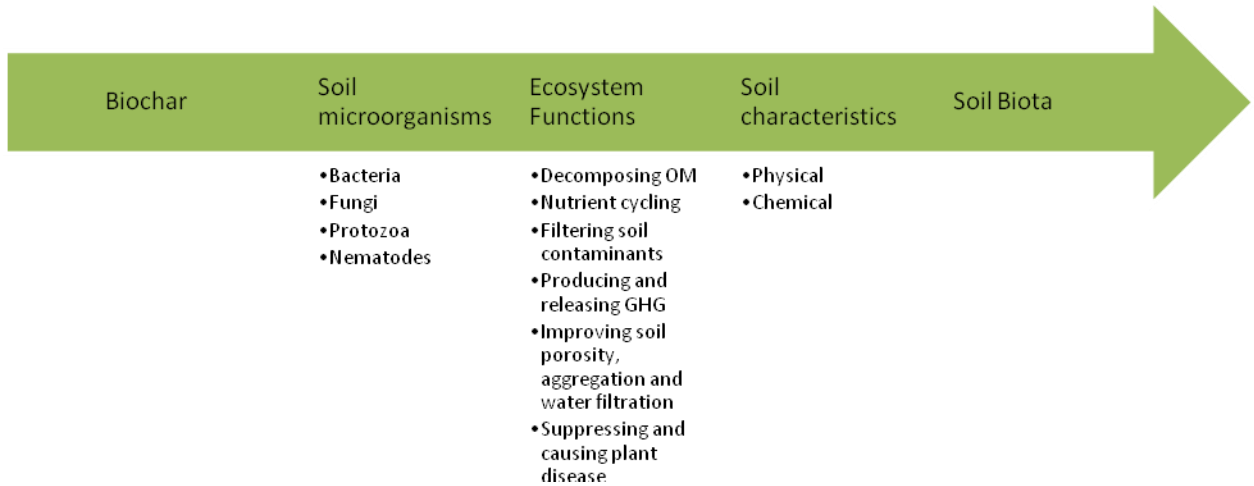


Figure 2.9 Pathways for biochar influence on biological soil properties

Populations that establish on the biochar surface will be those that are able to elaborate the enzymes necessary to metabolize the available substrates. The more unusual and complex a substrate is, the more restricted the population of organisms will be that can use it effectively as a source of energy, cell C and/or nutrients, and the longer it will take to be completely metabolized. The nature and strength of the adsorption of microbes, soil organic matter, extracellular enzymes and inorganic nutrients to biochar surfaces will determine the availability of C, energy and nutrients for colonizing microorganisms. Differences in these surface communities may, in turn, result in changes in e.g. the availability of nutrients to plants and the GHG emission levels from soil.

Chapter Summary

Biochar can act as a soil conditioner enhancing plant growth by supplying and, more importantly, retaining nutrients and by providing other services such as improving soil physical, chemical and biological properties. Biochar application leads to changes in the physical and chemical structure of soil.

Some important physical characteristics of biochar are high porosity and high surface area, which lead to high CEC and adsorption capacity. It possesses high mechanical strength, as is dominated by ordered graphene sheets. Biochar has a high carbon content and usually low content of other nutrients. With high nutrient retention and water-holding capacity, biochar can improve soil properties and enhance crop growth with less agronomic inputs. At the same time, carbon sequestration can be achieved thanks to the high C content and recalcitrant nature of biochar. Its physical characteristics also induce microbial colonization, which improves soil properties. Field based experience suggests that biochar application to soil in most cases delivers environmental benefits. The by-products of pyrolysis, syngas and bio-oil, are valuable since they have high energy contents and can be used to displace the use of fossil fuels.

CHAPTER 3

Global biogeochemical cycles and biochar in terrestrial ecosystems

The food and energy crises, and consequent environmental degradation, have profound impacts on global biogeochemical cycles, which determine to a large extent the conditions for life in the planet. This chapter revises how biochar production and application to soil can affect global biogeochemical cycles, in the look for a strategy to combat land degradation, climate change and poverty.

Introduction

Biogeochemical cycles are pathways by which elemental chemical compounds are transferred through the Earth subsystems. Exchange of these elements occurs in a closed system composed by the atmosphere, hydrosphere, cryosphere, litosphere and biosphere (IPCC, 2007b). They include macronutrients, such as carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), sulfur (S) and also potassium (K), calcium (Ca), iron (Fe) and magnesium (Mg); and micronutrients like boron (Bo), copper (Cu) and molybdenum (Mo), all of which play a role in supporting biological life.

Terrestrial ecosystems are an important component of the dynamics of biogeochemical cycles, serving as exchange pools (sources and sinks) of nutrients (McGuire and Lukina, 2007). More permanent storage sites are provided by e.g. oceans and geological reservoirs. In the overlapping of subsystems biosphere and lithosphere are terrestrial ecosystems, which contain human life and have the potential to influence the dynamics of global biogeochemical cycles in a way that has implications for the climate system and the welfare of humanity.

Of special relevance for the present work are the carbon and nitrogen cycles in terrestrial ecosystems.

Carbon and Nitrogen cycles

Carbon (C) and Nitrogen (N) are two of the main building blocks of life as their presence, or lack thereof, determines to a large extent the conditions for biological activity. C is responsible for the production of carbohydrates, fats and proteins, the major sources of food energy; while anthropogenic C emissions (CO_2 and CH_4) represent more than 90% of GHG emissions by source (IPCC, 2007). N uptake, along with photosynthesis, is the most influencing factor in plant growth, the initial step of the food web; while production of N fertilizers and excessive application in terrestrial ecosystems results in N mobilization, which causes significant environmental damage (Erisman et al, 2009), including land degradation, eutrophication and global warming. Both biogeochemical cycles are now presented separately.

3.1 Carbon cycle dynamics

During its cycling through the Earth´s climate subsystems, C is temporarily stored in reservoirs. In gigatons of C (GtC), plant biomass stores around 600, the atmosphere some 800 and soil organic carbon 1500, while the first two exchange 120 at all times (50% uptake and 50% emission), as shown in Figure

3.1. Annual anthropogenic GHG emissions account for 7 GtC, meaning that the annual C uptake by plants in the land surface is about 8 times greater than current annual anthropogenic C emissions (Gaunt and Cowie, 2009).

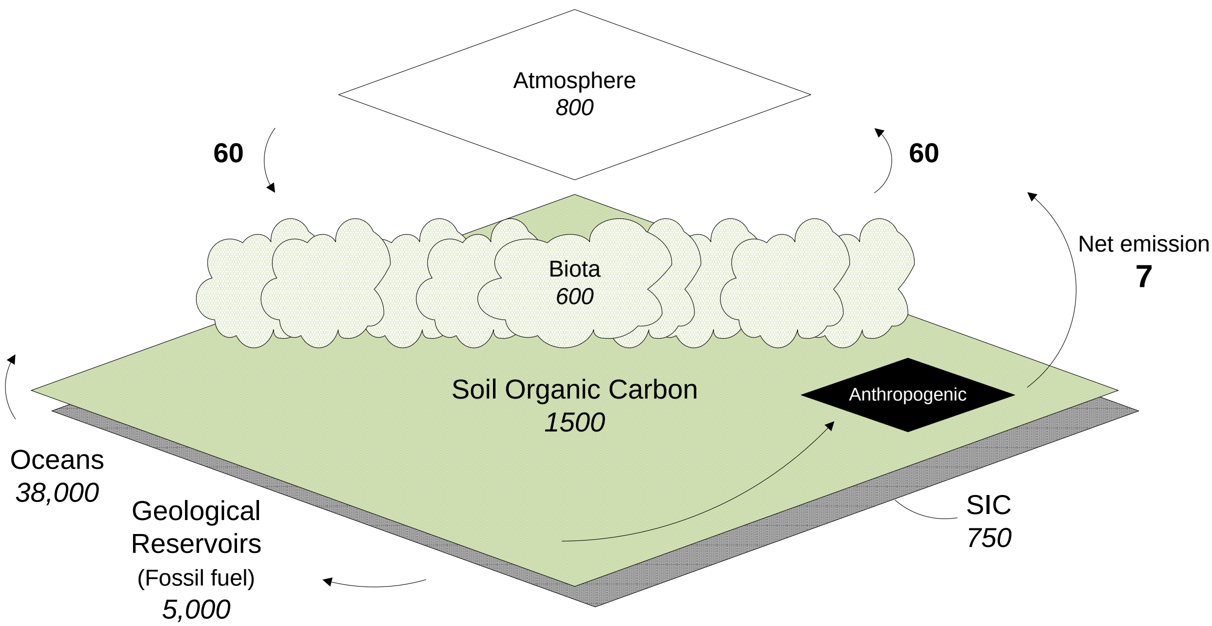


Figure 3.1 Simplified scheme of stocks (GtC, italic) and flows (GtC/yr, bold) of C from terrestrial pools to the atmosphere and back. SIC = soil inorganic C. Source: Data from Sabine et al (2004), Lal (2004) and Lal (2008)

3.1.1 Drivers and consequences of changes in the C cycle

The C cycle is altered by human-derived C emissions. The main driver of anthropogenic CO_2 emissions is fossil fuel use in sectors such as energy supply, transport, residential and commercial buildings, and industry; and of emissions of CH_4, with a global warming potential 25 times greater than that of CO_2, is agricultural and forestry activities. The IPCC (2007) reports that CO_2 (77%) and CH_4 (14%) emissions combined are responsible for more than 90% of current GHG emissions. The current concentration of atmospheric CO_2 and CH_4 has increased from pre-industrial level to unprecedented figures in the last several millennia (IPCC, 2001).

Land use also represents a significant cause of disturbance in the C cycle. Land-use change and land degradation in agriculture and forestry together represent roughly one third of the emissions causing global warming (IPCC, 2007). In particular, deforestation not only leads to a loss of terrestrial C sinks, but also causes detrimental environmental effects like ecosystem function loss and increased soil erosion. It too poses the risk of turning C sinks into sources, causing reinforcement of the climate change – land degradation cycle, with increased possibility of tipping points. Drivers and consequences of C cycle changes are summarized in Table 3.1.

Table 3.1 Drivers and consequences of anthropogenic changes to the C cycle, and observed effects of biochar application to soil in response to these changes

Changes in Carbon cycle	Drivers	Consequences	Effects of biochar application to soil
	Fossil fuel use (CO_2, CH_4 emissions)	Increased atmospheric C	Decreased atmospheric C Reduced fossil fuel use
Anthropogenic	Land use (CO_2, CH_4 emissions) - Land use change - Land degradation	Reduced C in terrestrial pools	Increased C in terrestrial pools Improved soil conditions

3.1.2 Biochar effects on the Carbon cycle

The mechanisms by which biochar production and application to soil alter the C cycle are currently being studied and further research is needed to understand the interactions more clearly. The current state of knowledge about these mechanisms is presented, based on the information presented by Gaunt and Cowie (2009), and divided into 3 categories.

- *By biochar production:*

Fossil fuel displacement – Energy contained in plant biomass could, in principal, cover up four times the human annual energy use, it is important to take advantage of this potential through optimized processes (Erisman et al, 2009). The products of pyrolysis, besides biochar, are syngas, bio-oil and heat, which can be used as energy sources instead of fossil fuels, displacing CO_2 and CH_4 related emissions. The production of renewable energies, including from biomass feedstocks, is recognized as an activity that displaces fossil fuel emissions, as stated in CDM methodologies AM0026, AM0027, ACM0002 (UNFCCC, 2010). A novel idea by Day et al (2005), suggests coupling the biochar pyrolysis process with the Haber-Bosch process, by using the pyrolysis syngas as a source of energy for N fixation, thus displacing natural gas required for hydrogen production via methane reforming. The final product would be an N-rich biochar.

- *By biochar application to soil:*

Stabilization of biomass C – Burial of black carbon in sediments prevents its decomposition, without which an equivalent amount of O2 accumulates in the atmosphere (Schmidt et al, 2003) Soil microbes digest organic matter present in soil through respiration, emitting CO_2 into the atmosphere while releasing plant nutrients. Adding organic matter resistant to decay results in an increase in soil C and in a decreased rate of C release from soil, which results in carbon sequestration. Already afforestation and reforestation project activities are eligible for carbon offsets under the Kyoto Protocol market-based mechanisms (UNFCCC, 2010a), even though serious questions have been posed about the fate of newly planted forests. C sequestration with biochar would likely solve the issue of permanency. Already a proposed methodology for accounting GHG emissions from biochar activities has been submitted to the Voluntary Carbon Standard (VCS, 2010), although with insufficient quality according to the comments by experts. Characterization of biochar is the necessary first step to being able to develop appropriate protocols for carbon credits (Reed, 2010).

Avoided methane emissions from soil – Biochar application to soil, by improving aeration, is believed to decrease the number of anaerobic micro-sites thus reducing the activity of methanogens and increasing that of methanotrophs, adsorbing more CH_4 than is released. Lower availability of decomposable organic matter and lower rate of C cycling is also believed to reduce the rate of CH_4 emissions. Some experiments show evidence of CH_4 emissions reduction: Rondon et al (2005) found that CH_4 emissions were completely suppressed after biochar application to soil for soybeans and tropical grass in Colombia.

Displaced fertilizer use – Production of inorganic fertilizers is energy intensive and over application causes environmental degradation. Biochar can displace fertilizer production and use by either directly supplying nutrients to the soil (mainly animal-derived biochars); or, more often, indirectly by increasing nutrient retention capacity in soil, therefore reducing the amounts of fertilizer required for agricultural production.

Increased plant C stock – By enhancing plant growth with biochar application, the C stored in plant biomass would accumulate. This increased plant C stock may lead to increased returns of organic C matter to soil, in a possible self-reinforcing cycle.

- *Through a change in management:*

Avoided emissions from biomass aerobic decomposition – Even though biomass decay is part of the natural C cycle, a change in management that avoids GHG emissions from it can be attributed emission reductions, as stated by the Clean Development Mechanism methodologies for small-scale projects AMS-III.E[1] and AMS-III.L[2] (UNFCCC, 2010). The amount of avoided emissions would depend on feedstock and starting management strategy of biomass, or baseline scenario.

[1] Avoidance of methane production from decay of biomass through controlled combustion, gasification or mechanical treatment – Version 16

[2] Avoidance of methane production from biomass decay through controlled pyrolysis – Version 2

Table 3.2 Mechanisms by which biochar systems influence the C cycle. Adapted from Gaunt and Cowie (2009)

Biochar production	❖ Fossil fuel displacement
Biochar application to soil	❖ Stabilization of biomass C ❖ Avoided methane emissions from soil ❖ Displaced fertilizer use ❖ Increased plant C stock
Change in management	❖ Avoided emissions from biomass decay

3.2 Nitrogen Cycle dynamics

Nitrogen is a building block of amino and nucleic acids, essential to life on Earth. The atmosphere is the largest pool of N and is composed mainly of nitrogen gas (N_2, 78% volume mixing ratio), oxygen (O, 21%) and argon (Ar, 1%) (IPCC, 2007b). Atmospheric N exists in a highly inert form. Other forms of N are trace gases such as nitrous oxide (N_2O), nitric oxide (NO), nitric dioxide (NO_2) and ammonia (NH_3). N can also dissolve in water in the form of gases or salts; and in solid phase takes the form of ammonium (NH_4), nitrites (NO^{-2}) and nitrates (NO^{-3}), more available forms for biological use. The N cycle operates in a closed system and has an important influence in the global energy balance.

The simplified pathways by which N flows though Earth subsystems are presented in figure 3.2 and described as follows. Nitrogen gas (N_2) is converted into available ammonia (NH_3) by *fixation*. This is a result of lightning, N-fixing bacteria and industrial fixation for production of fertilizers. In the next stage of the N cycle, ammonia is either assimilated by plants directly or naturally *mineralized* to produce ammonium (NH_4). Ammonium, through *nitrification*, is subsequently oxidized into nitrites (NO^{-2}) and then nitrates (NO^{-3}) which can be assimilated by plants to produce proteins and growth. During this stage, nitrous oxide (N_2O) is produced and emitted back to the atmosphere. As soil microbes require N for energy or storage, nitrates are then oxidized (N_2O and NO), and NH_3 and N_2 are also produced via *denitrification*. N_2, the final product of the complete process, is then released to the atmosphere, thus closing the cycle. Dissolved forms of N, like salts or acids, are mobilized to freshwaters, oceans and geological reservoirs, among others, where the N cycle is also carried out, although this escapes the scope of the present work.

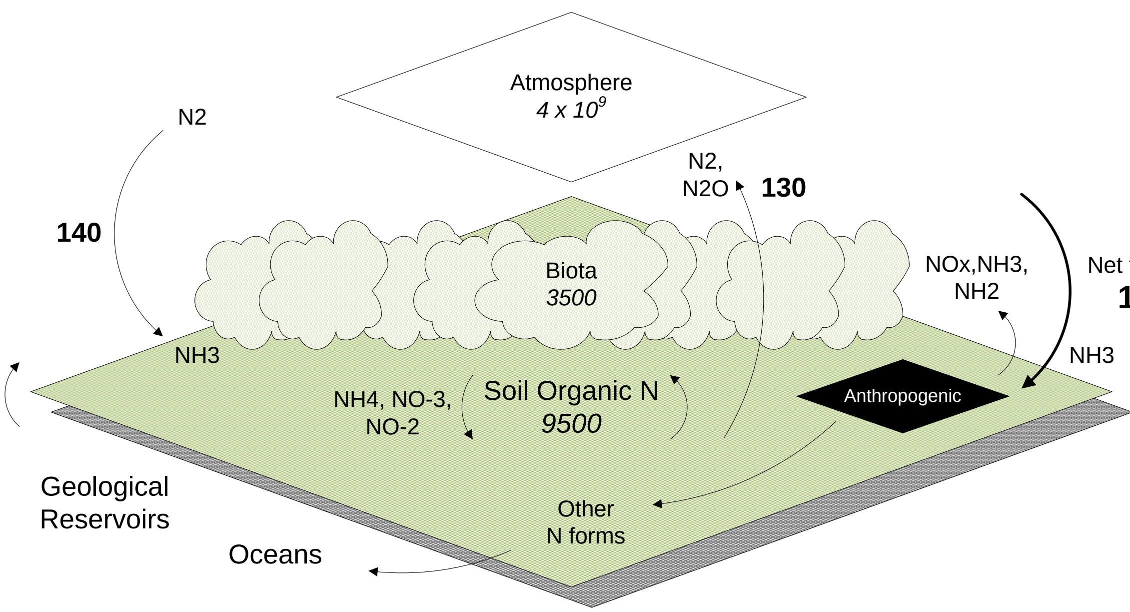


Figure 3.2 Simplified N cycle in terrestrial ecosystems. Relevant stocks and flows are indicated in italics (TgN) and bold (TgN/yr), respectively. Source: Soderlund and Rosswall (1982); Vitousek et al (1997)

3.2.1 Drivers and consequences of changes in the N cycle

The IPCC (2007c) states that the acceleration of the N cycle is very likely directly linked to human activity, including increased fertilizer use, intensification of agriculture and fossil fuel combustion. The global atmospheric N_2O concentration increased from a pre-industrial level of about 270 ppb to 319 ppb in 2005, which signifies around 8% of GHG-induced global warming (IPCC, 2007). Emissions of NO and NH_3 to the atmosphere have increased fivefold since pre-industrial times (Galloway et al, 2003), while atmospheric deposition rates now exceed historical rates by more than an order of magnitude (Erisman et al, 2009), specially in Northern European regions.

The main drivers of change in the N cycle are therefore man-made and divided here into: N flows from the atmosphere to terrestrial pools (fixation route), and N flows from terrestrial pools to the atmosphere and other pools (mobilization route).

In the first sub-category, industrial N-fixation is a major source of reactive N in terrestrial pools, with around 100 TgN being transferred every year (Karl et al, 2002), similar to natural fluxes. Through the Haber-Bosch process, atmospheric N_2 is converted into more reactive forms of N, such as ammonia, and can be further processed to obtain more accessible N-rich fertilizers, e.g. urea. Furthermore, fertilizer production, which is expected to continue growing along with world population, represents approx. 5% of global demand of natural gas - 1.2% of global energy use - and is responsible for 1.2% of total GHG emissions (Erisman et al, 2009).

The other N-fixing route is biological. Although carried out by soil microbes as part of the natural N cycle, some biological N-fixation is attributed to anthropogenic sources due to increased cultivation of N-fixing crops (e.g. beans and peas). The value of human-induced biological N-fixation is currently debated, but the quantity of N fixed by crops in general falls in the range of 30-50 TgN per year (Vitousek et al, 1997).

On the other hand, human activities increase the flow of N to the atmosphere through N mobilization. Nitrogen extracted from geological reservoirs in the form of coal, oil and natural gas, releases fixed N into the atmosphere during combustion, thus altering the global GHG and energy balance while causing significant air pollution. Other major sources of N mobilization are practices in agriculture and forestry, such as land-use change, biomass burning and drainage of wetlands. The latter represents a loss of an important N sink, which implies more N mobility. Similarly, ecosystem N-saturation facilitates mobility, which may result in further saturation of other ecosystems and biodiversity loss, as N is transported by erosion, runoff and leaching.

Given limited nitrogen uptake capacity of terrestrial pools, at increasing rates of fertilizer application, losses become larger, and thus, the N cycle is drastically changed through human creation of reactive nitrogen and its losses to the environment, causing a cascade of effects (Galloway et al, 2003; Erisman et al, 2009). N mobilization into N-limited terrestrial, marine and freshwater ecosystems leads to biodiversity loss due increased competition for resources from new species, i.e. algal bloom. In addition, increased N mobility is the cause of acid rain, photochemical smog, soil acidification, destruction of stratospheric ozone and alterations to other major biogeochemical cycles, such as the C cycle.

These two sub-categories contribute to a net overall fixation of approx. 140 TgN annually (Vitousek et al, 1997), resulting in an acceleration of the N cycle. Drivers and consequences of changes in the N cycle are summarized in Table 3.3.

It is important to highlight that the cycles of C and N are interrelated. For instance, increased availability of reactive N in terrestrial ecosystems impacts plant growth positively, thus increasing the terrestrial C pool which could, in turn, lead to further unbalance of the N cycle. The coupling of the N cycle with other macro- and micro-nutrient cycles is also important. For instance, higher retention of N in soils has been attributed to increased K availability (Rondon et al, 2006).

Table 3.3 Drivers and consequences of anthropogenic changes to the N cycle, and observed effects of biochar application to soil in response to these changes

Changes in Nitrogen cycle	Drivers	Consequences	Effects of biochar application to soil
	Fixation - Industrial N fixation - Induced biological fixation (agriculture) →	Increased reactive N in air, water and land	Increased N retention in biochar Reduced fertilizer needs
Anthropogenic	Mobilization - Fossil fuel use - Agriculture and forestry →	Increased reactive N in air, water and land ↓ Alteration of other cycles	Decreased leaching Reduced N_2O soil emissions Displaced fossil fuel use

3.2.2 Biochar effects on the N cycle

The mechanisms by which biochar production and application to soil alter the N cycle are currently being studied and further research is needed to understand the causes of change more clearly. The current state of knowledge about these mechanisms is presented, based on the information presented by van Zwieten et al (2009), divided into 3 categories.

- *By biochar production:*

Fossil fuel displacement – As in the case of the C cycle, the by-products of pyrolysis can be used to displace fossil fuel combustion and NO_x mobilization associated. Even when biochar is used for co-firing in coal-fired power plants, a reduction in NO_x emissions is achieved.

- *By biochar-soil interaction:*

Biochar application to soil can affect the N cycle chiefly by stimulating **N retention in biochar**. Nitrogen is the most sensitive macronutrient to pyrolysis temperature (starts volatizing at 200°C) therefore N-depleted biochar is less important as a direct source of nutrients as it is as a soil conditioner and driver of nutrient transformations. Biochar addition to soil may slightly decrease ammonification, given the high CEC which facilitates the adsorption of NH_4 into biochar surfaces. The result is reduced leaching of inorganic N to waterways and possibly increased uptake by plants.

At the same time, as denitrification (NO^{-3} to N_2, with intermediate NO_x by-products) requires organic C as a substrate, its rate will decrease due to lower organic availability after biochar addition. Furthermore, as water holding capacity is increased due to the porous structure of biochar, higher N retention is translated into an increase of soil nutrients in solution and likely to greater crop uptake and export. These mechanisms combined result in the following effects of biochar addition to soil:

Avoided N_2O emissions from soil – N_2O in soil is produced during two stages of nitrification ($NH_4 \rightarrow NO^{-3}$ and N_2O, and $NO^{-3} \rightarrow N_2O$) and dissociated during denitrification ($N_2O \rightarrow N_2$). Biochar is attributed a reduction in N_2O emissions as application to soil increases pH leading to an increased activity of the N_2 producing enzyme and facilitating adsorption of N_2O. Also, as soil aeration improves due to the porous nature of biochar, while simultaneously the availability of decomposable organic matter decreases, the production of N_2O from NO^{-3} is believed to decrease. Protection from grazing is another characteristic attributed to biochar that allows soil microbes to proliferate, thus increasing soil N immobilization with resulting N_2O emissions reduction. Some experiments show evidence of suppression of N_2O emissions: in an experiment with biochar on infertile soils, Rondon et al (2005) found that N_2O emissions were suppressed by 50% for soybean and 80% in grass plots. Another experiment, conducted by Rondon et al (2006), reported similar reductions in N_2O emissions after biochar application.

Decreased leaching of inorganic N – Greater N retention in soil (due to biochar adsorption capacity, high CEC and water holding capacity) also results in decreased leaching of inorganic N.

Displaced fertilizer use –Biochar application to soil can increase fertilizer use-efficiency either directly supplying nutrients to the soil (animal-derived biochars); or, most commonly, indirectly by increasing nutrient retention capacity in soil, therefore reducing the amounts of fertilizer required in agro-ecosystems and the fossil energy associated with its manufacture, which represents an overall reduction of N fixation and mobilization.

- *Through a change in management:*

Avoided emissions from biomass aerobic decomposition – A change in management of biomass that avoids N_2O emissions can be attributed GHG emission reductions. This might be achieved when avoiding the decay of N-rich biomass, such as manures.

The routes by which biochar production and application to soil can affect the biogeochemical cycles are summarized in Table 3.4.

Table 3.4 Mechanisms by which biochar systems influence the N cycle

Biochar production	❖ Fossil fuel displacement
Biochar application to soil	❖ N retention ▪ Avoided N_2O emissions from soil ▪ Reduced leaching ▪ Displaced fertilizer use
Change in management	❖ Avoided emissions from biomass decay

Negative aspects

Recent experiment results show that biochar addition reduced soil bulk density and nitrous oxide emissions while enhancing soil respiration and CO2 emissions (Rogovska et al, 2008). This is line with the hypothesis of fresh biochar implying a priming effect by incurring in additional CO_2 emissions from soil, thus leading to an initial loss of soil organic carbon (Verheijen et al, 2010). This effect, however, will be counterbalanced after some time, but could be considered when modeling the effects of biochar systems.

Other nutrient cycles

The implications of biochar on biogeochemical cycles of other macronutrients are also important to analyze. For example, as stated previously, biochars that supply K to the soil may increase the redox potential of the soil, inhibiting methane production. Also, as P is more resistant to heat than N and S, and has been found accessible in low temperature biochars, it could facilitate phosphate adsorption to the surfaces (Lehmann, 2007).

Mitigation potential

A vast range of option for climate change mitigation is currently available. According to McKinsey and Co. (2009), a reduction of roughly 38 $GtCO_2e$, representing about 80% of current GHG emissions (IPCC, 2007), can be achieved annually until 2030 at nearly zero-cost (figure 3.3). Biochar would probably be located around the 0 cost value in this curve, potentially being a carbon-negative option.

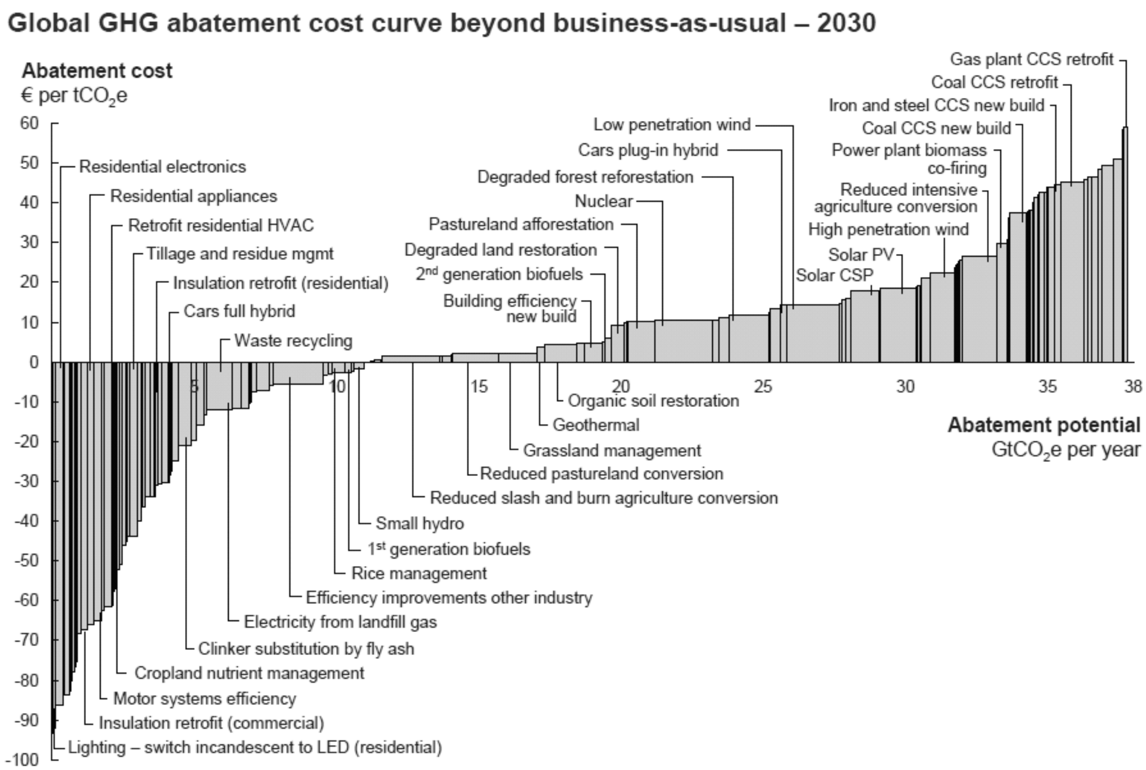


Figure 3.3 Global GHG abatement cost curve v.02. Source: McKinsey and Co. (2009)

The global GHG abatement potential of biochar systems is large: diverting 1 per cent of annual net plant uptake into biochar would mitigate almost 10 per cent of current anthropogenic C emissions (Lehmann and Joseph, 2009a).

Chapter conclusions

Human activities such as fossil fuel use and land degradation greatly alter most important biogeochemical cycles, such as the C and N cycles, leading to an exacerbation and reinforcement of the land degradation-poverty-climate change cycle, as depicted in figure 3.4.

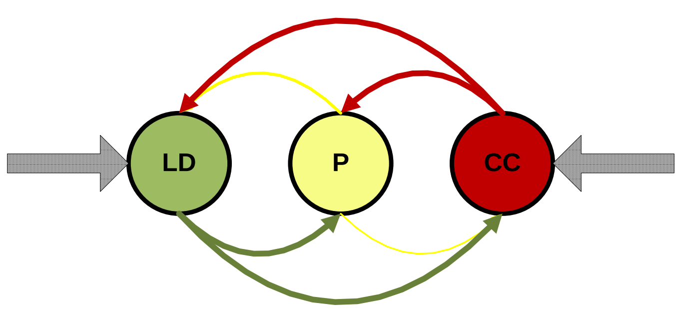


Figure 3.4 Pathways by which changes in the C and N cycles cause reinforcement of the land degradation-poverty -climate change cycle

As discussed here, biochar production and application to soil can offer a counter-balancing effect. By avoiding GHG emissions and sequestering C in soil, it could well be considered a mitigation pathway. It can also bring along agronomic benefits which make it a suitable adaptation strategy. The economic, technical and social feasibility of biochar systems will be determined by the extent of understanding of the multiple variables that affect its functioning in soil on a case-by-case basis. This is why further research is required on how different biochars affect a diversity of soils (biochar characterization, which is currently being carried out by different groups across the globe). Further research is also needed on how other biogeochemical cycles are affected by biochar production and addition to soil.

Technical feasibility is explored in an LCA-based analysis comparing biochar systems with other agricultural waste management options, in the following chapter.

CHAPTER 4

Comparative analysis of agricultural residue management options through a life-cycle approach

In the final chapter are explored the components of the energy, GHG and financial balances of three management options for agricultural waste, based on biochar and bioenergy life-cycle assessments in the literature. The purpose is to determine which management option performs better under these criteria and if either is a feasible strategy for sustainable land management, poverty reduction and climate change mitigation and adaptation. The socio-economic, political and geographic conditions considered for modeling are those of a developing country.

Introduction

Maize, after wheat and rice, is the most important cereal grain in the world, providing nutrients for humans and animals and serving as a basic raw material for the production of starch, oil and protein, alcoholic beverages, food sweeteners and, more recently, fuel (FAO, 1992). World production of maize has steadily increased during the last several decades, despite temporary decreases in recent years (FAOSTAT, 2009). This increase is caused by rising demand, derived mainly from population growth, and this upper trend is expected to also for associated price. Necessary for increasing production are expansion of the agricultural frontier and increased production and application of synthetic fertilizers, which are important drivers of climate change and land degradation.

Most of the maize production is mainly devoted for industrial use and animal feed in developed countries; in developing countries it is mainly used for human consumption (FAO, 1992). As mentioned in chapter 1, access to primary natural resources is particularly important for the rural poor (IFAD, 2010). This is why current development programs focus on improving the livelihoods of rural farmers by enhancing sustainable land practices, which means improving the conditions of the ecological capital from where income is "harvested".

This study is focused on the management of corn *residues*, in order to avoid discussion regarding impacts on food security and land use change. Characteristics of corn stover are presented in table 4.1 and more detail can be found in the subsequent sections. Although agricultural residues left on the field after harvest provide beneficial services for maintaining soil properties, they can also be valuable as feedstock for biochar production. The technical feasibility of three management options for corn stover, including biochar production, is analyzed under a life-cycle approach for energy and GHG emissions. One additional decision criterion, revenues, is analyzed with a simplified cost-benefit analysis.

Biochar systems are analyzed as proposed management options because they are believed to contribute to mitigation of climate change by increasing C in terrestrial pools, providing renewable energy, avoiding fossil fuel use, reducing fertilizer needs, and avoiding GHG emissions from soil. Simultaneously, their use can increase adaptation capacity. For instance, in areas low water availability, the increased water holding capacity and increased nutrient retention resulting from biochar application can become especially beneficial.

Table 4.1 General assumptions for corn stover and biochar produced from corn stover

	Value	Unit
Stover yield	4	ton/ha
Moisture	15	% mcwb
Removal rate	75	%
C-content stover	45	%
C-content biochar	75	%
Stable C in biochar	80	%
Pyrolysis yields		
Biochar	35	%wt feedstock
Syngas	35	%wt feedstock
Bio-oil	30	%wt feedstock

Context of the analysis

This chapter is based on the settings of a developing country. The country selected for the evaluation of technical feasibility is Bolivia, due to the relevance of agriculture in the economy, high rate of rural poverty and increasing impacts of climate change and land degradation. More detailed information about geographic, political, socio-economic and agricultural conditions in Bolivia can be found in the Appendix.

Methodology

Three options of management for corn residues were analyzed, presented in Table 4.2. The first is the current practice, which consists on leaving biomass residue in the field for reincorporation to soil, with consequent biological degradation. The second and third involve the collection of stover for biochar production, although with different purposes for final use. Each is detailed below. The intention is to compare the current management option with two alternatives involving biochar production.

Table 4.2 Management options for LCA-based comparison of energy and GHG balances

Management option	Description
M1 - Residue decomposition	Residues left in field after harvest of grain
M2 - Biochar for coal	Residues collected for production of biochar for co-firing in coal power plants
M3 - Biochar to soil	Residues collected for biochar production and application to agricultural soil

System boundaries are depicted in figure 4.1. The system includes energy and upstream emissions from the life-cycle of corn cultivation, from crop establishment to harvest. It continues for M2 and M3 to the production of biochar, and then independently for each final use of biochar, namely coal co-firing and soil application.

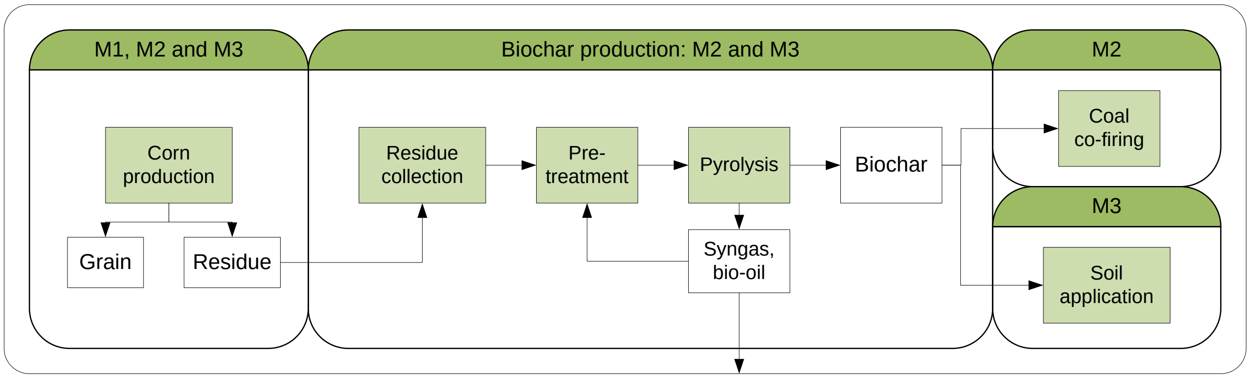


Figure 4.1 System boundaries for comparative LCA-based study. Processes in dark boxes; products in white. All processes have energy requirements with subsequent fossil fuel use. Pre-treatment involves transport, drying and milling. Transport also occurs after pyrolysis.

A life-cycle approach was used to determine the net energy balance (energy input vs. energy output) and the net GHG emissions balance (emissions vs. emission reductions) for each management option. The functional unit is 1 ton of dry feedstock. Additionally, some figures on costs and benefits were estimated. A hypothetical plot of 100 hectares was assumed as the baseline for financial calculations.

Description of management options

M1 – Residue decomposition

In current practices of maize production (Zea mays L. subsp. mays Indurata), harvest occurs annually and stover is left in the field after grain collection. Yields of corn grain in the Department of Santa Cruz, Bolivia, are in the range of 3 to 4.9 ton/ha (CAO[3], 2000), thus an average of 4 is assumed. Although the distribution may change, it is accepted that about half the dry matter of corn is grain and the other half is made up of plant residues excluding roots (Barber, 1979), which include stalk (50%wt), leaves (20%wt), cobs (20%wt) and husks (10%wt) (AFC, 2010[4]). Therefore, for a 100-ha plot, each year 400 tons of grain are collected and 400 tons of stover are left in the field. GHG emissions from soil were modeled according to the information from McCarl et al (2009), Gaunt and Cowie (2009), and CDM methodologies for small-scale projects AMS-III.E and AMS-III.L, considering that 15% of stover is reincorporated into the soil and the remaining 85% decomposes aerobically (EERE, 2002).

M2 – Biochar for coal

Given the usually available farming equipment in Bolivia, grain is collected in a first pass and stover in a second pass. A rate of stover removal of 75% is assumed, above the higher limit of usually reported values [40-50 up to 70% for no-till practices (Roberts et al, 2010)]. Lower removal rates are

[3] Cámara Agropecuaria del Oriente (Bolivia)
[4] Agriculture and Agri-food Canada

recommended to avoid soil erosion by wind and water (EERE, 2002). However, by leaving 1 ton stover per hectare, this practice falls within the limits of reduced tillage according to the definition by US EPA (2010). A positive aspect is that N_2O emissions have been reported to decrease with less degradable organic matter present in soil (Kim et al, 2009). After collection, stover is transported to a small-scale pyrolysis facility (2 ton/hr) located at the nearest storage site (average distance in Santa Cruz is 80 km at 0.10 $/ton-km) (CAO, 2000). Stover, with 15%wt moisture, is first dried and milled, requiring initial consumption of natural gas, which will be later replaced by syngas and exhaust gas derived from pyrolysis. Biochar is transported and used for co-firing in coal power plants.

M3 – Biochar to soil

Corn stover is also collected at 75% removal rate and transported to the nearest pyrolysis facility for biochar production. After pyrolysis, biochar is transported back to the field for application to soil at a rate of 5 ton/ha. Note that the initial removal of C is compensated as high-C biochar is returned to the soil, equating a net C removal of 50%. Handling losses are accounted as 5%, as for M2. Feedstock is converted into biochar, syngas and bio-oil with yields of 35, 35 and 30 %wt respectively. Stable C in biochar is assumed to be 80% of total C. Increases in yields and fertilizer savings result from M3, detailed below.

Results

Energy balance

Management option 1 (M1) considers energy required for corn production from Kim et al (2009) and Wang et al (2007), including agrochemicals such as N, P and K fertilizers, herbicides, insecticides and lime; and field operations involving consumption of diesel, gasoline, liquefied petroleum gas (LPG) and electricity for irrigation. The required levels of each production input were cross-checked with corn production information from Santa Cruz (CAO, 2007) to maintain compatibility. In the context of this study, no energy is considered to be produced from M1, although maize has a caloric value of about 16,000 MJ/ton (Erisman, 2009; Roberts et al, 2010).

M2 and M3 require additional energy for the biochar system, which includes stover harvest, transport, pre-treatment and pyrolysis. For M2, transport to the nearest coal power plant is considered at 80 km distance, while M3 incurs in fossil energy consumption as biochar is transported back to the field and applied, based on calculations by Gaunt and Lehmann (2008). Additional fertilizer needed to compensate for nutrient losses for M2 are taken from Kim et al (2009). Pyrolysis energy requirement is about 750 MJ/dry ton (Roberts et al, 2010). Both management options produce energy in the form of syngas and bio-oil. For M2, biochar is used in co-firing, for which an energy content of 4,900 MmBtu/ton was considered (McCarl et al, 2009), 40% of that of bituminous coal (IPCC, 2007c; Defra, 2009). Therefore it is assumed that more biochar (conservatively 2.5 times more) is needed to deliver the same amount of energy. M3 also accounts for displaced fertilizer use of 10% (McCarl, 2009). Results are shown in figure 4.2.

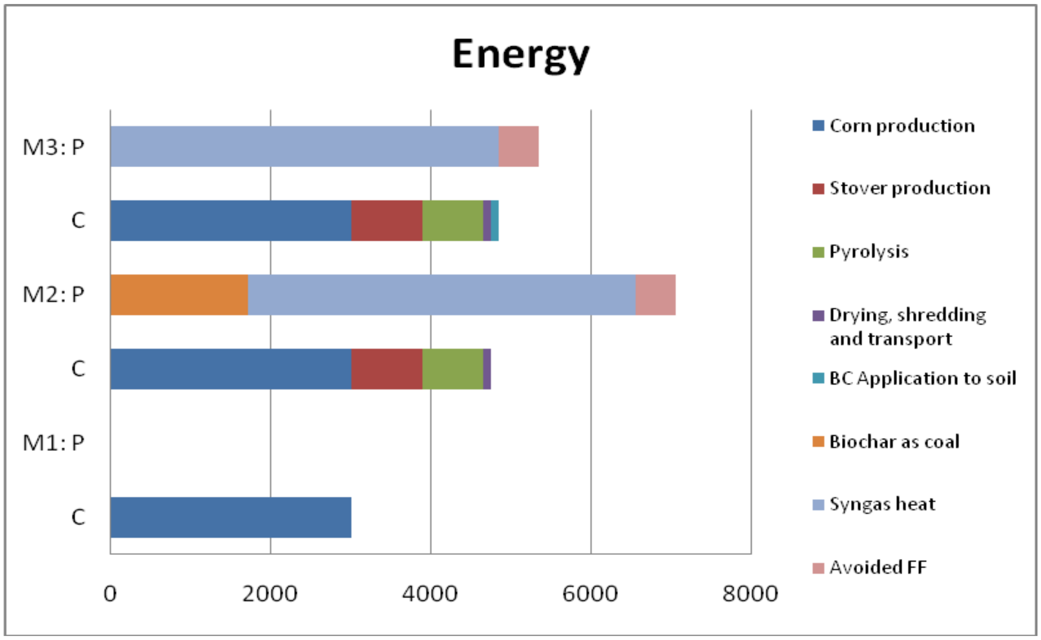


Figure 4.2 Energy balance for each management option (MJ/dry ton feedstock). P: production, C: consumption

Natural gas used to dry the feedstock is replaced by syngas and therefore avoided use of fossil fuel results. Syngas flows into a thermal oxidizer coupled with a heat exchanger, as assumed in the LCA by Roberts et al (2010).

By consuming and not producing energy, M1 presents a negative balance. Biochar for coal co-firing shows the most positive balance, producing above 2,000 MJ more than it consumes for the functional unit; followed by M3 which has a more modest positive balance of about 500 MJ/ton, or an energy yield of 1.10.

Greenhouse gases

GHG emissions related to corn production were taken as an average of the values presented by Kim et al (2009), at 350 kg CO2e/dry ton feedstock. This is consistent with the values by Farrell et al (2006) and Sheehan et al (2004) in LCA studies for corn ethanol. No reductions were attributed to M1, only emissions associated with biomass decay. Additional to corn production emissions, M2 and M3 include operations related to stover collection, transport and slow pyrolysis (HTT of 450°C and 30 min residence time), taken from Kim et al (2009) and Roberts et al (2010). Particularly for M2, the upstream emissions of additional fertilizer needed to compensate for nutrient loss are considered. This is not the case for M3, as nutrients (mostly C) are returned to the soil, indirectly enhancing nutrient retention and improving fertilizer use efficiency (Chapter 3).

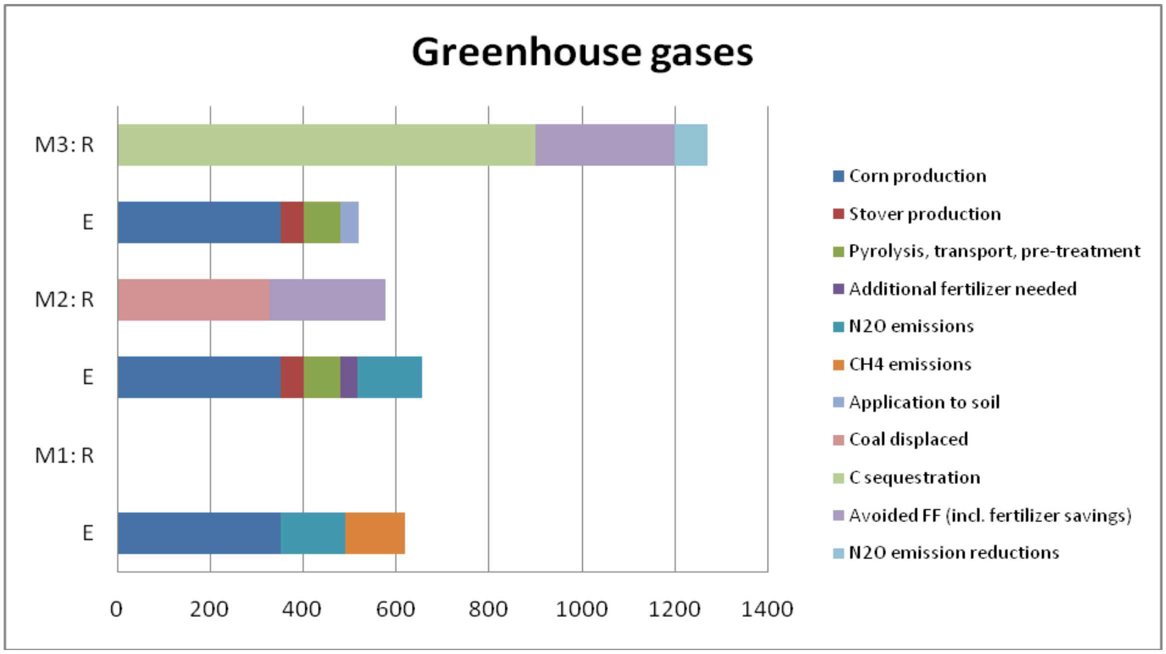


Figure 4.3 Greenhouse gas balance for management options (kg CO2e/dry ton feedstock). R: reductions, E: emissions.

At a rate of application of 5 ton biochar/ha, fertilizer savings of 20% can be achieved and 10% for irrigation and seeds (McCarl et al, 2009). In this study, fertilizer savings of 10% were considered and no savings in irrigation and seeds, in order to keep a conservative approach. Finally, M2 reduces emissions related to coal combustion for electricity generation, data taken from Defra (2009) and IPCC (2007c). M2 and M3 also displace fossil fuels with the by-products of pyrolysis. However M2 will incur in additional emissions for fertilizer use and field operations as soil productivity decreases over time, which is not captured in this snapshot, and will likely offset the effect of byproducts. Results are shown in Figure 4.3.

M1 incurs in net emissions of 620 kg CO2e/ton, presenting a negative GHG balance. M2 also shows more, 80 kg CO2e/ton, emissions than reductions. M3, on the other hand, has a positive balance with net reductions of 750 kg CO2e/ton. It is assumed that the energy required for coal combustion will be consumed independently of biochar use for co-firing. M3 presents significantly higher emission reductions, mostly due to C sequestration capacity.

Finally, M3 shows less potential of emission reductions than figures in the biochar literature [Roberts et al (2010) and McCarl et al (2009)], mainly due to the expanded LCA system boundaries, which in this study include the energy and GHG emissions related to corn production. Energy consumption for corn production is in line with the study by Gaunt and Lehmann (2008). The previous studies converge in a simplified average value of 1 ton CO2 avoided per ton of feedstock used for biochar production and soil application. This simplification can be useful for obtaining a general idea of emission reductions, although a detailed study including local conditions for every project is required for more precise figures. Further comments on this simplification are included in the Discussion section.

Revenues

As mentioned previously, this section is intended to provide a mere approximation of the costs and benefits derived from each management option. Calculations consider corn yield increases or decreases, and savings or additional requirements of agrochemical inputs, namely N-fertilizer. Costs include corn and stover production (stover harvest, transportation and storage). However, the capital and operational costs of the pyrolysis plant were not included. Therefore, profits for M2 and M3 need to be regarded with caution, as will be explained. Corn price of 137.50 $us/ton (PNCC[5], 2009; McCarl et al, 2009) and production cost of 100 $us/ton in Santa Cruz (CAO, 2007) were considered fixed in a 10 year time frame at 5% interest rate.

M1 considers a constant production of corn at 4 ton/ha in a 100-ha plot, while for M2 there is a decline of 5% in grain and stover yield after the first year and 10% from the second year, due to increased erosion and loss of SOC, and considers additional fertilizer costs of 10%. The sale price of biochar for coal co-firing is based on the June 2010 report on coal prices (US EIA, 2010), where a price of 11.60 $us/short ton (12.70 $us/metric ton) is indicated for Powder River Basin coal, with roughly twice as much energy content as biochar. Considering a linear relationship between price and energy content, a conservative price of biochar of 6 $us/metric ton is assumed. This selling price is significantly lower than the production cost of biochar from corn stover considering costs in the U.S. Corn Belt (McCarl et al, 2009), which are not likely to decline significantly in Bolivia, and can therefore be regarded only as a salvage value.

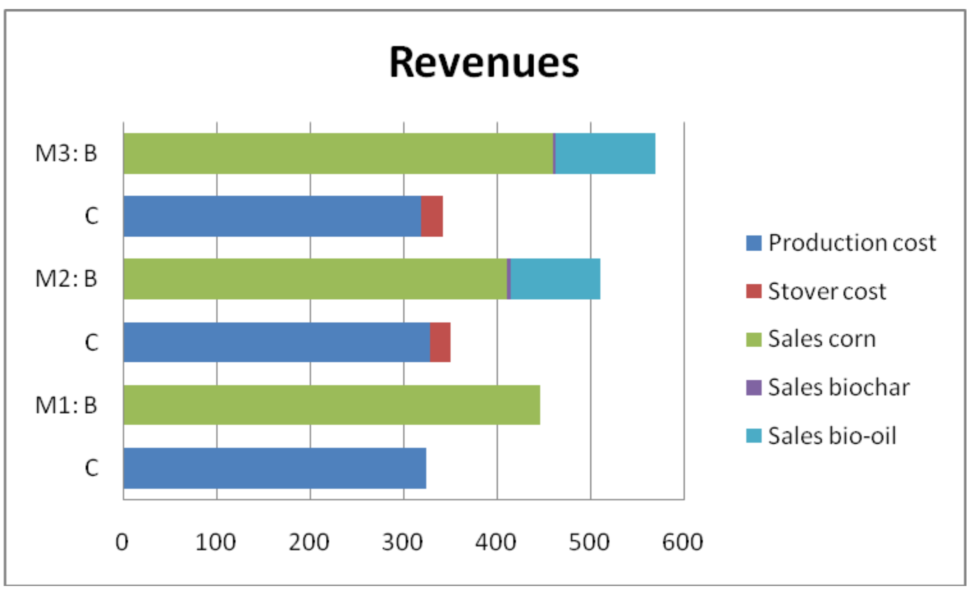


Figure 4.4 Costs and benefits for each management option for a 100-ha plot in a 10-year period (1,000 $us)

[5] Programa Nacional de Cambios Climáticos (National Climate Change Program), Bolivia

On the other hand, M3 considers a modest increase in yield of 5% on soil applied with biochar. After the first harvest, 285 tons of stover are transformed into approx. 100 ton biochar and then applied to some 20 ha (at application rate of 5 ton/ha). Yield is considered to increase for the next harvest only for the portion of land applied with biochar. Following this pattern, after the fifth harvest, all of the 100-ha plot has been applied with biochar, and the excess biochar produced can be applied to the soil, sold for co-firing or sold as charcoal. Biochar produced in the last four years is assumed to be sold at the salvage value. As stated before, fertilizer savings of 10% are considered for M3, with current N fertilizer use (urea, 140 kg/ha) and international prices (Fertilizerworks). Results are presented in figure 4.4. Finally, the sale price of bio-oil is determined by its caloric value, which is 38% of that of diesel, and is penalized as further processing is needed for it to reach car fuel standards.

M1 generates net revenues of $us 122,000. The figures for M2 and M3 must be understood relative to M1, given that capital and operational costs for pyrolysis facility are not taken into account. M2 shows revenues of $us 159,000, providing a margin of $37,000 for the pyrolysis facility over 10 years. M3 outperforms the other options, with net revenues of $us 210,000 which, relative to M1, means that as long as the fixed and variable costs of the pyrolysis facility do not exceed a NPV of $ 89,000, M3 would be the preferred option. This accounts for operating costs of 37$ per ton feedstock, in the range of revised values (McCarl et al, 2009), leaving the fixed cost of equipment for drying, milling and pyrolysis to be covered by farmer organizations aided by local governments, international cooperation and/or development agencies. Additionally, benefits that have not been monetized for M3 include: maintaining agro-biodiversity and ecosystem services, reducing water and energy required for irrigation, reducing seed costs, market price for syngas (which also applies for M2) and the possibility of selling carbon offsets, which could improve the financial performance of a biochar project.

If pyrolysis equipment with a capacity of 2 ton/hr would be installed in a (rural) community, by working 8 hr/day and 25 days per month during one year at 75% capacity, it could process the amount of stover collected in about 1,000 ha, at conditions for M2 and M3. This means that, allowing for 2 months of soil preparation without producing biochar, and given appropriate considerations for i.e. transportation and storage, the investment needed for the pyrolysis facility could be managed by a group of several small-scale farmers. Figures on equipment costs vary greatly, from a few thousands for low-tech equipment to i.e. approx. $400,000 in Europe (2 ton/hr, Green Charcoal International, 2010), to $480,000 in China (2 ton/hr, Xifeng, 2003) to a few millions (10 ton/hr, McCarl et al, 2009), depending on the capacity and conditions of equipment.

Overview of results

Collecting corn stover for biochar production, either for coal co-firing or application to soil, makes more energetic sense than the current practice. This is mainly due to the calorific value of the by-products of pyrolysis and the calorific value of biochar in the case of M2. M3 shows a more modest positive energy balance than M2, but by producing more energy than they consume, both can be regarded as desirable management options.

M3 shows net GHG emission reductions and is therefore carbon-negative. M1 only consumes energy without producing any, and M2 presents also a negative GHG balance as displaced emissions from coal combustion do not compensate for GHG emissions associated with e.g. corn and stover production. Also for M2, reduced SOC and increased erosion affect soil productivity negatively. Carbon sequestration is the main factor behind M3 emission reductions, with 70% of the weight; this option simultaneously brings environmental benefits, increasing soil productivity and fertilizer use efficiency.

In terms of revenues, all options are profitable, with M3 showing a higher margin over M1 than M2. Having excluded the cost of pyrolysis and pre-treatment equipment, the net revenues of M2 and M3 relative to M1 show the maximum size of investment for the pyrolysis facility (fixed and variable costs) for each option that would result in a NPV equal to 0. M3 leaves a margin of about $87,000, which would hardly suffice for the technology needed and would therefore require additional funding. M2 is even less promising. But if scale effects are taken into account, the overall cost per unit of output of a biochar project would decrease.

Even though M2 outperforms M3 in terms of energy balance, M3 is the preferred option in terms of GHG balance. M3 is also the option with higher revenues among the two. Additionally, it involves benefits that, if monetized, could only improve financial performance. Overall, taking advantage of agricultural residues for bioenergy production through biochar systems, whichever the final use of biochar, proves to make more energetic and climatic sense than current practices of corn stover in Bolivia.

The ideal facility for installation of pyrolysis equipment would be the nearest coal power plant. This does not imply that biochar production should exclusively be intended for displacing coal. Rather, that more value can be extracted from the by-products of pyrolysis on-site: syngas as an energy source for drying feedstock and the excess for replacing natural gas use for coal combustion; bio-oil for on-site energy purposes by direct heating or for sale. Bio-oil can help reduce diesel imports, which is a current financial burden to the State of Bolivia (La Prensa, 2009; Los Tiempos, 2010; El Diario, 2010) and to many countries around the world.

More precise formal models for soil dynamics with biochar application and more practical evidence from field studies may improve the assessment of the energy, GHG and financial balance of agricultural waste management options involving biochar.

General Discussion

A simplified figure of 1 ton CO2 avoided per ton of feedstock used for biochar conversion and application to soil, can be particularly useful for mitigation activities such as biochar projects that intend to trade emission offsets in voluntary or regulated carbon “markets”. Unfortunately for Bolivia, despite having signed international agreements like the Kyoto Protocol, the current government abstains from participating in carbon markets claiming that beneficiaries are mainly those who gain from transactions of carbon offsets, and that insufficient investment has been mobilized. The private sector can turn to voluntary markets but currently is not offered sufficient incentive to do so. A few local environmental organizations, like consultancy SASA[6], are engaged in promoting emission offsets in both public and private sector.

Regarding the energy and GHG balances and cost-benefit analysis, a sensitivity analysis of relevant variables is recommended, which could not be undertaken in this study due to time restrictions. Also, an expanded LCA would need to consider upstream GHG emissions and energy requirements for the installation and/or construction of a pyrolysis facility, as is performed in the LCA by Roberts et al (2010) (even though these variables seemed not to have a significant impact on final energy and GHG balances).

For farmers interested in sustainable land management through biochar systems, the model of cooperatives has proven fruitful for the provision of basic services such as water and electricity, especially in the Eastern region of Bolivia, and is suggested as a possible organization model for rural farmers. It is a model where every stakeholder is a shareholder of the organization and has a say in the decision process.

Microfinancial services and funding from municipal, state and central governments, as well as from international cooperation would also be needed to ensure the start-up, continuity and ultimately success of such activities.

[6] Servicios Ambientales S.A.: http://www.sasa-bolivia.com/

Conclusions

The final remarks of this thesis, including conclusions and recommendations, are presented in the context of the global issues that motivated this dissertation, namely the food, energy and climatic crises. Land degradation, poverty and climate change are the relevant associated processes requiring change in order to solve these crises. Biochar is analyzed as a possible strategy to achieve this. Here, the research questions are revised and answered according to the findings presented in the preceding chapters.

The main research question reads: Can the production of biochar for environmental management be considered a suitable strategy for combating increasing climate change, poverty and land degradation?

Chapter 2 summarizes the general characteristics of biochar. From here are highlighted the high C content, porosity, stability in soil, cation exchange capacity, adsorptive capacity, nutrient retention, water holding capacity, GHG emission reductions from soil and the fact that biochar can be a suitable habitat for microbial colonization. All of these contribute to increased soil fertility and reduced GHG emissions from various sources.

In Chapter 3 are presented the pathways through which biochar production and application to soil can alter the global biogeochemical cycles, important in determining conditions for life on the planet. Biochar exhibits properties that can help reverse current trends that are detrimental to human welfare. Regarding the C cycle, biochar application to soil can increase the C pool in terrestrial ecosystems and decrease the C accumulated in the atmosphere, while displacing fossil fuel use with by-products of pyrolysis. For the N cycle, biochar can contribute to "de-acceleration", by inducing a reduction in N fixation and mobilization. The most important feature is nutrient retention in soil, which causes a decrease in N lost to air, water and land. Biochar application to soil also achieves other environmental benefits, such as maintained agro-biodiversity, reduced water needs, and reduced N saturation in terrestrial, marine and other ecosystems due to reduced run-off, all of which contribute to higher ecosystem resilience.

In Chapter 4 is analyzed the technical feasibility of different management options for corn stover management, under the criteria of energy and GHG balances and total revenues, in the context of a developing country. For this purpose a comparative study based on a life-cycle approach and a cost-benefit analysis were produced. Results show that corn stover used for biochar production and application to soil (M3) is the preferred management option, over biochar intended for replacing coal in power plants (M2) and current practices (leaving residue on the field) (M1), when each criterion is assigned the same relative weight for the decision. M3 is the only option that produces more energy than it consumes and that is carbon-negative, while showing also a higher financial performance than M2. Even M2 makes more energetic and climatic sense than M1. However, robustness needs to be revised with a sensibility analysis, and the financial feasibility of biochar systems more thoroughly analyzed. It is important to emphasize that, establishing mechanisms by which the external environmental benefits can be monetized or internalized may be important to the adoption of biochar technologies (Lehmann et al, 2006).

So, in order to answer the research question (and supporting questions) appropriately, an analysis in the context of the relevant processes is presented as follows:

Land degradation

Biochar systems can contribute to tackle current land degradation problems under certain conditions. The performance will depend on the criteria used to evaluate, which in this study were energy and GHG balances. Biochar has proven to be a valuable soil conditioner, chiefly by retaining nutrients and in general by improving soil conditions. Higher crop yields and increased fertilizer use efficiency are results associated with biochar application. Production processes must be optimized and feedstocks carefully selected to obtain the majority of benefits offered by biochar systems. Waste management of agricultural residue through biochar systems, as analyzed here using energy and emissions criteria, can well be considered a sustainable option. When assuming waste as feedstock, discussion on issues regarding food security and land use change are avoided.

In sum, biochar can reduce land degradation caused by loss of organic C by adding stable C to soil, improving soil fertility. It can also reduce N-derived land degradation by retaining nutrients in soil and preventing leaching and erosion. Less production inputs could be required for cultivation. Its high water holding capacity is another important attribute that prevents land degradation by erosion. Application to soil may promote biological activity by providing suitable habitats for microbial colonization, affecting soil biota positively.

Climate Change

Given appropriate conditions, biochar systems can represent a mitigation and adaption strategy for climate change. Pyrolysis syngas and bio-oil can be used to replace fossil fuels. Biochar also presents capacity for carbon sequestration in soil. When the monetized benefits of biochar systems are clearly understood and explained, there is a huge potential for C sequestration if biochar projects are scaled to a global level. As previously stated, diverting only 1% of C released through biomass respiration would avoid about 10% of current global GHG emissions (Lehmann,et al 2006). Well managed biochar systems can be carbon-negative and prove useful in the fight against climate change. Biochar can be considered an adaptation mechanism for its characteristics, especially in locations where water is scarce and soils are degraded.

Poverty

Given the observed attributes of biochar, this study intended to frame the analysis as much as possible in the context of a developing country. Usually this is characterized by a high rate of rural poverty, high relevance of agricultural activities in the economy and increasing impacts of climate change and land degradation, felt mostly by vulnerable communities. Therefore the use of biochar for soil amendment represents an opportunity to enhance sustainable agricultural practices that at the same time can contribute to adaptation to climate change, and if scaled up could serve as an abatement option. In order for the benefits to accrue the main stakeholders, the rural families, coordinated efforts are needed from themselves, local governments, and international development and cooperation organizations. A well-defined communal organization model, such as cooperatives, supported by microfinancial institutions, especially to cover the up-front capital cost of the pyrolysis facility, would improve the possibility of success and continuity. Mechanisms by which the external benefits can be monetized, i.e. carbon offsets, may improve the financial performance of a biochar project.

Finally, it is left to present how the multiple vicious cycle of land degradation-poverty-climate change is altered by biochar systems (figure 5.1), under the conditions mentioned, to create a multiple virtuous cycle in which sustainable land management, poverty reduction and climate change mitigation reinforce each other in what can be considered a strategy emulating a raising spiral.

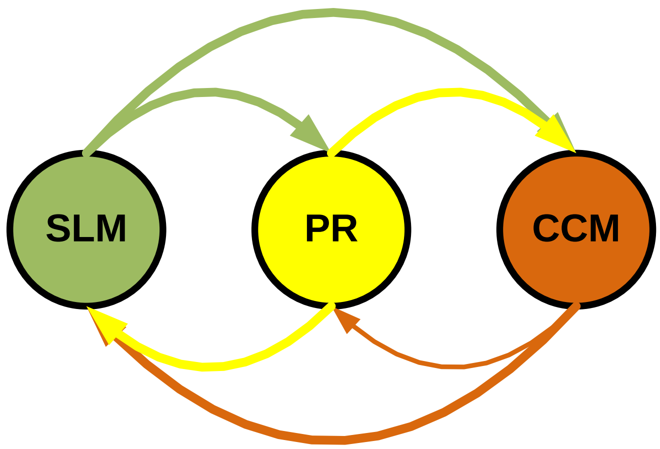


Figure 5.1 Cause-effect relationships between sustainable land management (SLM), poverty reduction (PR) and climate change mitigation and adaptation (CCM)

Sustainable land management through biochar utilization promotes poverty reduction, as it results in increased soil fertility and productivity, and reduced need of production inputs, which translate into more income. As economic benefits are obtained, farmers are encouraged to continue sustainable practices. As poverty reduction proceeds in this manner, benefits for the environment through biochar systems are obtained, in the context of climate change. As long as environmental benefits are not materialized or internalized, climate change mitigation might not promote poverty reduction. This is overcome by the fact that the sustainable land practices through biochar imply climate change mitigation, given the C sequestration potential of charred materials, and fossil fuel displacement from pyrolysis by-products, which need to be appropriately managed in order to extract the most benefit from biochar systems. Climate change mitigation may ultimately allow for more stable climatic patterns, which would avoid undesirable conditions and contribute to the continued sustainable land management practices.

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Appendix

I. Socio-economic, political and geographic conditions in Bolivia: suitable for biochar systems?

Bolivia possesses a huge variety of ecological conditions, e.g. with altitudes ranging from >6,000 to 90 m.a.s.l. in the highest and lowest points respectively, for which it is considered one of the "mega-diverse" countries (LMMC, 2002). Weather conditions vary with altitude, with temperatures and humidity increasing from west to east, presenting humid and tropical to cold and semiarid regions.

Population is expected to reach roughly 10 million in 2010, 60% of them living under the poverty line (CIA, 2010). Urban population accounts for 66% of the total, rural covering the rest. At the same time, approximately 40% of the economically active population is estimated to be engaged in the agricultural and livestock sector. In rural areas the corresponding figure is as high as 80% (MPD[7], 2006). The Human Development Index ranks Bolivia 113th in a list of 182 countries (UNDP, 2009). Common unsustainable and unhealthy practices include 80% of the rural population using firewood and other solid fuels for cooking and heating, which is a key cause of respiratory infections.

As many other natural resource-rich countries, Bolivia has failed to translate natural resource rents into a broad based development; instead, resource extraction has been characterized by boom and bust cycles and rent-seeking behavior, generating widespread inequality, social conflicts and environmental degradation (Slunge and Jaldin, 2007). The Government explicitly aims at economic growth and generation of employment opportunities through investments in natural resource-based sectors (MPD, 2006), although often with lack of specific directives, particularly in the agricultural sector. An additional factor influencing the relevance of the issue at hand is very unequal land distribution, with 80% of the farms utilizing 3% of cultivated lands (Slunge and Jaldin, 2007). This leads, especially in the high lands, to land fragmentation and soil over-exploitation, important drivers of land degradation.

Climate change affects agriculture in Bolivia by decreasing soil productive capacity, thus aggravating poverty. According to the National Program of Climate Change - PNCC (2009), among the evidences of climate change on agriculture (and food security) in Bolivia, we find:

- Variation in precipitation cycles
- Increased extreme weather events (e.g. El Niño)
- Increased surface temperature
    - Melting of glaciers, which decreases availability of irrigation water in the mid- and high-lands
    - Increased soil erosion

All these processes cause significant impacts, chiefly a decrease in soil productivity, but also loss of arable land and agro-biodiversity, changes in vegetation cover, emergence of new plagues and illnesses affecting crops, and only 10% of cultivated land disposing of permanent irrigation sources (MPD, 2006). Socio-economic impacts include increased rural-urban migration due to loss in productive capacity of the ecological capital, which, as stated, is often the only means for income generation, thus reinforcing the poverty trap (Van Beukering et al, 2009). Regarding the costs of extreme weather events, a study by CEPAL (2007) estimates that El Niño 2006-2007 caused total damages valued in US$ 443m, of which 80m correspond to agriculture or 14% of agricultural GDP, equivalent to 1% of national GDP. Loss of crop land

[7] Ministerio de Planificación del Desarrollo (Ministry of Development Planning) Bolivia

was 9% of total cultivated lands. The Government is currently engaged in adaptation to climate change (mainly through international cooperation funding), understanding that it represents a threat to strategies aiming at poverty reduction (MPD, 2006). The need for technology transfer for climate change mitigation is also recognized by the PNCC (2009), highlighting that the flow of investments to the country has fallen short of expectations.

The fact that agricultural soils in Bolivia have little depth, are fragile and easily erodible, makes the situation for the rural poor only grimmer. Among the land use change degradation processes, besides land fragmentation, deforestation has caused the loss of around 300,000 hectares annually in the period 2001-2005 (UDAPE, 2006). This occurs as a result of the expansion of the agricultural frontier, driven by rising local demand and higher commodity prices in the international food market. Between 1954 and 1996, the area of eroded soils increased by 86% from 24 to 43m hectares (European Commission, 2005), of a total national territory of 100m ha. Agriculture contributes to the GHG emissions budget of Bolivia with, on its own, 14% of the total, and if LULUCF is considered, much of it for claiming new crop lands, the figure increases to 60% (PNCC, 2009).

Maize production is a particularly relevant economic activity in the country given that is it cultivated in 8 of the 9 Departments; although it is exported, it is mainly produced for local consumption. By outcompeting traditionally predominant potato, corn was the third most produced crop in 2006 and 2007, after sugar cane and soybean (FAOSTAT, 2009; figure i), and represents the most grown cereal in the country. Maize production reached 800,000 tons in 2007 and down the following year to 770,000, although an increasing trend is expected. This represents nearly half of the cereal production in the country (FAO, 2009). In total, land devoted to corn production sums up to more than 13% of arable land nationwide (FAOSTAT, 2009a; CIA, 2010). Maize is grown mainly in valleys and tropical zones, by industries and chiefly subsistence farmers, normally using crop rotation with soybean and wheat, and rarely cultivated as a monoculture crop. The present analysis is based on maize production in the tropic, which is a significant sample as it represents more than 50% of national corn production. In terms of arable land, the Department of Santa Cruz represents half of arable lands in the country, of which 10% is devoted to growing maize (CAO[8], 2007; INE, 2010; FAOSTAT, 2009). There are around 13,500 farmers that cultivate maize in the Department, 99% of which are small (1-50 ha) (CAO, 2007). The Department of Santa Cruz has a mean annual temperature of 24°C and a mean relative humidity of 68%, and is composed of valleys and mostly humid and sub-humid tropics (INE, 2010). Annual precipitation is usually in the range of 1,000 to 2,000 mm (INE, 2010; UDAPE, 2006).

[8] Cámara Agropecuaria del Oriente – Agropecuary Chamber of the Orient

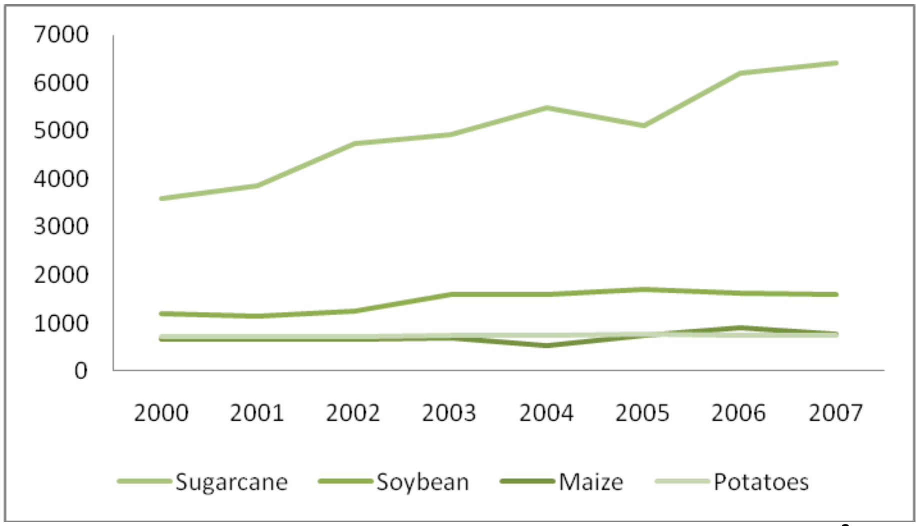

Figure i. Production levels of main agricultural products in Bolivia (10^3 metric tons)
Source: FAOSTAT

Sugarcane was not considered as a potential feedstock for biochar production due to its high moisture content (therefore requiring large amounts of energy to transport and dry), and because residues are well-suited for electricity co-generation, which is a current practice in some sugar refineries (Guabirá Sugar Refinery[9]). Soybean residues, although less in proportion of total biomass weight than corn stover, could well be considered as feedstock for biochar production and would need to include the effects of biochar on N-fixation through mycorrhizal bacteria. A detailed study on this subject can be found in Rondon et al (2007).

Finally, a large part of public spending in Bolivia is devoted to subsidies for seeds and imported fertilizer in agriculture; and diesel for energy generation in decentralized rural regions. Diesel imports surpassed one billion dollars in 2009 (La Prensa, 2010). Strategies that help alleviate the economic burden that these subsidies represent will help improve the financial health of the government, allowing new investments in high priority areas such as education and health.

[9] Available at http://www.guabira.com/

II. Ongoing Biochar Projects

A list of ongoing biochar projects can be found in the website of the International Biochar Initiative, which is in general a very useful source for biochar-related activities, research findings, publications, events, etc.

http://www.biochar-international.org/projects/practitioner/profiles

Here are included activities in countries like Canada, USA, Haiti, Senegal, Australia, Costa Rica, and others.

Another good source of ongoing projects is the book by Lehmann and Joseph (2009).

Biochar testing in Cameroon

From another source, the Biochar Fund, comes a pilot project started in Cameroon in 2009, of particular relevance for the present study. According to the information presented in the website, subsistence farmers have been participating in the largest-ever field trial testing the effects of biochar on crop productivity. Biochar trials are taking place in a region with soils ranging from poor and highly weathered oxisols to fertile soils. Biochar was produced from organic waste from small-holder farms (cassava stems, oil palm branches and common weeds) and wood (red wood and rubber wood). Maize fields are applied with biochar at rates of 10 and 20 ton/ha in different locations, and after early harvest, data is collected and processed.

The 75 test plots used during this pilot trial measure 54 square meters and are divided into 12 sub-plots, each demarcated by a buffer zone measuring 75 centimeters. Maize was planted at a high density of 62,500 seeds per hectare.

The sub-plots received different applications of inputs. A first line of four sub-plots functions as the control (no char) and received no inputs (X), organic fertilizer only (O), mineral fertilizer only (F) and a combination of organic and mineral fertilizer (OF). The second line is similar but also received the equivalent of 10 tons of char per hectare (C10, C10O, C10F and C10OF). Finally, the soil of the third line received biochar at a rate equivalent to 20 tons per hectare (C20, C20O, C20F and C20OF). Both the organic and mineral fertilizers were used at quantities recommended for maize in the humid tropics, and more specifically for the agro-ecological zone in which the trial takes place.

Conclusions show that soil amendment with biochar consistently improves both the biomass and grain production of maize. All combinations of soil inputs perform better than the control plots. More information please go to:

http://biocharfund.org/index.php?option=com_content&task=view&id=54&Itemid=74

III. Input data – LCA

M1 - BIOMASS DECAY

	ENERGY (MJ/dry ton)		GHG (kg CO_2e/dry ton)		COST-BENEFIT ($US)
Consumption	3000	Emissions	620	Costs	324313
Production	0	Reduction	0	Benefits	445930
	3000		620		121617
Corn production: agrochemicals, field operations			3000		
Production as food (grain = 16000 MJ/ton)			0		
Corn production: agrochemicals, field operations			350		
Decay CH_4			130		
Decay N_2O			140		
Corn production ($/ton)			100		
Corn sales ($/ton)			137.5		

M2 - BIOCHAR AS COAL

	ENERGY (MJ/dry ton)		GHG (kg CO2e/dry ton)		REVENUES ($US)
Consumption	4750	Emissions	657	Costs	350719
Production	6667	Reduction	322	Benefits	509390
	1917		335		158670

Corn production: agrochemicals, field operations	3000
Stover production: harvest and fertilizer	900
Pyrolysis	750
Drying, shredding and transport	100
Subtotal	**4750**
Coal calorific value	24000
Biochar LHV	9408
	1317
Syngas and bio-oil	4850
Avoided FF	500
Subtotal	**6667**
Corn production: agrochemicals, field operations	350
Stover production: harvest and fertilizer	50
Pyrolysis, transport, pre-treatment	80
Additional fertilizer needed	37
N2O emissions	140
Subtotal	**657**
Coal displaced	2300
	322
Subtotal	**322**
Stover collection and transport, decrease in yield, additional fertilizer needed	
Syngas, bio-oil	

M3 - BIOCHAR TO SOIL

	ENERGY (MJ/dry ton)		GHG (kg CO2e/dry ton)		COST-BENEFIT ($US)
Consumption	4850	Emissions	520	Costs	359714
Production	5350	Reduction	1270	Benefits	569961
	500		-750		210247
Corn production: agrochemicals, field operations			3000	Kim	
Stover production: harvest and fertilizer			900	Kim	2260
Pyrolysis			750	S23	
Drying, shredding and transport			100	S7, S10	110
BC Application to soil			100		
Subtotal			**4850**		
Syngas and bio-oil			4850	S23	
Avoided FF			500	Figure 2a Roberts	
Subtotal			**5350**		
Corn production: agrochemicals, field operations			350	Kim	
Stover production: harvest and fertilizer			50	Kim	
Pyrolysis, transport, pre-treatment			80	S23	
Application to soil			40		
Subtotal			**520**		
C sequestration			900	McCarl	
Avoided FF (incl. fertilizer savings)			300		
N2O emission reductions			70		
Subtotal			**1270**		
Stover collection, pyrolysis and transport					
Syngas, bio-oil, avoided FF, yield increase,					

IV. Input data – CBA

M1

COST PER TON	100	$US									
REVENUE FOR SALES IN 100 HA PLOT											
	Y0	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
PRODUCT	400	400	400	400	400	400	400	400	400	400	TONS
DISC FACTOR	1	0.95	0.91	0.86	0.82	0.78	0.75	0.71	0.68	0.64	
SALES	55000	55000	55000	55000	55000	55000	55000	55000	55000	55000	$
NPV SALES	55000	52381	49887	47511	45249	43094	41042	39087	37226	35453	
	445930										
COST	40000	40000	40000	40000	40000	40000	40000	40000	40000	40000	$
NPV COST	40000	38095	36281	34554	32908	31341	29849	28427	27074	25784	
	324313										
NPV REVENUE	121617	$US									

M2

COST PER TON	100	$US								
BC as COAL PRICE	6	$US/ton								
Bio-oil price	150	$US/ton								
	Y0	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9
PRODUCT	400	380	360	360	360	360	360	360	360	360
Stover collected	285	270.75	256.5	256.5	256.5	256.5	256.5	256.5	256.5	256.5
Biochar produced	100	95	90	90	90	90	90	90	90	90
Bio-oil produced	86	81	77	77	77	77	77	77	77	77
DISC FACTOR	1	0.95	0.91	0.86	0.82	0.78	0.75	0.71	0.68	0.64
Benefits										
SALES CORN	55000	52250	49500	49500	49500	49500	49500	49500	49500	49500
SALES BC AS COAL	599	569	539	539	539	539	539	539	539	539
SALES BIO-OIL	12825	12184	11543	11543	11543	11543	11543	11543	11543	11543
NPV SALES	68424	61907	55856	53196	50663	48250	45953	43765	41681	39696

	509390									
	12825	11604	10469	9971	9496	9044	8613	8203	7812	7440
COST PROD	40000	40000	40000	40000	40000	40000	40000	40000	40000	40000
COST ADD FERT	640	640	640	640	640	640	640	640	640	640
COST TRANSPORT, HVST, STRGE	2850	2707.5	2565	2565	2565	2565	2565	2565	2565	2565
PYROLYSIS PLANT	0									
SUBTOT COST	43490	43348	43205	43205	43205	43205	43205	43205	43205	43205
NPV COST	43490	41283	39188	37322	35545	33852	32240	30705	29243	27850
	350719									
NPV REVENUE	158670	$US								

M3

COST PER TON	100	$US
SYNGAS VALUE	40	$US/dry ton
Bio-oil value	150	$US/ton
Fertilizer cost	16	$us/ton corn

REVENUE FOR SALES IN 100 HA PLOT

	Y0	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9
Input data										
Grain/Stover production	400	404	408	413	417	420	420	420	420	420
Stover collection	285	288	291	294	297	299	299	299	299	299
Biochar produced	100	101	102	103	104	105	105	105	105	105
Discount factor	1	0.95	0.91	0.86	0.82	0.78	0.75	0.71	0.68	0.64
Bio-oil production	86	86	87	88	89	90	90	90	90	90
Benefits										

Grain sales	55000	55578	56161	56751	57347	57750	57750	57750	57750	57750
Sales bio-oil	12825	12960	13096	13233	13372	13466	13466	13466	13466	13466
Sales biochar as coal							628	628	628	628
NPV SALES	67825	65273	62818	60455	58181	55800	53612	51059	48627	46312
	569961									
Cost										
Grain/Stover production	40000	40000	40000	40000	40000	40000	40000	40000	40000	40000
Fertilizer savings	-640	-640	-640	-640	-640	-640	-640	-640	-640	-640
Cost transport, hvst, strge	2850	2880	2910	2941	2972	2993	2993	2993	2993	2993
Cost application	1995	2016	2037	2059	2080	2095	2095	2095	2095	2095
SUBTOT COST	44205	44256	44307	44359	44412	44447	44447	44447	44447	44447
NPV COST	44205	42148	40188	38319	36538	34826	33167	31588	30084	28651
	359714									
	2850	**2743**	**2640**	**2540**	**2445**	**2345**	**2233**	**2127**	**2025**	**1929**
NPV REVENUE	210247	$US								