Compost, biogas and biochar in Northern Ghana

Climate impact and economic feasibility in the context of voluntary carbon markets

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MSc Thesis in Industrial Ecology

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People have to understand that we have created a way of life that's fundamentally unsustainable, and that doesn't mean just that it's ecologically irresponsible, it means that it cannot continue

Richard Heinberg

Man is like every other species in being able to reproduce beyond the carrying capacity of any finite habitat. Man is like no other species in that he is capable of thinking about this fact and discovering its consequences.

William R. Catton, Jr

If development was a race you might say that we've left Africa way behind. Only, now we are realising we may have been running in the wrong direction.

Nora Feldmar

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Executive summary

In Tamale, a city of less than half a million inhabitants in the middle of the savannah, in the North of Ghana, like in many other African cities, there is no modern waste management infrastructure. The small share of the city's solid waste that is collected is carried to a nearby open landfill. Here the organic fraction, around 40% of that waste, decomposes and releases methane, a powerful greenhouse gas, in the atmosphere.

With composting, this waste could go from being a threat to the global climate to a resource for agriculture in the region, as organic fertiliser for the land around the city that badly needs organic matter replenishment. With anaerobic digestion the same methane that contributes to the greenhouse effect when released in the atmosphere could be collected and used to produce electricity to power lightbulbs, computers, refrigerators and mobile phones, which often in Northern Ghana sit unused because of of blackouts. With pyrolysis other flows of organic waste, byproducts of local agro-processing industries, could be used to produce biochar, a soil amendment that also sequesters large amounts of carbon in farmland. All these technologies, if implemented with labour intensive, low-tech approaches, could create employment in a city where there is almost no industry yet.

Here, like everywhere else, whether waste stays an environmental threat or becomes a resource for the local economy depends on a variety of factors. This research analyses the role that carbon markets could have in facilitating the implementation of these three technologies, composting, anaerobic digestion and biochar production, in Tamale.

A **life cycle assessment** of realistic implementation scenarios for these three technologies was first performed, in order to assess the potential contribution they could give to climate change mitigation, with the following results.

- Composting of the organic fractions of municipal solid waste can generate net greenhouse gas reductions for 0.74 tons of CO_2 equivalent (tCO_2eq) per ton of waste. Most of this reduction comes from avoiding the formation of methane in the city landfill and from the substitution of the use of conventional fertiliser.

- Carbon sequestration as increase of soil organic matter following the use of compost in agriculture can be another significant climate change mitigation mechanism but it is not easily quantified in a life cycle assessment, because organic carbon accumulation in soil is not linear and hard to model without data from field trials.

- Extracting energy from the waste with anaerobic digestion, before it undergoes the composting process, is estimated to bring an additional greenhouse gas emission abatement of about 0.15

tCO_2eq per ton of waste.

- Biochar production leads to a net carbon sequestration. Pyrolysis of rice husks from the Tamale rice mill was modelled and the results show that carbon for about 1.5 tCO_2eq per ton of rice husks charred could be sequestered. Producing biochar together with organic fertiliser could make the whole system carbon negative.
- The uncertainties in performing a life cycle assessment for this kind of context, a developing country where only little data is available, are many. However they are not likely to influence the overall outcome of the evaluation, which is that the implementation of these three technologies could give a significant contribution to climate change mitigation efforts.

To understand how access to carbon markets could bring benefits for the implementation of these organic waste management technologies, an **economic feasibility study** was carried out, looking at the costs and revenues which would be involved, both with and without the issuance of carbon credits. The influence of changes in carbon price on the feasibility of these technologies was also investigated.

- Presently these technologies cannot be implemented, with the considered small scale, labour intensive approach, without external subsidies, as estimated costs are higher than potential revenues.
- The prices at which the products, compost, electricity and biochar, could be sold in Tamale are a crucial uncertainty in the analysis. However even if the values used in the evaluation were to be underestimated, the considered implementation scenarios are likely to remain unfeasible, since price increases in the range of 30% (for compost) to 600% (for biochar) would be required for revenues to cover the costs.
- Carbon markets could provide the additional revenues required to achieve economic feasibility, but the present carbon price of 7 EUR per tCO_2eq is too low to make a difference. Revenues from selling carbon credits at this price would amount to just 2-7% of total revenues, and would not be sufficient to cover the losses.
- Anaerobic digestion and biochar production were studied as implemented in combination with composting. It was found that integrating anaerobic digestion with a composting system could improve the economic performance of the latter. On the other hand integrating biochar would only be profitable if it could issue carbon credits, as the price that farmers could pay for biochar is probably too low to cover production costs.
- If the price of carbon will start to rise, carbon markets would reward more the technologies which generate the higher amount of carbon credits, which is related to the actual net greenhouse gas emission reduction. The return on investment of biochar production is the one that would rise faster as a consequence of higher carbon prices, followed by anaerobic digestion and then composting.
- With the considered set of assumptions about the other economic conditions, minimum carbon prices to guarantee economic feasibility of the scenarios that were analysed should be of 31 EUR per ton of carbon for biochar production with composting, 52 EUR for anaerobic digestion with composting and 77 EUR per ton of carbon for composting alone.

- The accumulation of soil organic carbon in farmland following the use of compost could also issue carbon credits, in theory. The costs and revenues that such a system would generate are however hard to quantify. Here it was estimated that for each ton of municipal solid waste treated, averaged over 10 years, credits for about 0.17 tCO_2eq could be generated, about the same amount of those that extracting biogas and producing electricity could issue from the same amount of waste.

Ultimately carbon markets can help the realisation of small scale composting, anaerobic digestion and biochar projects, but only if carbon price will reach levels several times higher than current ones. Biochar production could achieve large climate benefits but it will only become economically feasible in contexts like that of Northern Ghana, where farmers cannot afford to pay high prices for soil amendments, if it will be approved as a land based climate change mitigation mechanism on carbon markets.

The main recommendations for climate policy are to include biochar in carbon markets, to review the credit generation methodology for landfill avoidance to avoid underestimation. Ultimately, however, the main conclusion is that if carbon markets are to support the realisation of small scale development project in the field of waste, with potentially high impact both in terms of climate benefits and sustainable development, carbon price must rise. Carbon markets are ineffective without demand for carbon credits, without emission reduction targets for industrialised countries.

The main recommendations for organic waste management are to further research the technical feasibility of low cost anaerobic digestion, and the agronomic quality of biochar from different feedstocks, in different soils and for different crops, as this technology will quickly become profitable when it enters carbon markets.

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Chapter 1

Introduction

Organic waste can be a valuable resource as much as a source of environmental problems. It contains nutrients that can be used for agriculture and energy that can be extracted and converted into useful forms. Organic waste can power lightbulbs and water pumps, and it can make a soil hold more water in a period of drought. But, left in a landfill, it releases methane in the atmosphere and contributes to warm up the global climate. Organic waste can be a gift or a threat, which one of these two options materialises depends from case to case.

This is a research about whether organic waste can become a resource in Tamale, a city in the middle of the Ghanaian savannah, and whether carbon markets can help create the right conditions for it to happen.

1.1 Background

1.1.1 Carbon markets as a tool to shape the development of emerging economies

Carbon markets are mechanisms created by the Kyoto Protocol to make the adoption of low-carbon technologies and the reduction of global greenhouse gas (GHG) emissions more economically efficient.

Low-carbon projects in developing countries can generate *emission reduction certificates* that can be bought on carbon markets in industrialised countries by companies that cannot meet their emission reduction targets. This system is called Clean Development Mechanisms (CDM), and is regulated by the UN Framework Convention on Climate Change (UNFCCC). CDM work within so called *regulatory* or *compliance* carbon markets, as opposed to *voluntary* ones, that allow the purchase of emission reduction certificates also by organisations that are *not* legally bound to reduce their emissions, like airlines or events.

Although trading of offsets on voluntary markets is not centrally regulated, these markets have seen the emergence of independent standards, such as the WWF's Gold Standard or the Climate Groups's Verified Carbon Standard, that guarantee that the certificates actually correspond to real GHG emission reductions (Reuster 2010). Some of these standards also require transparency over the impacts of projects on local communities, as projects that bring additional sustainability benefits can attract higher prices on the marketplace (Peter-Stanley et al. 2011).

In the past 10 years these markets have generated new flows of capital into developing countries, flows supposed to shape their development towards a more sustainable pathway than that of industrialised countries.

1.1.2 Sub Saharan Africa, big challenges, big opportunities

It is today common sense that Sub Saharan Africa is one of the poorest regions in the world. African countries rank at the world's bottom both for Gross Domestic Product (GDP) and Human Development Index, a combination of health, education and wealth indicators (Figures 1.1 and 1.2).

What is often not realised however is that African countries are diverse under many points of view. Although in western media news coverage from Africa is mostly about poverty, conflicts and natural

Figure 1.1: Bad news: Human Development Index by country, 2011 (UNDP 2012)

Figure 1.2: Bad news: GDP per capita by country, 2011 (UNDP 2012)

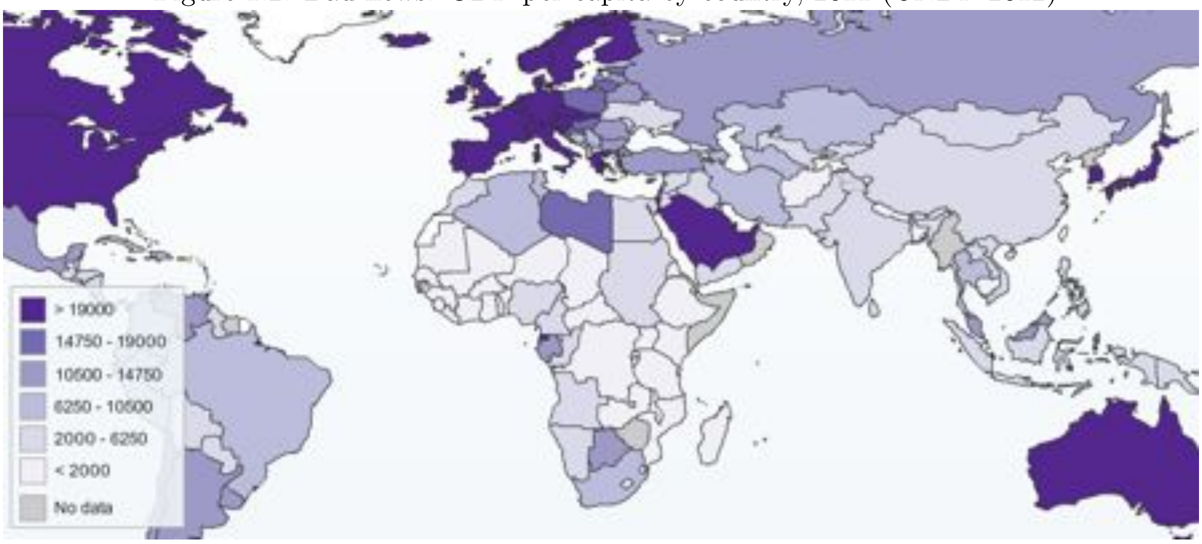


Figure 1.3: Good news: GDP growth 2007-2011 (World Bank 2012)

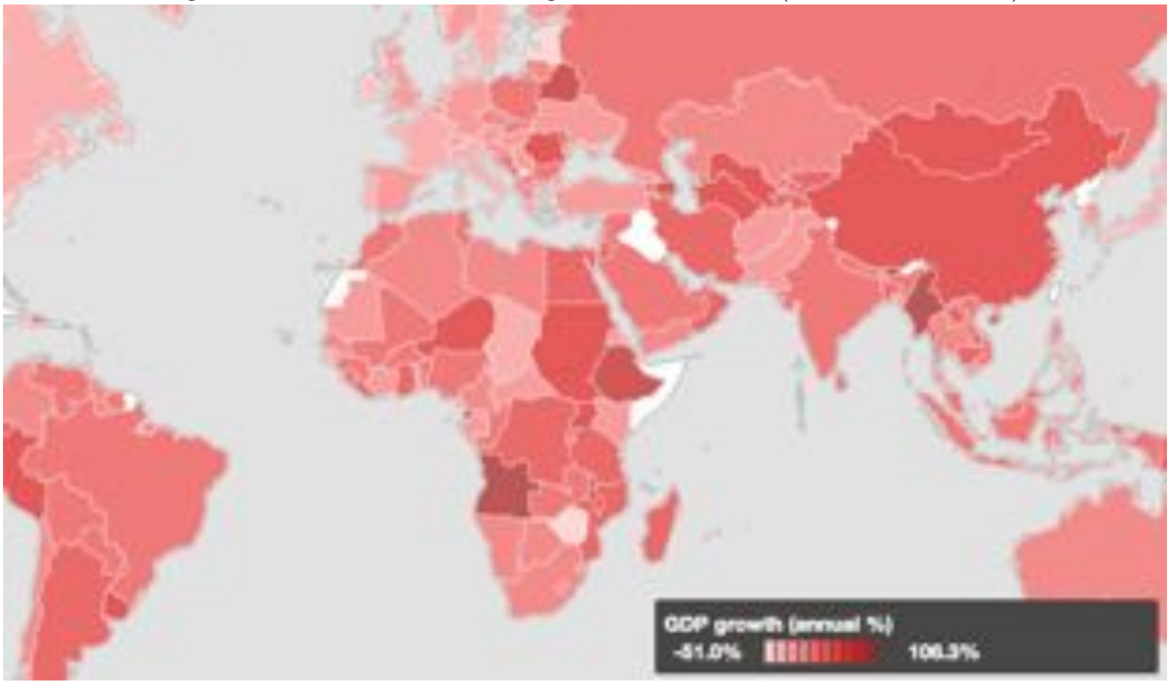


Figure 1.4: Good news: Industry growth 2007-2011 (World Bank 2012)

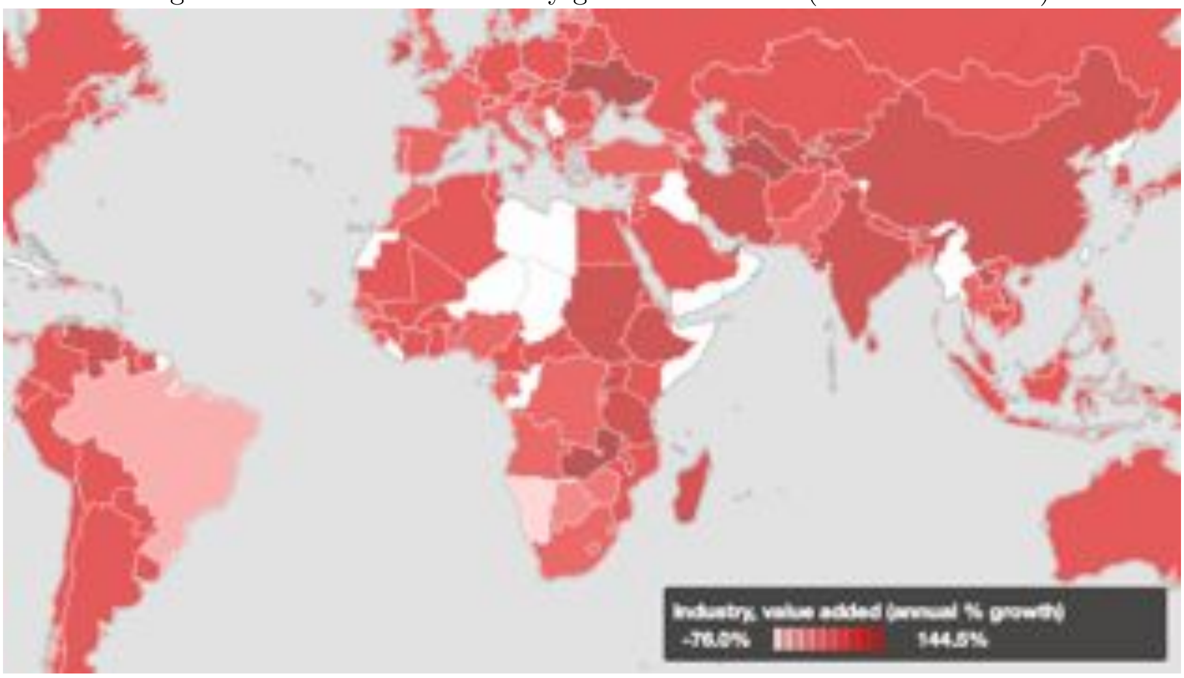


Figure 1.5: Location of carbon projects on regulatory carbon markets (CDM), by project size (UNFCCC 2012)

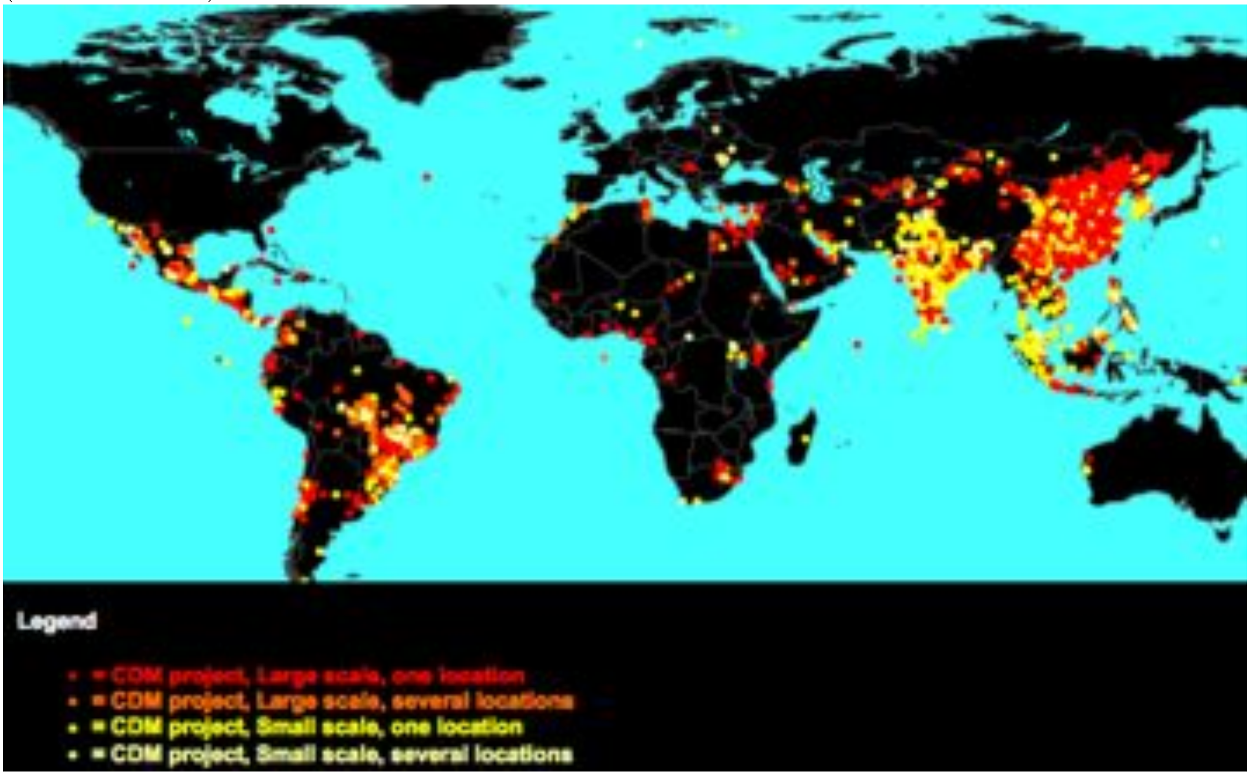
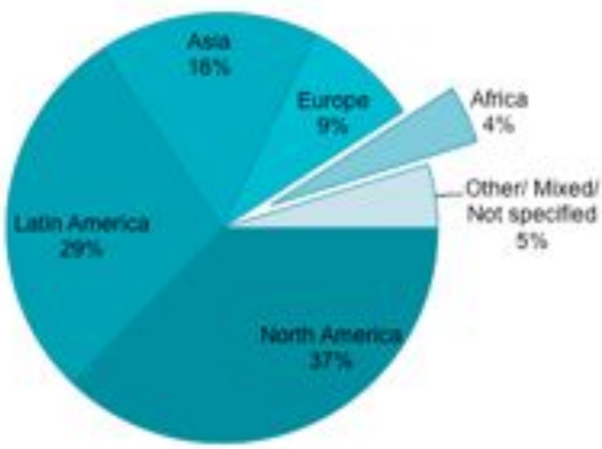


Figure 1.6: Location of carbon projects on voluntary markets, by amount of certificates traded in 2010 (Peter-Stanley et al. 2011)



disasters, many countries in the continent are today developing fast. In 2011 the GDP growth of Sub Saharan Africa was 4.9%, which is higher than the world average (3.8%) and 3 times the EU average (1.6%). Out of the 20 countries with the fastest growth in the world, 9 where from Sub Saharan African (IMF 2012).

If strong economic growth does not mean necessarily an improvement in living conditions for the majority of the population, it still implies a fast evolution in the economic fabric of a country, be it for industry, agriculture, mining, telecommunication, trade etc. Figures 1.3 and 1.4 show the growth of GDP and industry in various parts of the world. Africa is one of the regions with the highest rates, a region which is changing fast. With millions of people still waiting to get access to energy and purified water, with cities still lacking modern sanitation and waste collection, the characteristics of this evolution will be crucial to determine the sustainability of tomorrow's Sub Saharan Africa.

Waste management is an example of a critical issue in African cities. Collection and disposal services are failing to cope with the increasing waste generation that comes with the highest urban growth rates in the world. Few reliable statistics exist, but estimates say that it is common to only have 40% to 50% of the waste generated by urban household actually collected (Mwesigye 2009). Open landfills are the typical destination of the waste which is collected, and the rest ends up in uncontrolled dumps in the city, water bodies and by roadsides (Couth and Trois 2010, Otieno and Taiwo 2007). Beside being a threat for human health, decomposing organic waste is also a source of methane, a GHG 30 times as powerful as carbon dioxide.

African cities will have to develop their infrastructures in the coming decades, for waste management as for other industrial sectors. Whether the cleanest, safest, more environmentally friendly option will be chosen depends on various factors, and carbon markets could be one of them.

The outlook of carbon markets in Africa can look quite pessimistic (Figures 1.5 and 1.6). Sub Saharan Africa hosts only 2.6% of the world's CDM projects (UNEP Risoe Centre 2012). On the voluntary markets it is estimated that only 4% of the GHG emision reductions traded come from Africa (Peter-Stanley et al. 2011). The volumes are small, and several analysts have pointed out that CDM projects are not benefitting Africa and Africans as they are doing with other regions, because of the lack of human, technical and political capacity (Desanker 2005, Couth and Trois 2010, Whitman and Lehmann 2009).

1.1.3 Ghana, Northern Ghana, Tamale

Ghana, the rising star of West Africa

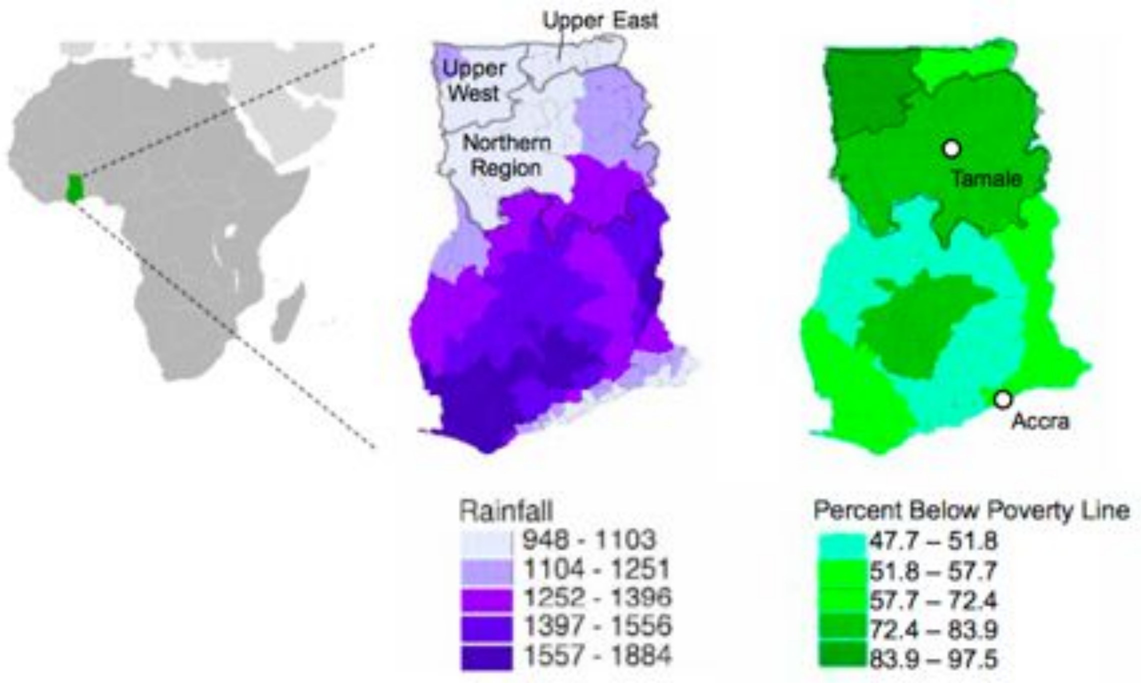
Ghana is a West African country about 6 times the size of the Netherlands, located between the Equator and the Tropic of Cancer, between Togo and Ivory Coast, on the Gulf of Guinea. It spans about 700 km from North to South, with a transition from dry savannah to tropical forest.

The country is a good example of a fast growing economy facing big opportunities and big challenges. According to the CIA Factbook Ghana was in 2011 the second fastest growing country in the world, with a growth rate of 13.5% (China for example had a growth rate of 9.5%. CIA 2012). On the other hand 38.5% of the population, over 9 million of people live below the poverty line (CIA 2012), and energy demand grows faster than supply: Ghana depends on energy imports from Ivory Coast and in rural areas a staggering 82% of the population depends on cherosene and candles for lighting (Yankey 2011).

In Ghana there are no active CDM projects yet. One has been approved and is being launched in 2012, in fact a large scale municipal solid waste (MSW) composting plant in Accra, the Ghanaian capital (Ghana Business News 2011). Despite the lack of centralised statistics about voluntary carbon market projects, some information is available about the existence of projects in the fields of forestry and improved cooking stoves (Thiel and Hawkins 2011, Gold Standard 2012).

The development challenges of Northern Ghana: the feedback loop between poverty and desertification

Figure 1.7: Location of Ghana and regional differences in rainfall and poverty (maps taken from CIA 2012 and Lipper and Osgood 2001)



Ghana is a rising economy in the African landscape, but the opportunities do not reach out equally to all of the population. The North of Ghana was described once as a place "where people eat rocks and it rains twice a year"[1].

Divided in three regions (Northern, Upper East and Upper West Region) the Northern part of the country has a different climate and is much less developed (Figure 1.7). The Northern part of the country has worse infrastructures, less fertile land, 45% of the country's poor and 57% of the country's cases of extreme poverty (Al-Hassan and Poulton 2009). Subsistence farming is by far the

[1] Definition actually heard from a development worker

first activity of households in rural areas, and 75% of household income in rural areas of the North comes from agriculture (GSS 2008).

Threats of desertification, decreasing crop yields and increasing need for fertilizer application have been reported (Diao and Sarpong 2007). In the past 2 years the government had to start subsidizing chemical fertilizer, a practice that had been abandoned in the 80s, to allow rural households to maintain sufficient crop yields for their subsistence. Decreasing soil fertility increases the vulnerability of the numerous rural households for whom land is the main asset for food and income provision. Its causes are the absence of nutrient and organic matter recycling practices, the elimination of vegetation cover due to land clearing with fire, and deforestation (Blench 2006). The vast majority of farming activity is rain-fed, and thus only possible during the rainy season, that lasts from May to August. The fact that soils are losing fertility means that their water holding capacity decreases, and with it the amount of rainless days that crops can survive and, subsequently, the income of a rural household.

Tamale

The main urban centre in the North of Ghana is Tamale, a fast growing city of 350,000 inhabitants. It is the capital of the Northern Region, as well as a commercial and political hub for the whole North of the country.

Tamale is a growing but poor city. It has been connected to the South of the country with a paved road for less than 10 years only, and although the whole of Tamale is connected to the power grid, blackouts are almost a daily occurrence in the city. There is no facility for wastewater treatment, collection or disposal in the whole city (Cofie et al. 2005).

Tamale has no industry beside three agro-processing plants (for rice, cotton and vegetable oil). All the formal jobs are in the trade sector, government jobs or in foreign aid-funded development projects. The most secure source of income is agriculture, and everybody who can afford it runs a farm in the peri-urban area. It is estimated that within the administrative boundaries of Tamale about 60% of the inhabitants are engaged in farming activities (Ghana Districts 2012).

Waste management in Tamale is contracted by the Tamale Municipal Authority to Zoomlion Ltd., a fast growing Ghanaian company active in the fields of waste management and sanitation. According to their estimates about 810 tons of MSW are generated daily in the city but only 13% is collected and sent to the only landfill of the city while the rest is left in informal dump sites and water bodies (Puopiel 2010). The organic content of MSW is relatively low compared to cities in the South of Ghana (40% vs 45-65% according to Drechsel et al. 2004, Ch. 4.1). Due to the low availability of biomass in the dry season, food waste is commonly eaten by goats and chicken that roam freely in the city: the municipality estimated the presence of 185'000 small ruminants in the 350'000 inhabitants city (Drechsel et al. 2004).

1.1.4 Organic waste from problem to resource: composting, anaerobic digestion and biochar production

In the Tamale area, struggling with decreasing soil fertility and shortage of energy and jobs, organic waste could indeed be turned from a problem for the global climate into a resource for local development.

This study will focus on three forms of recycling of organic waste that can be put in place to extract nutrients, energy and carbon to improve soil properties: composting, anaerobic digestion and biochar production.

Composting

Composting is the aerobic degradation of waste biomass, that is turned into humus by microorganisms. The product, compost, is a chemically stable organic fertilizer. Composting is practiced in industrialized countries as a form of recycling for organic household waste, in urban settings, and for farm waste in organic agriculture. In developing countries including Sub Saharan Africa it is advocated as a very good solution for environmental and economic problems connected to urban waste management (Couth and Trois 2010, Drechsel et al. 2004). As opposed to chemical fertiliser, organic fertiliser can help to counteract soil degradation by replenishing the soil organic carbon content which normally decreases in land under cultivation (Vagen et al. 2005, Vanlauwe and Giller 2006).

According to Rogger et al. (2011), there are only 37 registered CDM composting projects worldwide, of which 12 based on MSW, but none of them has managed to issue any emission reduction certificate yet. On the voluntary markets, credits (or VER, voluntary emission reduction) from composting are also rare, but for its potential contribution to rural development they are considered high quality credits (Tanja Schmidt, myclimate, personal communication 08.09.2011).

Anaerobic digestion

Anaerobic digestion is the production of biogas (a mix of methane, carbon dioxide and other trace gases) from the degradation of biomass in anaerobic conditions. In industrialized countries it is becoming more and more used to produce electricity or fuel for urban buses from household or industrial organic waste (Bogner et al. 2008). In developing countries it is also often recommended as appropriate technology to treat human or animal waste at different scales, being technically simple and addressing at the same time sanitation and energy access issues (Srinivasan 2008).

Biogas CDM projects are common, but rather than for processing MSW they focus on the household level, on wastewater or on agro-industrial waste (UNEP Risoe Centre 2012).

Biochar

An emerging technology in the field of organic waste management that could have the potential to represent a breakthrough for climate change mitigation is biochar.

Biochar is nothing but charcoal incorporated into agricultural land. It is produced with pyrolysis, combustion in anoxic conditions, of any type of biomass. Biochar is at the same time an extremely stable way of sequestering carbon and a powerful soil ameliorant, so it could be a very effective way of sequestering carbon in farmland while improving soil fertility (Lehmann et al. 2006, Schouten 2010).

Pyrolysis is an exothermic reaction, so it emits energy. It could thus potentially represent the first carbon negative form of electricity generation, as the amount of carbon that is sequestered in biochar is higher than the amount of carbon dioxide emitted during pyrolysis (Woolf 2008).

There is no approved methodology for claiming carbon credits from the use of biochar as yet, which means that carbon sequestration from the use of biochar cannot generate offsets. However a part of the scientific community is strongly advocating biochar technology for climate change mitigation (Woolf et al. 2010, Whitman and Lehmann 2009), so it could potentially be included as a land-based carbon management method, just like forestry, in future climate negotiations.

1.2 Research layout

1.2.1 Problem definition, research goal and research questions

The problem addressed by this research

Organic waste can be a resource, but at the moment in Tamale it is unused as well as a source of GHG emissions. It could be recycled into fertiliser, biogas or biochar with double benefits for climate and soil but in this context it is not, even though there are carbon markets in place to encourage this kind of projects

The goal of this study

The goal of this research is to look at possible future scenarios where organic waste is being used for energy production and soil fertility protection in northern Ghana, quantify the climate benefits, evaluate the conditions that would be necessary for their economic feasibility and what contribution from carbon markets would be needed to make these technologies feasible.

Research question

This research aims at answering the following research question:

What climate benefits can be achieved with composting of MSW, anaerobic digestion and biochar production in Tamale? Can access to carbon markets create the conditions for these technologies to be economically viable in that context?

The main research question is articulated into the sub-questions below:

- *What climate change mitigation benefits can be achieved with composting, anaerobic digestion and biochar in Tamale?*
- *Are they economically feasible or what are the necessary conditions for their economic feasibility? How would access to carbon markets change the situation?*
- *Do the benefits from access to carbon markets for organic waste management projects reflect their actual contribution towards climate change mitigation?*

1.2.2 Approach

The research questions defined above is addressed by following the steps outlined below, which are reflected in the structure of this report.

1. Define possible future scenarios for composting, anaerobic digestion and biochar production systems from the technological and business points of view (Chapter 2).
2. Perform a carbon footprint of each scenario (Chapter 3).
3. Assess the economic feasibility of the considered projects with and without access to carbon markets (Chapter 4).
4. Rank the scenarios from the perspectives of climate mitigation potential, economic feasibility in the present economic circumstances (with and without the generation of carbon credits) and benefits received from access to carbon markets (Chapter 5).

1.2.3 Industrial ecology perspective

This research is a graduation project for a master programme in industrial ecology, a discipline that studies complex sustainability issues from a systems perspective. Taking a systems perspective to solve a problem means aiming at broadening the question, rather than focussing on a specific side of it. This study aims at addressing the problem and research questions defined above using an industrial ecology approach by:

- Using a *multidisciplinary approach* where scenarios are evaluated looking at what new material flows as well as economic flows they create.
- Taking a *cross scale focus*, by examining the impact of the scenarios on the global issue of climate change while assessing their chances of success at the local scale.
- Assessing environmental performance using *life cycle thinking*, by looking at how the implementation of the scenarios would influence all the systems involved (agriculture, waste management, energy, infrastructure) in order to try to prevent possible environmental side effects.

1.2.4 Field research: internship at DeCo in Tamale

DeCo! Sustainable Farming[2] (DeCo) is a small German-Ghanaian social business/NGO which is working on waste composting in the Tamale area. It was founded in 2010 and entered the pilot implementation stage in 2011.

Part of the research necessary for this study was performed on the field during an internship at DeCo in Tamale that took place between April and June 2011. DeCo also provided economic and technical data used in the evaluation of the scenarios.

[2] www.deco-farming.com

Chapter 2

Scenarios definition

The scenarios that are compared are three different organic waste management systems for the city of Tamale. Three different technologies are considered: *composting*, *anaerobic digestion* and *pyrolysis for biochar production*.

2.1 Choice of technologies

There is a wide range of technical options for composting, anaerobic digestion and pyrolysis. The specific technologies used to build the scenarios were chosen based on the following criteria.

- They should be *labour intensive* technologies, in order to take advantage of low cost of labour in the region and to create employment.
- *Low tech* processes are preferred, to minimise the risks of technical failures. Availability of technical assistance and spare parts can be an issue in Ghana, especially in the Northern part of the country, which is more isolated and underdeveloped. Past experiences have shown that often in Africa technical failures can compromise the success of whole projects (see the review of composting projects in West Africa in Drechsel et al. 2004, Ch. 3).
- *Data* about the implementation of the technology in the context of Ghana should be available.

Below the technologies chosen for the definition of scenarios and the reasons determining the choices made are described.

2.1.1 Composting technology

The technology of *windrow composting* was selected. It does not require use of complex machinery, and DeCo made available data from its implementation experience in Tamale.

In windrow composting the biomass is piled up in heaps 1,5 m tall (Figure 1). The composting process takes about 2 months to complete, during which the heap is periodically turned, about 6-7 times in total, to avoid the formation of anaerobic conditions. Water is added for the moisture content to be optimal for the degradation reactions.

2.1.2 Anaerobic digestion technology

For anaerobic digestion a low cost *dry fermentation* reactor designed and realized within a ETH Zurich project at the Kwame Nkrumah University of Science and Technology (KNUST) in Kumasi, Ghana is used.

The choice of this technology is due to the fact that data about its costs and technical details was made available by the ETH Zurich project and that its cost is relatively low compared to other anaerobic digestion technologies used in developing countries (Burri and Martius 2011). Furthermore in dry fermentation the digestion residue is solid. This means that the digestate can be processed with windrow composting, while normally the residue from anaerobic digestion is liquid and cannot be further treated aerobically.

Figure 2.1: Windrow composting

Figure 2.2: The biogas digester at KNUST, in Kumasi

The reactor is a shipping container fitted with a water perculation system where water is pumped from a tank, trickles down from the ceiling and is collected again on the bottom[1] (Figure 2). Methane generated within the digester can be collected and fuel an electricity generator. One digester can process about 6 tons per batch, which takes 28 days to complete (Burri and Martius 2011).

2.1.3 Pyrolysis technology

For biochar production the details of no specific technology were available, so a hypothetical pyrolysis oven is considered, with characteristics based on the results of internet research.

The system is assumed to be a simple reactor where rice husks are loaded and then pyrolysed (combusted in absence of oxygen). Syngas, a mix of methane, carbon monoxide and other trace gases, is formed in a pyrolysis reaction. Here it is assumed to be recirculated into the oven to fuel the combustion reaction.

The only product is biochar[2].

2.2 Scenarios layout

These waste processing technologies are not mutually exclusive ways of treating organic waste but can in fact be combined, as the residue from anaerobic digestion can be composted and the use of biochar together with compost can improve its agronomic properties.

Combining these organic waste processing technologies can bring benefits for their implementation, if cost savings can be realised. Here three scenarios are constructed, as the integration of more than one of them.

The scenarios considered are the following, as depicted in Figure 2.3.

1. COMPOST (composting):

2. BIOGAS (anaerobic digestion and composting)

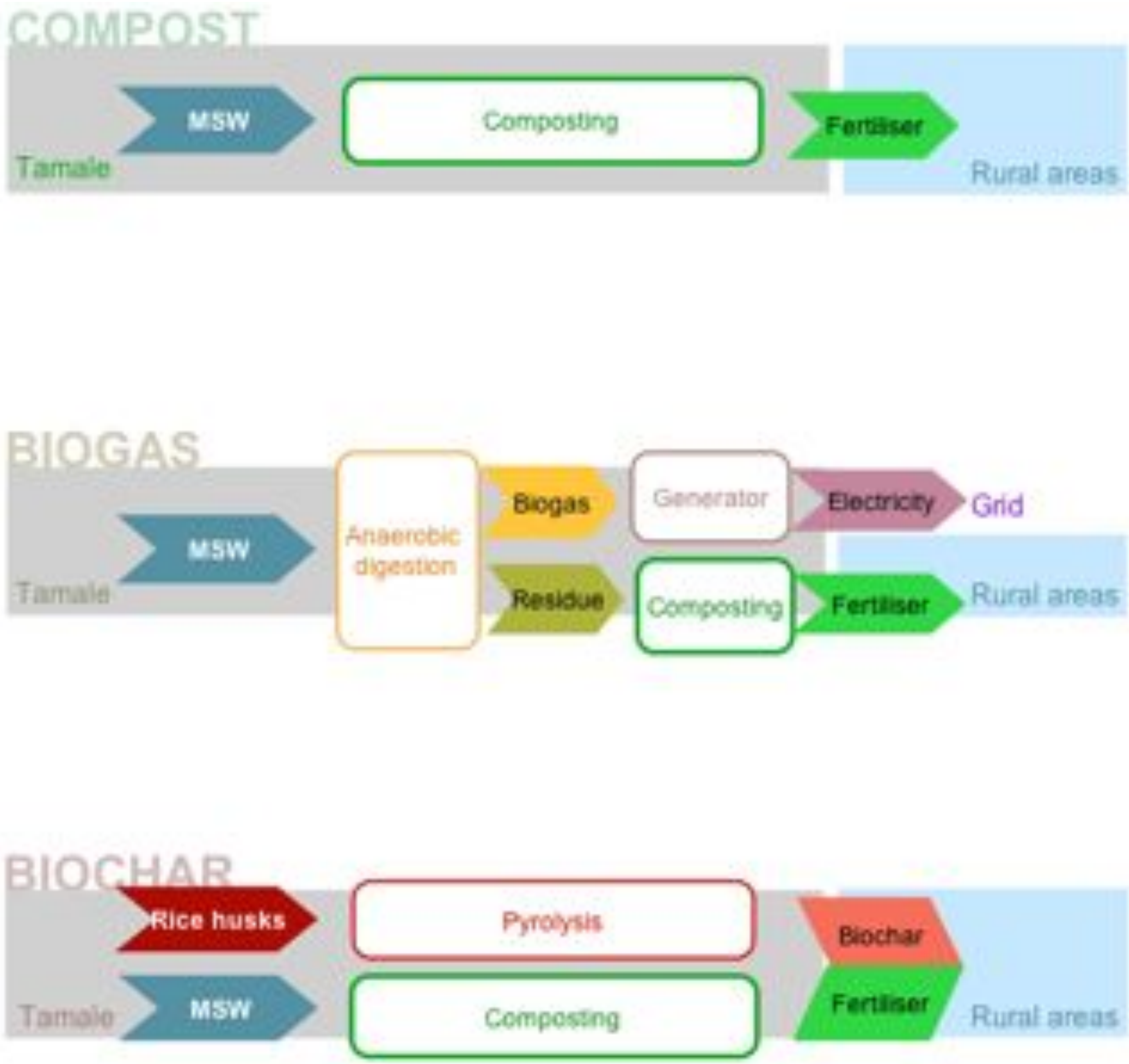
3. BIOCHAR (biochar production and composting)

This section describes the scenarios, covering the scale of operations, material inputs and outputs of the considered systems and the end use of their final products.

[1]Dry fermentation is not really dry, as water is crucial for the biological digestion processes, so the main difference between wet and dry processing is in fact the share of solids present in the feedstock.

[2]Electricity and bio-oil can also be produced through pyrolysis of waste but this kind of technologies are only efficient at larger scales. Heat is here a byproduct, but not a very valuable one in the climate of northern Ghana, with very high day temperatures all year round.

Figure 2.3: Layout of the three scenarios



2.2.1 Scale of operations

Composting and anaerobic digestion

The scale at which the technologies are implemented in the scenarios is defined as a plant with an output of *3,000 tons of organic fertiliser*.

This is a small scale project. For comparison, at this scale the project will treat about 10% of all the organic waste *collected* in the city, and less than 1% of all MSW *generated* in Tamale in one year, according to the best estimates available[3] (Puopiel 2010, ZoomLion Ghana ltd., personal communication 28.06.2011).

The choice of focussing on small scale was made because of the higher labour intensity of decentralised waste management,

where many small plants treat a city's waste instead of one large scale centralised one. The choice of focussing on only one plant is due to reasons of data availability, as data about operations of one composting venture of this scale in this context was provided by DeCo, while the costs involved of managing a larger network of plants could not be accurately estimated. The study of the economic feasibility and climate impact of one small scale plant can however provide insight into the potential benefits of extensive decentralised organic waste management.

This kind of throughput requires an input of 1,500 tons per year of source separated organic MSW, and 3,000 tons of other types of organic waste, in order to optimise the composting process and the final product's quality, according to information provided by DeCo.

Biochar production

Biochar production is a process mostly suited to industrial or agricultural organic waste flows, and no literature was found concerning the technical feasibility of biochar production from MSW.

If MSW is abundant in Tamale, not much large scale food processing is present in the city. The scale of the biochar system was then chosen based on the availability of feedstock in the local area.

In Tamale the one main agro-processing plant is a rice mill which can process up to 12,000 tons of rice per year (Braimah 2011). The feedstock of the biochar system is then considered to be rice husks, the residue of rice processing, obtained from this mill.

The pyrolysis system was assumed to process *2,400 tons per year of rice husks*, assuming rice husks generation is 20% of total rice production by the rice mill (Karve and Prabhune 2009 p.27).

[3]It is hard to estimate organic waste generation in the city of Tamale. Only about 13% of MSW is collected by the local waste management contractor and estimates of total organic waste available range from 60'000 tons to 160'000 tons. .

2.2.2 COMPOST scenario

In the COMPOST scenario the organic fraction of MSW is composted with other locally sourced organic waste. The compost is mixed with poultry manure to increase its nitrogen content and sold as organic fertiliser to farmers in the surrounding districts.

1. *Waste procurement.* 1,500 tons per year of source separated organic MSW are delivered by the local waste contractor to the composting plant. Beside organic MSW, other inputs are collected locally and used in the composting process (leaves, straw, residue from shea butter production) adding up to an extra 1,500 tons per year.

2. *Composting.* During the composting process, which lasts about 2 months, the mass of the waste decreases by 50%. Water is added regularly to keep the moisture content optimal.

3. *Mixing and packaging.* After the composting process 1,500 tons per year of poultry manure which is mixed with the compost into the final organic fertiliser product, to increase its nitrogen content and thus its quality. The poultry manure needs to be transported by road from Kumasi, the second biggest city in Ghana, where several intensive poultry farms are located. The organic fertiliser is packaged in 50 kg bags.

4. *Delivery to end market* The compost is delivered in equal parts to distribution points in Tamale and the two districts surrounding the city within a range of 70 km (see Figure 3.6 on page 33 for a map of the considered distribution points in the region), where it is sold to local farmers.

2.2.3 BIOGAS scenario

This scenario represents the integration of anaerobic digestion and electricity production from biogas with the composting operations described in COMPOST. Organic waste is used for producing biogas and its residue is then composted in windrows and sold as fertiliser. Electricity is produced on site and fed into the grid.

The assumption here used is that *the quality of the finished compost is the same both when the waste is directly composted*, as in COMPOST, *and when it first undergoes dry fermentation and then is composted*, as in BIOGAS[4].

1. *Waste procurement.* Same as COMPOST.

2. *Anaerobic digestion.* The waste processed in 25 container-sized digesters connected in parallel. Each has a capacity of 60 tons per year. The yield of biogas is 100 m^3 per ton with a methane content of 60%, or about 30'000 m^3 of methane per year (Martius and Burri)

3. *Electricity generation.* The methane is combusted in a 35 kW electric generator, with an efficiency of 35%, yielding about 300 MWh per year.

[4]No information was found about comparisons of the residue of dry fermentation and composting in tropical climates, so the validity of this assumption should be tested with practice.

4. *Composting.* After each batch the digestate is composted as in the COMPOST scenario. The combined mass reduction of the feedstock during stages 2.Anaerobic digestion and 4.Composting is considered to be the same as composting alone, 50%.

5. *Mixing and packaging.* Same as COMPOST.

6. *Delivery to end market.* Same as COMPOST.

2.2.4 BIOCHAR scenario

This scenario includes a pyrolysis system that produces biochar from the waste of the local rice mill and the composting system described in COMPOST.

Biochar production is considered to be carried out together with composting because combining the two leads to cost savings. The intended buyers and the distribution networks of compost and biochar would be the same, traders of agricultural inputs and farmers in the region, so marketing and logistic costs can be split between the two operations.

1. *Waste procurement.* Same as COMPOST, with the addition of the collection of 2,400 tons per year of rice husks.

2. *Composting.* Same as COMPOST.

3. *Biochar production* Rice husks are charred on site. The yield of the biochar system is of 25% by weight.

4. *Mixing and packaging.* Same as COMPOST for the organic fertiliser. The biochar is packed separately.

5. *Delivery to end market.* Biochar and compost are delivered to the same end users as in COMPOST. Biochar is considered to be applied at a rate of 10 tons per hectare[5] to different farms every year. Biochar is a stable substance in soil, so its benefits last for years and it does not need to be applied annually. Since the yearly production is of 600 tons, 60 hectares of farmland can be treated annually.

[5]More details in section 3.2.4.

Chapter 3

Climate impact

This chapter is about the evaluation of the climate change mitigation potential of the considered scenarios.

All the scenarios can achieve climate mitigation impacts by avoiding methane emissions from landfills, producing renewable energy, sequestering carbon in farmland and also substituting the use of chemical fertilizers. All scenarios however also create new emissions as they require the construction of new buildings and machinery as well as transportation of waste, compost, biochar and international project staff.

The goal of this evaluation is to quantify the *net* climate benefit (or cost) that each alternative has over the whole life cycle of organic waste management (composting, anaerobic digestion and biochar production), energy production and farming activities, *compared to business as usual*.

This chapter presents the methodology and the data used and the results of the assessment.

3.1 Methodology

The methodology used is a Life Cycle Assessment (LCA) limited to evaluating the climate change impact category.

The section below explains the steps needed to perform an LCA, which are the same steps that are followed in the rest of this chapter.

3.1.1 Life cycle assessment

Life Cycle Assessment, the most used tool for environmental impact assessment, is defined in ISO 14040 as *the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle* (Guinée 2002, p. 403) and is articulated in four distinct phases: goal and scope definition, inventory, impact assessment and interpretation.

In the *goal and scope definition* phase the boundaries and components of the systems to be evaluated and their functions are defined, as well as the types of impact to be assessed (sections 3.1.2 to 3.1.5).

Based on that in the *inventory* phase the material inputs (raw materials) and outputs (emissions and waste) of each process in the system are quantified and summed up. The results of the inventory are not presented in this chapter because some of the data used was already expressed in tons of CO_2 equivalent (tCO_2eq, the unit of climate change impact in LCA), bypassing the emissions of individual GHG.

With the *impact assessment*, then, the environmental impacts of the whole system are quantified based on the results of the inventory phase. Several types of analysis can also be performed on the data to get insight on the impact of different parts of the systems and the degree of uncertainty of the results (section 3.3).

In the *interpretation* phase the significance of the results in relation to the goal of the assessment is discussed. Here an interpretation of the results can be found in Chapter 5.

3.1.2 Alternatives

In order to estimate the *reductions* of GHG emissions, an additional scenario, BASELINE, needs to be considered, which represents the emissions of the business as usual situation, or the absence of any organic waste management project.

The alternatives to be compared are therefore the following four.

1. BASELINE, where the organic waste goes to landfill together with the rest of the collected MSW and the farmers use conventional NPK fertiliser.
2. COMPOST as described in Chapter 2.
3. BIOGAS as described in Chapter 2.
4. BIOCHAR as described in Chapter 2.

3.1.3 Functional unit and impact allocation

In order for the comparison between the emissions of each alternative to be meaningful, every alternative needs to have the same level of utility to society, to satisfy the same functions to the same extent.

For example since the systems in COMPOST, BIOGAS and BIOCHAR are assumed to treat 1,500 tons per year of organic MSW, then in BASELINE only the impacts of landfilling the same amount of waste, rather then the emissions of the whole Tamale landfill, should be accounted for.

LCA calls this the *functional unit* of the systems.

If here all alternatives have in common being a form of disposal of 1,500 tons of organic MSW, each alternative has also different extra "useful" outputs, it is *multifunctional*:

- COMPOST, BIOGAS and BIOCHAR provide fertiliser.
- BIOGAS provides electricity while the other scenarios do not.
- BIOCHAR, in addition, disposes of rice husks and provides a soil amendment, biochar.

How can the environmental impacts of such different systems be attributed to each function? This is a problem of *allocation* of environmental impacts.

Allocation method

The approach chosen here to deal with the multifunctionality of the considered systems is *system expansion*. The functional unit is extended to include all functions of all alternatives. The system of each alternative is expanded to include the processes corresponding to business as usual ways of fulfilling those functions it did not satisfy before, such as use of NPK fertiliser for fertilising land in BASELINE or use of diesel generators to prodce electricity in all scenarios but BIOGAS.

The choice of an allocation method over another can have a significant impact on the results of an LCA. Other possible ways of dealing with multifunctional systems are *economic allocation* and *allocation on mass basis*, and both do not require extending the functional unit. The former attributes the environmental impacts of the system to the various functions depending on the price at which each of them is sold, the latter depending on the mass of the products.

Allocation on mass basis could not be used here because one of the products, electricity, has no mass. The choice of system expansion over economic allocation is due to the fact that the market price of the products is not certain in this case. Biochar and organic fertiliser both do not have a market at the moment in Northern Ghana, electricity is a state monopoly and the price at which it could be sold to the government will depend on an *ad hoc* agreement, the price of waste disposal is also subject to negotiation with the local waste operator[1]. Conversely the way these functions can be performed in a business as usual situation is quite straightforward. High uncertainties in the selling price of the products indicate that economic allocation would have been more arbitrary than system expansion.

Functional unit

The functional unit is then defined as *disposal of 1,500 tons of organic fraction of MSW and of 2,400 tons of rice husks, fertilisation of 1,250 hectares of land and production of 301.7 MWh of electricity*, according to the following considerations.

- The magnitude of each function (i.e. the amount of electricity produced and land fertilised with 1,500 tons of organic waste) is calculated based on the assumptions explained in Chapter 2.

- Concerning the utility of fertiliser, different types of functional units can be used to compare compost with NPK: mass of nitrogen or other nutrients available to plants, area of land that can be treated, yield of crop harvested etc. Here the choice was for area of land fertilised, assuming that the compost will be applied by all farmers at the same rate, that which gives a yield equivalent to that of the rate of NPK fertiliser commonly used[2].

- Since there is no business as usual version of biochar, a new product with unique properties, here the choice was made not to include its benefits in the functional unit. The improvement of land treated with biochar is taken as a positive side effect of the BIOCHAR scenario.

- Similarly the other advantages of the use of compost as opposed to NPK for soil fertility, in terms of improved water retention capacity, cation exchange capacity or soil structure (Biala 2011) are considered as additional benefits and not included in the LCA[3].

[1] More information about the issue of product pricing can be found in Chapter 4.
[2] See section 3.2.4 for more details on assumptions on fertiliser use.
[3] In some contexts they can be included as reduced irrigation and fuel use for agricultural machines, but in Northern Ghana agriculture is rain-fed and non-mechanised.

3.1.4 System boundaries

The processes included in the inventory of each scenario are depicted below in Figures 3.1, 3.2, 3.3 and 3.4.

Included in the systems are the processing of organic waste, the transportation of waste to processing and of fertiliser to the farms, emissions of nitrous oxide (N_2O) from agricultural soil and carbon sequestration into them, emissions from the construction of capital goods (composting plant, biodigesters, generator, pyrolysis oven, trucks) and the travelling of the project's international staff[4].

The production of fuel and pumping of water are not included. For the impacts of material requirements of capital goods, cradle-to-gate values were used.

3.1.5 Inputs and outputs

In the inventory, the only outputs that are quantified are emissions of GHG, and only two inputs are included: organic matter and biochar in agricultural soils.

The conversion of GHG emission values into tCO_2eq, the unit of climate change impact, is performed using GWP100 factors. The factor used to convert soil carbon stock increases (for both organic carbon and carbon in biochar) is 44/12.

3.2 Data used

Primary data, collected during the field research in Tamale, provided by DeCo or by the researcher at KNUST was used whenever possible. The remaining data comes from the LCA database Ecoinvent (2010) or from literature belonging to various scientific fields.

The data and assumptions used to calculate the climate impact of the four systems are described in the rest of this section. Further details can be found in Appendix B.

3.2.1 Capital goods

The infrastructures necessary for a composting plant are considered to be a concrete platform for composting (200x200 m, 30 cm thick), a wooden storage shed with a corrugated steel roof (300 m^2, 3.5 m high) and 1 truck. Impact factors for concrete, steel and the vehicle are from Ecoinvent (2010) while the carbon footprint of local wood is taken from Eshun et al. (2010). As explained in Chapter 2, the method used for composting is labour intensive and no machines are used, in order to create more employment.

The components of the biogas system considered are 25 shipping containers and 1 generator. Material requirements for these components are also from Ecoinvent (2010).

Concerning the pyrolysis oven in BIOCHAR, the steel requirement is considered to be 3,500 kg,

[4]Assuming the project would be developed as international cooperation and not 100% by Ghanaian actors.

Figure 3.1: System definition: BASELINE scenario

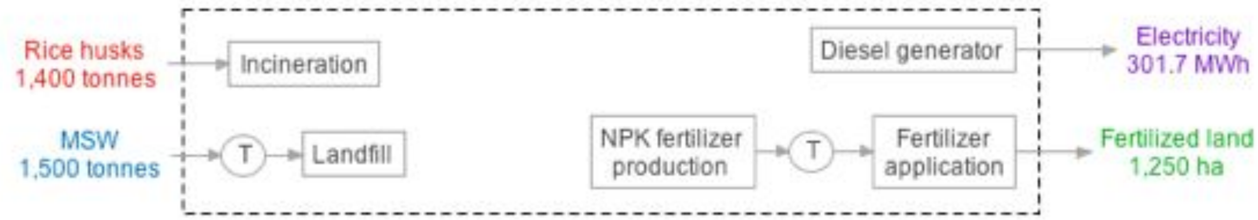


Figure 3.2: System definition: COMPOST scenario

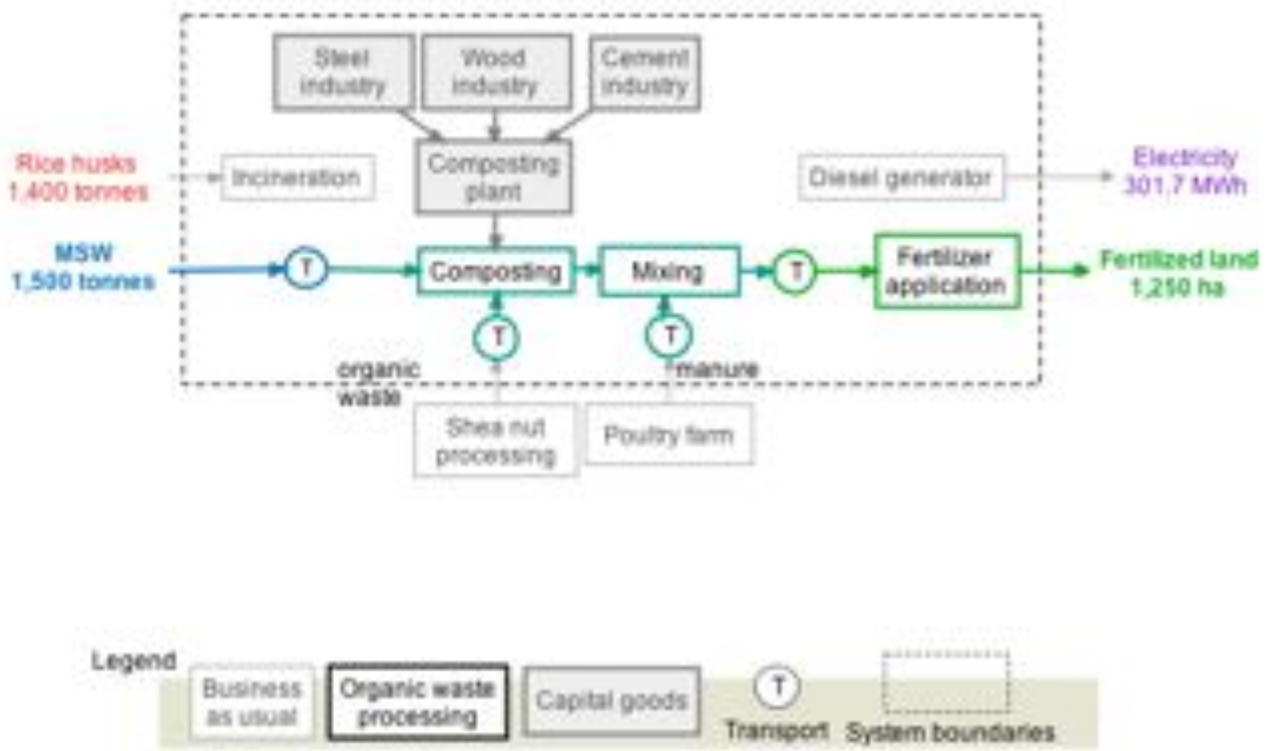


Figure 3.3: System definition: BIOGAS scenario

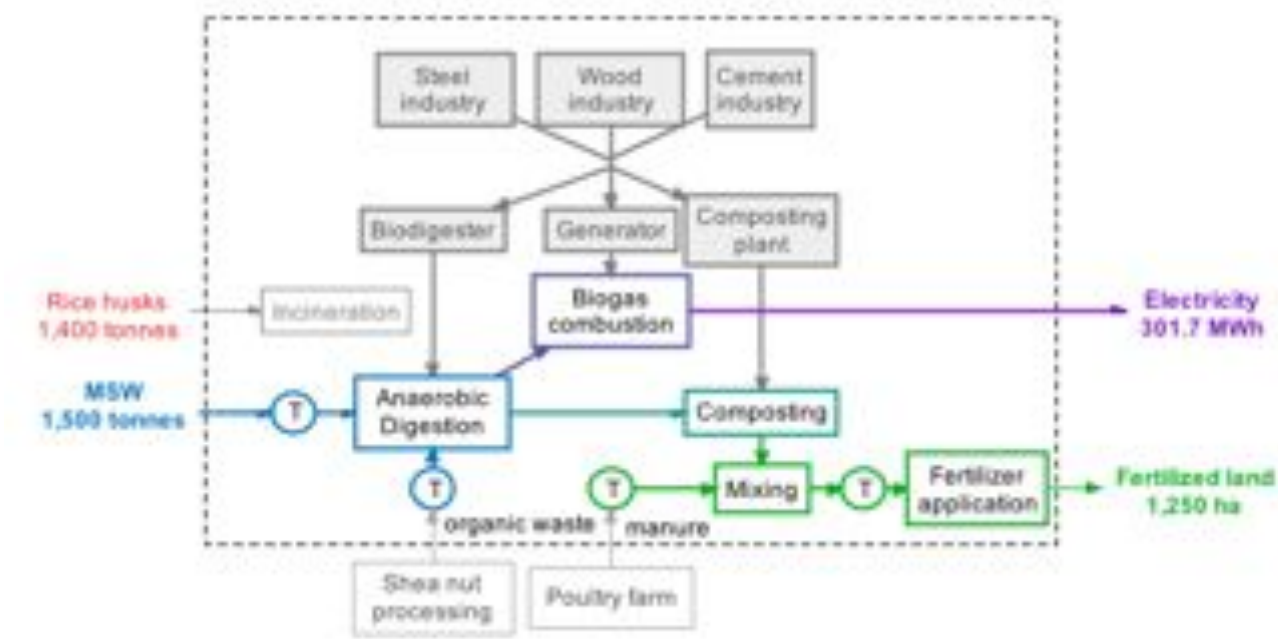
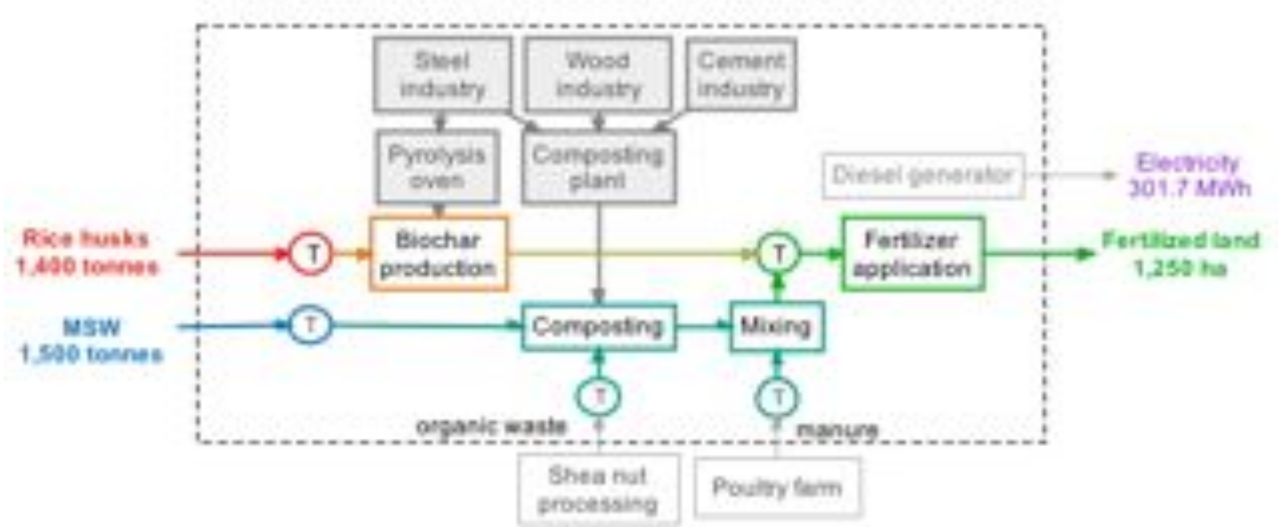


Figure 3.4: System definition: BIOCHAR scenario



from information provided by Biochar Solutions Inc. [5] (personal communication, 22.12.2011). In this scenario the buildings are considered to be 80% larger for the extra storage requirements (of rice husks and biochar).

Landfilling in BASELINE does not require any capital good, as the landfill is in fact just an open dump (ZoomLion Ghana Ltd., personal communication, 28.06.2011), except for the use of a bulldozer. Its carbon footprint is taken from Ecoinvent (2010) but only 9% of the total climate impact is considered, as this is how much 1,500 tons of organic waste represent in comparison to the total annual waste throughput of the landfill according to estimates quoted in Puopiel (2010).

The impacts of capital goods are divided by their assumed lifetime, since the functional unit corresponds to 1 year of project operation, ranging from 10 (for the generator) to 25 years (for the cement platform).

3.2.2 Waste processing

In landfills, anaerobic decomposition of organic waste generates methane (CH_4). Here methane generation is estimated using the approved Clean Development Mechanisms UNFCCC tool (UNFCCC 2010). The resulting emission factor for wet waste deposition in unmanaged landfills in dry tropical weather is 0.02 tons of CH_4 per ton of organic waste if the landfill depth is lower than 5 m and 0.04 if it is higher. Since no information was available about the depth of Tamale's landfill, the value of 0.03 ±0.01 was used. Additionally diesel fuel consumption of 1.97 litres per ton of landfilled waste was considered, accounting for bulldozer use at the landfill site (ZoomLion Ghana Ltd., personal communication, 28.06.2011).

GHG emissions from composting, basically generation of nitrous oxide (N_2O) and CH_4 by the microbiological processes in the compost heaps, are hard to estimate, since they depend heavily on climate, specific technology and inputs used. Values quoted in literature range from 30 to 8000 g per ton of waste for CH_4 and from 60 to 600 g per ton of waste for N_2O, according to a recent review (de Groot 2010). The conservative values of 4000 and 300 ±100% were assumed following IPCC recommendations (as quoted in the same study), since accurate data were not available for the specific context. The turning, moving and packaging of compost is done manually, therefore no additional emission was considered from the composting process.

Analogally, CH_4 and N_2O losses during anaerobic digestion are also difficult to estimate. N_2O emissions were considered negligible and CH_4 losses assumed to be 1000 g per ton of waste, also following IPCC recommendations, with an uncertainty of ±100% (de Groot 2010).

During the pyrolysis reaction CH_4 is formed in the syngas, but this is in turn recirculated in the reactor and combusted, so it is assumed that no GHG is formed during the reaction, exception made for biogenic carbon dioxide (CO_2) (following Roberts et al. 2010), which is not accounted for.

Additional CO_2 is emitted from the compost heaps, the biodigesters and the incineration of rice husks in business as usual scenarios. It is also of biogenic origin and therefore not accounted for.

[5] www.biocharsolutions.com

3.2.3 Energy production

In business as usual electricity generation, emissions from diesel generators were considered. Since Tamale suffers from daily power cuts, the electricity generated from biogas is not considered as substituting the electricity mix from the national grid but rather local production by privates that would not need to use their own generators if there were less blackouts. This choice is in contrast with the approved UNFCCC methodology (UNFCCC 2011), that states that the baseline for on-grid renewable energy projects should rather be calculated using the national electricity production mix.

The emission factor used was therefore 0.9 tCO_2eq/MWh (diesel generators) rather than 0.57 tCO_2eq/MWh (Ghana electricity grid mix) (IPCC 2006).

Emissions from electricity production from biogas were not included in the inventory, as the CO_2 formed during its combustion is biogenic.

3.2.4 Farm processes

Fertiliser application rates

Field trials of DeCo's organic fertiliser in Northern Ghana have found that an application rate of 2.4 tons per hectare (1 ton per acre) gives yields more or less comparable to the application of 2/3 of the recommended NPK application rate (SARI 2011).

The application rates considered in the calculations were therefore of 2.4 tons per hectare for organic fertiliser and of 0.24 tons per hectare for NPK[6]. These rates are much lower than those used in industrialised countries, but they are the rates commonly applied by local farmers, who mostly cannot afford to buy large quantities of fertiliser (Dr. Mathias Fosu, Savannah Agricultural Research Institute, personal communication, 22.06.2011).

Biochar application rate

Haefele et al. (2011) state that positive effects can be achieved with biochar application rates between 0.4 and 20 tons per hectare. Field experiments conducted by DeCo in Tamale have had the best results with an application rate of 10 tons per hectare, so this was the application rate assumed in the model. Since the annual biochar production is 600 tons, 60 hectares can be treated each year.

Biochar stability

The share of the carbon content of biochar that will be sequestered in the soil depends on the carbon content of the biochar itself, in particular the recalcitrant fraction, as opposed to the labile fraction which will degrade in short time and be turned into biogenic CO_2. Here the recalcitrant

[6] That is, two thirds of the recommended rate of 150 kg per acre, or 0.36 tons per hectare.

carbon content was assumed to be 56%, following Woolf et al. (2010, Supplementary information, p.34). Following Roberts et al. (2010) it is assumed that 80% of the recalcitrant carbon content will remain in soil for over 100 years. Therefore 0.45 tons of carbon are considered to be sequestered for each ton of biochar applied.

Nitrous oxide emissions from soil

Emissions of N_2O from farmland following fertiliser application are one of the major climate impacts of agriculture (Biala 2011). However it is very hard to estimate how much they amount to since a lot of factors play a role in N_2O formation in soils (i.e. soil temperature, aeration, moisture and pH) and no context-specific data was found. Following IPCC guidelines (De Klein et al. 2006) a value of 0.0157 kg of N_2O per kg of applied nitrogen was used. Nitrogen content was taken to be 15% for NPK (product specifications) and 1.59% for organic fertiliser (composition of the final product of pilot composting operations).

Studies have shown that in land treated with biochar, N_2O emissions have decreased. It is hard to estimate the magnitude of the reduction because it depends again heavily on local conditions. A review by Woolf et al (2010, Supplementary information, p.17) shows that the reduction can be in the range between 0 and 80%, and it was found to be between 50 and 80% in African savannah soils (similar to those of Northern Ghana) treated with 20 tons/ha of biochar. Here a value of 50% $\pm$ 40 was assumed. Since every year biochar is applied to 60 different hectares of land[7], the N_2O reduction will increase with time (by 6 kg of N_2O every year, or 1.86 tCO_2eq). The value used in the model is therefore the average reduction over 10 years.

Soil organic carbon

The use of organic fertiliser over the years replenishes the organic matter content in agricultural soils providing a form of carbon sequestration that can be significant (Biala 2011) but is hard to quantify without measurements, since it depends on a large variety of factors (including farming practices, initial soil carbon level, soil type, annual precipitations and temperature).

Another of the problems with incorporating this value in an LCA model is that soil carbon accumulation dynamics are not linear, while LCA is. The organic matter accumulation rate over the years is not constant, even with a constant rate of fertiliser application, but it decreases with time and stops when the maximum content of carbon in soil (which depends on factor such as yearly carbon addition, climate and soil type) is reached. For this reason in order to find a coefficient representing the marginal increase of soil carbon per ton of organic fertiliser an effort was made to model soil organic matter turnover.

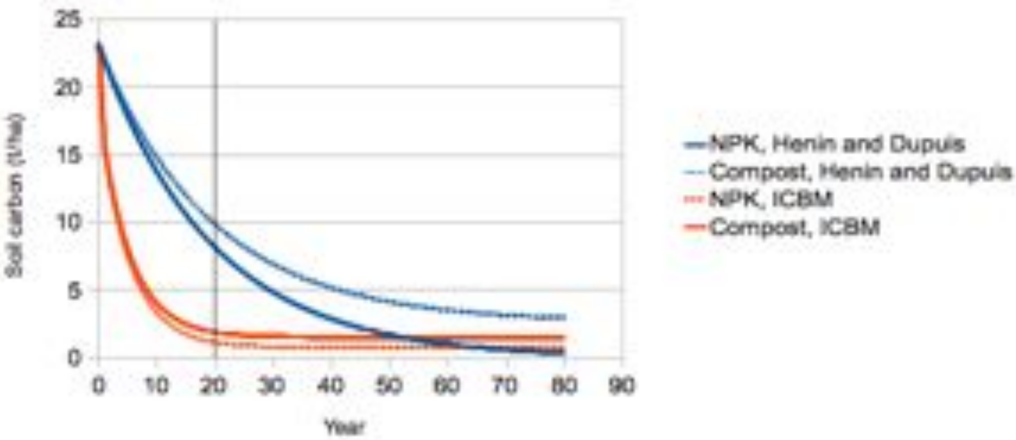
Two different models, Henin and Dupuis (1945) and the Introductory Carbon Balance Model (Andren and Katterer 1997) were used to calculate soil carbon values over time following application of 2.4 tons per hectare of organic fertiliser and for farming without the use of organic inputs. The ICBM model is more sophisticated then the Henin and Dupuis one, but not all the parameters of

[7] Biochar is stable so biochar treatment is one-off. 600 tons of biochar are produced every year and applied at a rate of 10 tons per hectare, as explained in the prevous section.

neither of them could be calibrated with real measurements, so a more complex model does not necessarily mean more accurate results. Parameters that came from measurements were rainfall, temperature and average soil content of carbon, sand, silt and clay.

The results of the two models were different (Figure 3.5) but both indicating that soil organic carbon levels, already extremely low in the region which is threatened by desertification, would decrease even using compost.

Figure 3.5: Soil carbon levels over time



Basically an application rate of 2.4 tons per hectare of organic fertiliser, although sufficient to maintain crop yields at present day, would only be sufficient to slow down the soil fertility loss in the long term but not to stop or overturn it. A difference in soil carbon levels with or without the use of compost can however be expected, and can be accounted for in an LCA model by averaging the soil carbon changes per hectare over a selected time period.

A change in farming practices (i.e. starting to farm a piece of land, or starting to use compost) brings changes in soil carbon levels until a new steady state is reached. The ICBM model showed that a steady state is reached in 20 years, while in the Henin and Dupuis model a longer time lapse is required, about 80 years. Here the choice was made to average soil carbon differences over 20 years, because it is in this time laps that the most changes happen according to the ICBM model and because this could be the time frame of a CDM project about soil organic carbon sequestration.

Over this time span, the difference between land treated with and without compost is of 0.04 tons per hectare per year according to the ICBM and of 0.08 according to the Henin and Dupuis model. A value of 0.06 ±50% tons of sequestered carbon per hectare per year was used. The uncertainty range accounts for the sensitivity of the results to the modelling choices. The amount of carbon sequestered according to the model used is in the same magnitude of the value given by the IPCC tool for estimation of changes in soil carbon stocks (0.10 tons per hectare) (IPCC und.) and Luske and van der Kamp (Luske and van der Kamp 2009) (14% of applied carbon, in this case 0.06 t/ha).

Other assumptions

Other emissions from farming were neglected. All farming processes are at present day performed by hand by the vast majority of farmers in the region, except for ploughing, but that would be the same in all scenarios.

The quality of the compost from digestate and that of the compost from fresh MSW were assumed to be equivalent, since no data was available about comparisons between compost and composted digestate from the same feedstock in tropical climates.

3.2.5 NPK fertiliser production

Emission data for the manufacturing of chemical fertiliser were taken from Ecoinvent (2010). The type of fertiliser considered is Yara NPK 15-15-15, the most commonly used in the region. Emissions for 1 kg of fertiliser were calculated to be of 0.43 kg of CO_2, 2.21 g of N_2O and 0.56 g of CH_4.

3.2.6 Transportation

Distances over which materials are transported were determined using Google Earth for known tracts (MSW to landfill or to the composting plant, poultry manure transport). The organic fertiliser was assumed to be sold in the three districts surrounding Tamale, delivered in equal quantities to 11 distribution points in the main urban centres, at an average distance of 37 km (Figure 3.6).

Shea nut processing waste, constituting 25% of the feedstock for compost, was assumed to be sourced in the range of 20 km, while the 25% of leaves and straw was assumed to be collected locally without need for transportation. Poultry manure comes from Kumasi, the second largest Ghanaian city, about 370 km south of Tamale.

The impact of transportation of NPK fertiliser was calculated assuming ship freight from Scandinavia (where the only fertiliser marketed in Tamale is manufactured, YARA 2011) to the port of Tema in Ghana and then road transport to Tamale.

Fuel consumption factors were calculated using data about actual fuel consumption by garbage trucks (0.07 litres of diesel per ton-km) and transportation of organic fertiliser (0.04 litres of diesel per ton-km). These values are quite high compared to those indicated by other research (Woods and Cooper und., Hine and Sinaga und.), but they are considered consistent with the fact that vehicles used in West Africa are often old and inefficient (Figure 3.7).

In order to account for the return trips of the empty trucks after deliveries a backhaul coefficient of 68% was used, meaning that fuel consumption of empty return trips was considered to be 68% of full load (Woods and Cooper und.).

The resulting emission factors for truck transport is 0.15 kg of CO_2 equivalent per ton-km and for sea freight transport 0.008 kg of CO_2 equivalent per ton-km (all emissions factor from Ecoinvent 2010)

Figure 3.6: Map of the distribution points for compost in the three districts around Tamale

Figure 3.7: Typical look of a Ghanain truck

3.3 Results

3.3.1 Impact assessment

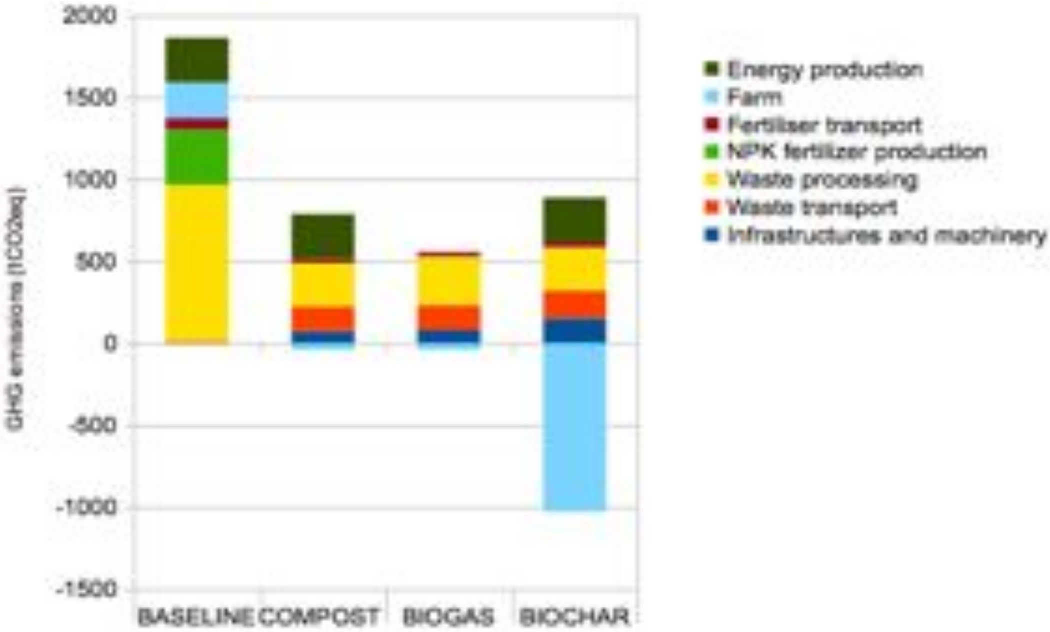
A comparison of the result of the impact assessment for each scenario is presented in Table 3.1, broken down by process. Although the results of the life cycle inventory step are not included, the emissions occurring during the farming stage are divided into N_2O emissions and soil carbon sequestration, to be able to isolate benefits from costs.

The BIOCHAR alternative is the one with the lowest impact, a negative impact in fact, since the sequestration of carbon is higher than the emissions incurred in the rest of the life cycle. BIOGAS is second best, thanks to the double benefits in terms of avoiding landfilling and generating electricity, summing up to a 72% total GHG emission reduction. The COMPOST scenario also brings significant benefits, with an emission reduction of about 60%.

3.3.2 Contribution analysis

Figure 3.8 shows where the major contributions to climate change impact come from in the considered scenarios.

Figure 3.8: GHG emissions breakdown by life cycle stage



- In the BASELINE scenario, CH_4 emissions from the landfill itself constitute more than 50% of the total climate impact, and alone represent a higher impact then the total impacts of each of the other scenarios. NPK fertiliser production has the second biggest impact, 18% of the total, with a similar magnitude as energy production (which accounts for 14%. This shows

Table 3.1: Climate change impact (all values in tCO_2eq)

Process	BASELINE	COMPOST	BIOGAS	BIOCHAR
Capital goods	2.71	72.13	79.97	140.7
Organic MSW to plant/landfill	8.02	7.54	7.54	7.54
Other organic waste to plant		2.29	2.29	2.29
Poultry manure to plant		142.58	142.58	142.58
Rice husks to plant				15.37
Landfilling	956.27			
Composting		265.5	265.5	265.5
Anaerobic digestion			31.5	
Rice husks incineration	0	0	0	
Rice husks pyrolysis				0
NPK fertiliser production	337.85			
NPK fertiliser transport	69.28			
Organic fertiliser/biochar transport		25.93	25.93	31.12
N_2O emissions from soil	219.21	231.64	231.64	228.03
Soil organic carbon sequestration		-273.86	-273.86	-273.86
Biochar sequestration				-985.6
Electricity production from diesel	271.53	271.53		271.53
Electricity production from biogas			0	
Flights		6.37	6.37	6.37
Total	**1864.88**	**751.64**	**519.45**	**-149.06**
Reduction compared to business as usual		-1113.24 (-59.7%)	-1345.43 (-72.2%)	-2013.94 (-108.0%)

that from a life cycle perspective composting and anaerobic digestion of the same amount of organic waste have similar benefits in terms of GHG emissions abatement from an avoided production (of electricity or fertiliser) perspective.

- The main difference between BIOGAS and COMPOST is obviously emissions from electricity production, which are null in BIOGAS while they amount to 36% of the total in COMPOST and are in fact the largest contributor to the total impact, together with emissions from compost heaps (35%). Emissions from anaerobic digestion are not very significant.

- In BIOCHAR the carbon sequestration during the farming stage is alone higher than all the GHG emissions across the rest of the life cycle, which are higher than in COMPOST and BIOGAS due to increased transportation and infrastructural requirements.

- The impact of the farming stage is negative in all scenarios but BASELINE, because of the estimated addition of organic matter into soils. N_2O emissions following fertiliser application are similar for NPK and compost, but they are offset by the decrease in the pace of organic carbon loss connected to the use of organic fertiliser.

- Interestingly the impact of fertiliser transport is the highest in BASELINE. Even though organic fertiliser is ten times bulkier than NPK, the latter has to be transported by truck all the way from the coast, so its distribution still has a higher carbon footprint.

- The impact of waste collection is negligible in BASELINE, ranging from 20 to 30% in COMPOST and BIOGAS and the highest in BIOCHAR, following increasing need for raw materials, as Table 3.1 shows.

3.3.3 Uncertainty analysis

Due to the scarcity of context-specific data (i.e. about transportation impact) and the many unknowns of soil carbon dynamics a lot of the values used in the inventory have a high level of uncertainty. This section presents the results of an uncertainty analysis performed using Monte Carlo simulation.

Uncertainty ranges were derived from a literature review of similar studies for the most uncertain values. Where the uncertainty was due to the variability of known processes in known conditions the probability distribution was assumed to be a normal curve. Where the uncertainty was rather due to the lack of reliable data for the considered conditions, and thus higher, a flat distribution was instead used. The uncertainty values are summarised in Table 3.2.

A Monte Carlo simulation was performed with 1 million runs. The outcome, shown in Figure 3.9 is an uncertainty range of the results of the impact assessment (the error bar) and their standard deviation (the hatched area).

Uncertainty ranges, which represent the distance between the extreme best and worse case scenarios, are very high, ranging from 80% for COMPOST to above 700% for BIOCHAR. Even within these ranges, however, the BASELINE scenario is likely to perform worse than the other three in most cases. The uncertainty ranges of COMPOST and BIOGAS overlap, meaning that the former could have a lower impact than the latter. In fact however that is not a likely outcome, since the main

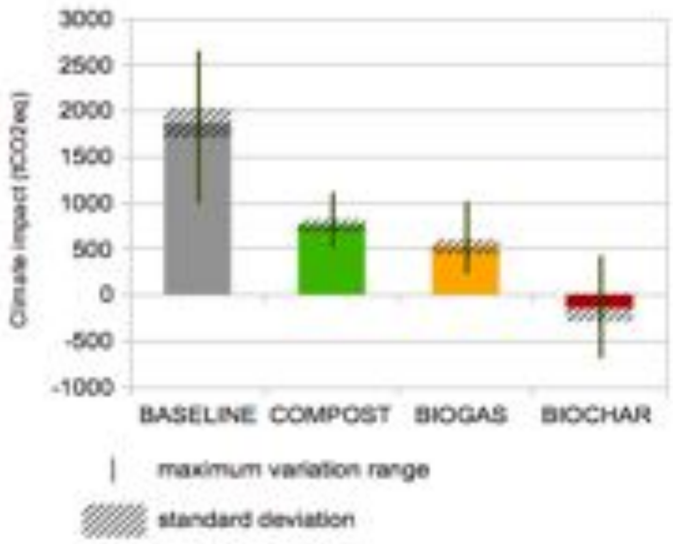
Table 3.2: Summary of uncertainties

Value	Uncertainty range	Probability curve
Emissions from road transport	±25%	Flat
CH_4 formation in landfill	±33.3%	Normal
N_2O and CH_4 from composting/anaerobic digestion	±100%	Flat
Soil carbon variation	±50%	Flat
Biogas yield	±25%	Normal
Compost yield	±20%	Normal
Biochar carbon sequestration	±33.3%	Normal
Soil N_2O emissions reduction with biochar	±80%	Normal

uncertainties in the two scenarios are the same (i.e. N_2O emissions from compost heaps, soil carbon conservation). BIOCHAR has the highest uncertainty in relative terms, but it is still lower than BASELINE in absolute ones.

Standard deviation values (the hatched area in Figure 3.9) are lower, around 8 to 9% in BASELINE and COMPOST, 15% in BIOGAS. It is higher in BIOCHAR at 100%, but again still lower than BASELINE in absolute terms. Within these ranges the ranking of the scenarios cannot change. The GHG abatement of the considered waste processing systems compared to landfilling is most likely significant, certainly higher than 50%.

Figure 3.9: Net GHG emissions with uncertainty



Process level uncertainties

To have an insight on which of the uncertain values are the most relevant to the overall results, the percent uncertainty ranges specified in Table 3.2 above, those for single processes, were calculated also as absolute values.

- For emissions of single processes, the magnitude of the uncertainty was calculated as double the product of uncertainty range and climate impact (expressed in tons of CO_2 equivalent):

$$\text{AbsoluteUncertainty} = 2 \times \text{UncertaintyRange} \times \text{ProcessImpact}$$

- The uncertainty of *biogas yield* and *compost yield*, which are not emission values but process efficiencies, was calculated with the same formula using the impact of avoided processes. This means assuming that in case of lower yields business as usual electricity and fertiliser are used to add up to the functional unit[8].

$$\text{AbsoluteUncertainty} = 2 \times \text{UncertaintyRange} \times \Sigma_i \text{AvoidedProcessImpact}_i$$

  For biogas yield conventional electricity production was used.

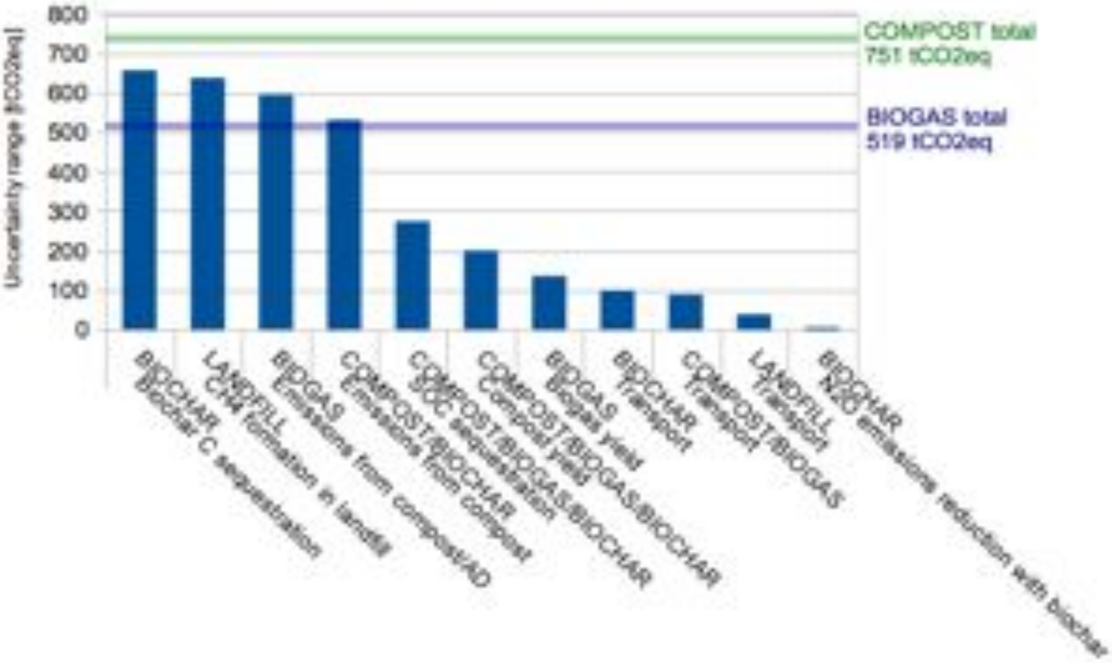
  For compost yield (which is mass of compost produced per mass of feedstock input), the magnitude of the uncertainty was calculated adding up the impacts of increased NPK fertiliser production and transport and lower soil carbon sequestration, but subtracting the impact of poultry manure transport, since the amount of poultry manure used depends on the amount of compost available.

The results are in shown in Figure 3.10, compared for reference to the total emissions of COMPOST and BIOGAS.

- The most important uncertainties in absolute terms are how much carbon is sequestered as biochar and how much CH_4 is formed in the landfill. The former depends on soil properties, biochar properties and climate, the latter on the depth of the landfill.
- How much GHG are formed during the composting process in COMPOST and BIOCHAR and in the composting and biogas production processes in BIOGAS are also very large uncertainties. Each alone amounts to more than two thirds of the total emissions of COMPOST and both are higher than the total emissions of BIOGAS. This high value is due to the fact that N_2O, which is a very powerful GHG, with a Global Warming Potential of 310, can form in compost heaps. The actual amount generated depends on how the heaps are managed and on feedstock properties and is hard to estimate.
- Other uncertain values are also significant, but less than the ones above. Sequestration of soil *organic* carbon sequestration (SOC in the graph) is the most uncertain value after those.

[8]If 20% less electricity is produced from MSW in the Biogas scenario because of low biogas yields, that amount will have to be produced conventionally. If higher biogas yields bring more electricity from MSW, then more conventional electricity production will be avoided

Figure 3.10: Main uncertainties



- The translation in tons of CO_2 equivalent of the uncertainty of biogas and compost yields, which in relative terms are of ±20%, translate respectively in ranges of 135 and 200 tCO_2eq, or 27% of the total GHG emissions for Compost and 65% (together) for Biogas.
- Uncertainties concerning transport emission factors are low in absolute terms compared to other uncertainties. The total uncertainty relating to the transport phase could however be underestimated, since uncertainty about the distance over which organic fertiliser is marketed is not included.

This type of analysis can also show where the collection of more information could reduce the overall uncertainty and lead to more precise results. Better information about the landfill characteristics could reduce uncertainty about CH_4 formation, and ultimately the uncertainty of the total climate impact taken as BASELINE. Anyway all the biggest uncertainties, biochar and organic matter sequestration, formation of CH_4 from compost heaps and the landfill, N_2O from compost heaps are hard to reduce. Their values depend on microbiological processes hard to model in general. The uncertainties of biogas and compost yields can instead be reduced more easily by collecting primary data from existing projects where the same technology is used in similar conditions.

3.4 Conclusions on climate impact

The results of the carbon footprint model described in this chapter show that the potential for climate change mitigation connected to the considered organic waste management options is high, with a net GHG emission reduction compared to business as usual ranging from 59 to 107%.

As expected, the main benefit from composting the organic fractions of MSW is the avoidance of CH_4 emissions from the landfill. However it was found that avoidance of NPK fertiliser production also plays a significant role, and organic carbon sequestration in farmland can potentially do the same. Together they account for 55% of the impact reduction in COMPOST. Although the considered compost application rate of 2.4 tons per hectare is very low and cannot stop soil carbon loss according to the model here used, it could still make a difference and offset N_2O emissions from the land.

Integrating anaerobic digestion with composting can further increase net GHG emission reductions, and adding biochar production could make the whole system carbon neutral. The BIOCHAR scenario is in fact the one with the best results, sequestering more carbon than it emits.

The global uncertainty of the results is relatively high, but it is not likely to change the ranking of the scenarios, and all the considered systems can achieve net GHG emission reductions compared to BASELINE.

Chapter 4

Economic feasibility

This chapter is about the economic requirement for the implementation of the considered technologies.

In Chapter 3 it was shown that processing organic waste with composting, anaerobic digestion and pyrolysis can bring significant climate benefit. This chapter looks at the economic flows in the considered scenarios and how access to carbon would influence them, to address the question of whether the considered technological configurations are economically feasible and whether their viability could improve by connecting them to voluntary carbon markets.

The methodology used for the assessment is explained in the first section, then the data used and the assumptions made are detailed. In the last part the results of the evaluation are presented and discussed.

4.1 Methodology

An economic model, with initial investment, operating costs and revenues associated to the start-up and operation of the considered systems was built and used to evaluate their economic feasibility and the influence upon it of revenues from the sale of carbon credit.

4.1.1 Carbon credits generation by composting, anaerobic digestion and biochar production

There are four mechanisms of climate change mitigation connected to composting, anaerobic digestion and biochar production, which could attract revenues from the sales of Voluntary Emission Reduction (VER) certificates.

1. *Landfill avoidance.* When organic waste is not deposited in landfills but treated otherwise (i.e. to produce compost or biogas) methane emissions are avoided and VER can be generated.

2. *Renewable energy generation.* Generation of electricity from biogas, a renewable, non fossil energy source, is also an approved method for the generation of carbon credits, as it offsets GHG emissions from conventional electricity production.

3. *Carbon sequestration in soil by use of biochar.* As a form of carbon sequestration biochar use could potentially also generate carbon credits, although it is not formally approved by the UNFCCC as yet.

4. *Carbon sequestration in soil by increase of organic matter content.* As explained in section 3.2.4, applying organic fertiliser on farmland increases over the years the content of organic matter in the soil, in fact a form of carbon sequestration. Although this is also not a recognised way of generating carbon credits according to the UNFCCC, due to issues of permanency of carbon sequestration, it is regarded by many as a promising way to contribute to climate change mitigation while at the same time supporting sustainable agriculture (Lal 2004, Ringius 2002, Whitman and Lehmann 2009). Here the potential contribution that linking this mechanism to carbon markets could give to composting projects is investigated.

If the third and fourth of these mechanisms are not as yet approved mechanisms for the generation of carbon credits by the UNFCCC, it is however interesting to investigate what impact they could have on projects like the ones here considered, that link rural development with climate change mitigation[1].

4.1.2 Alternatives

In order to explore separately the benefits of carbon credits from these four sources, a fourth scenario is evaluated here. The fourth scenario is called COMPOST+SOIL.

The choice to have an additional scenario was made in order to have four distinct scenarios built *based on the four types of climate change mitigating mechanisms* connected to organic waste recycling *that could generate carbon credits.*

1. COMPOST is the base case, where only carbon credits from landfill avoidance are claimed. This is the most common set up for composting projects connected to carbon markets (Rogger et al. 2011).
2. In BIOGAS also credits from renewable energy generation are issued.
3. BIOCHAR looks at the combination with credits from carbon sequestration in soil as biochar.
4. COMPOST+SOIL is an extension of COMPOST which includes the additional costs and revenues of generating carbon credits from carbon sequestration in agricultural soils through the increase in organic matter content. A description of this scenario is provided in the following section.

Table 4.1.1 summarises the four scenarios and the types of VER they can generate.

Table 4.1: Carbon credits generated in each scenario

	Landfill avoidance	Renewable energy	Biochar use	Soil organic matter increase
COMPOST	X			
BIOGAS	X	X		
BIOCHAR	X		X	
COMPOST+SOIL	X			X

[1]Two more potential climate mitigation impacts connected to the use of biochar and organic fertilizer, the avoided use of chemical fertilizer and the reduction of GHG emissions from agricultural soil, were shown in the previous chapter. However these two impacts have a very low chance of becoming part of emission trading, the former because of double accounting problems, and the latter because the science about it is not yet mature for developing a protocol for carbon trading (Weisberg et al. 2010), so they are omitted from this list.

COMPOST+SOIL

This scenario has the same technical layout as COMPOST, but there are some differences in the distribution stage.

The permanence of organic carbon in agricultural soil depends heavily on the farming practices adopted: tilling method, amount of organic fertiliser applied, treatment of residues. In order for a producer of organic fertiliser to be able to claim carbon credits from the increase in organic matter that its product creates, it must guarantee the fulfilment of at least two conditions:

- That the fertiliser sold is actually used for the intended purpose.
- That organic fertiliser will be used at the required application rate on each plot of land for a series of year.

It is therefore assumed that in COMPOST+SOIL a multi-year agreement is stipulated between the compost producer and farmers over the use of fertiliser. Farmers commit to using a certain amount of fertiliser over their land for at least 10 years, and the compost producers commit to delivering the fertiliser straight to the plot where it will be used and monitor its use. Specific crop residue management techniques or other farming practices can be integrated in the agreement too.

This set up will create additional costs: the cost of transporting the compost straight to the farm, the purchase of more trucks and the cost of communication and training needed for creating a network of farmers to be involved. Farmers are charged a small amount for the delivery of the compost.

4.1.3 Choice of feasibility indicator

Normally projects are evaluated using indicators based on time series of cash flows (i.e. forecasts of costs and revenues for the lifetime of the project) and a discount rate that compensates for the time value of money. There are many metrics based on discounted cash flows, the most used being Net Present Value and Internal Rate of Return (Biezma and Cristobal 2006).

In this case there are conditions of high uncertainty that make it hard to predict actual investment costs, operating costs and revenues for the coming 5 or 10 years. For instance compost, biochar, compost application and renewable electricity are not products that are normally traded in Northern Ghana as now, which means that the market price is not known. It is therefore hard to evaluate the performance of the investment for a long time span. Furthermore the context is that of a developing country, which often involves higher (business) risks because of lower political stability, lack of infrastructures, volatility of exchange rates, widespread poverty (among both staff and customers) etc. All this factors influence negatively the capacity to predict future costs.

Because of this high uncertainty a *single period ratio*, that is without time series of costs and revenues and with no need for discounting, was preferred. The ratio used is the Return on Investment (ROI).

If cash flows in a given year are so defined:

- *Operating costs*: labour, utilities, raw materials etc.

- *Annuity*: the annual cost of the repayment of the loan on the initial investment
- *Revenues* from sales of products, services and carbon credits

ROI is calculated as the ratio between the profit (the difference between revenues and costs) and the total expenses in a given year.

$$ROI = \frac{Revenues - (OperatingCosts + Annuity)}{OperatingCosts + Annuity}$$

Definition of economic feasibility

A *minimum acceptable rate of return*, or *hurdle rate* must be defined, the ROI above which the project is considered feasible. This rate is normally calculated to include the cost of capital and inflation and adjusted to the risks of that particular venture, with values that can range from 5 up to 50%, for projects with particularly high risks (Wikipedia 2011).

The answer to the question of which return rate would make the project feasible depends on who is the investor and what are its characteristics (i.e. aversion to risk, existing investment alternatives). A multinational corporation, a venture capital fund, a state aid fund or a charity fund would define a composting project in Sub Saharan Africa as *economically feasible* or *profitable* differently.

For this research the starting point is that profitability, in a development project like this, is not the end, but rather a means. When profitability is the only guide to investments in developing countries, the benefits for the local population and for the environment are often reduced. On the other end projects with great environmental and social impacts have failed because they were not economically sustainable (for the case of compost see Drechsel et al. 2004 Ch.3).

A scenario is here considered feasible if the costs can be covered by the revenues, without regards to existing investment alternatives. For these reason here the low hurdle rate of **ROI = 5%** was chosen. A higher rate would mirror more closely the preferences of large investors, but actually investors that are likely to fund a project like this will probably be interested in social and environmental returns more than in high profits.

4.1.4 Requirements for economic feasibility

The ROI can provide an overview of the feasibility of each scenario, but so many are the assumptions that contribute to the value of this metric that it is interesting to look at *the conditions at which* the projects become feasible.

Product prices

The economic analysis is characterised by high uncertainties in all compartments, including the prices at which the products (organic fertiliser, electricity, biochar) will be sold. Minimum selling prices to make the scenarios viable will be calculated. The products considered are

- 1 ton of organic fertiliser,
- 1 kWh of electricity and
- 1 ton of biochar.

Gate fee

Another parameter that can affect the feasibility of the project is the existence of a *gate fee*, a fee paid to the composting venture by the local authority or waste management operator for the disposal of the organic fraction of MSW.

This form of payment is customary in industrialised country, where recycling operators are rewarded by local governments for the service performed. This is not so in Tamale and other cities in developing countries, where municipalities have insufficient budgets for waste management and can in fact only afford to pay for the collection of a small share of the total generated MSW.

The baseline assumption used in the model is that the project has to pay a price for the organic MSW to be delivered to the plant, which is in fact the current agreement between DeCo and the local waste operator. Calculating the gate fee that would ensure the feasibility of the project is however a good indicator of the distance from economic feasibility, which makes the considered scenarios easily comparable.

4.1.5 Impact of access to carbon markets

The impact of carbon credit revenues on the economic feasibility of the scenarios is evaluated by looking at the following indicators.

- ROI with additional revenues from the sale of carbon credits at the current price.
- Carbon credit revenues per unit of product produced (i.e. per ton of compost, kWh of electricity or ton of biochar) with the current carbon price.
- Minimum carbon price required in each scenario to achieve a ROI of 5%.
- ROI sensitivity to carbon price.
- Change in required gate fee and products' selling prices for different carbon prices.

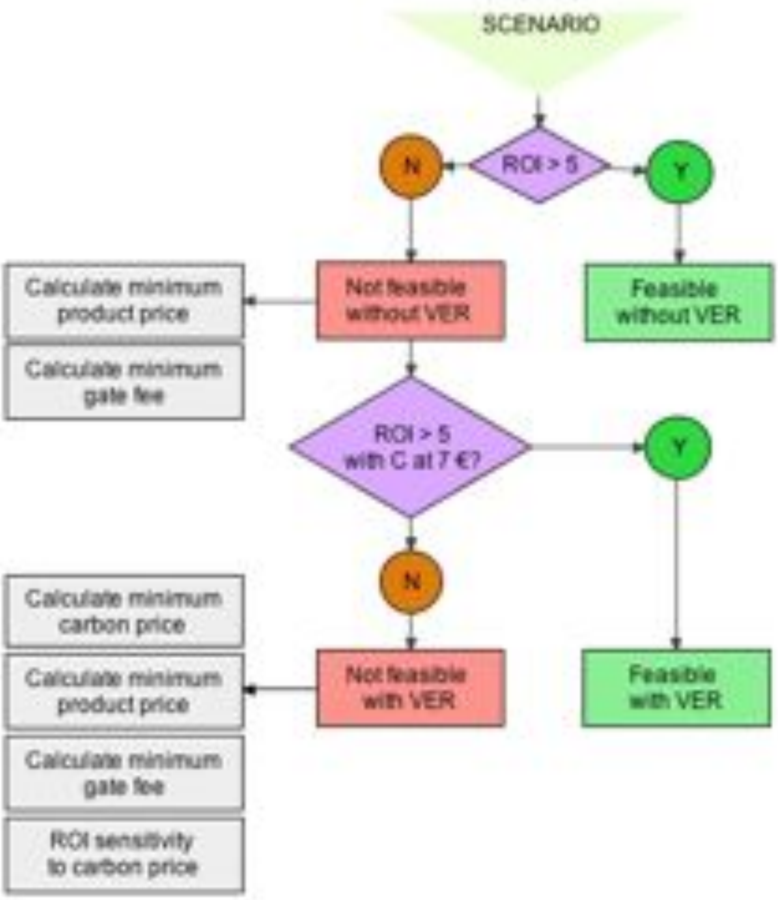
Figure 4.1 summarises the steps that will be used in the economic assessment.

4.2 Data used

4.2.1 Investment costs

Costs related to the initial investment include the cost of land, equipment, buildings, machines, reactors and vehicles. Costs that are not included are the costs of planning and design as well as

Figure 4.1: Steps for the evaluation of economic feasibility



insurance.

Costs for the composting plant and the digesters are based on figures provided by DeCo and on Burri and Martius 2011 while the costs of the biochar system and the biogas generator are assumptions based on internet research.

The cost of the initial investment is distributed over the project lifetime by calculating the annuity, the yearly value of the loan repayments, over a period of 10 years at an interest rate of 10%.

The values used in the model as investment costs are in Table 4.2.

Investment costs are the highest in BIOCHAR, while the cheapest option is COMPOST, as it does not involve the use of machines. For the same reason BIOGAS has the second highest investment costs. COMPOST+SOIL has the same costs as compost plus additional ones of 32,000 EUR for the purchase of the extra trucks required for deliveries.

Table 4.2: Initial investment

		COMPOST	+SOIL	BIOGAS	BIOCHAR
Plant (land, buildings, equipment)	EUR	68,100	68,400	69,540	78,100
Vehicles	EUR	16,000	48,000	16,000	16,000
Digesters	EUR			32,400	
Generator	EUR			6,000	
Biochar oven	EUR				50,000
Total investment costs	EUR	**84,100**	**116,400**	**123,940**	**144,100**
Loan repayment period	10 years				
Interest rate	10%				
Annuity	EUR	**13,687**	**18,944**	**20,171**	**23,452**

4.2.2 Operating costs

Operating costs include staff, purchase and transport of raw materials, utilities (electricity and water) and fuel costs. Taxes are not included but operating costs are increased by 5% for maintenance and overhead expenses.

COMPOST and BIOGAS include the costs of procuring the raw materials, running the plant and distributing the organic fertiliser in the major towns of the three districts surrounding Tamale (at an average distance of 37 km. See section 3.2.6 for more details). COMPOST+SOIL also includes the cost of deliverying organic fertiliser directly on the farms.

Staff costs include labourers, drivers, management and flights between Europe and Ghana (3 per year) for international employees, and are based on figures provided by DeCo, as are the cost of raw materials procurement and utilities in all scenarios. In BIOGAS, BIOCHAR and COMPOST+SOIL additional labour requirement is estimated according to Burri and Martius 2011 and assumptions based on discussions with local stakeholders.

Fuel consumption for delivering the organic fertiliser is estimated using the GHG footprint model presented in section 3.2.6. In COMPOST+SOIL it is estimated to be 50% higher. In BIOCHAR fuel consumption is the highest because of the necessity to transport the rice husks to the plant and the biochar to the farms. Fuel price is assumed to be 0.75 EUR/litre, based on the observed value in Tamale in June 2011.

In COMPOST+SOIL additional operating costs of 3,000 EUR/year are assumed, for the communication and training that would be necessary for setting up contracts with local farmers.

Operating costs of the four scenarios are summarised in Table 4.3

BIOCHAR has the highest operating costs, followed by BIOGAS and COMPOST+SOIL. The difference between BIOCHAR and the other scenarios is mainly due to the additional fuel costs, so it could be reduced by locating the plant near the rice mill where the feedstock for biochar comes

Table 4.3: Operating cost

		COMPOST	+SOIL	BIOGAS	BIOCHAR
Staff	EUR	49,900	50,800	64,360	52,264
Organic waste	EUR	71,250	71,250	71,250	71,250
Fuel	EUR	5,101	7,651	5,101	11,518
Utilities	EUR	400	400	1,140	400
Communication and training	EUR		3,000		
Overhead and maintenance	EUR	6,333	6,505	7,093	6,772
Total operating costs	EUR	**132,983**	**144,606**	**148,943**	**150,203**

from. BIOGAS has the highest staff costs, because it require more labourers, since all the organic waste needs to be loaded and unloaded into the digesters before being composted. Operating costs are higher in BIOGAS and BIOCHAR because they are the only scenarios that require skilled labour (technicians).

4.2.3 Revenues

This paragraph describes the revenues from the sale of products and services. Assumptions about the revenues associated to the generation of VER are explained in the next section 4.2.4.

Revenues are calculated as $UnitsSold \times UnitPrice$. It is assumed that 100% of the production is sold every year. For how the production levels are estimated see section 2.2.

In COMPOST the only revenues are from the sale of compost, BIOGAS has additionally the sale of electricity, BIOCHAR the sale of biochar and COMPOST+SOIL has revenues from compost sale and compost delivery charges.

In the North part of Ghana, all this products do not have a market at the moment. No one is selling commercially organic fertiliser, energy is a state monopoly and biochar is a new product. If this on one hand means that there will be no competition, it also means that the prices at which the products can be sold are not known.

The way assumptions about selling prices of each product were made is explained below.

- *Compost*: 40 EUR/ton. This is the price at which DeCo is planning to sell its organic fertiliser after the pilot phase, and corresponds more or less to the price of the amount of NPK fertiliser that 1 ton of it can substitute.
- *Electricity*: 0.08 EUR/kWh. The price of electricity depends on agreements with the national authority for energy (the buyer of the electricity produced) and eventually government subsidies. According to ISSER (2005) the retail price of electricity in Ghana is between 0.04 and 0.08 US$/kWh and it is subsidised by the government.
- *Biochar*: 15 EUR/ton. This is the price of the residue of traditional charcoal production,

something similar to biochar, which was used by DeCo for field trials in combination with compost. It is a mix of charcoal powder and dirt. Since biochar is not a product with an existing market in Ghana or in similar contexts, it is hard to estimate how much it could be traded for. Estimates of production costs in Shackley and Sohl (und.) range up to a few hundreds EUR/ton, while current retail price go up to a few thousands (Galgani unpublished).

- *Compost delivery*: 3 EUR/ton. The price is based on the estimated cost of the service.

The values of the revenues of each scenario are in Table 4.4.

Table 4.4: Revenues

		COMPOST	+SOIL	BIOGAS	BIOCHAR
Compost	EUR	120,000	120,000	120,000	120,000
Electricity	EUR			24,136	
Compost delivery	EUR		9,000		
Biochar	EUR				9,000
Total revenues	EUR	**120,000**	**129,000**	**144,136**	**129,000**

In all scenario the main revenues come from the sale of compost. Electricity sales in BIOGAS represent just 17% of the total revenues, the income from compost delivery and biochar sale is just 7% of revenues in COMPOST+SOIL and BIOCHAR.

4.2.4 Carbon credits

Carbon credits are traded on two types of markets, the regulatory CDM market and the voluntary market. Because the considered projects are small scale and the process for accreditation in the regulatory carbon market is more expensive, more suited for larger projects, here the characteristics of the voluntary market are considered.

On the voluntary market the credits are generated by projects of various kinds and bought by companies or other actors that want to offset their emissions (i.e. airlines or event organisers) through *brokers*: companies or NGOs that certify, buy and sell the credits. The unit of trading is called Voluntary Emission Reduction (VER), and is equivalent to a reduction of 1 ton of CO_2 equivalent of GHG emissions (Reuster 2010).

The financial conditions applied to the sale of VER by single projects (i.e. the price to be paid and the division of accreditation and monitoring costs) depend on agreements between the project itself and the broker, so assumptions had to be made about costs and revenues.

Accreditation costs are in the range of 50,000 to 100,000 EUR (Tanja Schmidt, myclimate, personal communication, 08.09.2011), a high cost for a small sized venture like the one here considered. The assumption used in the model is therefore that the selling price of 1 VER is on the low end, 7 EUR/VER, and *accreditation and monitoring costs are born entirely by the broker*, thus not included in the economic assessment.

Credits are generated by landfill avoidance, renewable energy generation, the use of biochar and carbon sequestration in soils through the increase of organic matter. The amount of credits generated by each of these four types of climate mitigation intervention is averaged per unit of product sold. The resulting values are in Table 4.5, together with the annual revenues for the considered scenarios.

Table 4.5: VER generation and revenues from VER

Unit	VER/unit	Source	VER/yr /year	Revenues EUR/year
1 t of organic waste not landfilled	0.14	(UNFCCC 2010)	405	2,835
1 MWh renewable energy	0.789	(UNFCCC 2011)	238	1,666
1 t of biochar	1.65	(see section 3.2.4)	989	6,899
1 t of organic fertiliser applied to land	0.025	(see section 3.2.4)	267	1,870

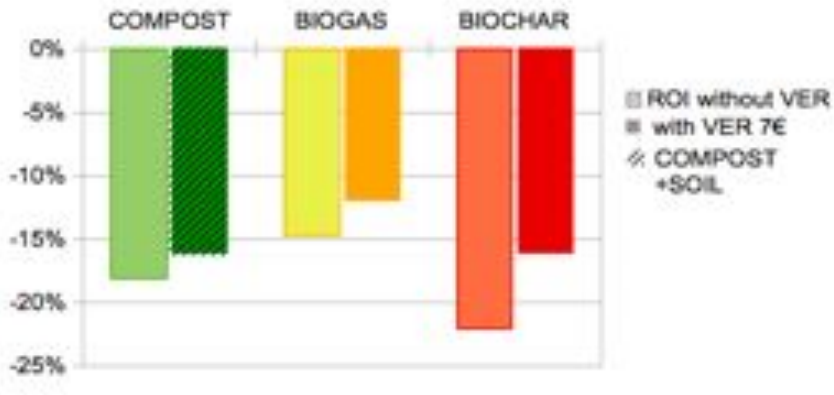
The values in the table are the same as the factors used in the LCA model, which are explained in section 3.2. The only difference is the factor used for renewable energy, which was here chosen following the approved UNFCCC methodology.

4.3 Results

4.3.1 Return on investment

Figure 4.2 shows the results of the economic assessment as ROI of each of the four organic waste recycling systems, with and without access to carbon markets.

Figure 4.2: ROI with and without the sale of VER



All alternatives have a negative ROI as the revenues are not sufficient to cover the costs. The difference between the results with and without carbon credits is not very significant, and the loss is higher than 10% of running costs in all scenarios.

The integration of a biogas system could improve the viability of a composting system, as shown by the fact that BIOGAS has a higher ROI than COMPOST. On the other hand integrating a biochar system would not be justified from an economic point of view without the additional revenues from the sale of carbon credits, since BIOCHAR has the lowest ROI without access to carbon markets.

With access to carbon markets none of the scenarios reaches a positive ROI. BIOGAS remains the best choice, but it is BIOCHAR, the scenario that generates the most credits, to show the most marked improvement. It goes from being the least viable scenario to having the same ROI as COMPOST.

The revenues from claiming carbon credits for soil carbon sequestration from the use of compost would not make a positive difference, at current carbon prices, as shown by the fact that COMPOST+SOIL is not better than COMPOST. This is due to the additional costs considered in COMPOST+SOIL, the cost of extra trucks and that of communication and training to farmers, which at this carbon price are higher than the additional revenues.

4.3.2 Economic feasibility without carbon credits

Table 4.6 shows costs, revenues, profit and ROI of three scenarios, without access to carbon credits. COMPOST+SOIL is not included in the comparison here because it is a scenario built just to evaluate costs and benefits of carbon credits from soil organic carbon sequestration.

Table 4.6: Costs, revenues and ROI without carbon credits

	COMPOST	BIOGAS	BIOCHAR
Total costs	146,670	169,114	165,655
Total revenues	120,000	144,136	129,000
Profit without carbon credits	-26,670	-24,978	-36,655
ROI without carbon credits	**-18.18%**	**-14.77%**	**-22.13%**

COMPOST has a negative ROI. Integrating anaerobic digestion would create an improvement, an increased ROI by 4 percentage points, but still not enough to make composting viable. Revenues from the sale of biochar are by far insufficient to cover the additional costs incurred, and BIOCHAR is the scenario with the highest losses.

Required product price

As explained in section 4.2.3, the prices at which each product could be sold are quite uncertain. This section looks at what prices for each of the products sold (compost, electricity and biochar) would make the scenarios feasible, all other things being equal.

Table 4.7 shows the results both in absolute terms (what is the required selling price for economic feasibility) and in relative ones (how much must the market price increase). In the case of BIOGAS and BIOCHAR, which produce two different products, the required price increase of each of them was calculated independently.

Table 4.7: Required product price for feasibility (without carbon credits)

	Organic fertiliser EUR/ton		Electricity EUR/kWh		Biochar EUR/ton	
Market price	40		0.08		15	
Required price (% increase)						
COMPOST	52	(30%)				
BIOGAS	52	(30%)	0.19	(137.5%)		
BIOCHAR	54	(35%)			90	(600%)

- Compost is the product that in relative terms would require the smallest price increase to reach feasibility, from 40 to 52 EUR/ton (54 for BIOCHAR). Whether the local farmers would be willing to pay such a price for compost is an open question. For comparison, however, in 2005 Danso et al. (2006) estimated the willingness to pay of Tamale's farmers for organic fertiliser to range between 21 to 39 EUR/ton, in 2011 farmers were paying for the equivalent amount of NPK fertiliser around 30 to 35 EUR[2], and in the pilot phase DeCo sold its compost in Tamale for less than 40 EUR/ton. Although 52 EUR/ton is a high price, it is however still realistic, and farmers might still be willing to pay it if soil improvement from using compost would translate in sufficiently higher yields.

- The sale of electricity produced from biogas can only make the project feasible if sold at 0,19 EUR/kWh, a price which is 137% higher than that assumed. The price at which electricity is sold depends on negotiations between the project and the national Ghanaian energy authority. Considering that the price of electricity for the Ghanaian household is around 0.07 EUR/kWh (ISSER 2005), such a high price is quite unrealistic, meaning that integrating biogas production cannot make composting profitable with the current prices. Government subsidies for renewable energy, for example as a feed-in tariff, would be needed to reach such a price.

- Biochar should be sold at 90 EUR/ton, or 6 times higher than the assumed price, to make the BIOCHAR scenario feasible. This could well be a plausible market price according to literature on the topic and current retail prices in industrialised countries (see section 4.2.3. Revenues), but probably too high for local low income farmers. At the considered application rate (10 tons per hectare) the cost of getting 1 hectare treated with biochar would be equivalent to the average *annual* rural household income in the North of Ghana (GSS 2008), so some form of financing would be required.

[2] A price which includes government subsidies.

Required gate fee

A gate fee is a payment for the disposal of waste made to a waste processing facility at the moment of the delivery. It is a customary practice in industrialised countries but not in developing ones, where budgets for waste management are often insufficient to ensure even waste collection, let alone pay extra for safe disposal or recycling.

In the economic model used here the organic fraction of MSW is rather considered to be delivered to the processing plant by Zoomlion, the local waste operator, at a cost of 12.5 EUR/ton. This price reflects the actual agreement in DeCo's pilot project and is considered a fee that can motivate the local waste operator to collaborate with separation and delivery of organic waste. In theory a different agreement could be stipulated, where the composting project is paid for the waste management service provided with a gate fee.

Looking at what gate fee would be required to make the operations viable if the prices of compost, electricity and biochar cannot be increased is a useful way of comparing the economic performance of the scenarios (Table 4.8). A lower required gate fee will mean that the scenario is more *close to feasibility.*

Table 4.8: Required gate fee for feasibility (without carbon credits)

Scenario	Required gate fee (EUR/ton MSW)
COMPOST	8.1
BIOGAS	7.7
BIOCHAR	14.7
Current	-12.50

A gate fee between 7 and 15 EUR/ton of waste would be required to make the scenarios feasible. The levels of the fee required in each scenario reflect the ranking of the alternatives by ROI mentioned before. If with a gate fee of around 8 EUR/ton of MSW COMPOST and BIOGAS would already become feasible, a fee of 14.70 EUR, almost twice as much, is needed to guarantee that biochar can be produced and sold at the considered price of 15 EUR/ton[3].

These values are quite low compared to industrialised countries. For comparison, in Europe gate fees for composting plants are in the range of 20 to 70 EUR/ton of waste (Hogg 2002, WRAP 2008). However in developing countries it is not common for waste treatment facilities to charge for waste disposal (Couth and Trois 2010, Sinha 2010, Aye and Widjaya 2006).

[3]In BIOCHAR, however, a fee could also be charged for the collection of rice husks from the rice mill, which here is assumed to be collected free of charge.

4.3.3 Impact of access to carbon markets

Return On Investment

Table 4.9 shows how the economic performance of the considered scenarios changes if potential revenues from the issuance of carbon credit are accounted for, at the current carbon price of 7 EUR/VER. Here the fourth scenario with carbon credit generation from soil carbon sequestration, COMPOST+SOIL, is included in the results.

Table 4.9: Profit and ROI change with carbon credits

	COMPOST	+SOIL	BIOGAS	BIOCHAR
Total costs	146,670	155,550	169,114	165,655
Total revenues	120,000	129,000	144,136	129,000
Profit without carbon credits	-26,670		-24,978	-36,655
ROI without carbon credits	**-18.18%**		**-14.77%**	**-22.13%**
Additional revenues from sales of carbon credits	2,835	4,705	4,501	9,734
Profit with carbon credits	-23,835	-26,147	-20,477	-26,921
ROI with carbon credits	**-16.25%**	**-16.36%**	**-12.11%**	**-16.25%**

Table 4.9 shows clearly that the additional revenues from the sale of carbon credits would be far from sufficient to cover the existing gap between costs and revenues, and no scenario reaches a positive ROI.

Even though the revenues from carbon credits are low they do make a difference, since they affect each scenario differently and change the ranking of the options.

- Producing biochar would increase significantly the amount of carbon credits generated. BIOCHAR had the worst economic performance without carbon credits, while here it has the same ROI as COMPOST and COMPOST+SOIL.
- Integrating anaerobic digestion with composting would generate less revenues from carbon markets than for biochar production but, due to the low price of carbon, BIOGAS remains the best performing scenario.
- Revenues from claiming carbon credits for soil sequestration by use of compost are not sufficient to cover the additional costs, and in COMPOST+SOIL the annual loss is higher than in COMPOST in absolute terms.

Carbon revenues per unit of product

Table 4.10 shows how much additional revenues from access to carbon markets would amount to per unit of product sold, or per ton of MSW treated.

Access to carbon markets at current carbon prices could increase the revenues from each ton of compost sold by 2.5% to 8%, but as shown above compost price should rise by 30% to 35% for the projects to become feasible. Credits for renewable energy generation would increase revenues from electricity production by 7% while a price increase by 137.5% was found to be required for BIOGAS to reach feasibility. For the case of biochar, carbon revenues would be more substantial, with each ton produced sold for 15 EUR and generating an extra 11.50 EUR from carbon credits. However for BIOCHAR to reach viability a biochar selling price of 90 EUR/ton would be needed.

Table 4.10: Additional revenues from sale of carbon credits

	COMPOST	+ SOIL	BIOGAS	BIOCHAR
VER revenues (carbon price 7 EUR/VER)				
EUR/ton of MSW[a]	1.89	3.14	3.00	6.49
EUR/ton of compost[a]	0.95	1.57	1.50	3.24
EUR/MWh of electricity[b]			5.52	
EUR/ton of biochar[c]				11.50
Current prices				
Cost of MSW	12.50	EUR/ton		
Compost price	40	EUR/ton		
Electricity price (assumed)	80	EUR/MWh		
Biochar price (assumed)	15	EUR/ton		

a All VER revenues
b VER revenues from renewable electricity only
c VER revenues from biochar sequestration only

As described in section 4.3.2, gate fees between 8 and 15 EUR would be needed for the projects to be economically viable, while presently MSW procurement is *paid* 12.50 EUR/t by the processing plant. It is in fact a negative fee, so an increase of 20 to above 35 EUR/ton would be needed to make the scenarios feasible. Additional revenues from carbon credits would only amount to 1.80 to 6.50 EUR/ton of MSW treated.

Minimum carbon price required for economic feasibility

If the analysis shows that at current conditions the projects do not meet the requirements for economic feasibility, it is interesting to look what the price of 1 VER should be for this to happen.

Table 4.11 shows the amount of carbon credits generated annually in each scenario, and the carbon price that would be needed for it to have a ROI above 5%.

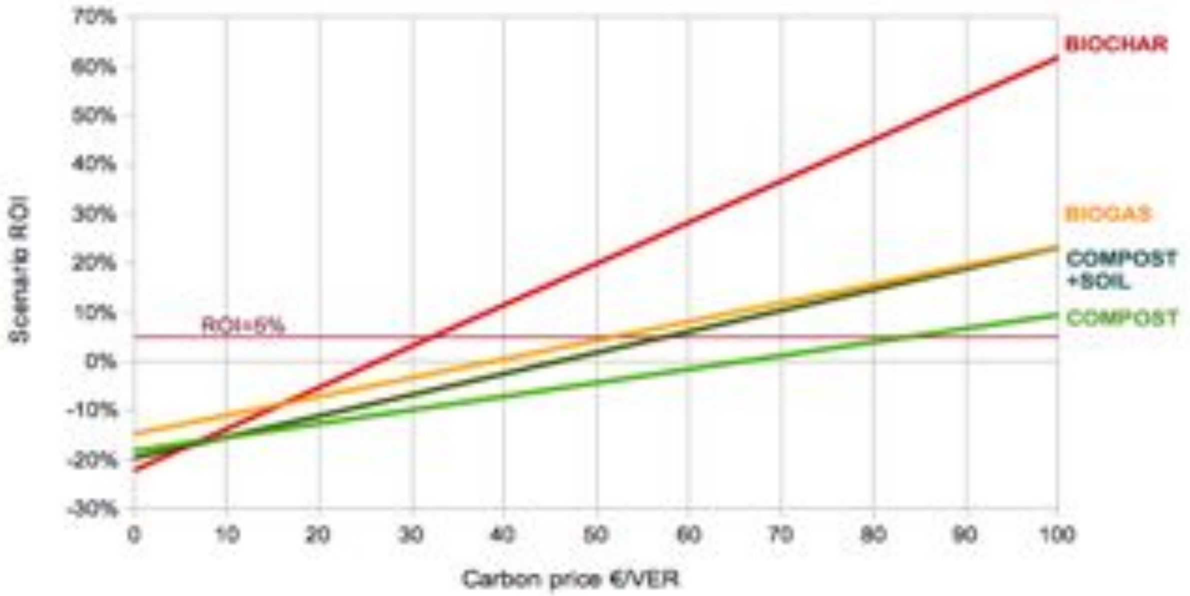
The scenario that issues the most VER, BIOCHAR, could become feasible with a carbon price of 31 EUR/VER, while COMPOST, which issues the least credits needs the highest price: 77 EUR/VER. BIOGAS and COMPOST+SOIL fall in between this range, with 48 and 52 EUR/VER.

Table 4.11: Required carbon price for ROI>5%

Scenario	VER generated (tCO_2eq/year)	Required carbon price (EUR/VER)
COMPOST	405	77
BIOGAS	643	48
BIOCHAR	1,391	31
COMPOST+SOIL	672	52

ROI sensitivity to carbon price

Figure 4.3: ROI sensitivity to VER price



The fact that BIOCHAR is the scenario with the lowest required carbon price, while it does not have the highest ROI with carbon credits at 7 EUR/VER implies that the economic performances of the four organic waste recycling systems compare differently at different carbon prices .

Figure 4.3 shows how the profitability of each scenario changes with the price of 1 VER. The slope of the curves depends on the amount of carbon credits generated, so BIOCHAR has the steepest slope, followed by COMPOST+SOIL and BIOGAS, while COMPOST's profitability is the one that grows the least with increasing carbon prices.

The ranking of the scenarios by economic performance at different carbon price levels is summarised in Table 4.12.

Table 4.12: Ranking of alternatives

	no VER	VER price				
		<7 EUR	7-10 EUR	10-16 EUR	16-100 EUR	>100 EUR
COMPOST	2	2	3	4	4	4
+SOIL		3	4	3	3	2
BIOGAS	1	1	1	1	2	3
BIOCHAR	3	4	2	2	1	1

- Below 7 EUR BIOGAS gives the best returns, followed by COMPOST and COMPOST+SOIL. BIOCHAR is the worst scenario.
- Between 7 and 16 EUR BIOGAS remains the most viable and BIOCHAR becomes the second best alternative. COMPOST and COMPOST+SOIL have similar returns, with the latter becoming better than the former above a carbon price of 10 EUR.
- Above just 16 EUR BIOCHAR becomes the scenario with the better returns.
- COMPOST+SOIL generates a slightly higher amount of credits than BIOGAS, so it would be more profitable than BIOGAS for carbon prices above 100 EUR/VER.

Impact of access to carbon markets on conditions for feasibility

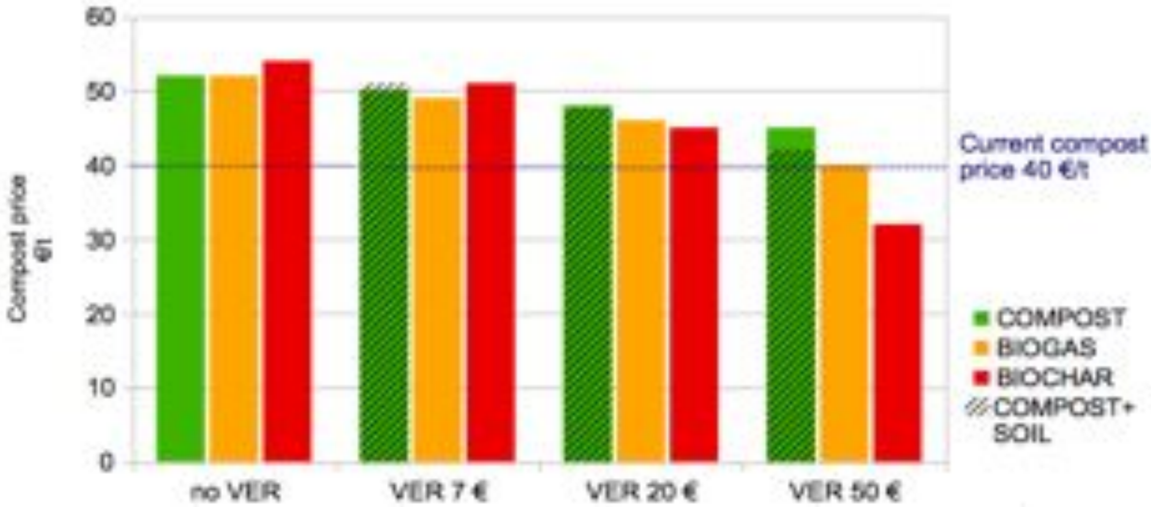
Higher carbon prices would lower the requirements for economic feasibility in terms of selling price of the products or payments for waste procurement. Figures 4.4 and 4.5 on page 59 show how the different organic waste processing systems considered would require different economic conditions to become viable depending on the price of VER certificates. The focus is on gate fees and selling price of compost, since these are the values over which the scenarios can more easily be compared, as in all four of them MSW is treated and compost is sold.

At a carbon price of around 20 EUR/VER the scenarios would start to become economically self sustaining without requiring to charge a gate fee for collecting MSW (Figure 4.4). If it is unlikely that the local waste company or local authority would be willing to pay a fee for waste disposal, it is however possible that an agreement could be made to get the organic waste delivered free of charge, thus making the project feasible already at lower carbon prices.

Revenues from carbon credits per ton of compost produced, on the other hand, would allow to decrease the price at which compost is sold to farmers only for high carbon prices. With a carbon price of 20 EUR/VER, three times higher than the current one, prices between 45 and 48 EUR/ton of compost would still need to be charged to cover production costs, while the assumed market price is 40 EUR/ton. With a higher carbon price of 50 EUR/VER, the revenues from the carbon credits connected to electricity generation and soil carbon sequestration could allow selling compost

Figure 4.4: Required gate fee for economic feasibility at different carbon prices

Figure 4.5: Required compost price for economic feasibility at different carbon prices



at prices more in the range of the current market ones, below 50 EUR/ton of compost, although only in BIOCHAR, where compost and biochar are sold together and carbon credits are generated from both, the required selling price of compost would be lower than the present one.

4.4 Conclusions on economic feasibility

The considered combinations of composting, anaerobic digestion and biochar production are not economically feasible under the considered set of assumptions. They all have a negative ROI, meaning that the revenues are not sufficient to cover the costs. Access to carbon markets, assumed to be at no cost with a carbon price of 7 EUR/VER, cannot improve the economic performance of the scenarios enough to reach a positive ROI.

At the assumed conditions, the addition of a biogas system could improve the economic performance of a composting venture even before taking into account the generation of carbon credits. Biochar could not be produced at a profit, but it could potentially generate a high amount of VER certificates, so whether it can be a valuable addition to a composting system or not depends on whether carbon offsets can be issued and at which price they can be sold.

Without considering carbon credits, the price received for compost, electricity or biochar should be significantly higher than the assumed values (from 30% for organic fertiliser to 600% for biochar) in order for the scenarios to become feasible. It is uncertain at which prices those products can actually be sold in the Tamale area, since no one is commercialising organic fertiliser and biochar in Northern Ghana and the electricity price will depend on ad hoc agreements with the public energy authority. However the difference between assumed selling prices and those required for economic viability is likely to be too high to successfully implement the scenarios.

Alternatively a gate fee could be charged for treating MSW, ranging from 8 (for COMPOST and BIOGAS) to 15 EUR/ton of MSW treated (for BIOCHAR). In developing countries waste treatment facilities do not usually charge for their service, and in Tamale DeCo pays the local waste operator 12.5 EUR/ton of organic waste delivered to the plant, although gate fees are customary in industrialised countries. For comparison in the EU gate fees at composting facilities are in the range of 20 to 70 EUR/ton of waste.

Adding carbon markets into the picture at current carbon prices does not allow any of the scenarios to reach a positive ROI, with carbon credits increasing total revenues by just 2-7% while an increase by 17% to 28% would be required just to cover the production costs. However access to carbon markets would lower the requirements for economic feasibility in terms of product prices or gate fee. Additional revenues with carbon price at 7 EUR/VER are in the range of 1.8 to 6.5 EUR/ton of compost, or 0.9 to 3.2 per ton of MSW treated, and increase proportionally to VER price.

BIOCHAR is the scenario with the worst performance without access to carbon credits as well as with carbon prices lower than 7 EUR/VER, but its ROI is closely related to carbon prices, and as soon as 1 VER certificate is sold for more than 16 EUR BIOCHAR becomes the best alternative. It issues about 3.5 times more credits than COMPOST and is in fact the scenario that would require the lowest carbon price to be feasible at current conditions, 31 EUR/VER. With the considered set of assumptions BIOGAS would become feasible when carbon price would reach 48 EUR, COMPOST+SOIL at 52 EUR and COMPOST at 77 EUR/VER. These prices

The benefits of claiming carbon credits for organic matter increase in farmland following the use of organic fertiliser have been explored in the scenario COMPOST+SOIL, and the results point to the fact that this type of project could be paying for its costs (i.e. has a higher ROI than COMPOST) for carbon prices above 10 EUR/ton of carbon, although with many uncertainties. For the considered amount of waste, the credits that could be generated this way are more or less equivalent to 60-70% of those that can be issued for landfill avoidance. Electricity production could generate about the same amount of credits as organic carbon sequestration, but it is more profitable for carbon prices below 100 EUR/VER.

The conclusion of this economic assessment is that the scenarios cannot be economically feasible without being subsidised. Access to carbon credits could help to create the conditions for the successful implementation of the considered scenarios but current carbon price levels are too low to have a significant impact on the economic feasibility of the considered projects.

Chapter 5

Integrated assessment

In the previous two chapters scenarios of how composting, anerobic digestion and biochar production could be implemented in the city of Tamale have been evaluated.

The scenarios consisted of different combinations of the three technologies, using several types of organic waste as input and producing a variety of products (Table 5.1).

Table 5.1: Summary of inputs and outputs of the scenarios

	Unit	COMPOST	BIOGAS	BIOCHAR
Inputs				
Organic MSW	t/yr	1,500	1,500	1,500
Other biomass	t/yr	1,500	1,500	1,500
Poultry manure	t/yr	1,500	1,500	1,500
Rice husks	t/yr			2,400
Outputs				
Organic fertiliser	t/yr	3,000	3,000	3,000
Electricity	MWh/yr		301.7	
Biochar	t/yr			600

The goal of the analysis was to quantify the climate benefits, the economic feasibility and the extent to which carbon markets could contribute to create conditions for the implementation of these organic waste recycling technologies. The main findings are summarised in Table 5.2 and are explained in the following section.

5.1 Composting

Small scale, low tech windrow composting was evaluated in the COMPOST scenario. It was found that it can provide climate benefits of many kinds, but the current market price of compost is not sufficient to cover production costs, so subsidies would be required to guarantee economic feasibility.

Composting the organic fraction of MSW in Tamale can reduce GHG emissions by 60% compared to business as usual over the whole life cycles of organic waste and fertiliser. It avoids methane generation in the landfill, and production and transport of NPK fertiliser. Organic matter sequestration in farmland following the use of compost can also be significant, and it was estimated to offset N_2O emissions from soil almost entirely, although this result is very sensitive to modelling choices.

In order for composting to become feasible without subsidies an increase in compost price by 30% would be required. Alternatively a gate fee of around 8 EUR/ton of MSW treated would be sufficient to make composting in Tamale economically self-sufficient. It is a low price compared to European levels, but in contexts like Ghana it is unlikely that local authorities could afford to pay for waste disposal, and currently in fact a price of 12.5 EUR/ton must be paid for MSW procurement *by* (not to) the composting plant. Carbon markets could be what provides these additional revenues, but the current carbon price (7 EUR/VER) is too low to significantly affect the economic performance

Table 5.2: Summary of results

	Unit	COMPOST	+SOIL	BIOGAS	BIOCHAR
Climate impact					
Net GHG emission reduction	tCO_2eq	1113.24		1345.43	2013.94
% of business as usual		59.7%		72.2%	108%
per unit waste treated	tCO_2eq/t	0.74[a]	0.74[a]	0.89[a]	0.38[b]
per unit fertiliser produced	tCO_2eq/t	0.37	0.37	0.45	1.52[c]
Economic feasibility					
Return On Investment		-18.2%		-14.8%	-22.1%
Gate fee required for feasibility	EUR/t[a]	8.1		7.7	14.7
Benefits from carbon markets					
ROI with VER (price 7 EUR)		-16.3%	-16.7%	-12.1%	-16.2%
increase with VER		+1.9%	+1.5%	+2.7%	+5.9%
Gate fee required for feasibility	EUR/t[a]	6.4	8.1	5	8.8
Carbon credits generated	VER/yr	405	672	643	1390
per unit waste treated	VER/t	0.27[a]	0.45[a]	0.43[a]	0.41[b]
per unit fertiliser produced	VER/t	0.14	0.23	0.22	1.64[c]
Carbon price required for economic feasibility (ROI≥5%)	EUR/VER	77	52	48	31

[a] per ton of MSW treated
[b] per ton of rice husks treated (excluding the composting system)
[c] per ton of biochar produced (excluding the composting system)

of such a composting venture. Losses would only decrease from 18% to 16% of annual costs selling landfill avoidance carbon credits. A higher carbon price would be required for carbon markets to make a real difference.

Each ton of MSW composted can abate GHG emissions by 0.74 tCO_2eq, and issue carbon credits for 0.27 tCO_2eq[1]. This value is equivalent to the additional revenues that an increase in VER price of 1 EUR would bring per unit of waste treated[2]. Income from the sales of these credits would only make composting profitable with carbon prices several times higher then present ones. A minimum carbon price of 77 EUR would be required to achieve a satisfactory rate of return.

Soil organic carbon sequestration is one of the climate benefits that are created by using organic

[1]Or half of that per ton of compost produced, since 3,000 tons of organic fertiliser are produced for every 1,500 tons of MSW treated.

[2]Or half of that per ton of compost produced, since 3,000 tons of organic fertiliser are produced for every 1,500 tons of MSW treated.

fertiliser and could also be translated into carbon credits. Here it was estimated to be around 0.18 tCO_2eq per ton of compost applied. Implementing a system to monitor organic carbon sequestration in the land of farmers that make use of compost could be economically viable depending on the additional costs involved and the price at which carbon credits could be sold. With the set of assumptions here used, a carbon price of 52 EUR/VER would be sufficient for revenues from carbon markets (soil carbon sequestration and landfill avoidance credits) to make the composting system economically viable.

5.2 Anaerobic digestion

Anaerobic digestion of MSW with a low cost dry fermentation reactor was analysed. In the BIOGAS scenario the implementation of this technology in combination with windrow composting was evaluated. Such a system allows to extract additional value from organic waste compared to composting alone, in the form of methane.

It was found that including dry fermentation in a composting system would increase both its climate benefits and its economic feasibility, although still not to an extent to make such a project profitable without subsidies.

Offsetting conventional electricity production was calculated to reduce GHG emissions by an additional 20% compared to composting alone, or by 0.15 tCO_2eq per ton of MSW treated (or 0.075 per ton of fertiliser sold).

Integrating a biogas system could improve the economic performance of composting only marginally without revenues from carbon markets, and annual losses as a share of costs would remain high, above 14%. Required gate fees would decrease by just 10% from 8.1 to 7.7 EUR/ton of MSW.

Access to carbon markets at the current carbon price of 7 EUR/VER would provide additional revenues but far from enough to make the project cover its costs. Producing renewable energy could generate 0.16 VER/ton of MSW digested, so for every EUR of increase in carbon prices, every ton of MSW treated in the biogas system could generate additional revenues for 0.16 EUR. With all other assumptions unchanged, the combined anaerobic digestion-composting system would then become viable in Tamale at a carbon price of 48 EUR/VER.

5.3 Pyrolysis for biochar production

The BIOCHAR scenario studied how a biochar system could be realised to process rice husks, a waste flow of the local rice mill. It was considered to be implemented together with composting in order to evaluate the importance of the economies of scale that could be realised by producing and marketing together two types of agricultural inputs (compost and biochar).

Producing biochar at this scale could offset all the emissions of the composting system connected to waste collection, waste processing, compost transport and compost use, resulting in a net carbon sequestration over the whole life cycle. The additional GHG emissions abatement would amount to

0.38 tCO_2eq per ton of rice husks treated, or 1.52 tCO_2eq per ton of biochar produced[3].

From the economic point of view, however, biochar production cannot be implemented at the considered scale. The price that local farmers would be able to pay for biochar is a big uncertainty, and here the price of the byproduct of traditional charcoal production was taken as a proxy. This price, 15 EUR/ton, is something even low income farmers could afford to pay, but the analysis showed that a price of at least 90 EUR/ton would be necessary for the combined composting-biochar system to guarantee an acceptable rate of return.

Alternatively, if biochar were to be approved as a land based climate change mitigation mechanism on carbon markets, the gap between production costs and revenues could be filled by the issuance and sale carbon credits. A system like the one considered here could generate a much higher amount of VER certificates than composting or anaerobic digestion, adding an extra 0.41 tCO_2eq per ton of rice husks treated (1.64 tCO_2eq per ton of biochar sold).

The additional revenues that could come from biochar sequestration credits sold at the current price of 7 EUR/VER would make the biochar system economically self-sufficient, and with higher carbon price it could easily become very profitable. With a VER price as low as 31 EUR integrating biochar production would make a composting venture in Tamale economically feasible.

5.4 From carbon footprint to carbon credits

Analysing the climate mitigation potential of composting, anaerobic digestion and biochar in the context of carbon markets it emerged that not all the actual climate benefits are liable to generate credits to be sold on international carbon markets. While for anaerobic digestion and biochar production VER certificates generation is almost the same as the effective climate benefits, in the case of composting less than 40% of the total GHG emission abatement estimated with the LCA model can be converted in carbon credits (Figure 5.1).

Emission reductions from electricity production from biogas or from biochar sequestration can easily be monitored and converted into carbon credits, but this is not the case for those from composting, since the climate benefits are distributed in different parts of the life cycle. If the increase of soil organic carbon following the use of compost could generate credits, the gap would only be partially filled.

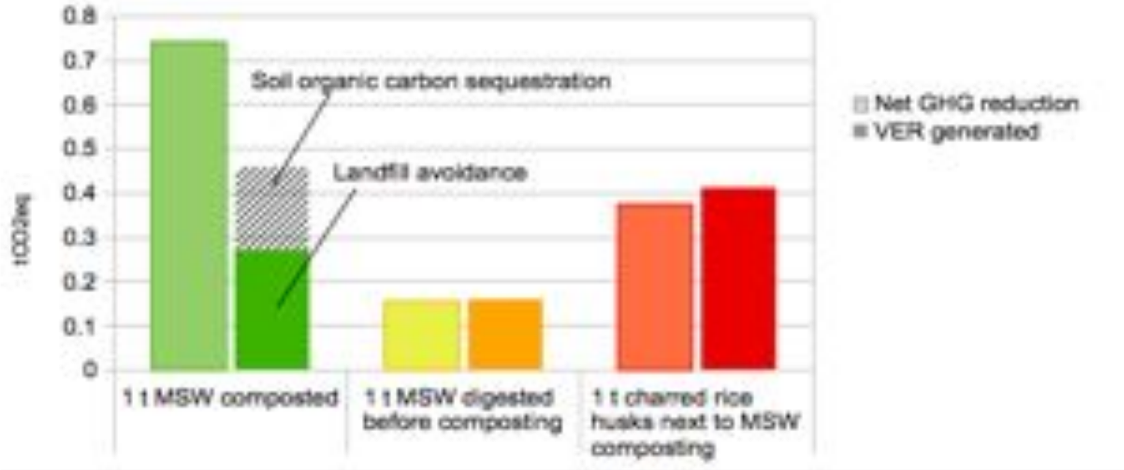
The two main areas where emission reductions from a composting system are not translated into payable carbon credits are in fact avoided NPK fertiliser production and landfill methane generation.

The avoided production and transport of NPK fertiliser is the largest unaccounted climate change mitigation benefit of composting, amounting to about 34% of the total emission reduction of COMPOST compared to business as usual (Chapter 3). It cannot be claimed by a composting operator as carbon credits in order to avoid double accounting, as the corresponding GHG emission reduction will be attributed to the NPK manufacturer or the shipping companies.

The avoidance of methane formation from the degradation of waste in landfills translates only partially in carbon credits generation because of the characteristics of the relevant UNFCCC method-

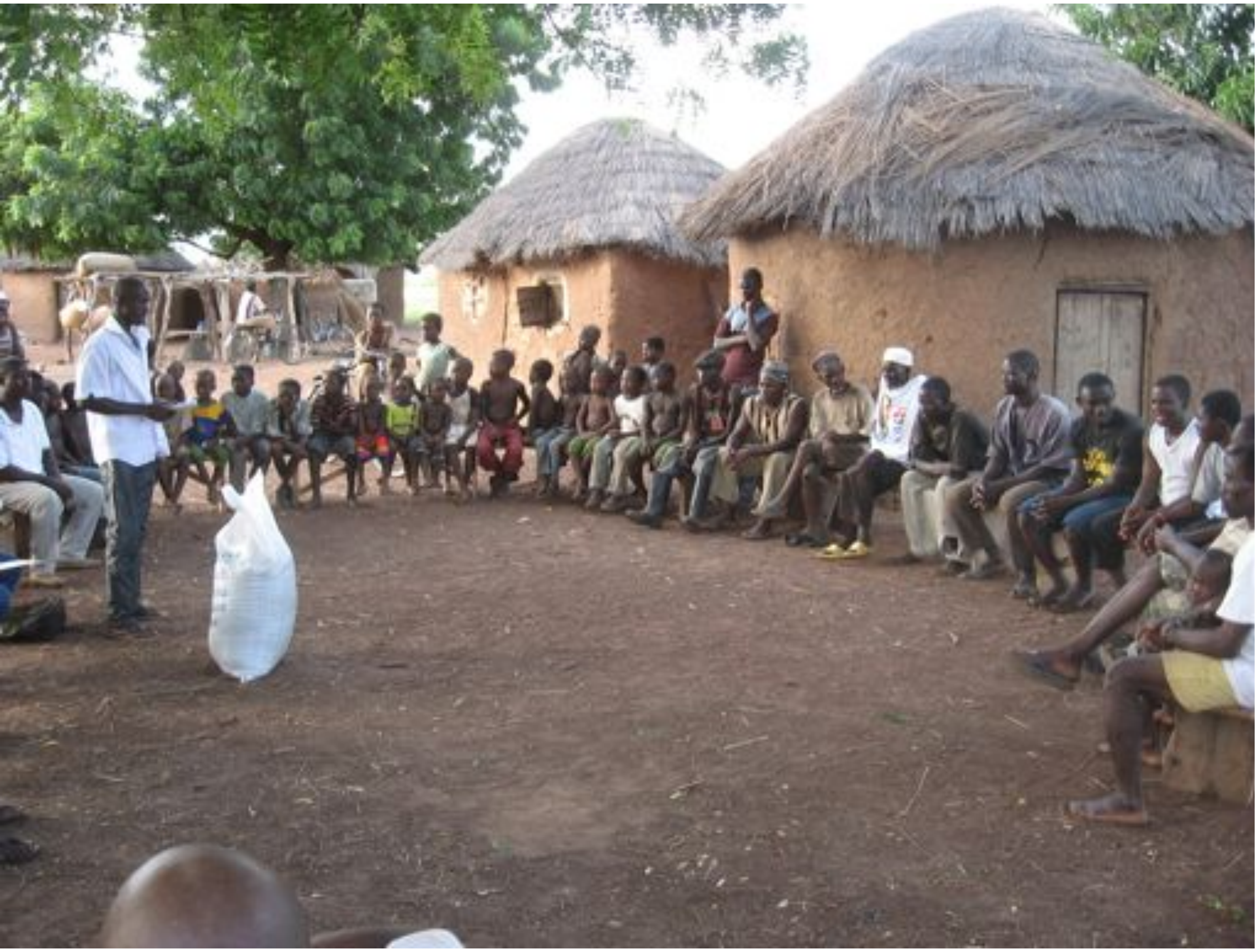
[3]Pyrolysis is assumed to have a yield of 25% by mass.

Figure 5.1: Net GHG reduction and VER generated



ology (UNFCCC 2010). Methane is formed for decades following waste deposition in the landfill, with annual emissions decreasing every year. The approved UNFCCC methodology states that every year VER can be sold corresponding to the avoided methane emissions *that would have occurred in that year* rather than the total ones that the waste that was not landfilled would have generated. This means that the avoidance of the emissions that would have occurred after the end of the project will not be converted into VER.

If for biochar sequestration and energy generation from biogas, as for other climate mitigation activities, the climate benefits can be easily packaged and sold as carbon credits, carbon markets can only reward some of the positive impacts of composting project. The revenues from one of the unaccounted impacts, soil organic carbon sequestration, were estimated in this study. The results here presented show that in fact avoided fertiliser production and unaccounted avoided methane generation in landfills are also significant benefits that carbon markets do not reward.



Chapter 6

Discussion

6.1 What is the uncertainty of the results?

Both the economic assessment and the carbon footprint model were built using data from a variety of sources, from literature and databases to field research, rough estimations and interviews with stakeholders. Every piece of data used has a different uncertainty level and the reliability of the results depends on these values.

Climate impact

Not many LCA studies are performed focussing on Africa, partly because of the low availability of reliable data, and often data referring to the European context have to be used (Ntiamoah and Afrane 2008, Eshun et al. 2010). Nonetheless this tool can give a significant contribution to the development of the region, where decisions about technology and investment have to balance delicate social and economic considerations and often overlook the environmental side.

Here an effort was made to incorporate the uncertainty in the results, with an uncertainty analysis. Realistic uncertainty ranges were defined for some of the assumptions, from transport emissions to GHG generation from waste decay to soil carbon dynamics, based on the value ranges found in the literature, with high variability values going from $\pm 20\%$ to $\pm 100\%$. Their influence on the reliability of the final results was quantified with a Monte Carlo analysis.

The maximum variation ranges of the total carbon footprint of the scenarios analysed resulted to be very high, ranging from 80% to 700%, although the standard deviations of the results were in the range of 8% to 15% for all scenarios but BIOCHAR (100%). How much carbon would be sequestered by using biochar is in fact the biggest uncertainty of the LCA in absolute terms. Other big uncertainties are how much methane would form from the decomposition of organic waste in the landfill and how much fugitive emissions of nitrous oxide and methane are formed during the composting and anaerobic digestion processes, which depend on how the compost heaps are managed and cannot be determined accurately if not with direct measurements.

If the uncertainty levels are extremely high, it was also found that they did not affect the ranking of the alternatives, as many uncertainties influence equally all scenarios, and some of the results have a high reliability. Losses of nitrous oxide and methane from organic waste treatment can neutralise large part of the climate benefits and their management should take consideration of this (for example ensuring proper aeration of the compost heaps, avoiding too high moisture levels and too low C:N ratio, Brown et al. 2008). Integrating anaerobic digestion with composting can improve its climate benefits, and biochar can do so even more, to the level of reaching a null or negative carbon footprint.

Economic feasibility

The economic analysis of the scenarios was also performed with many uncertainties regarding investment and running costs, selling prices and carbon credits generation mechanisms.

A quantitative analysis was performed regarding all parameters on the revenue side (gate fee, selling price of compost, electricity, biochar and carbon credits), which showed a high sensitivity of the results.

On the cost side the uncertainties are also significant. Because of the low profit margin (feasibility was defined as a profit of 5% of annual operation and capital costs, or 7,000 to 8,500 EUR per year) unexpected costs can also significantly affect the economic feasibility of the project, in both the construction or operation phase. An overview of the costs is given in Appendix C.

Estimates of capital costs of the composting and biogas systems were based on data provided by a compost plant and a biogas pilot project in Ghana so can be considered quite accurate, while the cost of the biochar oven, which represents one third of the total investment costs in BIOCHAR, was estimated through internet research and has therefore much higher uncertainty. Beside capital costs, unexpected costs could arise in the construction stage due to delays, a quite common occurrence in Ghana.

Operating costs also could have been underestimated in the assessment. One possible source of unexpected costs is marketing: local farmers are very wary of trying new types of products[1] (such as compost or biochar) on their land since they depend on the harvest for their lives and those of their families. A bad harvest would mean food insecurity, so the threshold to trying new things can be quite high, and communication and demonstration efforts required to sell them compost can rise accordingly. The cost of management is another important cost whose variability would strongly affect the results. Poor management is often one of the causes of failure of projects in this field that on paper had a strong business case in West Africa (Drechsel et al. 2004, Ch. 3), and the cost of good management is hard to estimate in a context with scarcity of local skilled labour and high disparity of wages between expatriates and locals. The question of how accurate the estimate of the project management budget used here could be is left to project developers to answer. The last big uncertainty on the cost side is the additional costs that would be necessary to set up a system for claiming carbon credits from soil carbon sequestration. Here the assumption was made that the requirement would be a contract between farmers and the composting operator where the former commit to use organic fertiliser and the latter to deliver it to the farm. Additional costs would be marketing, training for farmers and fuel costs and estimated to be around 6,500 EUR/year, although the real requirements to receive accreditation could be very different (i.e. formation of a farmer network organisation), and the costs too.

About the uncertainty of the revenues from carbon markets, today credits can be generated and sold for landfill avoidance and renewable energy generation, but not from soil organic carbon or biochar sequestration. The revenues from these two sources have been explored in the scenarios BIOCHAR and COMPOST+SOIL in the hypothetical situation that they will be approved. Their approval is being advocated as a way to combine food security, fight against desertification and climate mitigation by a part of the climate community (for organic carbon see de Brogniez et al. 2011, Biala 2011, Perez et al. 2007, for biochar see Woolf et al. 2010, Whitman and Lehmann 2009), although there is some agreement over the fact that the chances that organic carbon will become part of carbon markets are somewhat lower than for biochar because of issues of permanence (Vagen et al. 2005, Luske and van der Kamp 2009). The projections of the benefits of accessing carbon markets for the feasibility of the considered organic waste recycling systems are therefore realistic for COMPOST and BIOGAS, more explorative for BIOCHAR, and rather speculative in the case

[1] In fact the government and international agencies have been training them for the past half century to get them to start using NPK fertiliser.

of COMPOST+SOIL.

The reliability of the results about the economic performance of the considered technologies is dependent on a broad set of assumptions about costs and revenues, and some of the considered sources of carbon credits are only hypothetical. Costs of composting, electricity production from biogas, fertiliser distribution and sales have been evaluated using data provided by projects active in the local context, while in the case of biochar the estimation of investment costs is more rough and makes the uncertainty of the final results higher. The influence of selling prices for all products on the results has been explored for all scenarios and the results have been explained in the first part of this chapter and in Chapter 4. The remaining marketing and management costs are hard to evaluate, and how much the assumptions used are correct is a question that can best be answered by practice.

6.2 What are the limitation of the results due to modelling choices?

Beside the uncertainties of the data used in the LCA and the economic assessment, some choices made in the definition of the scenarios and the modelling process affect the significance of the results too.

Scale of operations

The results about economic feasibility could have been different if a different scale of operation and different types of technology would have been studied. Here the choice was for small scale of operation, because of the high unemployment rate in the region, with a low tech approach, to minimise the risk of technological failure that often hampers the success of international development projects (see the review of West African composting projects in Drechsel et al. 2004). Some economies of scale could however be realised by operating at a larger scale, decreasing production costs and thus increasing the profitability of the operations. Economies of scale could be realised in project management and marketing costs, for composting and fertiliser sales, and capital costs in the case of anaerobic digestion and pyrolysis for biochar production.

Soil carbon model

The choice of modelling organic carbon loss and accumulation added a layer of depth to the analysis. However the fact that soil carbon accumulation is not linear, and that the models used have not been fine tuned with real measurements, except for climate related parameters and initial soil carbon levels, make their results only indicative, although in line with similar case studies in the literature (Luske and van der Kamp 2011, Brown et al. 2008, Biala 2011). Also the considered application rate of compost was fixed. More compost per hectare would mean higher organic carbon sequestration. In fact a 10 to 20 times higher application rate would be required to achieve real carbon sequestration, rather than just a decrease of the carbon loss rate.

Time scale

Finally, because of the uncertainty of economic data, the choice was made to base the feasibility evaluation only on costs and revenues occurring in one year of operation at full scale. It does not take into account the costs and revenues that would occur during the time that it would take to reach full scale of operation, which in fact could be a strong determinant of the chances of a successful implementation of the technologies. The results, then, describe the performance of these technologies from an operation point of view (answering the question: can the project pay for its costs?) rather than from an investor point of view (how much is the return on the capital invested?), which would require a closer look at a multi-year plan.

Because of this choice to model only one year of operation, revenues from carbon credits from landfill avoidance and soil organic carbon sequestration, which vary every year, have been estimated for the duration of the project (10 years), and then converted in yearly averages. Soil carbon increases are likely to happen mostly in the first years, during which the carbon content of soil shifts to a new equilibrium level, and the revenues from carbon credits would follow the same trend. Credits from landfill avoidance have an opposite tendency, since they follow methane formation that would have occurred over the years following waste landfilling. Every ton of waste composted keeps generating certificates for the next 10 or more year, so the revenues at later years are higher than those during the first ones. In practice the economic performance of the project throughout its lifetime would then change, if looking at a multi year plan for the project rather than at one year. Soil carbon brings higher revenues in the first years and landfill avoidance in later years.

Costs of access to carbon markets

Finally access to carbon markets can happen with a variety of revenue models. On the voluntary market credits are sold to a carbon broker, an intermediary between the projects and the final buyers of the credits. The repartition of fixed costs and carbon revenues between the project and the broker is agreed on a case by case basis, and the price paid for every VER certificate depends not only on carbon market price but also on what share of the accreditation and monitoring costs must be born by the broker and how much by the project. Here it was assumed that all costs are born by the broker and a lower price is paid to the composting operator, but different ways of dividing the costs might turn out to be more profitable, at different scales of operation and with different market prices of carbon.

6.3 What are the non-economic barriers to implementation?

Beside economic barriers to feasibility, there are other requirements that were not analysed here but must however be taken into account when considering if composting, anaerobic digestion or biochar production can successfully turn waste into a resource in the considered context.

One of the requirements, the approval of biochar and soil organic carbon as mechanisms to issue carbon credits, has been discussed in section 6.1. The following section will look at other cultural and technical barriers to be overcome.

Working with traditional culture and institutions

The fact that in the North of Ghana two cultural and institutional systems coexist, a traditional, local one and the "modern", global one, can create some implementation challenges. Both systems have structures, norms and values that can be in contrast with each other, but exist side by side. The two main cultural challenges to be addressed in the implementation of the scenarios analysed here are acceptance of products and traditional land property rights.

Convincing local farmers to use new products, compost and biochar on their land, on which they depend for their and their families' survival, can prove a big challenge. A high quality product that gives good results is indeed the best way to convince a farmer, but spreading the idea that a product made from waste should substitute the "modern" chemical fertiliser which the government and international organisations have been promoting for decades might not be easy. It is however necessary for the success of these organic waste recycling systems.

Land property rights are an issue to be addressed in order to be able to claim carbon credits from soil carbon sequestration both as biochar and as organic matter. Land ownership in the whole of Africa can be unclear, as often there is no formal land property registry and traditional systems are in place to allocate the land to farmers. The ownership can stay in the hands of the community or traditional chiefs. Since soil carbon sequestration requires a long term commitment to certain farming practices, certainty regarding the ownership of the land must be ensured.

Both product acceptance and land property rights are context specific barriers that would need special attention in the implementation of these organic waste recycling projects in the context of carbon markets. As much as traditional values and structures could create problems, though, they could also create opportunities. Traditional values could be used to promote organic fertiliser, as using the body of traditional knowledge about farming could help farmers understand the importance of replenishing the content of organic matter in soil. Similarly traditional institutions at the village level could be leveraged to create systems to make farmers commit to increasing soil carbon levels in their land.

Technical feasibility

The economic feasibility of the three organic waste recycling technologies has been explored in some depth, but of course the technical feasibility has to be evaluated too to get some insight about the chances of success of their implementation.

The windrow composting technology is relatively proven and it is now in its second year of implementation in Tamale.

The anaerobic digestion system considered is in the pilot phase at the moment of writing and has not been tested in connection to a generator and the electric grid as yet. The data about its biogas and electricity yield used are those indicated by Burri and Martius (2011) do not come from experimental measurements. It follows that the results of both the carbon footprint and the economic assessment of the BIOGAS scenario is dependent on the success of the biogas system, and more tests are required. Furthermore the chemical properties of the digestion residue have not been investigated, and here the assumption was that when composted they would be equivalent to those of the same feedstock directly composted. This assumption must be verified by lab analysis and field trials.

Concerning the pyrolysis system used for biochar production, both costs and biochar yields were taken from literature and refer to an ideal pyrolysis oven with the required throughput. Furthermore the effectiveness of biochar from rice husks to improve local soils needs to be tested experimentally: the scenarios were designed taking into account biochar field trials performed in the area around Tamale, but these trials have been done using residual charcoal powder from traditional charcoal production, whose feedstock is wood. Agronomic properties of rice husks biochar are probably different from those of that used in the trials. Benefits for soil fertility are a requirement for the successful implementation of the biochar system considered in this study.

An important requirement for the technical feasibility of the considered scenarios is also feedstock availability. The availability of MSW is not an issue, but MSW alone is not sufficient to produce a good quality fertiliser or sustain the biodigestion process, and the sufficient availability of other residues, such as straw, leaves, shea butter processing waste and poultry manure is a requirement too.

Finally for the case of the issuance of carbon credits from the variation in organic matter levels in agricultural soil, an important requirement is the capacity to measure it. The variations of carbon in one year here extremely small and could not be picked up by common measurement instruments (as suggested by Ouédraogo et al. 2001 and Dr. Mathias Fosu, SARI, personal communication, 22.06.2011), therefore eliminating the option of bringing this carbon sequestration on the carbon markets. Accurate ways of measuring or modelling soil carbon levels are being explored and would be required for the scenario COMPOST+SOIL to be feasible.

6.4 Could composting, anaerobic digestion and biochar be all combined to maximise the economic and environmental benefits?

Both anaerobic digestion and biochar production, if integrated with composting, can improve its climate mitigation potential. Anaerobic digestion can also improve its economic viability, and in Chapter 4 it was shown that the same could be true for a biochar system if it could generate and sell carbon credits above a certain carbon price (see Table 4.12 on page 58).

Technically these two technologies are not mutually exclusive. Biogas was assumed to be produced from the organic fractions of MSW while biochar from rice husks, so in theory the benefits could be maximised with an integrated system where all the three technologies are combined. Biogas can be extracted from MSW, then the digestion residue can be composted into organic fertiliser, while on the side rice husks can be pyrolised to produce biochar. The electricity can be sold to the grid while biochar and compost are marketed to local farmers (separately or mixed).

Such an integrated composting-anaerobic digestion-biochar system would maximise the GHG emission reductions and the amount of carbon certificates that could be generate. Its investment costs would be higher than those of the other scenarios, since both the biogas and the biochar systems are expensive, so the economic benefits would be realised only with revenues from the sale of carbon credits. Such a project could issue more carbon credits than each of the scenarios considered in this study, and thus would outperform all the other combinations with increasing carbon prices in terms of profitability.

From potential to reality

If from the environmental and economic point of view this setup can look like the best option, it has to be kept in mind that each of these technologies brings its own technical, social and institutional implementation challenges. The success of an integrated waste processing system combining composting, anaerobic digestion and biochar production depends on the development of context specific solutions for all the non economic barriers described in section 6.3 *at once*. This can ultimately mean incurring in unexpected costs that would affect the economic viability of the project as a whole.

6.5 Can the results be extended to a broader geographical scope?

Tamale

One plant of the size considered here, with an output of 3,000 tons of fertiliser per year, would treat only about 10% of the organic waste *collected* in Tamale and less than 1% of all MSW *generated* in the city in one year.

All the waste of Tamale could potentially be treated by building more similar composting and anaerobic digestion plants, multiplying the climate benefits and creating jobs. If the organic fertiliser would prove to have a consistently high quality, marketing it should not be a problem since there is enough farmland surrounding the city to absorb all the supply. Here it was assumed that the compost is sold in the neighbouring three districts and would be sufficient for 1,250 hectares of land. In these three districts there are over 32,000 hectares of cultivated land, according to the Ghanaian Minister of Food and Agriculture (MoFA 2011). The main barriers for the realisation of such a system would be ensuring the commitment of other stakeholders. The local waste operator's cooperation to organise large scale source separation of organic waste is required, as it is the support of the municipality. It would also be necessary to ensure sufficient supplies of the other organic inputs needed for the composting and biodigestion processes (straw, leaves and other residues) which are right now collected locally from small scale agri-processing centers and in uncultivated areas outside the city. Implementing decentralised composting in the whole city could ultimately lead to economies of scale for management, distribution and marketing.

Northern Ghana

The whole North of Ghana is a region 2.5 times the size of the Netherlands. The region has two other main cities, Bolgatanga and Wa, and many large towns. It is quite uniform in terms of lifestyle, population density, farming practices, agro-industry, waste generation and infrastructure, so the results of this study concerning the feasibility and carbon footprint of these technologies could be extended to major urban centres of the region. The technologies could be adopted in smaller towns too, as long as separation of organic waste could be organised and connection to the power grid could be ensured, reaching out to the whole region, home to 2,000,000 inhabitants, mainly subsistence farmers, and with chronic energy scarcity and soil fertility loss problems (Kankam and Boon 2009, Diao and Sarpong 2007).

Biochar production could be extended as far as large amounts of agricultural waste are generated. In Northern Ghana there is not much large scale food processing industry that could provide organic waste, so feedstock availability would probably be the main barrier to a wider extension of this technology.

West African savannah region

Looking beyond Ghana, the considered biochar, anaerobic digestion and composting system could potentially realise their climate and development benefits in the whole savannah zone of West Africa, between the Sahel and the humid tropical forests, which has similar cities, climate, farming practices and desertification problems too. The main uncertainty in this case would be economic conditions (i.e. fuel price, labour cost, electricity price) so not all the results of the economic feasibility assessment can be extended. However in this study it was shown that higher carbon prices would stimulate composting and anaerobic digestion, and even more biochar production if approved as a carbon credit generation mechanism, and this result applies in different countries too.

6.6 What other sustainability issues must be taken into account?

Other factors than the carbon footprint play a role in determining how to best make of Tamale's organic waste a resource for sustainable development. A strict focus on reducing GHG emissions can in fact bring negative side effects in other realms related to people livelihoods and ecological integrity.

Soil as a crucial asset of the rural population

An important issue to consider carefully is the social and environmental impact of working with soil. Soil is one of the key asset of the majority of the population of Northern Ghana that lives off semi-subsistence agriculture. The commercialisation of soil amendments such as compost and biochar can open many opportunities for improving people livelihoods, but it comes with responsibilities. MSW is one of the feedstocks used for composting, and it has to be ensure that the final product does not contain unsafe levels of contaminants, such as heavy metals leaking from batteries present in the waste. Compost and biochar can be a resource to improve soil fertility but they could also become a source of land contamination. In the same line of thought, another risk is related to the fact that compost may contain weed seeds. If that is the case farmers might end up using more herbicides, which can also be source of land contamination, to get rid of the weeds that fertilising with compost would bring on their farms.

Finally issuing carbon credits from carbon sequestration in soils would require signing long term contracts with farmers to ensure its permanence. This would mean that the farmers would lose some degree of control over their main physical asset, their main resource to improve their livelihoods. It could happen that someday some agricultural technological improvement or some new market development could turn out to provide a way for semi-subsistence farmers to lift themselves out of poverty, so a long term agreements for soil carbon sequestration binding farmers to certain farming practices must be flexible enough to allow being harmonised with better solutions that might appear in the future.

Quantity and quality of jobs created

Another sustainability impact of development projects like those studied here is job creation. Not only the amount of jobs created is important, but also whether they are skilled or unskilled jobs. Creating skilled jobs means transferring technical knowledge and building local human capacity. In the North of Ghana there are two universities where every year hundreds of young people get trained in technical skills, although the amount of available jobs is low. Anaerobic digestion and biochar production can create some positions for skilled technicians, while composting alone mainly creates unskilled labouring jobs.

Related to this issue is that of operational health and safety. If soil is a key asset of low income rural population, health is another one and must be preserved. When working with waste it is important that some safety measures are put in place. Pyrolysis of rice husks can potentially generate carcinogenic compounds depending on process conditions (Major 2010) and compost heaps generate dusts that can be detrimental to respiratory health, and may contain blades and broken glasses (Tolvanen 2004, Ekelund and Nystrom 2007). Safety measures can sometimes be overlooked since providing an income is considered the number one priority in development projects. However there is little use in providing a family with additional income if having a job ends up causing chronic or fatal diseases.

Water

Finally another sustainability consideration related to the organic waste recycling projects studied is water use. The LCA performed here was limited to GHG emissions and water usage and pollution were not examined. Composting requires that a certan moisture level is kept in the heaps. In Tamale, with average daily temperatures around 30°C and rainfalls concentrated in 3 months a year, water must be added daily to the windrows. The anaerobic digestion process also requires water, although the technology here considered is that of dry fermentation, a form of anaerobic digestion which needs a very low moisture content. Water efficiency and quality preservation are important in a context where water is scarce for the most part of the year, so estimating the impact of the three technologies on these factors could give a more complete overview of their sustainability implications.

Chapter 7

Conclusion and recommendations

7.1 Conclusion

This research has looked at some sides of the question of whether in Tamale carbon markets can facilitate the realisation of organic waste recyclings potential to be a resource for society and the environment, through composting, anaerobic digestion and pyrolysis for biochar production. These technologies can reduce the carbon footprint of the waste sector but also bring benefits for soil fertility and energy supply.

Three scenarios based on low-tech, small scale variants of the three technologies were analysed from the point of view of GHG emission reduction potential, costs, revenues, and potential for carbon credit generation. It was found that these technologies can give a significant contribution to climate change mitigation, but they are not economically viable without receiving external subsidies. Carbon markets can help the realisation of these organic waste management systems, although not at current carbon price levels, which are too low.

What climate change mitigation benefits can be achieved with composting, anaerobic digestion and biochar in Tamale?

Processing organic waste with composting, anaerobic digestion and pyrolysis in Tamale can bring net GHG emission reductions, by extracting energy and producing fertiliser from organic waste normally decomposing in landfills.

Composting alone can reduce emissions by 60% compared to business as usual waste management, energy supply and fertiliser use, avoiding methane emissions from the landfill and production (and transport) of NPK fertiliser. Organic matter sequestration in farmland following the use of compost can also be significant.

Extracting energy from the waste with anaerobic digestion before it undergoes the composting process would reduce the carbon footprint by a further 12% of business as usual, offsetting conventional electricity production.

Integrating biochar production from locally available rice husks could offset all the emissions generated by the composting system. Net carbon sequestration would result since the accumulation of biochar in agricultural soils would be higher than all the GHG emissions over the whole life cycle of composting.

Are they economically feasible or what are the necessary conditions for their economic feasibility? How would access to carbon markets change the situation?

None of the system studied is economically viable at the assumed conditions. Among the three technologies, anaerobic digestion was found to have the best economic performance, when implemented in combination with composting. Without access to external subsidies, biochar production was found to be the least feasible technology.

Without access to carbon markets the assumed selling prices of the products (compost, electricity, biochar) would need to increase significantly for the projects to reach economic feasibility (from

30% for compost to 600% for biochar). Alternatively, charging a gate fee at the moment of the collection of MSW could help to achieve a sufficient return on investment.

Taking into account potential revenues from the sale of carbon credits at the carbon price of 7 EUR/VER, a realistic price at the time of writing for a project of this size on voluntary carbon markets, does not change the picture. The additional income would be far from sufficient to make the scenarios feasible.

With higher carbon prices, the contribution of carbon markets to the economic feasibility of all the three technologies could become more substantial. The amount of carbon credits that can be sold is related to the actual GHG emission reductions. Biochar production is therefore the activity that would benefit the most from access to carbon markets, although conditionally to the approval of biochar sequestration as a carbon credit generating mechanism. Extracting biogas from the waste would increase carbon revenues compared to composting alone by about 60%. The minimum carbon prices that would allow to reach an acceptable rate of return[1], would then be lowest for biochar production with composting (31 EUR/VER), highest for composting alone (77 EUR/VER) and in between for anaerobic digestion (52 EUR/VER).

Ultimately the feasibility of these technologies will depend on the evolution of the prices of carbon credits, organic fertiliser, renewable electricity and biochar in the coming years.

If soil organic carbon sequestration following the use of compost could also generate carbon credits, the amount issued would be also around 60% of landfill avoidance credits, although this result has a higher uncertainty.

Do the benefits from access to carbon markets for organic waste management projects reflect their actual contribution towards climate change mitigation?

Recycling organic waste into fertiliser brings three main types of GHG emission reductions, avoiding landfilling of the waste, displacing NPK fertiliser use and transportation, and organic carbon sequestration in soil. Only landfill avoidance can be translated into carbon credits, and the methodology used to issue the VER certificates leads to an underestimation of the actual climate benefits according to this study. All in all it was found that only 36% of the estimated GHG emission reductions of implementing composting could translate in carbon revenues.

Biochar sequestration could prove to be a strong and more easily accountable climate change mitigation mechanism, although it is not an approved way of issuing carbon credits as now. Benefits from electricity generation from biogas were found to be correctly rewarded by carbon markets.

[1] With compost, electricity and biochar sold at the assumed prices of 40 EUR/ton, 15 EUR/ton and 0.08 EUR/kWh.

7.2 Recommendations

7.2.1 For climate policy

This research had the goal of verifying the extent to which carbon markets can facilitate the success of more sustainable organic waste management technologies in an African context. Because of the specific challenges in terms of soil fertility loss, energy shortage and unemployment that Tamale faces, it was assumed that small scale, low-tech composting, anaerobic digestion and biochar production could transform organic waste into a resource for sustainable development. Ultimately only time will tell whether carbon markets will be able to steer the development of this and similar regions towards a direction where this potential is realised, but this study has given some insight on how to make this more likely to happen.

It was found that biochar use could give a significant contribution to climate change mitigation, higher than the other organic waste processing technologies considerd, but it is not an officially accepted technology for generating carbon credits yet. Its approval into the CDM as a land based GHG emission reduction mechanism would allow for this potential to be realised.

Furthermore the climate benefits of recycling the organic fraction of MSW in terms of landfill avoidance should be instantly rewarded with carbon credit generation. The approved CDM methodology for quantifying these benefits states that the credits should not be issued at the moment of the avoided waste deposition in landfill but at the moment at which methane emissions would have occurred (UNFCCC 2010). This means that carbon revenues from recycling 1 ton of MSW today will be distributed in the coming decades, making investments in organic waste processing less attractive.

Soil sequestration of carbon as organic matter from the use of compost as fertiliser has great potential to link climate change mitigation and benefits for sustainable development, but is harder to link to carbon markets. Soil organic carbon levels are very sensitive to farming practices, so in order to have a permanent carbon sequestration a commitment to the same farming techniques over time must be ensured. Furthermore if the rates at which organic fertiliser is applied are low, soil carbon level will actually decrease, although some degree of carbon sequestration from the use compost could be accounted for anyway, as organic matter content would probably *decrease less fast* than with conventional NPK fertiliser. At higher application rates, however the use of organic fertiliser could indeed increase soil organic carbon content with real benefits for soil fertility, whose decrease is a key problem for the lives of millions of rural inhabitants in Northern Ghana and similar regions in Africa. If a way of linking this form of carbon sequestration with carbon markets will be found, it would bring real benefits to million of poor in Northern Ghana and other African regions facing similar social and environmental challenges.

All in all carbon markets could incentivise the realisation of the promised benefits of small scale composting, anaerobic digestion and biochar production only if carbon would be traded for a much higher price than presently. A carbon market can be a powerful tool to mitigate GHG emissions worldwide, but without policies for the creation of demand for carbon credits, like setting caps and reduction targets, their value is bound to stay low, and the benefits for small scale projects almost insignificant.

7.2.2 For organic waste management in the context of carbon markets

This research has shown that pyrolysis for biochar production could generate much more carbon revenues per unit of waste treated than composting and anaerobic digestion. If biochar use will be approved for carbon credits generation, its production would very fast become a cost effective organic waste treatment technology once the price of carbon starts to rise. Testing the effectiveness of biochar from different feedstocks as a soil amendment for different types of crops and soils will be an important requirement for a successful implementation.

Combining dry fermentation with composting is also likely to prove profitable, if carbon credits for renewable energy generation could be issued and sold at prices higher than present ones. To reap the benefits of biogas production the technical performance of dry fermentation, as well as the suitability of resulting digestate as a feedstock for organic fertiliser production, should be further investigated.

Finally it was found that the formation of greenhouse gasses as in compost heaps can potentially offset much of the climate benefits of composting. Managing compost heaps so as to avoid the generation of these emissions can be done simply by avoiding the formation of anaerobic conditions (i.e. turn the heaps regularly and avoid too high water content) and controlling the quality of the feedstock used[2] and is strongly encouraged.

7.2.3 For sustainability research

This research has shown how an LCA can provide useful results even if performed in conditions of high uncertainty. This is often the case when focussing on developing countries. The uncertainty range of the results can be very high, but macro differences between alternatives can be identified, as well as the crucial processes that could generate the biggest environmental impacts. In order to do this missing data is better substituted by a range than by data about totally different contexts. More than an exact quantification of environmental impacts of a life cycle system, the goal should rather be pinpointing which of its parts are the most determinant.

Another interesting result for LCA research is that, among the environmental benefits of composting, substituting NPK fertiliser and increasing organic matter in this case played an important role. A LCA of composting is always going to be in between waste management and agriculture, but often the focus is mainly on the former. The underestimation of the benefits of composting can however turn out to be significant if the displacement of conventional fertiliser use is omitted from the assessment.

If conventional fertiliser can be quite easily included in am LCA study of organic waste recycling, incorporating organic matter addition into soil is much more tricky. The main issue is that organic carbon accumulation in soils is not linear over time, but tends to reach an equilibrium level. LCA is the most complete tool for environmental impact assessment, but it cannot capture this dynamics, because it does not have a time dimension and it does not quantify stocks. A tool that incorporates both stocks and flows, rather than only flows, would be best suited to assess changes in soil fertility. Substance Flow Analysis is an industrial ecology tool that could better model the influence of organic

[2]For more information see Brown et al. (2008).

waste recycling on soil carbon levels, and maybe it could be combined with LCA to incorporate this aspect into the environmental assessment of systems that include agriculture.

Fertile soil is a great resource to mankind, one that is easily destroyed and it can only be replenished at a slow pace and with high effort. The sustainability assessment of agricultural systems should not only focus on land, water and energy efficiency, but also on the preservation of soil fertility. Soil carbon dynamics, so closely related to many indicators of soil fertility, are at the intersection of two of the biggest sustainability issues we will face in the next century: climate and food. Being able to take into account in our decision making a better understanding of this topic would give a powerful contribution to tackling these challenges.

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Appendix A. Technical assumptions

	Unit		Source
Composting			
Compost inputs			
Organic fraction of MSW		50%	DeCo
Dry neem leaves		25%	DeCo
Shea processing residue		25%	DeCo
Fertiliser inputs			
Compost		50%	DeCo
Dry poultry manure		50%	DeCo
Composting mass reduction		50%	DeCo, Biala 2011, Ekelund and Nystrom 2007
Anaerobic digestion			
Digester specifications			
Fresh input per batch	ton	5.8	Burri and Martius 2011
Fresh feedstock per year	ton	60.2	Burri and Martius 2011
Retention time	days	28	Burri and Martius 2011
Biogas yield	m^3/ton_{input}	100	Burri and Martius 2011
Methane content in biogas		60%	Burri and Martius 2011
Calorific value of methane	kWh/m^3	9.94	Burri and Martius 2011
Generator efficiency		34%	Burri and Martius 2011
Anaerobic digestion + composting mass reduction		50%	Assumption
Pyrolysis			
Biochar yield		25%	Fournier 2009

Appendix B. LCA assumptions

Capital goods	Unit		Source[a]
Composting plant			
Cement platform			
Lifetime	years	25	
Layer thickness	cm	30	
Surface area	m^2	12,140	1 acre/ktons of fertiliser produced
Cement density	kg/m^2	3,300	Wikipedia
Storage shed			
Lifetime	years	20	
Floor area	m^2	300	100 m^2 per 1000 tons of fertiliser produced
Wooden wall thickness	cm	6	
Height	m	3.5	
Corrugated steel roof density	kg/m^2	5.5	www.cladco.co.uk
Vehicles	20		
Lifetime	years	20	
Size	tons	16	
Digesters (shipping containers)			
Lifetime	years	15	Palma Olivares 2010
Number of digesters	unit	25	
Steel (in each container)	kg	2,200	Palma Olivares 2010
Wood (in each container)	m^3	14.15	Palma Olivares 2010
Biogas generator[b]			
Lifetime	years	10	
Power	kWe	35	Burri and Martius 2011
Biochar system			
Lifetime	years	15	
Pyrolysis oven weight[c]	kg	3,500	Biochar Solutions Inc
Additional storage space required	m^2	9,700	80% higher than for composting

a If no source is specified, the value is an assumption
b Material requirements are taken from Ecoinvent
c Assumed to be 100% steel

Emissions from waste processing

	Unit		Source
Literature review			
Landfilling			
CH_4 generated per ton of organic waste	t/t	0.02	UNFCCC 2010 (landfill depth < 5m)
		0.04	UNFCCC 2010 (landfill depth > 5m)
N_2O emissions from landfill		negl.	Brown et al. 2008
Composting			
CH_4 generated per ton of waste	g/t	4 - 3,000	Butler and Hooper 2010
		30 - 8,000	IPCC, in de Groot 2010
		750	average NL, in de Groot 2010
N_2O generated per ton of waste	g/t	60 - 600	IPCC, in Butler and Hooper 2010
		300	average NL, in de Groot 2010
Anaerobic digestion			
CH_4 generated per ton of waste	g/t	0 - 8,000	IPCC, in de Groot 2010
		3,700	average NL, in de Groot 2010
N_2O generated per ton of waste	g/t	negl.	IPCC, in de Groot 2010
		120	average NL, in de Groot 2010
Assumptions			
Landfilling			
CH_4 generated per ton of waste	t/t	0.3	
N_2O generated per ton of waste	g/t	negl.	
Composting			
CH_4 generated per ton of waste	g/t	4,000	
N_2O generated per ton of waste	g/t	300	
Anaerobic digestion			
CH_4 losses per ton of waste	g/t	1,000	
N_2O losses per ton of waste	g/t	negl.	

Farm processes

	Unit		Source
Organic fertiliser application rate	t/ha	2.4	Assumption
NPK fertiliser application rate	kg/ha	0.24	Assumption
Direct N_2O emissions			
N content in compost		0.57%	DeCo
N_2O emissions per N applied	kg/kg	0.0157	De Klein et al. 2006 (Equation 11.1)
N_2O emissions per ton of organic fertiliser	kg/t	0.249	Calculation
Soil organic carbon sequestration			
Organic C content organic fertiliser		19.53%	DeCo
Organic C applied	t/ha yr	0.47	Calculation
Organic C sequestered			
Literature review			
30 years trials	t/ha yr	0.064[a]	Luske and van der Kamp 2009
Shift from low to medium use of organic inputs	t/ha yr	0.1	IPCC und.
Modelling (see Appendix C)			
Henin and Dupuis model	t/ha yr	0.085	
ICBM	t/ha yr	0.037	
Value used	t/ha yr	0.06	
Biochar use			
Carbon content in rice husks biochar		45%	Woolf et al. 2010, supplementary information
Biochar application rates			
Review			
Guidelines for rice husks biochar use	t/ha	10 - 20	Miles 2007
Range where effects occur	t/ha	0.4 - 20	Haefele et al. 2011
Rate used in tests with rice husks biochar	t/ha	41	Haefele et al. 2011
DeCo experiments	t/ha	3 - 10	DeCo
DeCo best results	t/ha	10	DeCo
Value used	t/ha	10	
Soil N_2O emission reductions			
Review			
Average reduction		25%	Woolf et al. 2010
Range		0 - 80%	Woolf et al. 2010
Reduction in savannah soils (20 t/ha biochar)		50 - 80%	Woolf et al. 2010
Value used		50%	

a 14% of applied carbon

NPK fertiliser

				Source
Fertiliser type:	NPK	15 15 15		DeCo
Fertiliser composition				
N	15%			www.yara.com
K_2O	15%			www.yara.com
P_2O_5	15%			www.yara.com

Manufacturing

	CO_2 (kg)	CH_4 (kg)	N_2O (kg)	Source
N 1 kg cradle to gate (EU)	1.72	0.0147	0.0037	Ecoinvent
K_2O 1 kg cradle to gate (EU)	0.45			Ecoinvent
P_2O_5 1 kg cradle to gate (EU)	0.7			Ecoinvent

Transport

Sea freight distance (Scandinavia - Accra)	km	8,200		www.searates.com
Truck transoprt (Accra - Tamale)	km	650		

Transportation

	Unit		Source
Fuel consumption factors			
Garbage truck (capacity 12.5 t)	km/l	1.25	ZoomLion Ghana, personal communication
	l/t km	0.07	
Fertiliser transportation (capacity 6.5 t)	km/l	4.31	Savannah Agricultural Research Institute, personal communication
	l/t km	0.04	
Distances			
Tamale - Abuabu landfill	km	11.7	
Tamale - waste processing plant	km	11	Location of DeCo plant
Rice mill - waste processing plant	km	42	
Shea processing residue transport	km	20	Assumption
Poultry manure transport	km	623	Kumasi - Tamale
Backhaul load		68%	Woods and Cooper und.
Emission factor diesel fuel	$kgCO_2eq$/litre	3.81	Ecoinvent
Emission factor sea freight	$kgCO_2eq$/tkm	7.8×10^{-6}	Ecoinvent

Compost distribution

Distribution points	Distance from plant (km)	Compost delivered (ton)	Biochar delivered (ton)
Tamale Metropolitan district			
Processing plant	0	272.7	54.5
Bangily	18.8	272.7	54.5
Zibogo	22.9	272.7	54.5
Tolon/Kumbungu district			
Nyankpala	25.3	272.7	54.5
Kumbungu	15.2	272.7	54.5
Tolon	34.5	272.7	54.5
Yabolugu	58.1	272.7	54.5
Singa	42.4	272.7	54.5
Savelugu/Nanton district			
Savelugu	27.7	272.7	54.5
Diari	56.5	272.7	54.5
Pigu	69.7	272.7	54.5

	Compost	Biochar
Total transport (tkm)	170,031	34,006

Appendix C. Soil carbon models

Henin and Dupuis

The Henin and Dupuis model calculates soil carbon levels in a given year based on organic carbon additions in that year and the decay of existing soil carbon.

$$\frac{\Delta C}{\Delta t} = \sum_i k_{1i} M_i - k_2 C$$

With:

ΔC = change in soil organic carbon in the time interval Δt
M_i = amount of the organic input i added in Δt.
k_{1i} = coefficient representing the degradability of the type of input i called the *isohumic coefficient*
C = initial organic carbon content of the soil
k_2 = coefficient representing the rate of natural degradation of organic matter in soil, which depends on soil composition, annual mean precipitations and annual mean temperature.

The value of k_2 was calculated, following Sofo et al. (2005), using this formula.

$$k_2 = \frac{1,200 f_0}{(200 + c)(200 + 0.3s)}$$

With:

$f_0 = 0.2(T - 0.5)$ where T is the yearly average temperature.
c = clay content of soil in g/kg.
s = silt content of soil in g/kg.

Introductory Carbon Balance Model (ICBM)

The Introductory Carbon Balance Model is described in (Andren and Katterer 1997). It is based on the Henin and Dupuis model, but it is more sophisticated. A research into how to adapt the ICBM to the African context can be found in (Andrén et al. 2007). The model and the documentation can be found at www.oandren.com/icbm.html.

Assumptions - Henin and Dupuis

Parameter	Value	Unit	Source
Mean annual temperature	28.5	°C	Cofie et al. 2005
Average clay content in Northern Region soils	398.1	g/kg	Braimoh and Vlek 2004
Average silt content in Northern Region soils	71.3	g/kg	Braimoh and Vlek 2004
Humification coefficient k_1	0.25		De Ridder and Van Keulen 1990, Cocozza und.
Initial soil carbon	23.1	t/ha	Mathias Fosu, SARI, personal communication[a]
Annual carbon input (organic fertiliser)	0.19	t/ha	
Annual carbon input (NPK)	0	t/ha	

[a] Average in the Northern Region of Ghana

Assumptions - ICBM

Parameter	Value	Unit	Source
Carbon input Organic fertiliser	0.047	kg/m^2	
Roots and straw	0.050	kg/m^2	Andren and Katterer 1997
Total organic	0.097	kg/m^2	
Total NPK	0.050	kg/m^2	
Initial soil carbon	23.1	t/ha	Mathias Fosu, SARI, personal communication[a]
Humification coefficient k_1	0.25		De Ridder and Van Keulen 1990, Cocozza und.
Climate factor r_eclim	4.7		Andrén et al. 2007[b]

a Average in the Northern Region of Ghana

b Assuming same climate as the same latitude in neighbouring Togo

Results

Year		0	5	10	20	40	60	80
Henin and Dupuis								
Carbon content (organic)	t/ha	23.1	18.4	14.8	9.9	5.2	3.5	2.9
Carbon content (NPK)	t/ha	23.1	17.8	13.7	8.2	2.9	1.0	0.4
Averages with different time spans								
Mean annual change (organic)	t/ha yr		-0.94	-0.83	-0.66	-0.45	-0.33	-0.25
Mean annual change (NPK)	t/ha yr		-1.06	-0.94	-0.75	-0.51	-0.37	-0.28
ICBM								
Carbon content (organic)	t/ha	23.1	8.0	4.0	1.9	1.5	1.5	1.5
Carbon content (NPK)	t/ha	23.1	7.5	3.3	1.2	0.8	0.8	0.8
Averages with different time spans								
Mean annual change (organic)	t/ha yr		-3.05	-1.93	-1.07	-0.54	-0.36	-0.27
Mean annual change (NPK)	t/ha yr		-3.17	-2.00	-1.11	-0.56	-0.38	-0.28
Henin and Dupuis								
Mean annual increase with organic	t/ha yr		0.121	0.107	0.085	0.058	0.042	0.032
ICBM								
Mean annual increase with organic	t/ha yr		0.111	0.070	0.037	0.019	0.012	0.009

Appendix D. Economic assumptions

Investment costs (EUR)	Amount	Unit cost	Total cost	Source
COMPOST(base)				
Land (acres)	3	1,200	3,600	DeCo
Buildings		54,000	DeCo	
Utilities connection		7,500	DeCo	
Trucks	1	16,000	16,000	DeCo
Equipment			3,000	DeCo
BIOGAS extra costs				
Digesters	25	1,350	32,400	Burri and Martius 2011
Generator	1		5,000	www.alibaba.com
Grid connection			1,000	Burri and Martius 2011
Extra land (acres)	1.2	1,200	1,440	Assumption
BIOCHAR extra costs				
Pyrolysis oven	1		50,000	Fournier 2009
Extra storage space			10,000	Assumption
+SOIL extra costs				
Trucks	2	16,000	32,000	Assumption

Operating costs (EUR)	Amount	Unit cost	Total cost	Source
COMPOST (base)				
Inputs[a] (tons)				
MSW (organic)	1,500	12,5	18,750	DeCo
Shea processing residue	750	10	7,500	DeCo
Neem leaves	750	20	15,000	DeCo
Poultry manure	1,500	20	30,000	DeCo
Labour (work days)				
Plant workers	6,240[b]	5	31,200	DeCo
Driver	120	5	600	DeCo
Plant manager	250	20	5,000	DeCo
Project manager	260	40	10,400	Assumption
Utilities				
Electricity			100	DeCo
Water			300	DeCo
Fuel (litres)	6,801	0.75	5,100	LCA model
Flights	3	900	2,700	
BIOGAS extra costs				
Labour (work days)				
Technician	260	20	5,200	Assumption, Burri and Martius 2011
Extra workers	1,560[c]	5	7,800	Assumption, Burri and Martius 2011
Security	730	2	1,460	Assumption
Utilities				
Extra water			840	Burri and Martius 2011
Electricity savings			-100	Assumption
BIOCHAR extra costs				
Rice husks			0	Assumption
Extra workers (work days)	470	5	2,320	Assumption
Technician (work days)	260	20	5,200	Assumption
Extra fuel (litres)	8,556	0.75	6,417	LCA model
+SOIL extra costs				
Fuel (litres)	3,400	0.75	2,550	Assumption
Extra labour (work days)	120	5	600	Assumption
Drivers (work days)	60	5	300	Assumption

a Includes transportation costs
b 24 workers × 260 days a year
c 6 workers × 260 days a year