University of East London
School of Computing and Technology
Docklands Campus
4-6 University Way
London
E16 2RD
Tel: +44 (0)208223300

Graduate School of the Environment
Centre for Alternative Technology
Machynlleth
Powys
Wales
SY20 9AZ
Tel: +44 (0)1654 704968

The potential for reducing atmospheric concentrations of CO_2 through Biochar in the UK

Mariska Evelein

Preface

Since the industrial revolution we have been burning fossil fuels in ever increasing quantities. This is now understood to create a change in our climate, with potentially catastrophic consequences for the survival of many species. Many countries have pledged to reduce carbon emissions, but action is still limited.

It can be argued that, as well as a reduction in carbon emissions, the removal of some level of atmospheric carbon is needed. Photosynthesis in vegetation is one of the most efficient mechanisms for removing carbon from the atmosphere, and biochar can be produced from vegetation to lock up the carbon from its tissue in a long term stable form. Biochar is a charcoal-like substance with high carbon content. Its half life of several hundred years creates the potential for it to be used as a long-term store for carbon as a measure to mitigate climate change.

This thesis assesses the climate change mitigation potential of biochar in the UK through a quantification of the resources available for its production, focusing on forestry residues and waste biomass. The forestry residue potential is assessed in three scenarios: first in a business as usual scenario, in which only material that is currently unmarketed would become available. Second through availability of extra biomass diverted from existing markets to biochar production, and using extra land to grow biochar crops.

This report critiques and analyses the available literature on biochar, focusing on the environmental impact and energy balance of biochar production, subjects often neglected in contemporary research.

The outcomes of this thesis suggest that there is a significant carbon sequestration and energy potential from biochar in the UK, but care needs to be taken to select appropriate clean technologies for biochar production.

Acknowledgments

I would like to thank the course director, Mike Thompson, for his inspiration and enthusiasm for the course. Judith, for her guidance throughout the course, for being a great tutor and for providing a reality check to all crazy ideas. Thanks to Gerry for his support and advice in putting this thesis together. And to the many friends this course has introduced to me.

I would especially like to acknowledge Ian Tubby from the Forestry Commission, Adriana Downie from BEST Energies, Bob Hawkins from Eprida, Guido van Hofwegen from Resilience, Thom Kuyper from Wageningen University and Jeroen Dijkshoorn from BRASS for their invaluable advice and access to data for this project.

And, finally, to Tim for his love and support, and for making this world a better place to live in.

Table of Contents

List of Abbreviations

BC	Black Carbon
C	Carbon
CCS	Carbon Capture and Storage
CEC	Cation Exchange Capacity; a measure of the negative charge in the soil
CH_4	Methane
CO	Carbon mono-oxide
CO_2	Carbon dioxide
DBERR	Department for Business, Enterprise and Regulatory Reform
Defra	Department for Environment, Food and Rural Affairs
EPA	Environmental Protection Agency of the US
EU	European Union
FAO	Food and Agriculture Organisation of the UN
FC	Forestry Commission
GHG	Greenhouse Gas
GIS	Geographic Information System
GWP	Global Warming Potential; climate effect of a substance relative to CO_2
ha	Hectare; a unit of measurement for an area (1 ha = 10.000 m^2)
IPCC	Intergovernmental Panel on Climate Change
kWh	Kilowatt-Hour; standard unit of electricity consumed
ppm	Parts per million
MJ	Mega Joule; unit of measurement for energy
MSW	Municipal Solid Waste
Mtoe	Metric tonne of oil equivalent; unit of measurement for energy
N_2O	Nitrous Oxide
ODT	Oven dry tonne
SOC	Soil Organic Carbon
SRC	Short Rotation Coppice
tC	tonne carbon
TWh	Terra Watt Hour
UK	United Kingdom of Great Britain and Northern Ireland
UN	United Nations
VOC	Volatile Organic Compound
yr	Year

List of Figures

List of Tables

Introduction

This thesis focuses on the question of whether and to what extent biochar can be a suitable material for carbon sequestration in the UK.

Climate change is a contemporary issue; it is in the consciousness of our whole society – from general public to policy makers and is increasingly recognised as a serious issue that needs to be addressed globally. Although research on climate change has been suggesting serious risks of global warming for many decades, solutions to the problem are still rarely implemented. Conventional solutions to climate change focus on limiting greenhouse gas emissions. This is done through reducing fossil fuel energy use, replacement of fossil fuels with renewable energies, or through the technology of carbon capture and storage (CCS). The latter removes large parts of the CO_2 emissions from the combustion gases of large power stations, which is then stored in geological storage.

It could be argued that solutions that focus on limiting emissions cannot offer a complete solution to climate change on their own; greenhouse gases have a long lifetime in the atmosphere, and when released will continue to influence climate change for many decades. An additional solution is needed which incorporates long-term *removal* of some level of greenhouse gases from the atmosphere.

Vegetation naturally removes carbon dioxide, the main greenhouse gas, from the atmosphere through photosynthesis, and stores it in the cell tissue. This biomass naturally returns to the atmosphere when the plant dies, within a few decades. Photosynthesis is efficient in the removal of atmospheric CO_2. Other processes have been designed to remove carbon from the atmosphere chemically[1], but none have been as efficient.

This thesis proposes that biomass could be used to produce charcoal – or biochar[2]. Biochar is the same material as charcoal; a light, brittle, porous sponge-like material, which mostly consists of carbon (around 85-95%) with small amounts of volatiles and ash. It is produced by oxygen-free burning of biomass, called pyrolysis. Biochar contains a large part of the initial biomass-carbon, which is thought to be inert in the environment and does not return the carbon to the atmosphere for centuries. By doing this, carbon could potentially be prevented from re-entering the atmosphere and therefore help to curb climate change. The vegetations would remove excess atmospheric carbon dioxide, and put this in long-term storage by turning it into biochar.

The main context of past research on biochar is in relation to Terra Preta; ancient dark soils which were found in the Amazon. The idea of using biochar arose from the discovery of these Terra Preta soils, which appeared to contain much charcoal and were significantly

---

[1] e.g. Synthetic Trees binding atmospheric CO_2 using a recyclable solvent (Lackner et. al, 1999), which energy requirement would be prohibitive (Keith et. al, 2006)

[2] Biochar usually refers to the use of this material as agricultural supplement, whereas charcoal mostly refers to the use of this material as a fuel. Char is used as a term for the by-product of pyrolysis, which is again the same material. Throughout this thesis all these three terms will be used, which will in all cases refer to the same material.

more productive than the surrounding poor soils (Lehmann et. al, 2004). Since some of the charcoal in these soils has been dated at over 6000 years old, it was assumed that charcoal could form a long-term stable pool of carbon and act as a soil improver (Lehmann et. al, 2006). Much of the current research on biochar is in the area of soil fertility, and little research focuses on the wider environmental benefit and impact of using charcoal for carbon sequestration.

The research question that underpins this thesis is: *"What is the potential for reducing atmospheric concentrations of* CO_2 *through biochar in the UK?"* This thesis will assess the biomass that could become available in the UK to produce biochar, and how this could influence atmospheric CO_2 levels. It will aim to assess the suitability of biochar for climate change mitigation in the UK. This will be done using secondary research on biochar, forestry and waste in the UK. Total biomass availability will be assessed, and from this the potential biochar production will be modelled.

This thesis will also review and question the available literature on biochar and scrutinise the assumptions that have been made in the past. This will include the stability of charcoal in the environment, and the environmental impact of charcoal production. Both of these are often ignored in contemporary research.

The main contribution to scientific understanding that this work will bring forward is an assessment of the quantification as well as the value of using biochar for carbon sequestration in the UK. It has to be noted that this thesis has taken a theoretical approach to this question. It does not take into account economic considerations, logistical issues or socio-political factors that might influence the outcomes or practicability of this research, because of time constraints.

The focus of this work will be on the United Kingdom. In the first stages of this work the author focused on Wales. However, the scope of the work was widened to include the whole of the UK because the same or better information from secondary sources was available. It was thought that if this thesis could provide some new insights, these could then inform our climate policy at a national level.

There are several hypotheses underpinning the research question:

- the available material from waste streams and forestry in the UK is large enough to make biochar production a possible climate change mitigation tool;
- the emissions of the charcoal production will not outweigh the benefits of the sequestration potential;
- biochar can have a positive influence on agricultural production through improved soil fertility;
- sequestering carbon as biochar is more beneficial in carbon savings than the use of the same biomass for energy.

To test these hypotheses the following methods are used:

1. review from current academic literature and government policy statements to establish what climate change action should be taken, and define to a target for the UK;
2. assessment of the potential wood production and waste available in the UK;
3. a likely production efficiency is determined and applied to these results to produce a total potential charcoal production for the UK.

This thesis is built on the following structure:

- The **Literature Review** and **Methodology** give the research framework.
- **Chapter 1 - Climate Change and Biochar** frames the climate change issue, reviews methods for climate change mitigation, and assesses the suitability and potential for biochar to fulfil this role.
- **Chapter 2 - Biochar Production** looks at the production of biochar, involving a general overview of pyrolysis technology and principles, feedstock suitability, energy production and emissions from pyrolysis.
- **Chapter 3 - Biochar use** looks at the different uses for biochar, focussing in on three uses: charcoal as a fuel, biochar as a soil amendment and biochar as a filtration medium.
- **Chapter 4 - Forestry biomass** looks specifically at the situation in the UK, to assess the available material from forestry and waste that could be available for biochar production, and give estimates for the carbon sink potential and energy production potential from using this technology.
- **Chapter 5 – Waste biomass** establishes the available waste in the UK and the associated biochar production.
- **Chapter 6 - Analysis** analyses the results from chapters 4 and 5.
- **Chapter 7 - Conclusion** includes the limitations of the research and any further research necessary.

Literature Review

Biochar is relatively new as a line of research. There have been three broad streams to this research: its production, the effect of biochar on soil fertility and its role in carbon sequestration.

However, the published work specifically looking at biochar is still limited and biased towards the soil fertility and Terra Preta research. Within this research area there is a split between the analysis and characterization of ancient soils, and research into charcoal as a soil additive in general. Some of the main researchers in this field are Johannes Lehmann from Cornell University and Christoph Steiner from Bayreuth University, but the list is large, and fast growing. The leading publication in this field is from Lehmann et. al, (2004): *Amazonian Dark Earths: Origin, Properties, management.* This has been a source of inspiration for this thesis, but has only in a few places been seen to be relevant to this particular research question.

There has been little biochar carbon sequestration research. One work of Lehmann et.al, (2006) looks at the carbon sequestration of making biochar by replacing slash-and-burn with slash-and-char in traditional shifting cultivation. Fowles (2007) has assessed the carbon balance of biochar carbon sequestration as an alternative to the use of the biomass for energy production. He found that in most cases black carbon sequestration is more efficient at reducing atmospheric carbon than displacing fossil fuel with biomass energy. The only exception would be when biomass could efficiently displace coal in a coal-fired power station. This thesis will work with the conclusions from Fowles and will assess the biochar that could be made, assuming that material otherwise used for biomass energy production will become available for biochar.

Research that has been limited in this area is on the environmental impact of biochar production, and the energy produced from pyrolysis. These are both important research areas, particularly when looking at the potential for biochar as a carbon sequestration medium. In certain circumstances biochar production could be more polluting than the sequestered carbon is worth. The energy produced during the process could add an extra benefit to the use of biochar for carbon sequestration. Both these issues will be assessed in this thesis.

This thesis, although heavily reliant on the work done by previous researchers, takes a different angle than most, focusing on climate change mitigation using biochar, with application to the UK. Its key difference is in its approach to the problem; it assesses the resource available and works from there to predict the biochar that could be made. Most other research works in a top-down approach where the quantity of biochar needed to offset carbon emissions is calculated first, without necessarily relating this to a real world situation by discussing how this could be supplied. No other research was found that focuses specifically at this question, looking at different scenarios in which the UK can use this technology to create a carbon sink. Another aspect the scientific literature does not discuss is the environmental impact of biochar production. This thesis will aim to cover this.

This thesis draws at certain points of research on charcoal production that is not directly related to biochar. On top of this it uses some research from biochar production companies, specifically from BEST Energies and EPRIDA. Although these companies risk being labelled as biased, they do at the moment provide useful information while other sources focusing specifically on biochar production are limited.

The data to determine the available biomass resource for biochar production have come from statistical sources and government organisations. They are at its source unrelated to biochar. To these data findings from biochar researchers are applied, mainly on the conversion efficiency of biomass carbon into biochar carbon.

Methodology

The research question *"What is the potential for reducing atmospheric concentrations of CO_2 through biochar in the UK?"* holds two sub-questions that are answered. These are:

1. what are the key biochar production parameters
2. how much biomass resource could be available in the UK

The key features that need to be known of the biochar production are the yield of biochar and carbon, and the energy production. This could be measured for each individual feedstock type through pyrolysis experiments, but this equipment is not available. For this research these figures will be found from the available literature.

There are several possible methods to assess the available resource in the UK. This could be done through interviews with key processors, companies, measuring waste from households, using remote sensing and GIS to model current and future forestry potential, or using data from other research and statistics.

For this thesis it was decided the above methods were not feasible within the scope, time and resources available. It was decided the preferred method to answer the research question is through the analysis of previous research. By reanalysing their data this new research question is answered, providing new conclusions.

Much research has been done on individual aspects of this research question that would be too lengthy and inappropriate to repeat for this thesis. This is for example, extensive research on charcoal production, on the assessment of resources in the UK, and on the behaviour of charcoal in soils. However none of them have been combined to provide an answer to how much carbon can this process can sequester in the UK.

The main merit of this approach is that in a relatively short time period some useful figures can be found. The disadvantage is that there is possibly a limited amount of data to base conclusions on, and some data might be of little relevance to the research question. The consequences of this are:

1. The basis of the thesis is entirely dependent on other research, which might be unable to provide the necessary data
2. It might be unable to provide data of enough detail to be suitable for use in this thesis
3. The research method of the original reports could be unclear, making it possibly difficult to compare findings of different reports.

To assess the relevance of the documents used several aspects were considered

1. the detail of the information
2. description of research methods
3. applicability to this research

Applying this would lead to a judgement of the data source. This could either lead to only one document being suitable, or there could be multiple documents equally suitable. In the first case the data from this single report would be used, in the last case an average of all data would be taken to work with. Whichever method is chosen it will be made clear in the text.

Method

Data was collected using the World Wide Web, with extensive use of on-line scientific journal databases, University Library and National Library. To provide supplementary data or data that was unavailable in any of these sources specialists were contacted.

Data sources were ranked on:
1. the detail of the information
2. description of research methods
3. applicability to this research

Biochar Production

Data on biochar production was collected using the Internet through the search engine Google and Google Scholar, and using on-line journal databases with Athens access.

When searching some of the keywords used were for example: Pyrolysis, Charcoal Production, Energy balance of pyrolysis and Biochar production. In the Google Search engine it was found that any specific keywords would lead to information on patents, or pyrolysis equipment manufacturers. Unbiased information was limited.

The results from Google Scholar brought up more reliable sources, since Google Scholar selects books and scientific journals. However, the information of these reports was often too detailed to be useful for this thesis, reporting specific solutions or research on technological detail of the production process. This was found to be similar for searches in scientific journal databases.

‘Science Direct’ search engine brought up some more general articles, with keywords such as biochar production, char and charcoal production. Some scientific articles that seemed potentially useful were unavailable, particularly from the Springer Link publisher, to which UEL Athens did not provide access.

Information on the energy production and emissions from biochar production was especially difficult to find in any of these three sources. It was decided to contact biochar specialists with this question. Individuals from the major biochar companies, as well as professors from leading universities were contacted by e-mail. Several authors on an upcoming book on biochar were contacted. There was a limited response. There was a reply from four individuals, including one from a professor who apologised for the fact that this information was not available. Two other relevant emails were selected (see Appendix V) for potential use.

Informal discussions were held with members from a Terra Preta forum[3], a discussion group of biochar and Terra Preta enthusiasts, as well as leading researchers and employees of renowned biochar companies. Although this was an excellent starting point for contact building, information available on this list was of limited scientific value; most statements were not supported with articles or results from experiments.

Biomass

The data collection was again similar to that for the biochar production. At the start of the research much use was made of government organisations; the Forestry Commission, and BRASS, and several universities. Ian Tubby was an early contact from the FC, who helped to find suitable research to determine the forestry material available in the UK. Much information on waste and general forestry statistics was also available on the internet, on websites from Defra and the National Statistics.

Since the initial focus of this research was on Wales before it was decided to expand to the UK, it was of more importance to get detailed information, which for Wales only was more limited. Eventually the Woodfuel in Britain report was found which covered Wales and UK in the same detail, so the change over from Wales to the UK was not problematic.

---

[3] http://terrapreta.bioenergylists.org [accessed 20/01/08]

Chapter 1 – Climate Change and Biochar

This chapter will introduce climate change and the global carbon cycle as framing concepts for this thesis. It will discuss the current state of climate change and carbon emissions, and what the role of biochar in this can be.
First climate change and the global carbon cycle are discussed, introducing the concepts of active and passive carbon pools. Section 1.2 gives an overview of current carbon emissions and climate change mitigation, and in section 1.3 the role of biochar in this is discussed.

1.1 Climate Change and the Global Carbon Cycle

Climate change has fast become the environmental issue of the 21 century. It is in the daily media and in the consciousness of our whole society. Climate change has been foreseen since the beginning of the 19th century with the discovery of the greenhouse effect by Fourier (Houghton, 2004 p 17). However, it has only recently started to receive more public attention since the founding of the Intergovernmental Panel on Climate Change (IPCC). This is the collaborative body of climate scientists who inform governments and policy makers on the state of climate change. The IPCC climate models predict up to 6.4°C temperature rise within the next century (IPCC, 2007 p 13). This is high; a temperature increase of 2°C is expected to threaten the extinction of species, and increase the risk of extreme weather events like tropical cyclones, droughts and heat waves (Schneider et. al, 2007 pp 795-796). The IPCC states with very high confidence that a temperature increase of 4°C "would lead to major increases in vulnerability, exceeding the adaptive capacity of many systems." (Schneider et. al, 2007 p 781)

It is established scientific understanding that climate change is caused at least partly by anthropogenic carbon emissions (Solomon et. al, 2007; Houghton, 2004). Carbon dioxide and other greenhouse gases increase the radiative forcing which is "the change in average net radiation at the top of the troposphere" (Houghton, 2004 p 29). A positive radiative forcing means there is more energy coming in than going out of the atmosphere. This in turn leads to an increase of total energy in the earth system, with consequent warming.

The climate system is filled with positive feedbacks; increased warming sets off other processes that release more greenhouse gases, causing more warming[4]. The full understanding of these feedbacks is still limited, causing uncertainty in the outcomes of most climate models (Solomon et. al, 2007 p 77). One of the effects of positive climate feedbacks is that it creates a non-linear system in which a small trigger can set off a much bigger effect.

---

[4] An example of a feedback is the release of Methane (CH_4) from melting of permafrost after warming, causing an increase in radiative forcing and hence further increased warming.

There is an intricate link between the climate and the Carbon Cycle. The global carbon cycle is a model of the flows and pools of carbon in the earth system. Figure 1 gives a representation of this. There are several 'pools' of carbon; terrestrial (plants and soils), atmospheric, ocean and geological, between which carbon flows. In these pools carbon exists in different forms, and the 'lifetime' in each is different. For example, the expected lifetime of carbon in the geological pool, in which carbon is mostly in a solid state, is much larger[5] than in the atmospheric pool, in which carbon exists mainly in a gaseous form. "About one-fifth of the total amount in the atmosphere is cycled in and out each year" (Houghton, 2004 p 30). Although the focus of most climate change discussion is on atmospheric carbon concentrations, it is certainly not the largest pool of carbon on earth. Most carbon exists in the form of fossil carbon, rock carbonates and in the ocean. The atmospheric carbon pool is in constant interaction with other carbon pools, which forms what could be called an `active carbon pool`. Indeed a division can be made between a passive and active pool (see Figure 1 below).

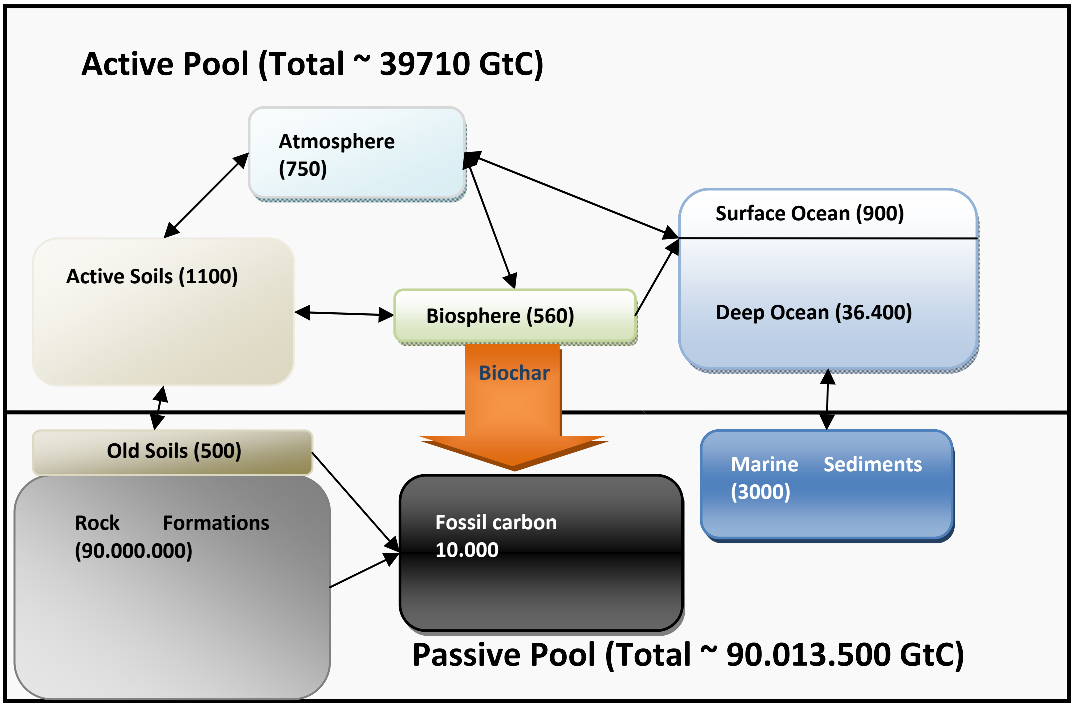

Figure 1 Active and Passive Carbon pool, approximate representation of stocks and flows, showing the effect of biochar with the orange arrow. Source data taken from Jacobson et, al, (2000)

The passive pool contains carbon that is stable or inert, and not expected to move for long periods of time. This includes geological formations and deep ocean sediments. The active pool consists of carbon that is moving between pools fast. This includes certain parts of the atmosphere, plant and soil carbon and some layers in the ocean. This active carbon pool is a constant exchange of carbon between atmosphere, biosphere and ocean through photosynthesis, respiration, chemical adsorption and desorption, always reaching a steady state (Jacobson et. al, 2000). The result of this is that any attempt to remove carbon from the atmosphere will be short-lived unless the carbon is removed into the passive pool.

---

[5] Up to millions of years in the case of fossil fuels (if they were not mined)

1.2 Carbon Emissions and Climate Change Mitigation

Below is an overview of the carbon emissions globally and in the UK, since 1751. The total Global carbon emissions were 7.9 metric Giga tonnes of carbon (GtC) in 2004, compared with 3MtC in 1751 (Marland et. al, 2007; see Figure 2). The UK Carbon emissions were 160 MtC in 2004, compared with 2.5 MtC in 1751 (Marland et. al, 2007; see Figure 3).

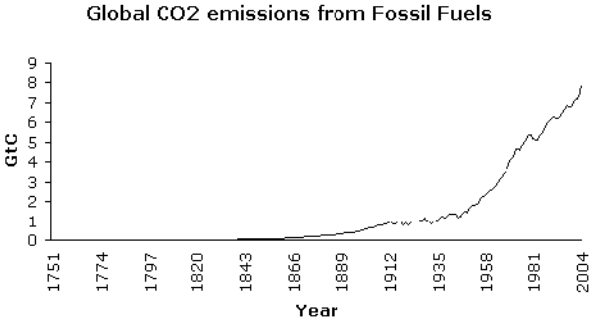

Figure 3 Global CO_2 emissions from fossil fuels. Source CDIAC (Marland et. al, 2007)

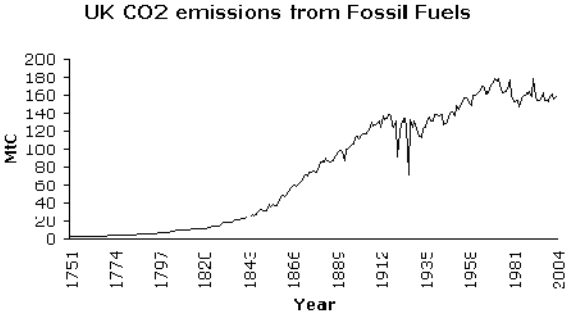

Figure 2 UK CO_2 emissions from fossil fuels. Source CDIAC (Marland et. al, 2007)

These figures show steadily rising carbon dioxide emissions over the last century. Because of a backlog in the climate response to these emissions, the result of this rise is still to be felt (Scheffer et. al, 2006; Kerr, 2007). Any further emissions will increase the radiative forcing more, which will result in more warming. Even after stabilising emissions more warming is expected (Houghton, 2004 p 39). To prevent dangerous runaway climate change a cut of carbon emissions to a safe level is needed. This exact safe level is much debated, but it can be argued that it should keep the global warming below 2°C. A cut in Global carbon emissions to 50-85% of 2000 levels by 2050 would result in an increased radiative forcing of 2.5-3.0 W/m^2 or 2.0-2.4°C warming (Barker et. al, 2007 p 39). With evidence that the natural sinks are already failing (Piao et. al, 2008) this might be underestimated. This suggests that a reduction of 100% or more by 2050 (or before) might be needed to stay below the 2°C warming level. To achieve this, a cut of atmospheric greenhouse gas levels to pre-industrial levels is needed through reduction of emissions and active removal of greenhouse gases from the "active pool".

By signing United Nations Framework Convention on Climate change in 1992 over 160 countries expressed their concern about climate change. They expressed their aim to mitigate climate change to a "level which would prevent dangerous anthropogenic interference with the climate system" (Houghton, 2004 p 242). This has more recently come into a more solid form with the ratification of the Kyoto protocol, which the UK signed in 1998 and has come into force in 2005. With this the UK has committed to an 8% reduction in CO_2 emissions from the 1990 baseline emissions, to be achieved by 2008 to 2012 (United Nations, 1998). Although this is a significant first step on the road to preventing dangerous climate change, much larger reductions are needed soon.

Methods to achieve this reduction in emissions include energy efficiency measures, Carbon Capture and Storage, the Renewable Energy Obligation, Carbon offsetting, and reducing deforestation. All focus on limiting the greenhouse gas emissions, which is necessary to start addressing the issue of climate change, but more action is needed.

1.3 Biochar for Climate Change Mitigation

The rationale behind using biochar for climate change mitigation is the following: We have been increasing the 'active carbon pool' for over a century. Decreasing the flow of carbon from fossil fuels[6] into the active pool would be necessary to curb climate change. However, the active pool would still contain a build up of past carbon emissions, will continue to increase warming.

Biochar production could provide a shortcut – it could create a flow of carbon from the active pool into the passive pool. This will effectively be rapid fossilisation. Plants continually absorb atmospheric CO_2 and store it in their cell tissue. Normally this would break down after the plant dies, and the carbon would return to the atmosphere within decades. If this material is instead used for biochar production this carbon would enter the passive pool. Charcoal is considered to be inert and will not move with any speed back into the active pool.

Biochar Lifetime

One of the first questions that needs to be asked when considering biochar, or any other material for carbon sequestration purposes, is what its lifetime and resistance to biological and chemical weathering are. The single purpose of carbon sequestration is to remove carbon from the atmosphere and keep it 'out of harm's way'; in a place or form that will prevent it from re-entering the atmosphere for many decades or centuries. For this purpose a long lifetime and high resistance to weathering and other decay is essential

The assumption in the literature is currently that biochar has a long lifetime, because the Terra Preta soils contain much ancient charcoal (Lehmann et. al, 2006). Charcoal is also generally used for carbon dating of soils and rocks, and archaeological sites (e.g. Gavin et. al, 2003; Figueiral et. al, 2000). However, measuring the half-life of charcoal is difficult because it is so long, and no real evidence exists on what influences the degradation of charcoal.

The fact that charcoal of over 6000 years old exists doesn't of course mean that all the charcoal that was formed at that time is still left there; some of it could have degraded over this period. To assess the applicability of biochar for carbon sequestration this needs to be considered.

Black Carbon (BC), which are tiny charcoal particles, is formed by forest fires, and can serve for geological dating. Masiello (2004) has reported some controversies of the stability of this black carbon. He discovered that the theoretical occurrence of BC, in the quantities it should be found at if it was produced at today's rate, was much larger than the actual quantities that are found. "BC should account for 25–125% of the total soil organic carbon pool. "Although a few measurements of soil BC/SOC are as large as 25%, even this lower bound is unrealistic for the entire soil carbon pool…". The problem is that the theoretical amount of BC that should be present if there was no degradation would

---

[6] Fossil fuels are theoretically in the passive pool if we wouldn't interfere with them

have to be much higher than the occurring quantities, even with a loss process of a thousand years. Some loss mechanisms were found however; Masiello (2004) detected loss of BC through microbial break down, but estimated it to be small. Cheng et. al, (2006) found some evidence of oxidation through a-biotic processes, but this has not directly lead to predictions of charcoal lifetime.

So although most biochar researchers have so far assumed a long lifetime of charcoal in the soil, this might not be accurate. More research on charcoal movement and degradation mechanisms is needed to give a solid proof on how resistant it is in the natural environment and exactly what processes would contribute to its loss.

In perspective

Using biochar with an uncertain lifetime would then depend on the perceived urgency of climate change, the expected ‘range’ of the biochar half-life, the performance of biochar vs. other technologies, the cost of biochar vs. other technologies and the half-life of wood in other forms (for example in landfill, in nature).

Key Findings and Recommendations from Chapter 1

- Climate change is a serious issue that needs to be addressed globally
- The UK has committed to 8% cut in carbon dioxide emissions from 1990 levels
- A 100% reduction in carbon emissions is needed to prevent dangerous climate change
- Ideally carbon should be removed from the ‘active carbon pool’ into the ‘passive carbon pool’
- Current measures to mitigate climate change focus on limiting the GHG emissions
- Additional removal of CO_2 from the atmosphere would be necessary
- Biochar can be produced to remove carbon dioxide from the atmosphere
- Biochar is expected to have a long lifetime in the environment but there are some uncertainties that need further investigation

Chapter 2 – Biochar Production

2.1 Introduction

Biochar is a recent term for char derived from biomass. It is also sometimes called agrichar, usually for use as agricultural fertiliser. The term charcoal is mostly used as a reference to the residue for fuel purposes. The term char is generally used in the context of the production, independent of what the end use will be. These three terms all refer to the same physical material in different contexts.

Char (or biochar or charcoal) is a carbon-rich residue that remains after anaerobic burning of woody biomass; pyrolysis. Char is not pure carbon; it consists of around 85% carbon, the remaining is ash and tar remnants. Char is by nature a light and porous material, which compares to a sponge. This is the structural residue after all the other molecules in the biomass are burnt off.

Char is produced in so-called retorts. Retorts are the vessels used for pyrolysis and can come in many forms. Traditional retorts for example are simple earth based kilns, which are made from a hole in the ground, covered with earth to seal it. Modern retorts are more complicated and usually involve several communicating vessels. Pyrolysis in these retorts is often powered by the gas that is produced, which is recycled to provide the necessary heat.

This chapter will discuss the charcoal production in more detail how charcoal, what types of retort could be suitable, and what the environmental and energy considerations are of its production. This will aim to inform the main body of research on the following factors:
1. the efficiency of charcoal production
2. predicted yields for a range of feedstock[7] types
3. possible pollution from charcoal production

First, pyrolysis in general is discussed in section 2.2; the different types of pyrolysis and retorts. Then the effect of feedstock on the process is discussed in section 2.3, followed by the environmental impact in section 2.4 and the energy balance of pyrolysis in 2.5.

2.2 Pyrolysis

Charcoal is produced by pyrolysis; the burning of biomass in the near absence of oxygen. The main products of pyrolysis are oil, char and gas (also referred to as syngas). The relative amounts of each depend on the processing temperature, heating rate, feedstock, feedstock size and moisture content.

This section will look first at the different types of pyrolysis that exist, at the pyrolysis process in detail and its thermodynamics, and the types of retort available.

---

[7] Feedstock is literally “raw material to supply a machine or industrial process” (Oxford Concise English dictionary).

2.2.1 Types of Pyrolysis

There are three types of pyrolysis: slow pyrolysis (or carbonisation), fast pyrolysis and flash pyrolysis. Table 1 below gives an outline of the main features of these processes. The major differences between the three processing types are the operating time and temperature, with slow pyrolysis having the lowest operating temperature and longest residence time, and flash pyrolysis having the highest operating temperature and shortest residence time.

Operating Parameters of the three forms of pyrolysis			
	Slow Pyrolysis (carbonization)	**Fast Pyrolysis**	**Flash Pyrolysis (gasification)**
Operating temperature (°C)	300-700	600-1000	800-1000
Heating rate (°C/s)	0.1-1	10-200	>1000
Solid residence time (s)	600-6 000	0.5-5	< 0.5
Particle size (mm)	5-50	< 1	Dust

Table 1 Range of the main operating parameters for Pyrolysis processes. Source: Maschio et. al (1992)

Because of this difference in operating parameters, these three processes produce fundamentally different products. Slow pyrolysis generally yields more char and gas, and fast and flash pyrolysis produce more liquid and gaseous products, and less char (see Table 2). The underlying cause for this decrease in char yield is the decomposition of char into gas at high temperatures through combustion.

Yields of different products per operating condition				
Mode	**Conditions**	**Bio-oil**	**Biochar**	**Gas**
Fast	Moderate temperatures (500°C) for 1 second	75%	12%	13%
Intermediate	Moderate temperatures (500°C) for 10–20 seconds	50%	20%	30%
Slow (carbonisation)	Low temperature, (400°C), very long solids residence time	30%	35%	35%
Gasification	High temperature, 800°C, long vapour residency time	5%	10%	85%

Table 2 Yields of different products per operating condition. Source: International Energy Agency 2007 In: Winsley (2007 p 6)

Other pyrolysis methods also exist that could be suitable for biochar production. Antonietti from the Max Planck institute has developed a new process for char production, which uses a steam cooker and heating the product to 180°C for 12 hours (Antonietti, 2006). This hydrothermal pyrolysis produced only char and water. This could be an interesting development if this leads to a char product of good quality, with less loss of carbon and other products from pyrolysis. However, neither the composition of the char and its structure, nor the energy use of this process was stated in his published results. Until more evidence about this becomes available, the focus for this research will be on the three forms of conventional pyrolysis.

After having discussed the three types of pyrolysis, the next section will consider the thermodynamics of pyrolysis in more detail.

2.2.2 Process

Char formation starts with drying of the feedstock, followed by pyrolysis and finally cooling of the products. This section focuses on the details of the pyrolysis.

Pyrolysis is complex but can be simplified into the following three stages (Demirbas 2004):

Biomass → Water + Unreacted residue (1)
Unreacted residue → (Volatile + Gases) + Char (2)
Char → (Volatile + Gases) + Char (3)

In the first stage (1) the feedstock is heated between 100°C and 170°C, which drives off any remaining moisture as well as some volatile gases (CO_2, CO, formic acid, and acetic acid).
In the second stage (2) the wood is further heated to around 270°C, at which point char starts to be formed. This is an exothermic process; it releases energy.
In the third stage (3) the char breaks down even further, which reduces the total char quantity and drives off any remaining tar. This stage takes place around 500°C and needs some further energy. The energy input for the endothermic stages is usually derived from the biomass feedstock, but could come from an external heat source.

This reaction can be described stoichiometrically by the following chemical formula (Antal et. al, 2003):

$2C_{42}H_{60}O_{28}$ (biomass) $\rightarrow$ $3C_{16}H_{10}O_2$ (char) + $28H_2O$ + $5CO_2$ + $3CO$ + $1.08C_{28}H_{34}O_9$(tar)

Figure 4 below shows at which stages the different pyrolysis by-products form. First the biomass breaks down into gas, tar and char, after which the tar breaks down into gas and char through secondary reactions. "Up to 270 °C primary reactions, such as hydrolysis and isomerizations, take place predominantly. Above 270 °C, secondary reactions, in which molecules split and recombine by condensation and polymerization prevail." (Ullmann's, 2000)

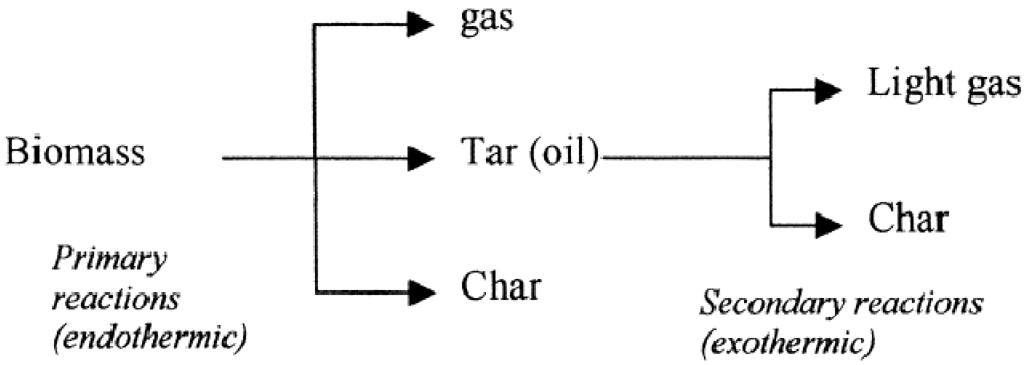

Figure 4 pyrolysis reaction Broido–Shafizadeh mechanism. Source: Demirbas (2001)

This simplified process works slightly different in reality; it is not so easy to distinguish between the different stages. Also the energy needed for the endothermic reactions and the by-products created depend on the feedstock. Chapter 2.3 will further discuss this after a brief discussion of the pyrolysis retorts in section 2.2.3.

2.2.3 Pyrolysis Retorts

There is a range of choices available on pyrolysis retort types. A retort is literally “a container or furnace for carrying out a chemical process on a large or industrial scale.”[8] It is not the aim of this thesis to discuss the technical details of this, but it will briefly touch on the different types of retorts available and the characteristics that are needed for successful biochar production.

Biochar production can be optimised for several competing objectives:

1. low environmental impact
2. high efficiency
3. high carbon recovery
4. potentially mobile retort
5. cost

The role of the pyrolysis retort in this is large; different types of processing (slow, fast and flash) need specialised retorts. The emissions change with the retort type and some have a high initial cost associated while having low running costs or vice versa. This section first focuses on traditional pyrolysis retorts, which are simpler and less costly than modern retorts, but usually run with a lower efficiency and increased pollution. After that the modern retorts are discussed.

Figure 5 Traditional charcoal mound in West Africa, Guinea. Source: Girard (2002)

The UN Food and Agriculture Organisation (FAO, 1987) gives an extensive overview of the earlier pyrolysis retorts. Traditional charcoal production was performed in a pit or in earth or brick kilns which were dug in the ground, with an earth cover to create an oxygen free environment. Examples of this method can be seen in Figure 5 on the right and in Figure 6 below. The size of this pit is around 30 m^3, slightly sloping to the back where the wood is stacked. The pyrolysis is fuelled by the partial burning of some of the wood. This type of processing is still used in developing countries because of the low investment costs. Generally this type of production is least efficient [9]; the air inlet is difficult to control, causing unnecessary loss of biomass. Also this processing has associated pollution since there is no capture of the pyrolysis gas.

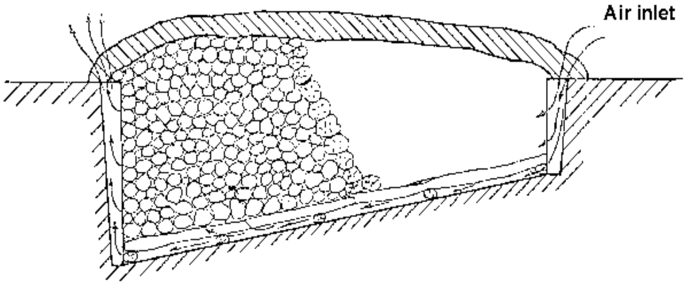

Figure 6 Traditional Charcoal Pit - Longitudinal section. Source (FAO, 1987)

---

[8] According to the Concise Oxford English dictionary

[9] typical yields of 1 kg of charcoal from 8 to 12 kg or more of wood (Stassen, 2002)

Figure 7 Improved traditional charcoal production: a Brazilian-type brick kiln in Cuba. Source Stassen (2002)

Another traditional retort is the metal or brick kiln (see Figure 7), which has an improved seal over the earth dug pit method. It has a better efficiency, with charcoal yields of 1 kg of charcoal from 6 to 8 kg of wood (Stassen, 2002).

Over the last century many different types of retorts have been developed, originally with the purpose of charcoal production and products for the chemical industry, but more recently most pyrolysis focus on bio-oil production. More recently environmental considerations have also been considered. Yields from modern efficient retorts, of which a picture can be seen in Figure 8, can be as high as 1 kg of charcoal from 3 to 4 kg of wood (Stassen, 2002). Information on the details of many of these technologies are not freely distributed, and are protected by patents.[10]

Several companies are specifically producing biochar, under which BEST Energies in America and Australia, and EPRIDA in America. Details on the retort types of both companies are not available.

A Canadian company Agritherm has developed a mobile retort, which is designed for bio-oil production. The advantage of this is that it can be taken to the feedstock, and so reduces transport costs of distributing the feedstock over large distances. So far mobile retorts for biochar have not been developed.

Figure 8 Industrial charcoal retort in the Netherlands, Source Stassen (2002)

After having set out the different types of retorts available for pyrolysis, the next section will discuss the effect of feedstock composition on the char yield. It will estimate biochar and carbon yields from the available biomass in the UK for carbon sequestration.

---

[10] The main reference used in this thesis for information on these technologies is the FAO. Although these documents are all around 20 years old, they are giving the clearest overview of the retort types.

2.3 Feedstock

Feedstock is literally “raw material to supply a machine or industrial process” (Oxford Concise English dictionary). The feedstock type and composition has a large influence on the quantity of pyrolysis products. The following feedstock parameters influence the yields from pyrolysis:

1. Moisture content
2. Size
3. Composition

The moisture content of the feedstock influences the energy needed for pyrolysis. If this energy is supplied by the biomass feedstock rather than an outside energy source, will decrease the yields of the pyrolysis by-products. This is the same for the size; larger feedstock parts will pyrolyse slower and less efficiently.

Within the feedstock, each material has its specific decomposition pattern. The main compounds that biomass is built of are cellulose, hemicellulose and lignin. These have different characteristics, and influence the pyrolysis process and the yields of the different char, gas and oil products. The UN Food and Agriculture Organisation has compiled a table on the composition of different biomass types (see Table 3 below).

Composition of feedstock

Type	CL	HCL	LIG	EXT	Ash
Soft wood	41	24	28	2	0.4
Hard wood	39	35	20	3	0.3
Pine bark	34	16	34	14	2
Straw (wheat)	40	28	17	11	7
Rice husks	30	25	12	18	16
Peat	10	32	44	11	6

Table 3 Composition of Different Biomass Types: CL - Cellulose; HCL-Hemicellulose; LIG-lignin; EXT-Extractives (Source: FAO, 1987)

According to the FAO (1987), both cellulose and hemicellulose decompose with little char formation at temperatures above 500°C. Lignin contains phenolic units, strong aromatic carbon structures, which make it slower to break down. It is a major component of the remaining char, which reflects the phenolic units of the lignin in its structure. Figure 9 below shows the findings from research by Demirbas, pointing to a strong positive correlation between the lignin content and the char yield.

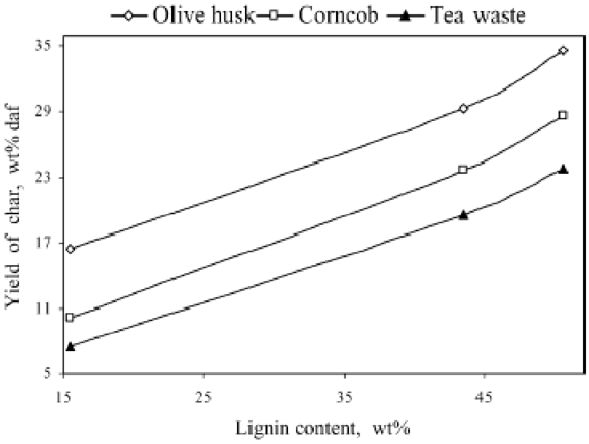

Figure 9 Effect of lignin content on yield of bio-char at 950 K final temperature. Particle size: 1.5–2.2 mm. Source (Demirbas, 2004)

Demirbas and Arin (2002) describe the temperatures at which the different parts break down as reflecting what would happen if the components would pyrolyse separately. First the hemicelluloses break down at temperatures of 470 to 530 K. Cellulose follows in the temperature range 510 to 620 K, and lignin is the last component to pyrolyse at temperatures of 550 to 770 K.

This short introduction has served as an indication of the complexity of pyrolysis, and the role of the feedstock composition in this. The next section will aim to predict biochar yields from different feedstock types.

2.3.1 Char and Carbon Yield Prediction

This section aims to give an estimate for the char and carbon yields that can be expected for certain biomass types. The char and carbon yield are usually different; char is not pure carbon but contains other molecules as well. The carbon yield from the biomass feedstock is an important parameter in this research. If the carbon yield from a particular biomass is known, the carbon sequestration potential can be estimated from the total available biomass.

Since performing tests to establish the charcoal and carbon yields from pyrolysis falls outside the scope of this thesis, this information has to be drawn from other research. The main parameters that can inform this are; the char yield, the carbon content of the char and the carbon content of the original material. From this the fixed carbon content of the char as part of the carbon content of the original feedstock can be derived.

Demirbas has published several articles looking specifically at char production from different biomass types. Also Downie et. al (2007) from BEST Energies has produced a report on biochar production from different feedstocks. These and other reports have been integrated in Table 4 which shows the findings on the carbon recovered from the biomass in the charcoal. Ryu et. al, (2007) and Downie et. al (2007) gave these results in their report, for the other sources this was calculated using their findings on the carbon content of the original material, the char yield, and the carbon content of the char[11].

Carbon yield from pyrolysis of different biomass materials

Feedstock	Temperature (°C)	% Carbon in char from carbon in feedstock	Research
Straw	500-900	50-57	Fagbemi et. al, 2001
Coconut shell	500-900	42-53	
Wood	500-900	39-48	
Hazelnut kernel husk	550-850	63-68	Demirbas, 2001
Olive husk	550-850	58-64	
Hazelnut shell	550-850	55-58	
Spruce wood	550-850	47-52	
Beech wood	550-850	43-50	
Corn cob	550-850	38-45	
RDF 1.5 cm	350-700	31-62	Ryu et.al, 2007
RCG 5cm long air dried	350-700	44-52	
Pine Wood cubes 2 cm	350-700	41-54	
Feedlot Manure	550 ±30	63	Downie et. al, 2007
Poultry Litter			
Paper Sludge			
Cotton Trash			
Woody weeds			
Green Waste			
Wood Waste			
Rice Hulls			
Corn Trash			
Meat Meal			

Table 4 Carbon Yield from the pyrolysis of different biomass materials. Calculated using data on biomass Carbon content, char yield and char carbon content. Taken from different sources (see far right column).

It has to be noted that the process parameters for the different sources were different, the reactor types were different and the experiments had different temperature ranges, which the reports did not always state. Thus they cannot directly be compared, but could at the least suggest the range in which the values would fall.

As can be seen from Table 4 the range of carbon yields was high; from 31% to 68%. This was strongly related to the processing temperature; with the lowest processing temperature in each case giving the highest yield of carbon, and vice versa. The feedstock material also had a large impact on the carbon recovered. This indicates again that biochar production needs low processing temperatures, to achieve optimum carbon yields. If it is assumed that this is optimised, a prediction could be made for the carbon

---

[11] Carbon yield = char yield * carbon in char / carbon in feedstock. A range of 40-50% carbon was found in the biomass in the reports used.

yield, using the optimum yields from Table 4. They range between 45% for corn cob (Ryu et. al, 2007) and 68% for hazelnut kernel husk (Demirbas, 2001).

The research from Downie et. al (2007) is indicative of the type of processing and material that is expected to be available for biochar production in the UK; a mixture of waste, sludge and wood, unlike the other reports. The 63% retrieval of the biomass carbon in the biochar according to Downie et. al is fair estimate of the expected figure in this case, and will be used as a benchmark figure throughout this thesis.

The last two sections of this chapter will look at the environmental impact and energy balance of biochar production. These two factors receive little attention in scientific literature. These chapters will aim to find all available evidence on these two issues to inform this thesis and the scientific debate on biochar and its environmental merits and limitations.

2.4 Environmental Impact

The environmental impact of biochar production is a complicated issue which highly depends on the retort used and the feedstock and moisture content of the material. The US Environment protection agency (EPA) has reported the products and by-products from charcoal; charcoal, non-condensable gases (CO, CO_2, methane, and ethane), pyroacids (acetic acid and methanol), tars and heavy oils, and water. All of these (except charcoal) are emitted with the kiln exhaust. Handling charcoal creates particles, which is another form of pollution.

Broadly speaking traditional kilns are especially polluting since most do not collect gases and tars, and modern kilns are relatively clean since most by-products are collected. Traditionally, charcoal was made in earth kilns, from which the gases and tars could easily escape and cause air and water pollution.

Modern retorts collect this syngas and use it to generate heat and electricity. This creates a closed system and limits pollution. However, according to Ullmann’s (2000) there is some pollution possible from the wastewater, which must be biologically treated.

The sections below explore in more detail the environmental impact of these emissions, focusing on Methane, Volatile Organic Compounds and Particles.

2.4.1 Methane

Methane (CH_4) is one of the gases emitted in the syngas and could cause a negative overall climate impact if released. The overall contribution of methane to climate change has been 24% (Houghton et. al, 2004 p 28). It has a lifetime of 12 years in the atmosphere and its global warming potential (GWP) is 72 times larger than CO_2 in the short term (20 years). This decreases to 25 times the GWP in a 100-year time-frame[12] and 7.6 in a 500-year time-frame (Solomon et. al, 2007 p 33). In general the GWP of the 100-year time-frame is used and this will also be done in this thesis. This extended impact of methane on the climate is caused by its indirect effect on ozone and water vapour in the long terms.

No research has been found that looked at the direct impact of methane release from biochar production on climate change. A suggestion of the climate impact of this methane release can be quite simply calculated using reports on methane production. This will be done below using data from Best Energies. These are data from a modern retort, which is optimised for char and gas production. In a retort that would release the gas these figures are likely to be different, but these data do not exist.

The gas analysis reported by Best Energies shows 8.5% Methane, 16% Hydrogen, 20% Carbon Monoxide, 16% Carbon Dioxide and 38% Nitrogen, as well as minor fractions of Ethylene, Ethane and Acetylene (Downie et. al, 2007). This is produced in a modern retort which combusts these gases for electricity and heat production, leaving only CO_2 and water. In this research 63 % of the carbon is converted into char, and 37% of the biomass carbon is released as gas[13], which contains 8.5% CH_4, 20% CO, and 16% CO_2.

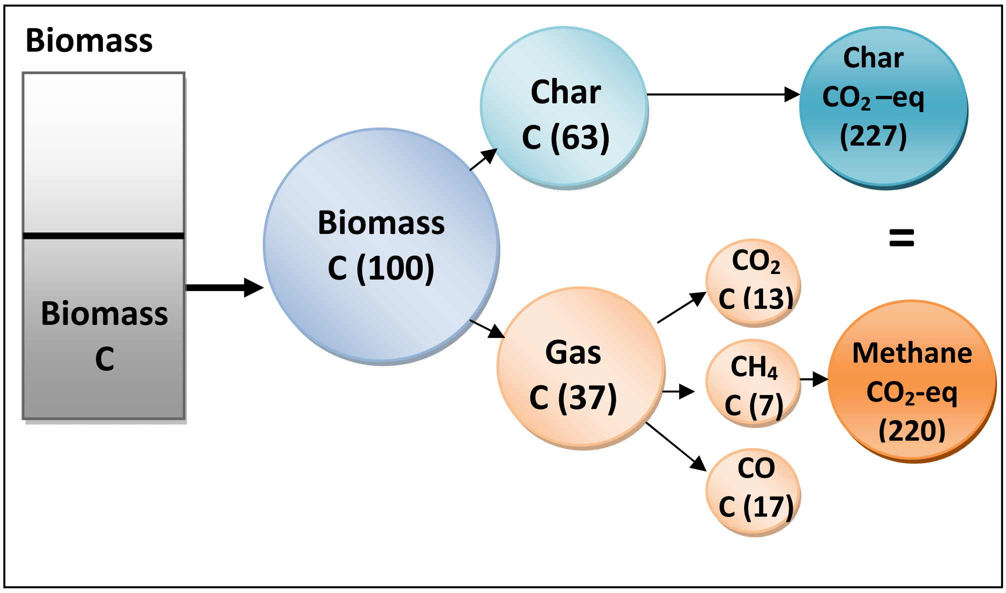

Figure 10 Schematic overview of CO_2 equivalence of methane in pyrolysis syngas

From this the climate impact of releasing methane can be calculated. Figure 10 above can serve as a clarification to the following calculations. Say there is 100 kg Carbon in the biomass. 63 kg of this is sequestered in the biochar, and 37 kg is released in the gas. 7.06

---

[12] The previous value from the IPCC Second Assessment Report was 21, but the latest IPCC report has published a higher figure of 25. This thesis will work with the latest science.

[13] This is confirmed in an email correspondence with Downie (See Appendix V page 81)

of this is contained as carbon in the methane.[14] This can be converted into a CO_2 equivalent, by calculating the total weight of the methane. This is 8.8 kg.[15] With a GWP of methane of 25 in a 100 –year timeframe, this translates into 220 kg CO_2 equivalent of this methane.[16] The CO_2 equivalent of the biochar carbon is 227 kg.[17]

This leads to the conclusion that by releasing methane in the syngas, the net climate impact of this is about the same as all the carbon stored in the biochar. Doing this would counterbalance any positive effects from creating the biochar for sequestration and should be avoided. This can be achieved through the exclusive use of retorts that combust the syngas. Conventional biochar research that focuses on biochar for agricultural use does not usually specify this need; instead a report by Lehmann concludes that slash-and-char on a field scale could be a viable route to climate mitigation (Lehmann, et. al, 2006 p 409) as an alternative to the much-debated slash-and-burn in shifting cultivation. This concluding advice not only threatens to destabilise our atmosphere further if it was implemented, it also threatens to undermine confidence in a technology which has the potential as a major contribution to tackling climate change.

2.4.2 Volatile Organic Compounds

A volatile organic compound (VOC) is an organic substance that evaporates easily. It is usually connected with indoor air pollution from for example paints and dyes, and is known to cause health issues like eye nose and throat irritation, damage to the central nervous system and cancer.[18] Methane is technically a VOC but has a different impact than most other VOCs. Almost all others are ozone precursors, whereas methane has a more direct impact on climate change than on ozone levels (Defra 2007d).

Table 35 on page 76 in Appendix III shows a list of compounds that were found in a study from the EPA (Lemieux, 2001) on emissions from carbonization kilns and the effect of afterburners. Benzene was found in the EPA study in maximum quantities of 17,000 $\mu g/m^3$, and is a human carcinogen. This is high; the objective for benzene quantity in air in England and Wales is 5 $\mu g/m^3$ (Defra, 2007d). The emissions of VOC from pyrolysis in general are unclear. VOCs are expected to be collected and burnt with the syngas in controlled pyrolysis.

2.4.3 Particulates

Particulates arise from the processing and in particular from crushing charcoal to create bricks. Particulates can be dangerous to human health if inhaled (Defra 2007d).

On top of this, these particles have a direct effect on radiative forcing, which is 'negative' (Solomon, 2007 p 32). A negative radiative forcing effectively means that more radiation

---

[14] Carbon in gas * percentage of methane in gas / (methane+CO_2+ CO percentages) = 37*8.5/(8.5+20+16) = 7.06%

[15] The molecular weight of CH_4 is 16, while that of carbon is 12 and that of hydrogen is 1 (per atom). To calculate the CO_2 equivalent, the weight of the 4 hydrogen atoms should be included = weight of carbon + weight of hydrogen = (7.06 + 7.06*(4/16)

[16] Percentage of carbon in methane * global warming potential = 7.6*25

[17] 1 g C = 3.664 g CO_2. This means 63 kg Carbon times 3,664 is 227 kg Carbon dioxide equivalent.

[18] Environment Protection Agency of the US: http://www.epa.gov/iaq/voc.html [accessed 11/01/08]

from the Sun 'bounces back' into space, causing a net decrease of energy entering the atmosphere. Particles also have an indirect effect on radiative forcing through their impact on cloud formation (Houghton, 2004 p 49). Clouds reflect sunlight back into space and therefore also create a negative radiative forcing.

The effect of particulates on health will be mainly a local effect, and especially with extensive crushing and transport of the material. It is also an important issue if the biochar is scattered on the land, in which case a method should be created that eliminates the escape of particles during distribution, such as spraying with water or mist.

2.5 Energy balance

Information on the energy balance of pyrolysis is scattered and limited. Most sources talk of collection of gases from pyrolysis for energy use but do not record the quantities. For this section a range of sources were consulted, including individual researchers by e-mail. All information suggests the yields are highly process and feedstock dependent.

The FAO (1985) give the most useful information on this issue; it has listed the energy yield from pyrolysis, but also mentions that these will vary for the nature and moisture content of the feedstock. The figures in Table 5 below are estimates for the energy yields of 1000 kg dry wood. Some of this energy is likely to be used for the pyrolysis. This might be further established by a figure given in the Ullmann's Industrial Chemistry Encyclopaedia.

Energy yield from pyrolysis	
Charcoal	9500 MJ
Wood Gas	1500 MJ
Condensibles including Tar	8000 MJ

Table 5 Energy yields from pyrolysis per 1000 kg of dry wood. Source FAO (1985)

The Ullmann's Encyclopaedia gives a figure of 250 MJ of heat, 27 MJ of electrical power and 5 m^3 of water needed to produce 100 kg of charcoal, including to dry the wood (Ullmann's 2000). For a 30% charcoal yield, this translates into 750 MJ of heat, 81 MJ of electrical power and 15 m^3 of water per tonne of dry wood needed.[19] Assuming the charcoal is not used for energy production and the gas and condensibles are collected for heat and energy production this leaves around 8600 MJ of energy that could be available per tonne of dry wood. This is equal to around 2400 kWh/tonne of wood.

Without available peer reviewed studies confirming this, there was the need to resort to e-mail correspondence with industry experts to confirm these estimates. Bob Hawkins, a technology expert from EPRIDA provides some estimates in an e-mail correspondence (see Appendix V page 78): *"In general terms for an average woody biomass, you could expect to see about 3500 MJ (1000 kWh) per 1000kg of biomass if you were to generate electricity."*

---

[19] 1 tonne of dry wood yields around 300 kg of charcoal, which would have three times the associated heat, electricity and water use. This is 750 MJ heat, 81 MJ electricity and 15 m3 water

In another e-mail correspondence Robert Brown, professor at the Iowa State University and author of a chapter on biochar production technology in an upcoming book on biochar, states (see Appendix V page 78): *"As much as 75% of the energy can be recovered as non-charcoal forms (gas and oil), but this depends upon many factors."*

Because these figures are only an indication for the energy yield of wood, more research is needed to establish the energy yield for different feedstock types and processing conditions. However, to provide an estimate figure of the available energy throughout the rest of this report, it is chosen to work with the estimate given by Hawkins, since this is a figure derived from experience of biochar production. The figures from the FAO and the Ullmann's Encyclopaedia, although more authoritative, are theoretical figures that could be false because of unaccounted losses. It has to be noted though the figure of 1000 kWh/tonne can only provide a rough estimate of the expected quantities, but for any more detailed analysis more research is needed.

2.6 Summary

This chapter has aimed to give an overview of biochar production, pyrolysis and its optimisation, yield prediction and environmental impact. Pyrolysis is complex and dependent on many factors. This makes it difficult to predict the exact quantities of desirable outputs (char, oil gas) and of undesirable pollutants. For this thesis then, the figures that were found in this chapter can only serve as *indicators* of the potential carbon and energy that could be available from biochar production in the UK. Biomass feedstock composition influences the total char yield, as does its moisture content and operating temperature. The current literature does not record these specific parameters consistently, making it impossible to compare findings from different laboratories. Since the target feedstock of this thesis might be of a different composition than feedstock that can the literature discusses, these findings are not necessarily applicable.

In general it was found that a lower processing temperature gives a higher char yield and higher overall carbon yield. High lignin content also increases the char yield. It was found there are many different types of pyrolysis retorts, with the key distinctions being the type of heating they are designed for and whether they use batch or continuous processing.

Pollution that can occur from pyrolysis is in the form of methane, VOCs and particles. Modern retorts usually capture and burn these to provide energy. Traditional retorts, which are still in use in developing countries do not have this option, and so have a negative environmental impact. It was calculated the CO_2 equivalent of the methane emissions is around the same as that of the carbon stored in the Biochar. This balances out the climate benefit that the biochar would have delivered, and makes this type of processing unsuitable for carbon sequestration purposes. VOCs and particles could also cause negative environmental impact, but no quantification of this was found.

The carbon yield was predicted using data from Best Energies, who have experimented with similar material that could be available for biochar production in the UK. They found a 63% conversion of biomass carbon into biochar carbon. Other research has predicted higher and lower values for this, which correlated with the operating temperature and biomass feedstock. It was assumed that both these parameters would be optimised for biochar production, and that the research from Best Energies gives a good indication of the expected value.

Little data was available on energy production from pyrolysis. It was estimated to be around 1000 kWh per tonne of biomass. This could serve as an initial indicator, although more research needs to be done to establish this further. The same can be said for all parameters; to increase certainty of carbon yield, energy and pollution, further testing of the specific feedstock and equipment is necessary.

Key Findings and Recommendations from Chapter 2

- There are three types of pyrolysis; slow, fast and flash
- The main outputs from pyrolysis are gas, oil and char
- The quantities of these depend on the feedstock composition and processing conditions
- 63% can be used as an indication for the conversion parameter of biomass carbon to biochar carbon
- CO_2 equivalent of the methane emissions is the same as that of the carbon stored in the Biochar
- Current understanding fails to recognise the effect of these methane emissions
- Other pollutants from pyrolysis are VOCs and particles
- Traditional production systems are inefficient and released these pollutants
- Modern retorts that combust the syngas should be used to limit the pollutants
- The potential electricity generation from biochar production can be expected to be in the order of 1000 kWh/tonne of biomass

Chapter 3 - Biochar Applications

After assessing how biochar can be made, it should be considered what to do with it. Although the material could just be landfilled, having a use might make it more viable. Amongst potentially many others, the following uses will be discussed in this chapter:

1. use as a fuel
2. use as an agricultural supplement
3. use as a filtration medium

The following three sections will outline and discuss the relevance of these three different options. In this the potential of these applications for carbon sequestration is kept as a priority.

3.1 Fuel

The aim of biochar in this thesis is to look at biochar potential for carbon sequestration. The use of the charcoal as a fuel would contradict this and should be automatically dropped. However, charcoal is a valuable commodity and is in many countries still used as a major heating fuel (FAO, 1987).

The balance that has to be struck here is between energy production and carbon sequestration. For optimum energy production the biochar is used as fuel, or maybe not even turned into biochar if there is a more efficient technology to recover the energy from the biomass. For optimum carbon sequestration the maximum amount of carbon is stored in the biochar.

The balance then, if ignoring economic considerations, depends on our view of climate change and the urgency of the problem versus our need for energy. It is also dependent on our window of opportunity to prevent runaway climate change. If we have a specific time-frame in which to solve climate change, it might be possible to store the biochar for use as a fuel in times when the prospects of a safer climate are better. This would effectively remove the carbon for a limited time from the atmosphere. It can be argued then that for example old growth forest could be just as effective in storing this carbon as biochar would be. The advantage of the biochar product is its extremely long half-life compared with any other form of carbon.

3.2 Agricultural supplement

In the literature the use of biochar as an agricultural supplement is most popular; this is how the idea of biochar carbon sequestration started.

Much research has been done on the effect of biochar on tropical soils, based on the Terra Preta findings. Terra Preta, literally Dark Earth, is an ancient soil type from the Amazon. It is characteristic of its dark colour and fertility amid the extremely poor soils unsuitable for agriculture normally found there (Lehmann et. al, 2004).

In the last few decades much research has focused on how these soils work, what makes them so fertile and how we can reproduce them. One of the main ingredients of these soils was found to be charcoal, which has led to much speculation about potential benefits of charcoal as a soil improver (Lehmann et. al, 2006).

There is no clear understanding of the behaviour of biochar in the soil. Tryon (1948) has identified some characteristics of charcoal in soils. He found that it has a positive effect on the moisture content, moisture availability to plants, pH and germination of seeds. Another major impact of charcoal on soils is an increase in nutrient retention through an improved Cation Exchange Capacity (CEC) (Liang et. al, 2006) and potential for larger fungal and mycorrhizal activity (Warnock et. al, 2007).

Most of the research on the effect of biochar on soils focuses on tropical soils. The results show benefits to plant growth. Rondon et. al (2006) published results from a research project in Colombia. He found that three years after biochar additions to the soil the crop yields increased with around 50%. Much research has also been done in Japan where charcoal is used to combat low phosphorus levels (Nishio, 1996).

However, no research on similar climates and soil types to the UK has been published. Improvements on tropical soils do not mean that this will be the same in this climate; a high CEC in effect causes a larger nutrient retention in the soil. There is a potential for charcoal to have a negative impact on fertile soils, because of an increase in CEC and uptake of nutrients by the charcoal, which might be immobilized. But it could also be beneficial in areas with high nutrient leaching from agricultural land and associated eutrophication of surface waters. Also Rondon et. al (2006) fount that after biochar application the methane and nitrous oxide emissions from the soil would decrease. Nitrous oxide (N_2O) and methane (CH_4) are both potent greenhouse gases; the GWP of CH_4 is 25, but that of N_2O is 298 [20] (Solomon et. al, 2007 p 33), so reduction of this will be beneficial in mitigating climate change.

Overall more research is needed specifically in the UK and Europe to establish the effect of charcoal in more temperate climates and fertile soils, and assess in which situations biochar application could be beneficial.

---

[20] Any nitrous oxide that is released is almost 300 times more potent than CO_2, and 10 times more potent than methane

3.3 Filtration medium

Biochar has a high surface reactivity. This could make it suitable to remove impurities from drinking water. Activated carbon is a common component of water purification filters. This is in effect charcoal treated with hot steam or other activators to increase its surface reactivity. A high surface reactivity improves the capacity of the charcoal to remove unwanted organic substances from the water.

Azargohar and Dalai (1996) have assessed the fitness of biochar as a precursor for activated carbon, by treatment with potassium hydroxide. They found a biochar surface area of 10 m^2/g which increased to 660 m^2/g after the treatment, a 50 times increase of the surface area of the biochar.

The author is not aware of application of this in practice, but it clearly offers potential for added value to the biochar. It would not lose its potential for carbon sequestration purposes as long as the material is not burnt.

Key Findings and Recommendations from Chapter 3

- Charcoal is a valuable source of energy in many countries
- Using biochar as a fuel would not suit its purpose for carbon sequestration
- There is much research being done on the use of biochar as an agricultural supplement
- This research mostly focuses on tropical countries
- The effect of biochar could be positive or negative in European soils
- It might be able to reduce nutrient leaching and CH_4 and N_2O emissions
- It could also be used as a filtration medium
- More research is needed on specific UK and European soils

Chapter 4 – Forest Biomass

4.1 Introduction

The last few chapters have discussed the general information that is in the public domain on biochar and biochar production. This chapter will now explore in more detail the forestry resources available in the UK for biochar production, and how this could contribute to carbon sequestration. To answer the research question of this thesis the total biomass in the UK will be established, and parameters found in the last few chapters on biochar production will be applied to this. First this chapter gives a general introduction to the UK and its land use. After that the available resource from forestry is discussed, and different scenarios and their outcomes are modelled. The potential of biochar production from waste is calculated and discussed in chapter 5. Both will be mainly based on findings from other research and statistics that are available in the public domain.

The main purpose for the biochar will be carbon sequestration, and the effect of the biochar production on the UK's contribution to mitigating climate change is assessed.
Each of the following subsections will have a summary at the end which translates the available resource in a biochar estimate and a yearly carbon sequestration figure.

4.2 UK land use

The UK has a population of around 60.6 million (National statistics, 2007). About 85% of the population lives in England, while Northern Ireland has the smallest population of only 3% of total (see Figure 11).

The total land area of the UK is 24 million hectares. Forest and woodlands take up 12% of this land, and 14% is urbanised. Agriculture takes up most of this land; around 18.5 million hectares (see Figure 13). Of this over 70% is grazed land and grass, around 25% is arable land and around 3% set-aside land (see Figure 12 and 13). Set-aside land stands for land that has been taken out of intensive agricultural production, to increase biodiversity and protect the soil. This land is not available for food production, but non-food crops like fibres or energy crops could be grown on it. Having a certain percentage of land as set-aside land is an obligation for farmers in some sectors who want to be eligible for EU funding.

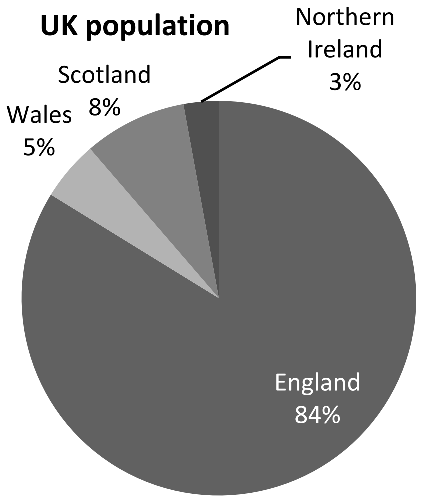

Figure 11 UK population. Source: National Statistics (2007) Total population 60.587.300

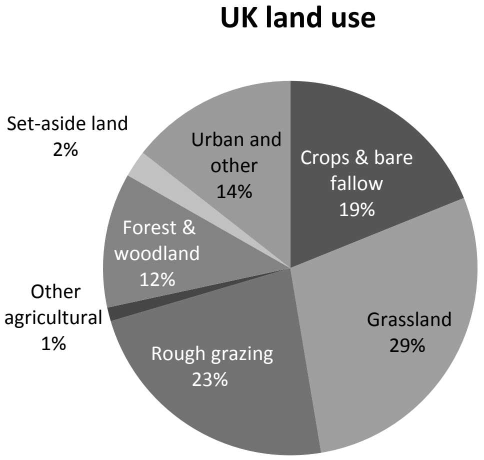

Figure 13 UK land use 2005 (Defra, 2006a) See for more details Table 27 in Appendix Total land area 24 million hectares

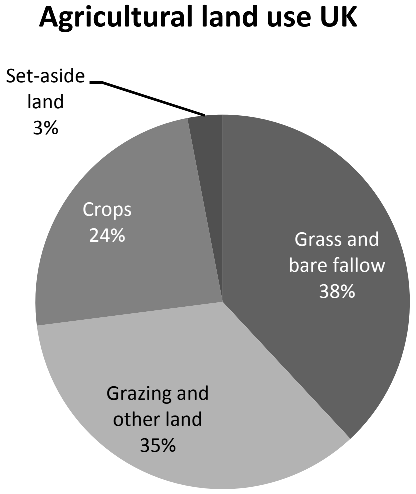

Figure 12 Agricultural land use UK 2005 (Defra, 2006b) Total agricultural land 18.508.000 ha

4.3 Method

A thorough outline of the methodology for this research has been set out earlier in this thesis. This section will not repeat this, but rather add some more detail on the method used for this chapter. A grading scheme was used to assess the relevance of different reports to this thesis. Table 6 below gives an overview of the documents used to gather information for this research, specifically on forestry and biomass energy potential. The documents are marked 1 to 3. 1 Is good, 2 is medium and 3 bad. This is specified for the level of detail of the document, the quality of the research and the applicability to this thesis. The applicability was assessed by taking the average of the detail and quality of research. Chapter 5 will discuss the data on waste, and will use this same grading and analysis system.

Overview of Data sources for UK Forestry resource				
Author	**Title**	**Level of relevant Detail**	**Quality of research**	**Applica-bility**
McKay et.al (2003a)	Woodfuel Potential Britain	1	1	1
Forestry Commission (2006)	Forestry Facts and Figures (2006)	3	3*	3
Karjalainen et.al (2004)	Estimation of Energy Wood Potential in Europe	2	1	2
EEA (2006)	How much bio-energy can Europe produce without harming the environment?	2	1	2
Defra (2007c)	UK Biomass Strategy	1	1	1

*Table 6 Overview of data sources used for this research * unknown research methods and data sources*

The level of relevant detail was defined by the availability of data in the reports and the description of the methodology. The adequacy of the scope of the report for use in this thesis was a major importance in this. Some documents were consistent and high-quality reports, but the scale of the research did not match the information needed for this thesis.

The information that was in the report on the research procedures and the clarity of this information defined the mark for the quality of the research. A mark for the applicability arose from the average of the level of detail and the quality of research.

Karjalainen et. al, (2004) and EEA (2006) were only partly applicable because the scope of the research was too large to give much useful information about the UK. The reports from McKay et.al (2003a), and Defra (2007c) scored best and were most suitable for this thesis on all levels.

The next section will now discuss the outcomes for the biomass available from forestry according to these different sources.

4.4 Resource

Forestry could be a major source of biochar feedstock. Much of the forestry resource is wasted; there are inefficiencies in the harvesting and supply chain, leaving much of the smaller and lower quality material unused. Small round wood and tips of stems, as well as poor quality stems are for example forestry products that could become available. Roundwood is defined as the portion of the forestry material that

It is assumed that good quality forestry products with a stable market[21] will not be available. There is also a potential for more production and improvement of current production. This chapter will aim to provide estimates of this resource.

This available resource from forestry in the UK could be assessed in several ways:

1. The assumption can be that the forestry operates under business as usual market conditions, and the wood available for biochar production is the portion that is not currently used.
2. A step further from this would be to assume that more wood could become available by redirecting current use of forestry residues to biochar carbon sequestration.
3. Even another step further would be to reconsider our current approach to farming and start growing as much crops for carbon sequestration on agricultural land as ecologically possible.

This report will consider these three different scenarios and predict the available forestry products and charcoal that could these can bring forward. Existing studies will form a basis for these calculations. Section 4.3 has discussed the relevance of these reports. Table 7 below gives the baseline of the available biomass from forestry in the UK of each report.

---

[21] For example timber

Overview of results from different studies		
Source	**UK Biomass available from forestry**	**Applicability**
McKay et. al, (2003a)	1,011,962 ODT/yr	Good
Karjalainen et. al (2004)	7,900,000 m^3/yr over bark	Data from both Karjalainen and EEA data not directly usable due to conversion difficulties
EEA (2006)	1.5 Mtoe	
Defra (2007c)	1,312,000 ODT/yr	Source data: McKay et. al, (2003a)

*Table 7 Overview of results from different studies *assuming 50% carbon in woody biomass, with 63% conversion efficiency to biochar*

The table above suggests that only the McKay et. al, (2003a) data is usable to predict the Biochar potential for the UK; the data used by Defra (2007c) originated from this same report. The data from the other two reports are not convertible into Oven Dried Tonnes (ODT)[22], which is the most accurate unit of measure to convert into biochar production.

In the following three scenarios the biochar potential from forestry products in the UK will be calculated using the data from McKay et. al, (2003a).

4.4.1 SCENARIO 1 – Forestry under a Business-As-Usual scenario

This scenario will assess the availability of forestry waste under a business as usual scenario. At the end of this section the biochar production will be calculated from this.

The assumption in this business as usual scenario is that existing markets will remain as they are. Any currently unmarketed products from forestry are assumed to become available for biochar production. The report by McKay et. al, (2003a) gives data on the current wood fuel availability in Britain. These are given in Table 31 on page 74 in Appendix II. This data is split between primary products (roundwood and poor quality stemwood, stem tips and branches) and secondary products (material from clearance of utilities and roadside maintenance and sawmill conversion products).

The assumptions that were made by McKay et. al, (2003a) on the market availability of these products are:

- 10% of the small roundwood
- 10% of sawmill conversion products
- 100% of the poor quality stemwood, stem tips and branches
- 100% of the unmarketed arboricultural arisings
- 100% of material from clearance of utilities and roadside maintenance
- 80% of the short rotation coppice (SRC) in England, 100% of SRC in Wales

---

[22] The density and energy content of the biomass need to be known, which were not give in this report.

To gain more detailed data and data on the future availability of the wood, an on-line database[23] which had detailed results from this research had to be consulted. The results of this interrogation gave the following relevant information:

- Forestry production for each Forest district in Britain
- The production for each wood type (pines, spruces, other conifer, broadleaves)
- For each Forecasting period (2003-2006, 2007-2011, 2012-2016 and 2017-2021)
- And for each wood product (Stemwood 7-14 cm, Stemwood 14-16 cm, Stemwood 18+ cm, Poor Quality Stemwood, Tips, Branches and Foliage)

These data are shown in Table 28 to Table 30 in APPENDIX II. The table below gives a summary of all the findings: in 2007-2021 the biomass available for each timeframe from scenario 1 in oven dried tonnes is around 1.5 million tonnes a year, with a peak in 2012-2021.

Biomass available from forestry in the in the UK in scenario 1	
	Biomass (ODT/year)
2007-2011	1,452,962
2012-2016	1,653,431
2016-2021	1,468,130

Table 8 Biomass available from forestry in the UK in scenario1

Figure 14 below gives a more detailed overview of the available biomass per region and time frame, with a distinction made between primary and secondary products.

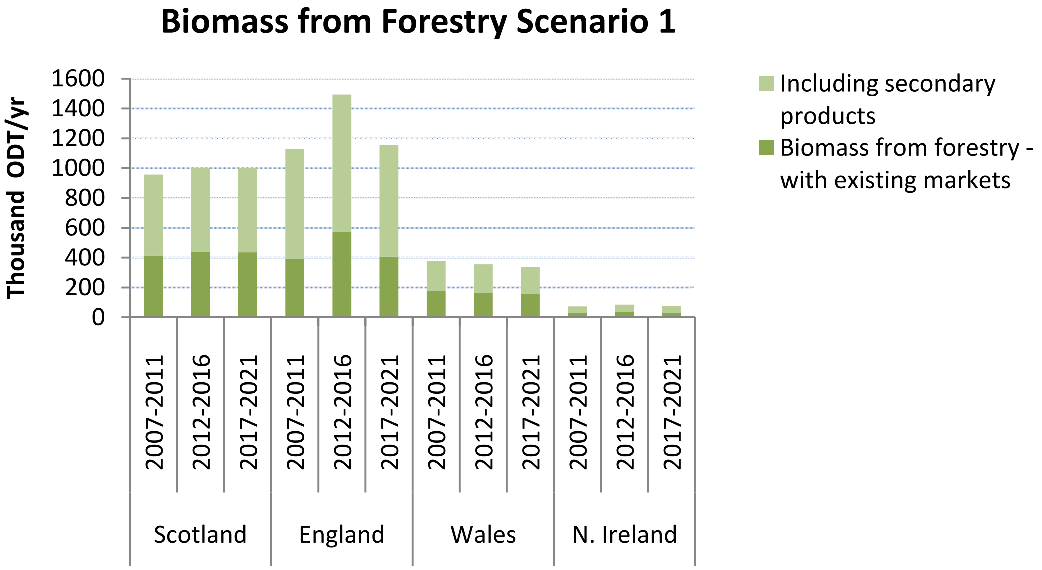

Figure 14 Biomass availability from scenario 1 in the UK, per country and year. See Table 33 on page 75 in Appendix II for source data

This graph gives a summary of the available biomass in the UK for each region taking account of existing markets, and including secondary products. It shows the secondary products double the total available biomass, and so are a significant resource to be

---

[23] http://www.eforestry.gov.uk/woodfuel/ (accessed 03-12-07). This database was interrogated to the following options; forest districts, all districts, forest & woodland, forecast, all years, forestry and private combined, thinned and felled combined.

tapped. Most material would be available in Scotland and England, which is not surprising since most forestry takes place in these regions.

This data will now be used to quantify the biochar production and carbon sequestration potential from this scenario.

Biochar Production

To quantify how much biochar could be made the findings from chapter 2 on biochar are used. It found a wide range of outcomes, which were largely dependent on the pyrolysis processing conditions. A useful method is using a “carbon conversion efficiency” which is a conversion from biomass carbon to charcoal carbon.

The figure for the carbon conversion efficiency that will be used in this report is 63%. Assuming the carbon content of biomass is 50%, and 63% of this converts into biochar carbon, around 470.000 tonnes of carbon can be stored as biochar each year. This is equivalent to around 0.3% of the current carbon emissions of 160 million tonnes per year. The total carbon that can be sequestered in the 15-year time-frame is 7 million tonnes.

Biochar Production in the UK - Scenario 1				
	Biomass (ODT/year)	**Carbon in biomass (tC)**	**Carbon in Biochar (tC)**	**Carbon sequestered per year***
2007-2011	1,452,962	726,481	457,683	0.29%
2012-2016	1,653,431	826,715.5	520,830.8	0.33%
2016-2021	1,468,130	734,065	462,461	0.29%
Total carbon sequestered in 15 year time frame (tC)			7,204,874	

*Table 9 Biochar Production in Scenario 1 * as percentage of the current emissions of 160 million tonnes/yr*

4.4.2 SCENARIO 2 – No presence of markets for residues

Scenario 1 assumed that only biomass which is currently unmarketed can become available for biochar production. The assumption was that 100% of the forestry residues and 10% of the small round wood and sawmill conversion products would be available. This scenario follows the same method, but this time assuming that *all the* residues and small round wood will be available. It is assumed that larger roundwood is excluded from this. On top of this, all the arboricultural arisings, Short Rotation Coppice and Primary Processing Co-Products will be available.

The results of this can be seen in Table 10 on the left and Figure 15 on page 44, whose source data can be found in Table 33 on page 75 in Appendix II. The outcome for the three time periods in the UK is around 3.5 million ODT/yr of biomass available through this. The production peaks in the 2012-2016 period. Figure 15 shows that Scotland and England have a similar overall availability of biomass products. Scotland makes up around 45% and England 40% of the total biomass contribution, but the availability of secondary products is much larger in England than in Scotland. Wales and Northern

Total Biomass UK Scenario 2 (ODT/year)	
2007-2011	3,378,356
2012-2016	3,683,558
2016-2021	3,350,148

Table 10 Total Biomass UK in Scenario 2
Source: McKay et. al, (2003a)

Ireland contribute relatively little to the biomass potential; 12 and 3% respectively. This reflects the small proportion of total forested land in those two countries.

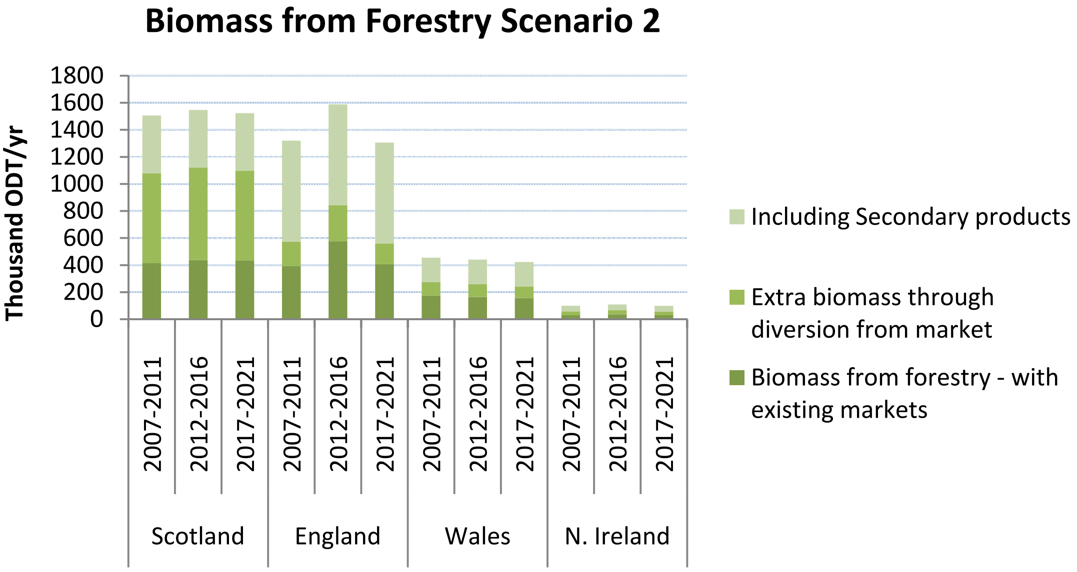

Figure 15 Biomass available from forestry scenario 2, per region and time frame. See Table 33 on page 75 in Appendix II for source data

Figure 16 to 18 below show the distribution of this material in England, Scotland and Wales. Data for this is unavailable for Northern Ireland. Figure 17 shows that most English regions have limited biomass availability, apart from South East England. Scottish regions have a higher availability of biomass. In Scotland a larger part of the total material is already in use; the availability of wood products per region when markets are taken into account is half or less than when markets are ignored. This will be further discussed in the analysis in Chapter 6.

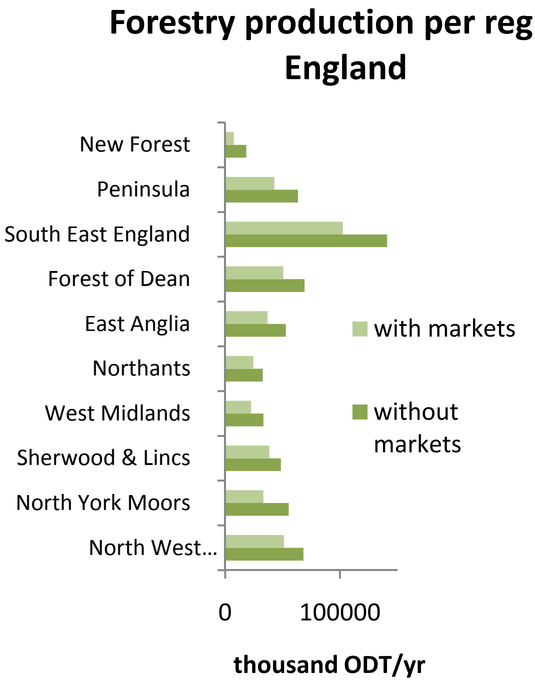

Figure 17 Forest Production per region (England) Source data McKay et. al, (200a3) see Table 28 on page 71

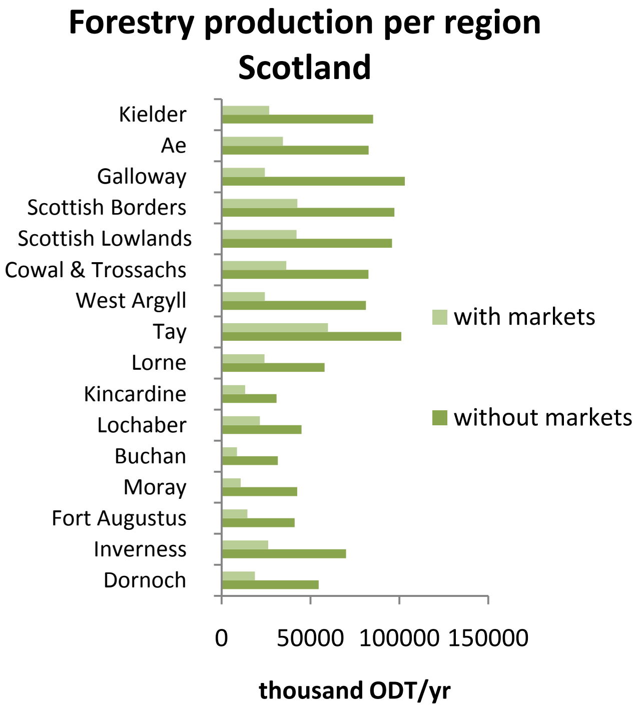

Figure 16 Forest Production per region (Scotland) Source data McKay et. al, (2003a) see Table 29 on page 73

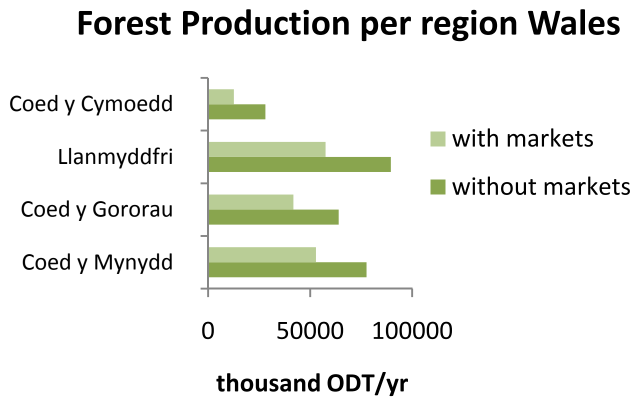

Figure 18 Forest Production per region (Wales) Source data McKay et. al, (2003a) see Table 30 on page 73

Biochar Production

As in scenario 1, the established availability of biomass resource can be turned into a prediction for biochar production. This is again done using a carbon conversion efficiency of 63%, and assuming the carbon content of the biomass is 50%. This leads to around 1 million tonnes of carbon that can be sequestered as biochar each year. This is equivalent to a mere 0.7% of the total annual carbon emissions in the UK. The total carbon that can be sequestered over the 15-year time-frame is around 16 million tonnes of carbon.

Biochar Production UK - Scenario 2				
	Biomass (ODT/year)	**Carbon in biomass (tC)**	**Carbon in Biochar (tC)**	**Carbon Sequestered per year***
2007-2011	3,378,356	1,689,178	1,064,182	0.67%
2012-2016	3,683,558	1,841,779	1,160,321	0.73%
2016-2021	3,350,148	1,675,074	1,055,297	0.66%
Total carbon sequestered in 15 year time frame (tC)			16,398,998	

*Table 11 Biochar Production on Scenario 2 *as part of annual UK carbon emissions of 160 million tonnes/yr*

4.4.3 SCENARIO 3 – Carbon Farming: Growing Biochar crops on Agricultural Land

The last two scenarios have looked at current forestry, and how much biochar could be produced if the forestry residues would be used. This scenario will look at using extra land to grow crops for biochar production.

Currently, large parts of land are under set-aside. To be able to qualify for EU funding under the Single Payment Scheme, farmers have to set aside a portion of their land, during which this land can only be used for non-food purposes (Defra, 2006c). This can be grass or natural regeneration, but it can also be used to grow energy or fibre crops like miscanthus, hemp or short rotation coppice.

Aside from this extra agricultural land could become available. The EEA has done a major assessment on the environmental impact of growing energy crops, which would become the main limitation for the land that would be used.

3.4.3.1 Defining the land availability according to environmental constraints

"While environmental considerations in most cases restrict the technically available amount of biomass from waste, agriculture and forestry, there can also be co-benefits between biomass production and nature conservation." (EEA, 2006 p 9)

In its report "How much bio-energy can Europe produce without harming the environment" the European Environment Agency has outlined a set of parameters that can limit the technically available biomass for energy in Europe. These include pressure on soil structure, water availability, nutrient leaching and biodiversity. They suggest this can be limited by having some set aside land, using the land extensively or using crops with a low environmental impact and leaving some deadfall and foliage to return nutrients and support biodiversity. For forestry production it advises to return the foliage and needles to the site trough harvest in winter, or by leaving the material to dry before collection. It also advices to exclude roots from the harvest to protect the soil structure and prevent erosion, and leave about 5% of the standing volume of wood on the site as dead wood, to increase biodiversity.

3.4.3.2 Conclusion

The EEA (2006) report has concluded the arable land that could become available for environmentally compatible bio-energy production in the UK will be around 800 thousand hectares in 2010. This would be 1.1 million hectares in 2020 and 1.6 million hectares in 2030. This will be available on top of the already available forestry. If this land was used for Short Rotation Coppice or miscanthus, the yield could be in the range of 10-15 ODT/ha/yr once established (Defra 2007c, p 39).

Extra Biomass production from arable land available		
Year	**Extra land available***	**Biomass production ****
2010	800,000 ha	8-12 million ODT/yr
2020	1,100,000 ha	11-16.5 million ODT/yr
2030	1,600,000 ha	16-24 milion ODT/yr

*Table 12 Extra Biomass production from arable land available. * source (Defra 2007c, p 39). ** assuming a yield of 10-15 ODT/ha*

The results from this added to the results from scenario 2 are given in Figure 15 below. It shows that the biomass potential is drastically increased by introducing energy crops grown on arable land. The extra biomass that could become available through repurposing agricultural land would add three to five times the biomass that would be available if only forestry residues would be available.

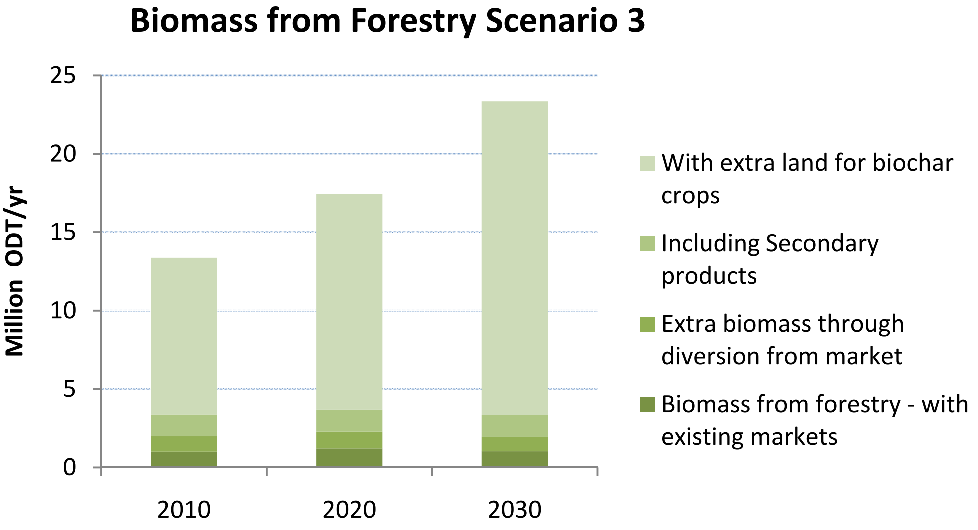

Figure 19 Biomass from Forestry Scenario 3; Including the extra land available for biochar crops

3.4.3.3 Biochar Production

Again, the results from this section can be translated into a biochar prediction. Table 13 below shows the results of this. The yearly carbon that can be sequestered in biochar is starting around 4 million tonnes of carbon per year in 2010 and going up to nearly 7.5 million tonnes of carbon per year in 2030. This is equivalent to around 2.5 – 5 % of the current carbon emissions.

Biochar Production				
	Biomass (ODT/year)	**Carbon in biomass (tC)**	**Carbon in Biochar (tC)**	**Carbon Sequestration per year**
2010	13,378,356	6,689,178	4,214,182	2.63%
2020	17,433,558	8,716,779	5,491,571	3.43%
2030	23,350,148	11,675,074	7,355,297	4.60%
Total carbon in time frame (tC)				*15 years:* 69,599,675 *30 years:* 170,610,500

Table 13 Biochar production in scenario 3

4.4.4 Overview and analysis of the Scenario Results

This section has looked at the potential biomass resource for biochar production from forestry in the UK, in three scenarios:

1. Using unmarketed forestry residues and secondary products
2. Using all forestry residues (including those with existing markets) and secondary products
3. Using extra land to grow biomass crops for biochar production

Table 14 on page 48 and Figure 20 below summarise the results from the three scenarios. The assumptions are that 50% of the forestry biomass is carbon, and that the carbon conversion efficiency into biochar carbon is 63%. These figures were discussed in chapter 2, and although they have their limitations, they can give a valuable suggestion of the scale on which biochar production can work.

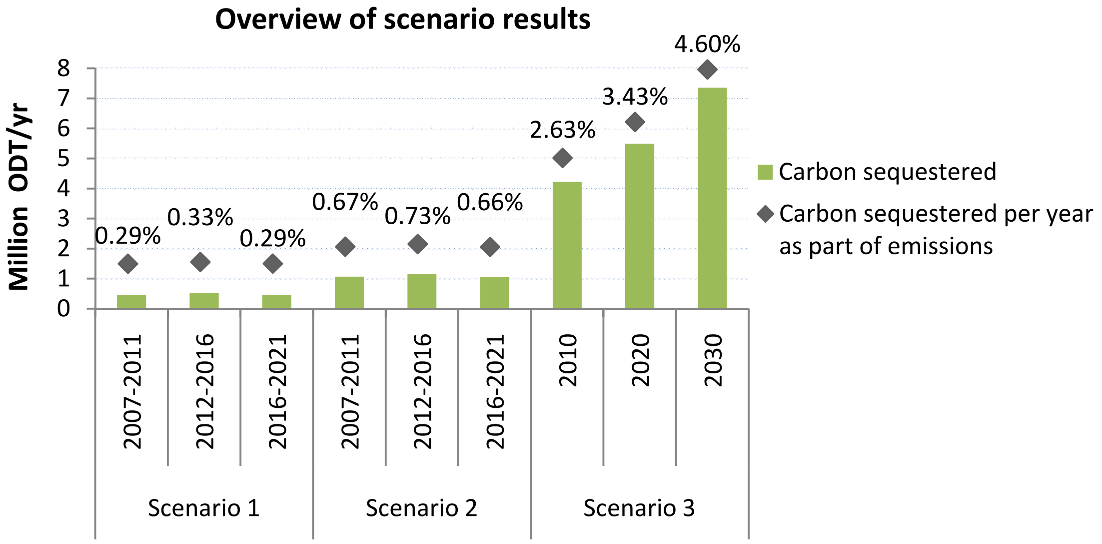

Figure 20 Overview of the scenario results. The bars indicate the total carbon sequestered per year, and the points indicate the percentage of carbon sequestered as part of the total UK carbon emissions

Figure 20 shows that in scenario 1 and 2, in which only current available forestry residues are used, the potential carbon mitigation is low; it is equivalent to 0.3 and 0.76% of current carbon emissions.

Overview of the Scenario Results

	SCENARIO 1			**SCENARIO 2**			**SCENARIO 3**		
	2007-2011	2012-2016	2016-2021	2007-2011	2012-2016	2016-2021	2010	2020	2030
Biomass available (average million ODT/yr)	1,45	1,65	1,47	3	4	3	13	17	23
Carbon in Biomass MtC	0,7	0,8	0,7	1,6	1,8	1,7	7	9	12
Biochar potential MtC (63% efficiency)	0,45	0,52	0,46	1,06	1,16	1,05	4,2	5,5	7,4
Carbon sequestered/yr (%)	0.30%	0.34%	0.30%	0.70%	0.76%	0.69%	2.75%	3.59%	4.81%
Total carbon sequestered in time frame (MtC)	7			16			15 years: 70 30 years: 170		

Table 14 Summary of Scenario results

However, this increases by almost a factor of ten if extra land becomes available, as in scenario 3. Considering environmental limits on bio-energy crop production, the carbon mitigation potential from biochar has risen to 2.75-4.81% in 2030 in the third scenario.

The large difference in biochar potential between scenario 1 and 2, and scenario 3 is not surprising, considering in the first two scenario's only "waste" products were considered. They assumed that round wood above 14 cm diameter would not be available. In Scenario 3 however, it was assumed that all the biomass that would be grown on the extra land would be used for biochar crop production. This enormous benefit of the extra available land raises the issue whether it is worth diverting biomass material from existing markets to be used for biochar production. This might not be worthwhile if the overall contribution of this is negligible in its carbon sequestration potential.

To make the spatial availability of forestry products clearer, the results from scenario 1 and 2 are visualised in Figure 21 on the right. Data for this was only available for forestry products in scenario 1 and 2, and only for Britain (which does not include Northern Ireland).

It can be seen that the areas where most of the biomass is located are in North Wales and the south of Scotland, and South East England. Limited biomass is available from the Mid England, East Anglia and the New Forest.

The extra land that could be available for scenario 3 was not specified per region, so this cannot be integrated.

The next chapter will explore the waste that is, or could become available for biochar production on top of the forestry material that this chapter has assessed. An overall analysis and conclusion to these results will be given in chapter 6 and 7.

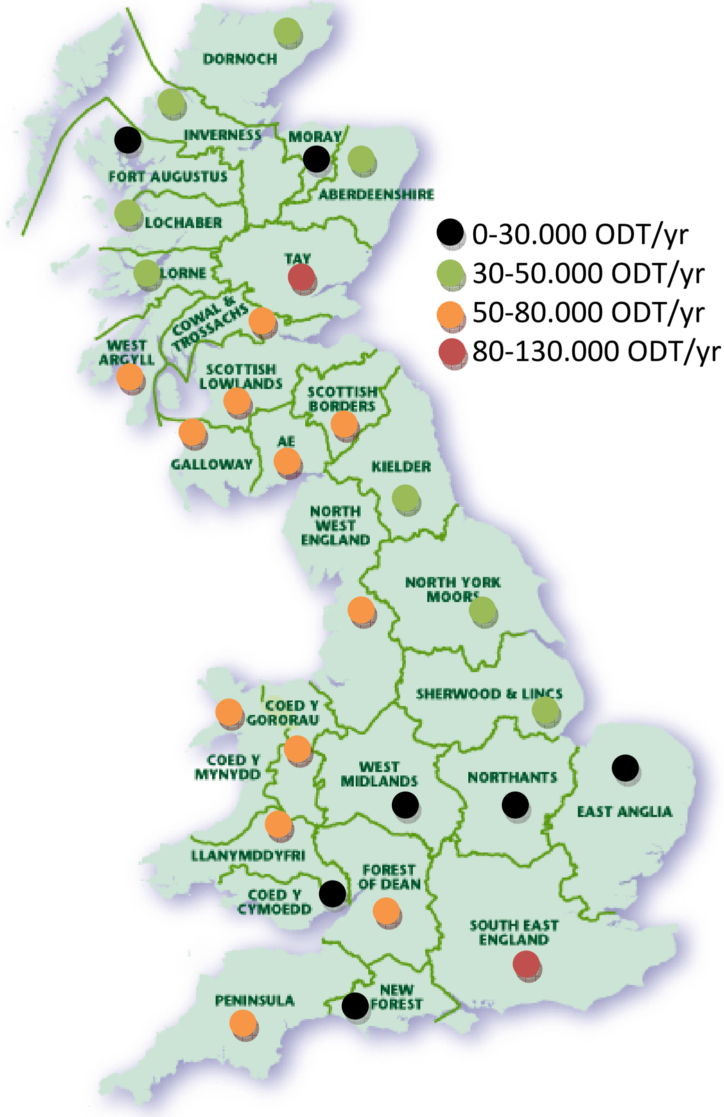

Figure 21 Spatial availability of forestry products, an average of forestry scenario 1 and 2 (see Figure 16 to 18 on page 44). Background map taken from the forestry commission online *http://www.forestry.gov.uk/forestry/hcou-4u4hzv* *[accessed 20/01/08]*

Chapter 5 - Waste Biomass

In chapter 2 biochar production has been discussed. Although conventional charcoal production always uses wood or sawdust, for biochar production some waste could be suitable. There is much waste deposited in the UK each year. According to the Environment Agency there is a production of waste of around 330 million tonnes per year.[24] Since 2002 each country within the UK has to set its own targets and legislation for waste management. For example Wales has created a policy document on waste titled "Wise about Waste Wales" document (Welsh Assembly Government, 2002). Some challenging targets are set of which to achieve at least 40% recycling and composting and to reduce the biodegradable industrial and commercial waste going to landfill to 80% of that landfilled in 1998 by 2010. Biochar could fit in this target as a reduction method for biodegradable waste while creating a new commodity.

There is however little comprehensive research done on the exact composition of waste in the UK, which will need to be known to assess the presence of material that could be suitable for biochar production. The main consideration for the suitability of the material is moisture content; if the material is too moist too much energy is needed to fuel the pyrolysis, resulting in large declines in yield. Other considerations for its suitability are contamination with toxins and availability of the material.

Table 15 below gives an overview of the data sources that were found to give information on the biodegradable waste available that could be suitable for biochar production. They are not easily comparable; each research looks at a specific niche. The same method and grading system has been used as in chapter 4; the documents have been marked 1 to 3, 1 is good, 2 is medium and 3 bad. The applicability was assessed by taking the average of the detail and quality of research.

Overview of Data sources for UK Waste resource				
Author	**Title**	**Level of relevant Detail**	**Quality of research**	**Applica-bility**
WRAP (Nikitas et. al, 2005)	Reference document on the status of wood waste arisings and management in the UK	1	1	1
Magin (2001)	An introduction to wood Waste in the UK.	3	2	2
Defra (2007c)	UK Biomass Strategy	1	1	1
Defra (2007a)	EU Waste Statistics	2	1	2

Table 15 Overview of data source for the UK Waste resource

It can be concluded that the WRAP research (Nikitas et. al, 2005) and Defra (2007c) both give the best level of detail, research clarity and applicability to this thesis. Some more detail of these sources can be seen in Table 16 below.

---

[24] Environment agency online http://www.environment-agency.gov.uk/subjects/waste/?lang=_e [accessed 12/1/08]

Overview of data sources on waste			
Source	**Focus**	**Method**	**Verdict**
WRAP (Nikitas et. al, 2005)	Wood Waste in the UK	Desk top research	Thorough overview and useful data
Magin (2001)	Wood waste in the UK	Questionnaire	Only looking at part of the wood waste available
Defra (2007a)	All waste in the UK	Using range of research	Useful, wide range of raw information on resource
Defra (2007c)	All material suitable for bio-energy production	Using range of research	Useful, but potentially limiting

Table 16 Overview of the available information sources

The WRAP research was found to be a thorough and in depth research with a useful level of detail to determine the wood waste available in the UK. The research from Magin (2001) however which also focused on wood waste, was thought to be too limited to be applicable to this thesis.

Both Defra reports were thought to be applicable to this thesis, but the EU Waste Statistics (Defra, 2007a) was thought to be less suitable because of a less detailed examination of the waste types. This was a necessary distinction to make to determine toxicity and moisture levels of the materials. However the UK Biomass Strategy Defra (2007c) did make this distinction, which made this report the most suitable.

This chapter will give an overview of the results from the studies and will draw new conclusions on biochar production and carbon sequestration from combining this data. The information given in this chapter will be split in wood waste and non-wood waste.

5.1 Non-Wood Waste

This section looks at non-wood waste suitable for biochar production. As mentioned earlier, there are several reports available on this, and the data from these sources are given below. Table 16 in the last section showed how the main information sources for non-wood waste are the UK Biomass Strategy from Defra (2007c) and the EU Waste Statistics Regulation report for 2004 (Defra 2007a).

Non-wood waste can be categorised in animal waste, food waste and other wastes. There is much waste from food processing, urine and faeces and agricultural products like straw. Animal wastes are often too wet, which would be unsuitable for biochar production. The data in Table 17 below are from the EU Waste statistics (Defra, 2007a). They give a solid and reliable overview of the wastes that are available, but do not specify enough detail to decide on the suitability of these materials; for example the moisture contents of these waste streams is not mentioned. It has to be noted that the paper and cardboard waste from this source would be suitable for biochar production.

Waste Composition UK 2004 from EU Waste Statistics Regulation report 2004 (thousand tonnes)					
	England	**Wales**	**Scotland**	**Northern Ireland**	**UK**
Paper and cardboard wastes	10,691	520	1098	214	12,524
Wood wastes	3,337	280	298	66	3,980
Animal and vegetable wastes	7,284	370	293	158	8,105
Animal waste of food preparation and products	1,522	138	3	3	1,665
Animal faeces, urine and manure	107	12	0	-	118
Total	**22,941**	**1,320**	**1,692**	**441**	**26,392**

Table 17 Waste composition UK in 2004 (thousand tonnes) Reproduced from Defra (2007a) see for more detail Table 36 on page 77 in Appendix IV

The UK Biomass strategy however, has specifically focused on biomass that could be available for energy production, and separated this in wet and dry materials available. Table 18 below shows the results of the dry materials. These data also included waste wood. This will be excluded in this section, but will be covered in depth in section 5.2 on wood waste.

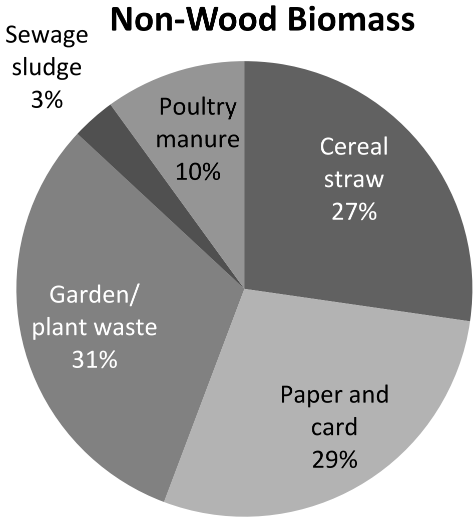

Figure 22 Non-Wood biomass (Defra, 2007 p38)

Figure 22 on the right clearly shows that the occurring straw, paper and card and garden waste is of a similar size (around 3 million dry tonnes per year). The figure for availability of paper and card in this report is much smaller than that from the EU Waste statistics (see Table 17). The figure for paper and cardboard in the UK Biomass Strategy includes the current use of paper and cardboard for energy recovery. Since the purpose of this thesis is to establish the potential biochar production, it was chosen to work with the figure from the EU waste statistics. This gives the total paper and cardboard material without considering its current use for energy production.

Available non-wood biomass - UK Biomass Strategy	
	Available Tonnage (dry tonnes/yr)
Cereal straw	3,000,000
Paper and card	3,132,000
Garden/plant waste	3,429,000
Waste wood	5,563,000
Sewage sludge (dry solids)	340,000
Poultry manure – Meat birds (60% DM)	1,098,900
Total (excl wood waste)	**10,999,900**

Table 18 Available non-wood biomass. Reproduced from, Defra (2007c, p38)

The availability of poultry manure is 1 million dry tonnes/yr and that of sewage sludge 340 thousand dry tonnes/yr. This animal manures and sewage sludge only includes “dry” material; dry solids of the sewage sludge and only the specific poultry manure that has a higher content of dry matter. The wet biomass would not be suitable for biochar production. These figures also consider uses that exist for the material, for example the use of straw for animal bedding.

These data are directly usable for this thesis because the material type is clearly defined and the descriptions of purpose are close to those of the original report. More analysis will be done in chapter 6 to integrate and analyse all the results.

5.2 Wood waste

The last section has looked at the non-wood waste available in the UK; this section determines the quantity of wood waste that is available in the UK. The documents that are used for this have been graded and discussed on page 50. The report from the Waste Resources Action Programme (WRAP) by Nikitas et. al (2005) *Reference document on the status of wood waste arisings and management in the UK* and the UK Biomass report from Defra (2007c) are thought to be the most suitable to answer the questions in this section.

The main sectors covered in the WRAP research were Municipal Wood Waste, Commercial and Industrial Wood Waste, Construction and Demolition Wood Waste, and Packaging Wood Waste. This research was done by collecting all published reports available on this topic, which they graded according to the quality of the research method. The main findings of this research will be presented starting with the municipal wood waste.

5.2.1 Municipal Wood Waste

Municipal solid waste (MSW) is the fraction of waste that is collected from households, streets, offices and civic amenity sites. The wood waste in MSW was assessed separately for furniture and non-furniture wood. Non-furniture wood could be from DIY or street sweeping. Table 19 below give the figures for the wood quantities in MSW in the UK. This fraction of the waste adds up to 1,667,000 tonnes in 2003/4. Over half of this is collected from civic amenity sites.

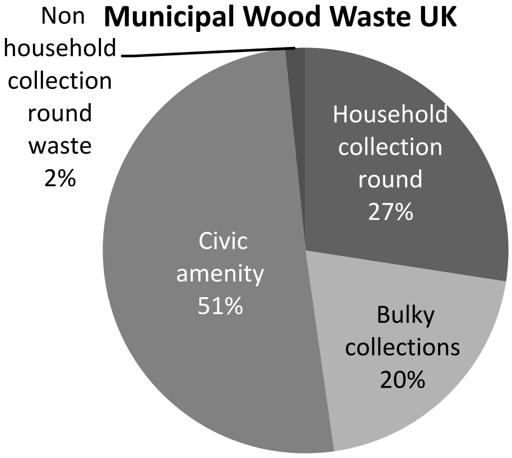

Figure 23 Municipal wood waste in the UK. Source Nikitas et. al, (2005)

Wood quantities including furniture in municipal waste in the UK thousand tonnes – 2003/4 estimates	
Waste Stream	**Thousand Tonnes**
Household collection round	457
Bulky collections	338
Civic amenity	843
Non household collection round waste	27
Total Wood in MSW	**1667**

Table 19 Wood quantities including furniture in municipal waste in the UK thousand tonnes – 2003/4 estimates. Reproduced From: (Nikitas et. al, 2005)

5.2.2 Commercial and Industrial Wood Waste

This section examines the wood waste from commercial and industrial sources. The data for this are again drawn from the WRAP study. The data from this study came from a large range of reports, of which the WRAP report made a best estimate for the total wood waste arisings from this sector. Figure 24 and Table 20 show the results of this. The total is almost 4.5 million tonnes, with over half originating from 'other sources', which is mostly packaging. A quarter of the waste from this sector also came from producing panel boards.

It has to be noted that some of these results were for England and Wales only. In the WRAP study this was not corrected to include Scotland and Northern Ireland, and it has not been possible to find the relevant data for this thesis. It is expected that Scotland and Northern Ireland will only add little to this sector. It is assumed that the lack of data for this particular sector can be ignored when assessing the overall biomass availability for the UK.

Figure 24 Wood waste in Commercial and Industrial waste stream UK. Reproduced from (Nikitas et. al, 2005)

Waste type	Tonnage
Furniture manufacture	530,511
Manufacture of panel boards	1,107,074
Manufacture of wood products for the construction industry	201,298
Manufacture of wooden packaging	40,000
Total wood wastes from industry and commerce other than furniture manufacture, wastes from sawmills or the wood products industry*	2,552,312
Railway sleepers arising	26,000
Utility poles	23,500
Total (rounded to nearest thousand tonnes)	**4,481,000**

*Table 20 Commercial and Industrial Waste in the UK *England and Wales only. Reproduced from (Nikitas et. al, 2005)*

5.2.3 Construction and Demolition Wood Waste

The data for construction and demolition wood waste are again taken from the WRAP study. This has used several sourced (BRE, Enviros, Nottingham Trent University) and combined the results to give best estimates. These can be found in Table 21 below, with the proposed most realistic figures being the average of the minimum and maximum estimate.

Estimates of wood waste arising in the C&D waste stream in the UK 2003/4 (thousand tonnes)	
NOT including reclaimed wood	**UK**
Minimum estimate	1,517
Maximum estimate	7,295
Average of min and max estimate	4,406

INCLUDING reclaimed wood	
Minimum estimate	2,151
Maximum estimate	7,929
Average of minimum and maximum estimates – best overall estimate	5,040

Table 21 Estimates of wood waste arising in the C&D waste stream in the UK – 2003/4 (thousand tonnes) Reproduced from Nikitas et. al, (2005)

The total wood waste available from construction and demolition could fall in a large range of 1.5 – 5 thousand tonnes, with a likely average of 4.4 thousand tonnes excluding reclaimed wood and 5 thousand tonnes including reclaimed wood.

5.2.4 Packaging Wood Waste

Figures for total packaging wood waste can be seen in Table 22 below. This mostly consists of pallets and wooden boxes. It is unclear what currently happens with this material. This thesis will use the 2003 figure for the following calculations, because it is the most recent. Also, from the figures it can be seen that the wood packaging has been steadily rising, and this might be continuing, in which case this might be a conservative estimate.

Packaging Wood Waste in the UK waste stream 1998-2003 (tonnes)			
	1998	2002	2003
Packaging wood waste	1,300,000	1,397,938	1,403,694

Table 22 Packaging Wood Waste in the UK waste stream 1998-2003. Reproduced from Nikitas et. al, 2005

5.3 Summary of all wastes

This section has looked at the waste that arises yearly in the UK. It has assessed the quantity of biodegradable waste that would be suitable for biochar production, using secondary research and the repurposing of those findings. Table 23 below gives a summary of all these findings.

Total Waste production in the UK (tonnes)	
	Total
Wood	
MSW Wood (1)	1,667,000
Commercial & Industrial Wood (1)	4,481,000
Construction & Demolition Wood (1)	219,000
Packaging wood waste (1)	1,403,694
Total wood wastes from WRAP	7,770,694
Wood wastes (2)	3,980,000
Waste wood (3)	5,563,000
Animal and Food Waste	
Animal and vegetable wastes (2)	8,105,000
Animal waste of food preparation and products (2)	1,665,000
Animal faeces, urine and manure (2)	118,000
Poultry manure – Meat birds (60% DM) (3)	1,098,900
Sewage (dry solids) (3)	340,000
Other	
Paper and cardboard wastes (2)	12,524,000
Cereal straw (3)	3,000,000
Garden/plant waste (3)	3,429,000

Table 23 Total biodegradable waste production in the UK and the portion suitable for biochar production (thousand tonnes) (1) Source Nikitas et. al, (2005), (2) Defra (2007a), (3) Defra (2007c)

These data are also shown in Figure 25 below. Paper and Cardboard is with 44% the largest fraction of all wastes suitable for biochar production. Wood waste from the Commercial and Industrial sector also takes up a large proportion of total waste. The total wood waste is around 30% of all waste available.

Because the animal, vegetable and food waste had unknown moisture contents, and no more specific information was available, it was assumed that they were unsuitable for pyrolysis. The poultry manure and sewage by Defra (2007c) was the dry fraction given, which was thought to be suitable.

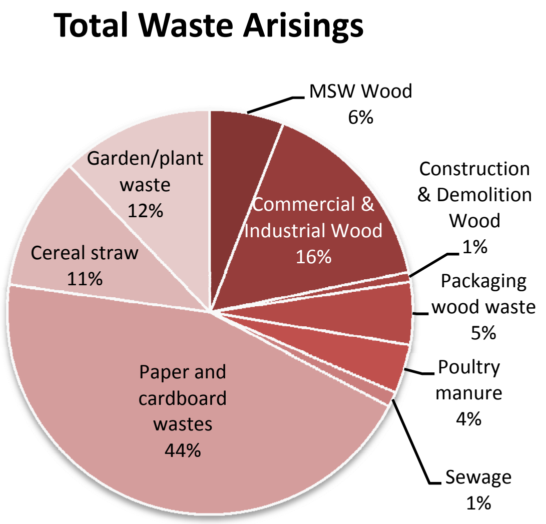

Figure 25 Total waste suitable for biochar production. Data see Table 23 on page 56

Not all occasions of recycling and energy recovery of these data that are taking place have been considered. Also there might be some double accounting, particularly in the wood waste section. It is assumed the wood wastes from Defra (2007a) have already been included in the other wood wastes so are ignored. The difference between the results from the WRAP strudy and Defra (2007c) is that the Defra report takes into account recycling whereas the WRAP study does not.

Table 24 below has translated the results given in Table 23 into a biochar figure. It shows the waste type in the left column, with the biochar that can be produced from that given in the column on the right.

Total Biochar production from Waste in the UK (tonnes)		
	Total Waste	**Biochar**
Wood		
MSW Wood (1)	1,667,000	525,105 *
Commercial & Industrial Wood (1)	4,481,000	1,411,515 *
Construction & Demolition Wood (1)	219,000	68,985 *
Packaging wood waste (1)	1,403,694	442,163.61 *
Wood wastes taking account of recycling (3)	5,563,000	1,752,345 *
Animal and Food Waste		
Animal and vegetable wastes (2)	8,105,000	- **
Animal waste of food preparation and products (2)	1,665,000	- **
Animal faeces, urine and manure (2)	118,000	- **
Poultry manure – Meat birds (60% DM) (3)	1,098,900	138,461.4 ***
Sewage (dry solids) (3)	340,000	96390 *
Other		
Paper and cardboard wastes (2)	12,524,000	3,550,554 *
Cereal straw (3)	3,000,000	850,500 *
Garden/plant waste (3)	3,429,000	972,121.5 *
Total	**49,036,694**	**8055795.51**

Table 24 Total biodegradable waste production in the UK and the portion suitable for biochar production (tonnes) (1) Source Nikitas et. al, (2005), (2) Defra (2007a), (3) Defra (2007c)

** it is assumed that this fraction contains 50% carbon with a 63% conversion efficiency*

*** the moisture content of these waste is unknown. It is assumed that this is unsuitable for charcoal production due to too high moisture contents and unclarity about the effect of this on the pyrolysis process. This is due to information given in Defra 2007b about the moisture contents of these sources (around 80%)*

**** 40% moisture content and assumed 50% carbon content after correction for moisture, 63% carbon conversion efficiency.*

The total biochar that could be produced from waste per year is 8 million tonnes. The biochar that can be produced from wood waste is 2.5 million tonnes per year, which is only 1.7 if recycled wood is excluded. The biochar potential from non-wood waste is 5.5 million tonnes per year.

Chapter 6 - Analysis

Chapter 4 and 5 have assessed the available biomass for carbon sequestration using biochar in the UK. Specific research has been defined for each section that could provide reliable data to inform this. The biochar production was predicted for all the forestry waste and biomass, using conversion ratios defined in chapter 2. This chapter will now analyse and discuss these results. First the biomass availability will be discussed, followed by the energy production from this in section 6.2, and the Environmental Impact in section 6.3. Section 6.4 will put these results in context by calculating how much land would be needed to produce the biochar necessary to sequester all UK carbon emissions.

6.1 Resource

The table below gives an overview of all the data found in chapter 4 and 5. The top half shows the results from the forestry scenarios and the bottom half shows the results from wood and non-wood waste. The forestry data are given as averages of the time periods.

In the second column the results of total biomass available are given. Biochar conversion rates[25] have been applied to this, which gives a total biochar carbon sequestration per year for each scenario in the third column. This is translated into a percentage of current UK Carbon emissions in the fourth column. The column added on the right is the electricity potential, based on the estimate of 1000 kWh per tonne of biomass from chapter 2 [26].

The results shown in this table are also given in Figure 26 on page 59.

Overview of all forestry and waste biomass potential for biochar per year				
Source	**Biomass (tonnes/yr)**	**Biochar (tC/yr)**	**Carbon Sequestered %**	**Electricity Potential (TWh/yr)****
Forestry				
Forestry Scenario 1 *	1,524,841	480,325	0.31%	1.5
Forestry Scenario 2 *	3,470,687	1,093,267	0.72%	3.5
Forestry Scenario 3 *	18,054,021	5,687,017	3.72%	18
Waste				
Wood waste excl. recycled	5,563,014	1,752,351	1.10%	5.6
Wood waste	7,770,694	2,447,769	1.60%	7.8
Non-wood waste	20,391,900	5,608,027	3.67%	20.3
Total waste	*28,162,594*	*8,055,796*	*5.27%*	*28*

*Table 25 Overview of all forestry and waste biomass potential for biochar * the average for the three time frames has been taken since no time forecasts for the wastes is available. ** Using the estimate for energy generation of 1000 kWh/tonne of biomass from chapter 2*

The available biomass from forestry for biochar is limited, unless more land becomes available. In scenario 1 and 2 it was assumed that forestry residues would be available.

---

[25] Carbon in biomass is 50%, and 63% of this converts into biochar carbon. See section 2.3.1

[26] see section 2.5

This biomass would be mostly available from North Wales, South Scotland, and South East England. Scenario 1 took into account the existing markets, while scenario 2 assumed that this material would become available. Scenario 3 has assumed that more land would be available, and has taken these values from an EEA report (2006), which has estimated the land available for bio-energy crops, within environmental limits.

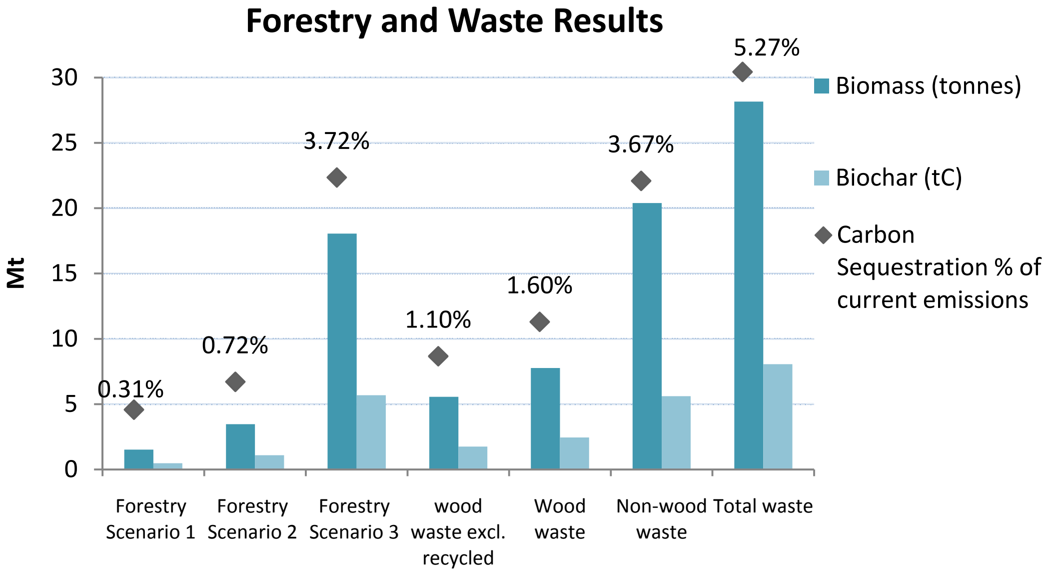

Figure 26 Overview of all the results from the forestry scenarios and the wood, non-wood and total waste

Figure 26 shows the total biomass available from the different scenarios and sources. The largest resource is clearly the waste, specifically the non-wood fraction. The potential contribution of forestry in scenario 1 and 2, which are both closest to the current forestry practice in the UK, is remarkably low. The availability of extra land would make a large difference and bring the total carbon sequestration potential up from around 0.5 to over 3.5% of current emissions. In a 15 year time-frame between 7 and 70 MtC can be sequestered (see Table 14 on page 48).

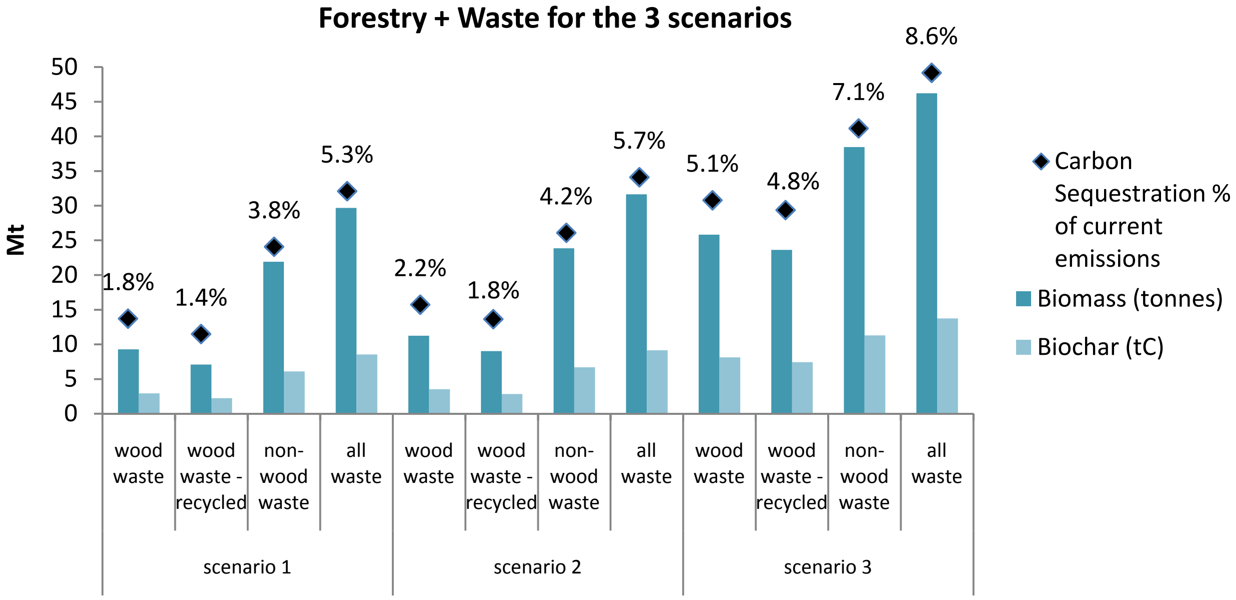

Figure 27 Waste added to the three scenarios

In Figure 27 above the waste is added to the results from the forestry scenarios, which shows all the combinations of forestry residues and waste that can be made.
The outcomes from this range between 1.4% and 8.6% carbon sequestered of the UK carbon emissions. The lowest yielding option would be from forestry scenario 1, which only uses the forestry residues that are not currently in use, combined with wood waste after taking account of recycling. The result from this is a 1.4% carbon sequestration potential of the current emissions. For both scenario 1 and 2 waste contributes more than the forestry residues to the figures above. The scenario that would yield most biomass and therefore biochar is forestry scenario 3 with all waste added, where the carbon sequestration potential is 8.6%.

The resource potentially available from non-wood waste and the total waste is in all cases larger than that available from forestry. The difference between the total wood waste and the wood waste taking account of current recycling levels is low. Paper and cardboard waste account with 44% for most of the available resource.

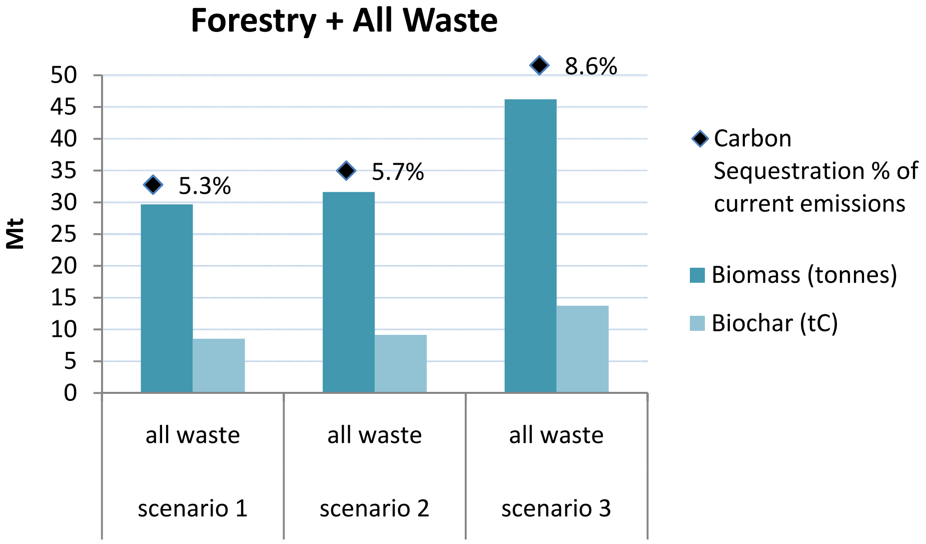

Figure 28 Total biochar from forestry and waste for the three forestry scenarios with total waste added

Figure 28 above is a simplified version of Figure 27, with now only the total waste added to the outcomes from the three forestry scenario. It is assumed that the available resource from waste will be the same for each scenario. It has to be noted that in the first two scenarios most of the material comes from the waste. In the third scenario waste is around two thirds of the total material available.

We can now consider the situation in which all forestry residues, extra carbon crops grown on current agricultural land and all biodegradable waste were to be converted into biochar. The carbon that could be removed from the atmosphere in this case could in itself provide enough carbon storage for 8,6% of our current emissions. This translates into 8,7% of the 1990 emissions, which is 0,7% above the UK Kyoto obligation. If direct carbon removal from the atmosphere using biochar is included in the Kyoto protocol, biochar alone could fulfil this commitment.

This report has until now assumed that all biomass could become available for biochar production. In reality there are many competitors for this material, for example the biomass energy industry and particle board manufacturers. Figure 29 below shows how much biochar carbon can be sequestered if only a portion of the total biomass was available. It shows the results for the three forestry scenarios with the total waste added, if only 5%, 25%, 50%, or 75% of all biomass would be available after it has been divided between other competitors. Again also the carbon sequestration as part of current carbon emissions is shown.

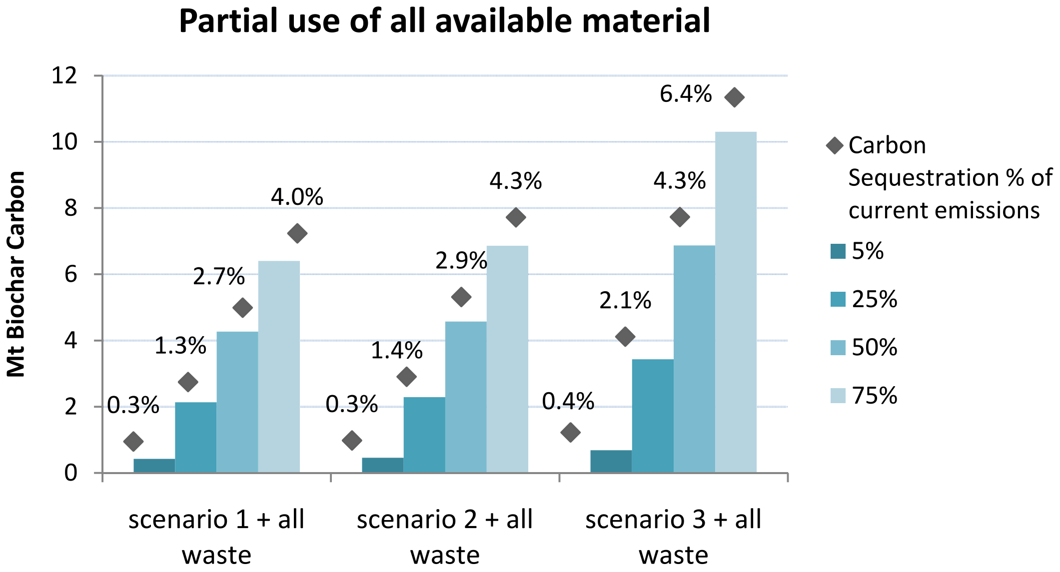

Figure 29 Partial use of all available material after competition with other industries

This shows that even with part of all the biomass available the carbon sequestered with biochar could be significant. Over half of the UK Kyoto commitment could be fulfilled by using 75% of all biomass from scenario 1 and 2 plus the waste, and by using only 50% of the biomass from scenario 2 and all the waste. This would leave space for other competing markets to use up some of the share of biomass, while still offering some potential for biochar carbon sequestration. The balance of how this would be shared out is expected to depend on the economic returns on each of the uses of the material which has not been addressed in this research.

The next section will assess the energy that could be produced from biochar production of the different waste streams and forestry biomass available.

6.2 Energy

The energy production from the pyrolysis could be significant. In chapter 2 some initial estimates were given for the energy production from pyrolysis. The figure that has been used for this report is 1000 kWh/tonne of biomass. It was however recognised that more research is needed to give an exact prediction for the energy produced for each feedstock type. In particular more experiments are needed with the UK biochar feedstock and process that would be used. Figure 30 below gives the results of this figure applied to the different resource streams, giving an initial indication of the expected energy from the biochar production.

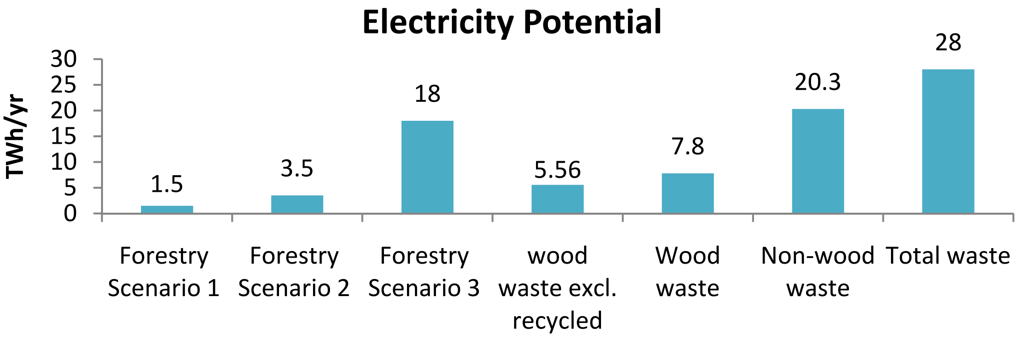

Figure 30 Electricity potential from pyrolysis of the different biomass resources

This energy produced could be as low as 1.5 TWh/yr for forestry scenario 1, or as high as 46 TWh/yr for forestry scenario 3 plus the total waste. The total electricity demand in the UK was 405,764 GWh in 2006 (DBERR, 2007 p 128). Assuming this stays constant, electricity generation from biochar production could deliver between 0.4 and 11 % of this total electricity demand.[27] This has an associated carbon sink of around 300 tC/kWh.[28]

Defra (2007c) estimates the energy potential of the biomass. This can serve as a benchmark figure to compare the energy production from biochar against.[29] For 18 million tonnes of dry biomass it estimates an electricity potential of 17-20 TWh (Defra, 2007c p 38).[30] This is comparable, if not slightly higher than the 1 MWh/tonne of biomass that has been used for this thesis.

Although less energy is produced from biochar production than in ideal use of biomass through for example co-firing or CHP, the energy that is produced is carbon negative, rather than carbon neutral. Trees remove the carbon dioxide from the atmosphere, which is returned by burning the biomass, and removed from the atmosphere again by new plantations. Biochar removes part of the carbon from this cycle and so creates a net sink of carbon for each unit of energy produced.

---

[27] Using 1.5-46 TWh/yr as the range established in this thesis, divided by the total electricity demand.

[28] Carbon balance = Biochar carbon produced/energy production

[29] This could not be calculated exactly for the feedstock that was found in this thesis due to limited time.

[30] The total energy recovery is higher when heat is also used. (50-57 TWHe&h/ tonne)

6.3 Environmental Impact

The environmental impact of pyrolysis was discussed in section 2.4.1 to 2.4.3. Of the VOC, particles and methane emissions, only the latter can be quantified, using the figure calculated in 2.4.1.

In 2.4.1 the climate impact of the methane emissions was calculated, using the gas composition from Downie et, al (2007). The part of the original biomass carbon that is contained in the methane is 7.06 %. The CO_2 equivalent of this methane was calculated to be the same as that of the carbon stored in the biochar.

Using these figures, the methane emissions of pyrolysis are calculated. This is to illustrate the relative effect of these emissions if the pyrolysis was done in a retort without gas combustion.

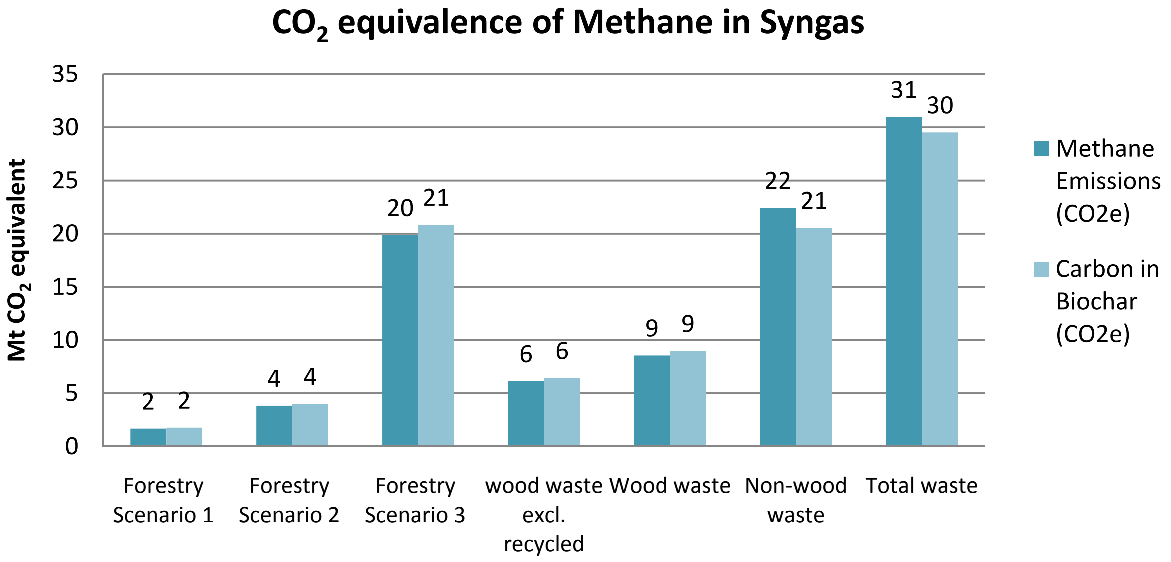

Figure 31 CO_2 equivalence of methane in syngas. This figure shows the relative CO_2 equivalence of the methane in the gas, versus the CO_2 equivalence of the carbon stored in the biochar.

Figure 31 shows the CO_2 equivalence of the methane in the syngas from pyrolysis of the biomass in the different sections if it would be released into the atmosphere instead of combusted. The CO_2 equivalence of these emissions is similar to the CO_2 equivalence of the carbon stored in the biochar. Releasing this methane would balance out the positive effect of the biochar production.

6.4 Biochar needed to sequester all CO_2 emissions

The last few sections have established the production potential for biochar in the UK. To set this in context, this section will establish at the quantity of biochar needed to offset all the current carbon emissions.

UK

The total carbon emissions in the UK are currently 160 million tonnes of Carbon equivalent. To create a sink for this using only biochar, the amount of carbon in the char will have to be the same as the total emissions. With a conversion of biomass carbon to charcoal carbon of 63%, 254 million tonnes of carbon in biomass is needed to produce this biochar. If half of this biomass mass is carbon, a total biomass weight of 508 million tonnes would be needed. For a biomass yield of 15 ODT/ha per year[31], a land area of 34 million hectares is needed. Since the total land area in the UK is 24 million hectares[32], it could only supply 71% of the land needed to sequester all current carbon emissions, by growing only biochar crops on all land surface in the country including urbanised land. Table 26 below gives the outcomes of this sequence of calculations.

Biochar for UK carbon sequestration	
C emissions (tonnes)	160,000,000
Carbon needed in char (tonnes)	160,000,000
Carbon needed in biomass (tonnes)	254,000,000
Total biomass needed (tonnes)	508,000,000
Total land needed (ha)	33,800,000
UK land area (ha)	24,000,000
Potential to provide per year	71%

Table 26 Biochar needed to sequester all carbon emissions in the UK

All the assumptions for the calculation above are rough estimates, and would need careful consideration. However, for the purposes of this thesis they give a useful benchmark. It is likely that more land would be needed.

This shows how biochar could neither provide enough sink to balance out all the carbon emissions in the UK, nor be the only solution needed to our climate change problem.

World

This same algorithm was applied to the world's carbon emissions and land area. This does show some potential for biochar as a magic bullet in an ideal world. Around 11% of the world's land area would be needed to grow biomass for biochar production to offset all the world's carbon emissions[33], which is about the land coverage of Russia. To also return atmospheric carbon dioxide levels to pre-industrial times, an additional area the size of Canada would need to be used for biochar crops and biochar production for 60 years.[34] Again the assumptions made for this, and the implication of this scenario on the environment in general would need careful investigation.

---

[31] This is the top end of the estimate from Defra (2007c, p39) of 10-15 ODT/ha

[32] This includes Urbanised land and water

[33] The world land area is 148.94 Million square kilometres, and emissions are 7.9 GtC/yr (Marland et. al, 2007)

[34] Carbon Dioxide needs to be reduced from 379 ppm to 280 ppm, this is 253 GtC. Using the same assumptions as before

Key Findings and Recommendations from Chapter 4, 5 and 6

- The largest biomass resource is non-wood waste.
- The potential contribution of forestry in scenario 1 and 2 is low
- The availability of extra land from scenario 3 would make a large difference
- The total carbon sequestration in scenario 3 is over 3.5%, up from around 0.5 in scenario 1 and 2
- Most forestry biomass is available in North Wales, South Scotland and South-East England
- The difference between the total wood waste and the wood waste minus recycling is low.
- The total carbon sequestration can be up to 8,7% of the 1990 emissions, which is 0,7% above the UK Kyoto obligation
- The energy produced would be between 1.5 TWh/yr and 46 TWh/yr
- This is 0.4 - 11 % of the total electricity demand.
- This has an associated carbon sink of around 300 tC/kWh
- The CO_2 equivalence of the methane emissions is similar to the CO_2 equivalence of the carbon stored in the biochar.
- If all UK land was used for biochar crops around 71% of the emissions could be sequestered
- Initial calculations show that to sequester all the worlds emissions a land area the size of Russia would be needed

Chapter 7 – Conclusions

This thesis has aimed to assess the potential for atmospheric CO_2 reduction through biochar in the UK. It has done so by assessing the scientific literature on biochar production and the available biomass in the UK for this. This conclusion summarises these main results and discussion. It starts with looking at the biochar production, biochar use, and resources in the UK. It also discusses its limitations, the further research that needs to be done, and the wider context that this thesis sits in.

7.1 Biochar Production

From assessing the available literature on biochar production the complexity of pyrolysis became clear. There are many different variables that influence research outcomes. Any estimates of biochar yield, energy yield and carbon yield cannot be directly transferable to another situation where other feedstock or retorts are used. They can only indicate the range of values that could be expected. Some values were chosen for the purposes of this thesis, to estimate biochar production and associated climate change mitigation. It was reasoned that using this as an indication rather than a definite figure would still be valuable. It helps us to decide whether this technology could be of any value in the future for climate change mitigation, and to establish research areas that would need to be expanded.

The values that this analysis has used are: 50% of biomass consists of carbon, 63% of this carbon converts into biochar carbon during pyrolysis, and during this each tonne of biomass produces 1 MWh of electrical energy. This was based on estimates from several sources.

It was found that in some cases pyrolysis causes environmental pollution. This is especially so in traditional charcoal production in a pit or simple kiln, which does not capture pyrolysis by-products. It was calculated that CO_2 equivalent of methane release from this is equivalent to that of carbon stored in the biochar. This is an important finding. Current researchers often focus on biochar fertiliser potential, and suggest that producing biochar on a field scale would be valid to produce this fertiliser, and will sequester carbon. However, this method would release methane. This would seriously undermine the climate benefit that would have been created.

Another potential form of pollution from pyrolysis could be Volatile Organic Compounds, or particles, but the effect of this has not been quantified in this thesis, or in the literature. More research is needed to quantify this and show the effect of this pollution on the environment and the human population.

7.2 Resource

This thesis has assessed the biomass that could become available in the UK for biochar production. The biomass that is available in the UK would have removed carbon dioxide from the atmosphere in its lifetime. By using this to produce biochar, this carbon is bound in a solid from. The assessment of the material that could be available was based on secondary research and did not consider associated costs or the logistics involved. The material was assessed in two sections; forestry and waste. One of the conclusions drawn from this is that the material that could currently become available from forestry is limited. This would not be much improved even by redirecting forestry residues from existing markets for forestry residues.

Using the values given in section 7.1, it was estimated that 1.5-3.4 million tonnes of biomass could become available each year in the UK, which would have a biochar carbon sequestration potential of 0.5-1 million tonnes of carbon per year. This is equivalent to 0.3-0.7% of the UK's current carbon emissions. Appointing extra land dedicated to growing biochar crops would make a large difference. It was estimated that up to 18 million tonnes of biomass could become available per year if this was done. This translates into 5.6 million tonnes of carbon in biochar per year, which is equivalent to 3.7% of the current carbon emissions. The total carbon sequestered in a 15 year time-frame could be between 7 and 70 MtC.

The feedstock that could become available from waste is significantly larger than the forestry resource. The total waste biomass that could be available is 28 million tonnes per year. This converts into 8 million tonnes of biochar carbon per year, which is equivalent to 5.27% of current carbon emissions. Of this waste around 8 million tonnes is wood waste, and around 20 million tonnes is non-wood waste. Again, the values found for biochar production would need to be tested for these specific materials.

This research has proven that carbon sequestration using biochar can make a significant difference, but it cannot be a solution on its own. The range of carbon emissions that could be offset in the UK are between 0.3 and 9%, which would be enough to help the UK hit the Kyoto targets if creating a carbon sink was included in this. But the ultimate aim of creating a zero carbon nation to reduce the risk of dangerous climate change cannot be fulfilled through the production and use of biochar. If all the land in the UK, including urbanised land, would somehow be used for biochar, still only 71% of the current emissions could be sequestered.

On an international level however, biochar could be a solution. A simple calculation has shown that a land area the size of Russia would be needed to remove all carbon emissions from the atmosphere. Also, to remove the overshoot of carbon dioxide in the atmosphere a land area the size of Canada would be needed for biochar crop production over a period of 60 years. This shows some potential for biochar to be a magic bullet in solving climate change, but the assumptions made for these calculations and the environmental impact of this scenario would need careful consideration.

This has confirmed the hypotheses set at the introduction. Biochar could offer a significant tool for climate change mitigation in the UK. The emissions are not expected outweigh the benefits of biochar sequestration if the syngas from pyrolysis is combusted. This has been assessed for methane. There could be potential other pollutants that have been missed.

7.3 Limitations

The limitations of this research are in two areas: the methodology and the scope of the research.

The methodology used has some clear limitations. Due to the complications of the pyrolysis process, secondary research findings were not comparable or applicable to the specific research questions of this thesis, or even to provide an estimate. Some of the values found were thought to be suitable for use in this thesis, but some outcomes may not be correct because of these uncertainties.

For many sections there was only limited research available thought to be suitable to provide data for the specific research question. The data available could lack necessary detail. This was, for example, the case with the data on waste available in the UK, which in most reports was not specified for each waste type. In the reports that *did* specify this, the location of the waste was still not clear. Primary research could have overcome these problems through more specific design of research questions and method, but the time available did not allow this type of research.

Another limitation of this research method is of course that some reports could have been missed out that would have provided important data to this thesis. The author is confident that this risk is limited. A thorough assessment of material on the Internet, and on-line scientific journals was made, using different search engines and a range of key words, yielding a large amount of information. Literature was gathered from the university library. Where data was unavailable through these sources, organisations and individuals were contacted to gather more specific information.

Some gaps that could be defined after this research are on the location of the available biomass and the pyrolysis parameters for this specific feedstock. Also the economics of this question have not been assessed. Limited information was available on the cost of pyrolysis, and again this would be dependent on retort type and feedstock material. This is an important issue that needs more research done in the future.

Some merits of this research are that within limited time some useful figures have been established that have not been published before. Although some of the assumptions made might be crude, future research can work with the findings from this report and investigate these assumptions in more detail.

7.4 Further Research

This thesis has evaluated the biochar production and biomass available in the UK, with a focus on climate change mitigation. This has implications for many other areas not touched on, but would need further investigation.

More research is essential to find out exact figures for biochar yield, carbon yield and energy production from pyrolysis. A figure that was thought to be closest to the findings in this particular case has been used, but it was also found that the feedstock composition has a large influence on these outcomes. Future research would need to use the target feedstock and pyrolysis retort.

For this thesis it was assumed that biochar carbon sequestration would replace biomass energy. This was based on research done by Fowles (2007). How this would happen in terms of socio-economics and policy has not been discussed. More research needs to be done in the future to establish the validity of the assumption that this replacement is possible.

Further investigation is also needed on the effect of biochar application to soils in the UK climate and soil types. Most research has taken place in tropical areas on poor soils which are a poor comparison to the UK's climate and soils. Although most of this research has found large benefits for biochar application, this cannot be assumed to be the case for the UK. It was outside the scope of this thesis to take on this task.

Biodiversity is an important issue that has only been briefly discussed. Currently some parts of the forestry resource are left behind on the land, providing habitats for wildlife. The suggestion to increase the output from forestry, and thereby increase the extraction of forestry products from the land, could have an adverse effect on wildlife that is dependent on this habitat. Although in scenario 3 the environmental effect of growing "carbon sequestration crops" was considered, more research needs to be done into the overall effect.

Another important issue is the logistics of biochar production, transport of forestry material and eventual transport of the biochar to its point of use. This was too large for the scope of this thesis. This is issue will need further research. There has been some suggestion of mobile pyrolysis plants, which would limit the cost and energy use for transport of forestry residues to the pyrolysis plant. The development of these is in an early stage, and due to a lack of material could not be discussed. However, the evaluation of biochar production areas and logistics involved in this is essential if this technology were to be seriously considered for implementation in the UK.

The same is the case for the economics of biochar for climate change mitigation. This has not been examined here, but would be a necessary task to enable decision making at higher levels. This will involve exploring the cost of forestry including logging and transport, cost of waste recovery and transport, the costs of pyrolysis equipment and running costs, and the cost of final transport of the biochar. Income from this could include income from carbon permits, through sale of biochar for agricultural application and potentially through the sale of energy and other by-products recovered from pyrolysis.

Appendices

APPENDIX I Land Use

	Agricultural land						
	Crops and bare fallow	Grasses and rough grazing[1]	Other [2]	Forest and woodland[3]	Urban land and land not Otherwise specified[4]	Total Land = 100%	Inland Water
England	*30.05*	*37.08*	*5.13*	*8.59*	*19.15*	13,028	76
Wales	*3.17*	*72.29*	*0.96*	*13.80*	*9.79*	2,073	13
Scotland	*7.07*	*66.42*	*1.93*	*17.12*	*7.45*	7,792	169
Great Britain	*19.80*	*50.26*	*3.66*	*11.97*	*14.32*	22,893	258
N. Ireland	*3.79*	*72.85*	*0.70*	*6.26*	*16.39*	1,358	64
UK	*18.90*	*51.52*	*3.50*	*11.65*	*14.43*	24,251	325

Table 27 Land use in the UK, thousand hectares Source Defra (2006a).

1) Includes grasses over and under 5 years old, and sole right and common rough grazing.

2) Set aside and other land on agricultural holdings, e.g. farm roads, yards, buildings, gardens, ponds. Excludes woodland on agricultural holdings which is included in 'Forest and woodland'.

3) Forestry data for GB is compiled by the Forestry Commission and covers both private and state-owned land.

4) Figures are derived by subtracting land used for agricultural and forestry purposes from the Total land area.

Accounting for Forestry in Northern Ireland

From the table above can be seen that the total land are of Northern Ireland is 1.358 thousand hectares. Of this 6.26% is forestry

1358 * 6.26% = 85010 hectares

To adjust findings for Britain to include forestry in Northern Ireland, total forestry in Britain should be calculated. This can be seen from the table above to be:

22893 * 11.97% = 2.740.000 hectares

To see what needs to be added to the Great Britain figures to account for Northern Ireland:

85010/2740000 = 3.1%

APPENDIX II Forest Residues

Forestry Production England (thousand ODT/yr)							
		without markets			**with markets**		
		Stemwood	**residues**	**total**	**Stemwood**	**residues**	**total**
North West England	**2007-2011**	20280	50325	70605	2028	50325	52353
	2012-2016	19386	50406	69792	1938.6	50406	52344.6
	2017-2021	17127	46926	64053	1712.7	46926	48638.7
North York Moors	**2007-2011**	26015	29876	55891	2601.5	29876	32477.5
	2012-2016	25006	30990	55996	2500.6	30990	33490.6
	2017-2021	22441	31782	54223	2244.1	31782	34026.1
Sherwood & Lincs	**2007-2011**	13417	39018	52435	1341.7	39018	40359.7
	2012-2016	10321	36737	47058	1032.1	36737	37769.1
	2017-2021	9586	36344	45930	958.6	36344	37302.6
West Midlands	**2007-2011**	15419	21999	37418	1541.9	21999	23540.9
	2012-2016	14562	22037	36599	1456.2	22037	23493.2
	2017-2021	12454	21081	33535	1245.4	21081	22326.4
Northants	**2007-2011**	5592	20206	25798	559.2	20206	20765.2
	2012-2016	5453	19893	25346	545.3	19893	20438.3
	2017-2021	4913	18573	23486	491.3	18573	19064.3
East Anglia	**2007-2011**	20861	35734	56595	2086.1	35734	37820.1
	2012-2016	18472	35191	53663	1847.2	35191	37038.2
	2017-2021	17115	36088	53203	1711.5	36088	37799.5
Forest of Dean	**2007-2011**	13965	33778	47743	1396.5	33778	35174.5
	2012-2016	12613	35280	47893	1261.3	35280	36541.3
	2017-2021	11027	35041	46068	1102.7	35041	36143.7
South East England	**2007-2011**	44608	90025	134633	4460.8	90025	94485.8
	2012-2016	43811	100493	144304	4381.1	100493	104874.1
	2017-2021	40635	103792	144427	4063.5	103792	107855.5
Peninsula	**2007-2011**	26997	45729	72726	2699.7	45729	48428.7
	2012-2016	27649	55630	83279	2764.9	55630	58394.9
	2017-2021	24311	53700	78011	2431.1	53700	56131.1
New Forest	**2007-2011**	13092	6723	19815	1309.2	6723	8032.2
	2012-2016	11764	6178	17942	1176.4	6178	7354.4
	2017-2021	11502	5898	17400	1150.2	5898	7048.2

Table 28 Forestry Production England (thousand ODT/yr) source McKay et. al, (2003a) and the associated online database http://www.eforestry.gov.uk/woodfuel/ [accessed 20/01/08]

Forestry Production Scotland (thousand ODT/yr)

		without markets			with markets		
		stemwood	residues	total	stemwood	residues	total
Dornoch	**2007-2011**	35653	16357	52010	3565.3	16357	19922.3
	2012-2016	42274	14547	56821	4227.4	14547	18774.4
	2017-2021	41643	13439	55082	4164.3	13439	17603.3
Inverness	**2007-2011**	49582	23105	72687	4958.2	23105	28063.2
	2012-2016	49113	20063	69176	4911.3	20063	24974.3
	2017-2021	47392	20765	68157	4739.2	20765	25504.2
Fort Augustus	**2007-2011**	23894	11766	35660	2389.4	11766	14155.4
	2012-2016	28548	11880	40428	2854.8	11880	14734.8
	2017-2021	36390	10867	47257	3639	10867	14506
Moray	**2007-2011**	36502	6250	42752	3650.2	6250	9900.2
	2012-2016	36105	7459	43564	3610.5	7459	11069.5
	2017-2021	33466	7893	41359	3346.6	7893	11239.6
Buchan	**2007-2011**	24888	5923	30811	2488.8	5923	8411.8
	2012-2016	28069	6285	34354	2806.9	6285	9091.9
	2017-2021	23620	6019	29639	2362	6019	8381
Lochaber	**2007-2011**	23114	18345	41459	2311.4	18345	20656.4
	2012-2016	27190	19387	46577	2719	19387	22106
	2017-2021	27819	19064	46883	2781.9	19064	21845.9
Kincardine	**2007-2011**	20660	10932	31592	2066	10932	12998
	2012-2016	19703	11251	30954	1970.3	11251	13221.3
	2017-2021	18704	11525	30229	1870.4	11525	13395.4
Lorne	**2007-2011**	30795	17271	48066	3079.5	17271	20350.5
	2012-2016	36572	20821	57393	3657.2	20821	24478.2
	2017-2021	45334	23105	68439	4533.4	23105	27638.4
Tay	**2007-2011**	47316	51644	98960	4731.6	51644	56375.6
	2012-2016	44976	55661	100637	4497.6	55661	60158.6
	2017-2021	45400	58370	103770	4540	58370	62910
West Argyll	**2007-2011**	65802	18290	84092	6580.2	18290	24870.2
	2012-2016	58306	16525	74831	5830.6	16525	22355.6
	2017-2021	65566	19121	84687	6556.6	19121	25677.6
Cowal & Trossachs	**2007-2011**	51923	30732	82655	5192.3	30732	35924.3
	2012-2016	50935	31685	82620	5093.5	31685	36778.5
	2017-2021	45428	30476	75904	4542.8	30476	35018.8
Scottish Lowlands	**2007-2011**	55947	34325	90272	5594.7	34325	39919.7
	2012-2016	63426	38014	101440	6342.6	38014	44356.6
	2017-2021	61634	39271	100905	6163.4	39271	45434.4
Scottish Borders	**2007-2011**	58588	33685	92273	5858.8	33685	39543.8
	2012-2016	62782	39429	102211	6278.2	39429	45707.2
	2017-2021	51275	37016	88291	5127.5	37016	42143.5
Galloway	**2007-2011**	89826	14166	103992	8982.6	14166	23148.6
	2012-2016	87514	16127	103641	8751.4	16127	24878.4
	2017-2021	85135	16336	101471	8513.5	16336	24849.5
Ae	**2007-2011**	55152	26337	81489	5515.2	26337	31852.2
	2012-2016	56688	32272	88960	5668.8	32272	37940.8
	2017-2021	48995	28758	77753	4899.5	28758	33657.5

Kielder	**2007-2011**	69349	21073	90422	6934.9	21073	28007.9
	2012-2016	67600	20181	87781	6760	20181	26941
	2017-2021	57967	19564	77531	5796.7	19564	25360.7

Table 29 Forestry Production Scotland (thousand ODT/yr) source McKay et. al, (2003a) and the associated online database http://www.eforestry.gov.uk/woodfuel/ [accessed 20/01/08]

Forestry Production Wales (thousand ODT/yr)

		without markets			**With markets**		
		stemwood	**residues**	**total**	**stemwoo**	**residue**	**total**
Coed y Mynydd	**2007-2011**	30851	56582	87433	3085.1	56582	59667.1
	2012-2016	28874	48807	77681	2887.4	48807	51694.4
	2017-2021	22901	44948	67849	2290.1	44948	47238.1
Coed y Gororau	**2007-2011**	26009	40743	66752	2600.9	40743	43343.9
	2012-2016	25068	39997	65065	2506.8	39997	42503.8
	2017-2021	22999	37159	60158	2299.9	37159	39458.9
Llanmyddfri	**2007-2011**	35244	55569	90813	3524.4	55569	59093.4
	2012-2016	36322	53359	89681	3632.2	53359	56991.2
	2017-2021	35030	53097	88127	3503	53097	56600
Coed y Cymoedd	**2007-2011**	18835	10962	29797	1883.5	10962	12845.5
	2012-2016	16895	11027	27922	1689.5	11027	12716.5
	2017-2021	15575	10857	26432	1557.5	10857	12414.5

Table 30 Forestry Production Wales (thousand ODT/yr) source McKay et. al, (2003a) and the associated online database http://www.eforestry.gov.uk/woodfuel/ [accessed 20/01/08]

Current Woodfuel Potential in the UK with competing markets (thousand oven dried tonnes/year)						
Product	**Scotland**	**England**	**Wales**	**Britain**	**Northern Ireland***	**UK***
Stemwood 7-14cm diameter	70	34	15	119	4	123
Poor quality stemwood	113	94	70	278	9	287
Stem tips	14	15	6	35	1	36
Branches	126	237	78	441	14	455
Sawmill conversion products	40	29	17	86	3	89
Arboricultural arisings	18	313	10	341	11	352
Short rotation coppice	0.6	13	0.2	14	0	14
Total	**381**	**735**	**196**	**1,314**	**42**	**1,355**

*Table 31 Current Woodfuel Potential for Britain with competing markets (thousand oven dried tonnes / year) Reproduced from: McKay et. al, (2003a)*Northern Ireland assumed 3% of Britain data. (see Appendix II)*

Current Woodfuel Potential for the UK without Competing Markets (thousand oven dried tonnes/year)						
	Scotland	**England**	**Wales**	**Britain**	**Northern Ireland***	**UK***
Stemwood 7-14cm diameter	699	337	154	1190	37	1227
Poor quality stemwood	113	94	70	278	9	287
Stem tips	14	15	6	35	1	36
Branches	126	237	78	441	14	455
Sawmill conversion products	404	290	166	859	27	886
Arboricultural arisings	22	456	14	492	15	507
Short rotation coppice	0.6	16	0.2	17	1	18
Total	**1,379**	**1,445**	**488**	**3,312**	**103**	**3415**

*Table 32 Current Woodfuel Potential for Britain without competing markets (thousand oven dried tonnes / year) Reproduced from: McKay et. al, (2003a)*Northern Ireland assumed 3% added onto Britain data. (see Appendix II)*

Future Woodfuel Potential in the UK (thousand ODT/yr)

		without markets			with markets		
		stemwood	residues	total	stemwood	residues	total
Scotland	**2007-2011**	738991	340201	1079192	73899	340201	414100
	2012-2016	759801	361587	1121388	75980	361587	437567
	2017-2021	735768	361589	1097357	73577	361589	435166
England	**2007-2011**	200246	373413	573659	20025	373413	393438
	2012-2016	296196	546025	842221	29620	546025	575645
	2017-2021	171111	389225	560336	17111	389225	406336
Wales	**2007-2011**	110939	163856	274795	11094	163856	174950
	2012-2016	107159	153190	260349	10716	153190	163906
	2017-2021	96505	146061	242566	9651	146061	155712
Britain	**2007-2011**	1050176	877470	1927646	105018	877470	982488
	2012-2016	1163156	1060802	2223958	116316	1060802	1177118
	2017-2021	1003384	896875	1900259	100338	896875	997213
NI	**2007-2011**	31505	26324	57829	3151	26324	29475
	2012-2016	34895	31824	66719	3489	31824	35314
	2017-2021	30102	26906	57008	3010	26906	29916
UK	**2007-2011**	1081681	903794	1985475	108168	903794	1011962
	2012-2016	1198051	1092626	2290677	119805	1092626	1212431
	2017-2021	1033486	923781	1957267	103349	923781	1027130

Table 33 Forestry Production UK (thousand ODT/yr) source McKay et. al, (2003a) and the associated online database http://www.eforestry.gov.uk/woodfuel/ [accessed 20/01/08]

Theoretical forest fuel production in the UK (mill m^3/yr overbark)

	Stem wood loss	Stem	Branches	Tops	Needles	Stump wood
Felling residues	1.03	8.47	2.37	0.24	0.74	1.78
Balance = NAI-Fellings	0.56	4.53	1.31	0.13	0.43	0.94

Table 34 Theoretical forest fuel production in the UK (mill m3/yr overbark) Source Karjalainen et. al, (2004)

APPENDIX III Emissions from charcoal production

Upper Concentration ranges for byproduct compounds		
Compound		**Upper Concentration (µg/m3)**
Aldehydes & Ketones		
	Methanol	2500
	Formaldehyde	100
	Acetaldehyde	10
	Propanal	1
VOCs		
	Benzene	17,000
	Toluene	2000
	Xylenes	1800
	Acetophenone	400
	Styrene	200
	Ethylbenzene	100
SVOCs		
	Phenol	12000
	4-Methylphenol	4000
	2-Methylphenol	3000
	2,4-Dimethylphenol	3000
PAHs		
	Naphthalene	7500
	Acenaphthalene	2000
	Phenanthrene	1800
	2-Methylnaphthalene	1200
	Dibenzofuran	720
	Pyrene	700
	Fluoranthene	700
	Fluorene	500
	Anthracene	300
	Benz[a]anthracene	200
	Acenaphthene	200
	Chrysene	150
	Benz[a]fluorene	100

Table 35 Compounds Measured in Dilution Tunnel (Reproduced from Lemieux, 2001)

APPENDIX IV Waste Composition UK

Waste Composition UK 2004 (thousand tonnes)					
Waste Type description (h=hazardous)	**England**	**Wales**	**Scotland**	**Northern Ireland**	**UK**
Chemical wastes	2,470	49	2	17	2,539
Chemical wastes excluding used oils (h)	2,605	148	367	38	3,158
Used oils (h)	356	27	61	19	463
Health care and biological wastes	132	4	15	23	174
Health care and biological wastes (h)	251	18	0	0	269
Metallic wastes	6,851	116	698	485	8,150
Metallic wastes (h)	29	1	2	1	32
Glass wastes	1,799	80	146	94	2,119
Glass wastes (h)	-	6	0	-	6
Paper and cardboard wastes	**10,691**	**520**	**1098**	**214**	**12,524**
Rubber wastes	164	11	1	-	176
Plastic wastes	1,710	88	176	64	2,039
Wood wastes	**3,337**	**280**	**298**	**66**	**3,980**
Textile wastes	344	7	6	20	377
Waste containing PCB (h)	-	-	0	-	0
Animal and vegetal wastes	**7,284**	**370**	**293**	**158**	**8,105**
Animal waste of food preparation and products	**1,522**	**138**	**3**	**3**	**1,665**
Animal faeces, urine and manure	**107**	**12**	**0**	**-**	**118**
Household and similar wastes	39,549	2,388	8992	1,434	52,363
Mixed and undifferentiated materials	1,834	314	378	160	2,686
Mixed and undifferentiated materials (h)	184	7	1	-	191
Sorting residues	630	44	0	0	674
Sorting residues (h)	-	-	1	-	1
Common sludges	27,699	265	1579	188	29,731
Mineral wastes	149,673	18,084	15667	5,933	189,358
Mineral wastes (h)	409	30	205	2	646
Other Wastes	3,065	143	208	81	3,497
Other wastes (h)	156	18	31	31	236
Total, non-hazardous	**258,862**	**22,912**	**29560**	**8,940**	**320,274**
Total, hazardous	**3,990**	**255**	**667**	**91**	**5,003**
Total, general	**262,851**	**23,168**	**30,227**	**9,031**	**325,277**

Table 36 Waste composition UK in 2004. Reproduced from: Defra (2007a)

APPENDIX V Email Correspondences

Bob Hawkins, EPRIDA
bob.hawkins@eprida.com

On Dec 12, 2007 10:35 AM, Mariska Evelein wrote:

Dear Bob

I am researching the carbon sequestration potential of biochar for the UK through the Centre for Alternative Technology and found your name in relation to the biochar technology development at EPRIDA.

I have reviewed most of the literature but have been unable to answer some of my questions.

Could you help me to get the following:
- prediction of the carbon yield from the pyrolysis
- quantification of the energy produced from the process
- quantification of the emissions from the production process

I am looking at using wood waste and other biodegradable waste, so it would be a range of feedstocks.

Have you got any information on these or could you point me in the right direction?

Kind Regards

Reply:
Date: 12 Dec 2007 20:21

Mariska,

Thank you for your interest in biochar as a carbon sequestration agent. I will do my best to answer your questions, but I can only give general values. Each biomass stream will have different yields along with generating different types of char. Testing of the specific feedstock to be used must be done in order to determine accurate data for that biomass stream.

Typical char yields in biochar production are around 30% by weight. Biochar contains 70-75% carbon. If you were to convert 100kg of wood waste, you could expect to get 30kg of char which contains around 21 kg of C. If this carbon was previously in the form of CO_2, then the 21 kg of carbon would represent the removal of 77kg of CO_2 from the atmosphere.

The amount of energy produced can vary depending on the biomass stream, the design of the equipment, and what type of energy you are trying to utilize. The syngas that is produced can be used to provide heat, steam, electricity, low grade heating oil, or liquid fuels such as F-T diesel, ethanol, methanol, gasoline, and/or DME. It would be difficult to produce any significant quantities of these if you tried to produce them all, so the best way is to pick what form you want your energy in. This choice is most commonly made based on the cost of the equipment required. In general terms for an average woody biomass, you could expect to see about 3500MJ (1000kWhr) per 1000kg of biomass if you were to generate electricity. If you wanted to make F-T diesel, yields of 75-100 gallons of diesel per 1000kg of biomass would be typical.

The contents of the syngas are hydrogen, carbon dioxide, carbon monoxide and methane. Carbon monoxide and methane can be eliminated, but a higher energy input is required thus lowering the energy generation potential. However, if running a hydrogen fuel cell is the target, pure hydrogen can be generated. Burning or combustion of the syngas will yield water and CO_2. There is no sulfur in the fuel, so no sulfur oxide emissions are present. Nitrous oxides might be present, but would be significantly lower than with burning natural gas. This syngas is the cleanest burning fuel you can find other than pure hydrogen, which can be produced with this system as mentioned above. Yes, CO_2 is emitted from the system, but this CO_2 came from biomass, and can therefore be traded as a carbon emissions offset. Also, with Eprida's technology and equipment, the amount of CO_2 removed and stored in the ground via biochar is greater than the amount emitted into the atmosphere. Eprida has invented technology that will remove the CO_2 from the exhaust and solidify it as a nitrogen fertilizer that is inside the biochar, thus greatly increasing the carbon sequestering ability of the biochar. The removal of CO_2 from an exhaust stream and converting it into fertilizer is a technology that is unique to Eprida.

I hope this helps you. If you have any more questions, let me know.

Thanks,
Bob Hawkins

Eprida
706-316-1765

Robert Brown
rcbrown@iastate.edu

Date: 12 Dec 2007 15:57

Mariska:

There are few places to turn for the information you seek. The International Biochar Initiative (see Web) is trying to compile a book of such information, but it is still a year before publication.

Char yields vary from 10% to 30% of the biomass feedstock depending upon biomass composition and operating conditions. There is no "formula" to predict this as of yet.

Energy yield depends upon operating conditions. As much as 75% of the energy can be recovered as non-charcoal forms (gas and oil), but this depends upon many factors.

A traditional kiln produces terrible pollution emissions. Properly done, though, the emissions can be controlled to an acceptable level (afterburners, etc.).I suggest that you Google FAO + charcoal kilns. This organization has an excellent on-line publication on charcoal kilns.

Sorry that I cannot point you to a consolidate source of information at this time.

Robert Brown

Char Half-life

Andrew Zimmerman
azimmer@ufl.edu

Received 15 Nov 2007 15:01
Mariska

It is generally assumed that charcoal (black carbon) is not very biodegradable because of its chemical composition (highly aromatic, with relatively little nitrogen, etc) and simply because it remains in the soil for long periods of time. However, recent work (papers attached) has shown that microbes can indeed respire and abiotic reactions can breakdown this material to at least some extent, especially when more labile organic matter is also added (so called 'priming' effect). In fact, my laboratory has found the same and is currently working on defining the properties of biochar and its remineralization rates better.

Andrew R. Zimmerman, PhD
Assistant Professor
Department of Geological Sciences
241 Williamson Hall
P.O. Box 112120
University of Florida
Gainesville, FL 32611
Office: (352) 392-0070
Fax: (352) 392-9294
azimmer@ufl.edu
www.clas.ufl.edu/users/azimmer/index.html

Methane Emissions

Adriana Downie
adriana@bestenergies.com.au

Sent 17 Jan 2008 18:16

Dear Adriana

I am trying to work out the global warming potential of methane that is produced during pyrolysis. For this I have been using your data from the paper for the bioenergy conference in Finland.

It would be good to get some clarification on one factor.
You give the gas composition in this paper, which shows that 8.5% of the gas consists of methane. Could you tell me how much gas there was, and how much of the carbon was released in this gas (you state quite clearly that 63% of the original carbon is contained in the char, do you know this for the gas too?)

I imagine that some of the carbon was also released as tar, so would it be an oversimplification to assume that 37% of the original carbon is contained in the gas?

It would be good to hear your thoughts on this

Kind Regards

Mariska Evelein

Received 17 Jan 2008 22:11

Hi Mariska,
We don't produce any tar in our process, all higher hydrocarbons are cracked in the gas clean-up. So yes, the balance of the carbon is in the gas.
All of the syngas, including the methane, is combusted in the gas engine or flared. In carbon accounting terms this is considered to return to the 'short term carbon cycle'. Gas combustion systems are very efficient due to the very effective mixing of gaseous fuels with oxygen. Hence the emissions profile for making a syngas and then combusting it is much cleaner than combusting the original solid, which is limited by the mass transfer of oxygen into the particles.
I would be happy to review and contribute to your calculations further for co-authorship on any publications.
Regards,

Adriana.
BEST Energies

Bibliography

Adger WN, Brown K, Shielt RS, Whitby MC, (1992) *Carbon Dynamics of Land Use in Great Britain* Journal of Environmental Management, 36, 117-133

Antal, MJ Jr, Grønli M, (2003) *The Art, Science, and Technology of Charcoal Production* Industrial and Engineering Chemistry Research, 42 pp 1619-1640

Antonietti M, (2006) *Magic Coal from the Steam Cooker*, Max Planck Research [online] Available at http://www.mpg.de/english/illustrationsDocumentation/multimedia/mpResearch/2006/heft03/3_06MPR_20_25.pdf [accessed 20/01/08]

Azargohar R. and Dalai AK, (1996) *Biochar as a precursor of activated carbon. (Abstract)* Applied Biochemistry and Biotechnology, 131 (1-3)

Baggott SL, Cardenas L, Downes M, Garnett E, Jackson J, Li Y, Passant N, Thomson A (2006) *Greenhouse Gas Inventories for England, Scotland, Wales and Northern Ireland: 1990 – 2004.* Climate, Energy Science and Analysis (CESA) Division Research Programme of the Department for Environment, Food and Rural Affairs (DEFRA)

Baker AJ, (1983) *Wood fuel properties and fuel products from woods.* In: Fuelwood management and utilization seminar: Proceedings. East Lansing, MI; 1982 November 9-11. East Lansing. MI: Michigan State University; (1983): 14-25

Barker T., I. Bashmakov, L. Bernstein, J. E. Bogner, P. R. Bosch, R. Dave, O. R. Davidson, B. S. Fisher, S. Gupta, K. Halsnæs, G.J. Heij, S. Kahn Ribeiro, S. Kobayashi, M. D. Levine, D. L. Martino, O. Masera, B. Metz, L. A. Meyer, G.-J. Nabuurs, A. Najam, N. Nakicenovic, H. -H. Rogner, J. Roy, J. Sathaye, R. Schock, P. Shukla, R. E. H. Sims, P. Smith, D. A. Tirpak, D. Urge-Vorsatz, D. Zhou, 2007: Technical Summary. In: *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, L. A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Bridgwater AV, (1980) *Waste incineration and pyrolysis* Resource Recovery and Conservation, 5 pp 99-115

Brown S, (1997) *Forests and climate change: role of forest lands as carbon sinks*, in FAO, XI World Forestry Congress, Antalya, Turkey, 13 to 22 October 1997

Burnley SJ, Ellis JC, Flowerdew R, Poll AJ, Prosser H, (2007) *Assessing the composition of municipal solid waste in Wales* Resources, Conservation and Recycling, 49 pp 264–283

Carbon Equity Project (2007) *The 2-degree target - How far should carbon emissions be cut?* [online] Available at www.carbonequity.info/PDFs/2degree.pdf [accessed 20/01/08]

Cheng C, Lehmann J, Thies JE, Burton SD, Engelhard MH, (2006) *Oxidation of black carbon by biotic and abiotic processes.* Organic Geochemistry, 37 pp 1477–1488

Day D, Evans RJ, Lee JW, Reicosky D, (2005) *Economical CO2, SOx, and NOx capture from fossil-fuel utilization with combined renewable hydrogen production and large-scale carbon sequestration,* Energy, 30 pp. 2558-2579

DBERR (2007) *Digest of United Kingdom Energy Statistics 2007*, National Statistics

Defra (2006a) *Land use by Agricultural and other uses: 2005* [online] Available at http://www.defra.gov.uk/environment/statistics/land/kf/ldkf08.htm [accessed 20/01/08]

Defra (2006b) *Agricultural land use: 1986-2005* E-digest Environmental statistics [online] Available at http://www.defra.gov.uk/environment/statistics/land/kf/ldkf05.htm [accessed 20/01/08]

Defra (2006c) *Set aside land*. [online] Available at http://www.defra.gov.uk/farm/environment/land-manage/setaside.htm [accessed 29-11-07]

Defra (2007a) *EU Waste Statistics Regulation (EC 2150/2002)* [online] Available at http://www.defra.gov.uk/environment/statistics/waste/wreuwastestats.htm [accessed 20/01/08]

Defra (2007b) *Estimated emissions of carbon dioxide (CO2) by UNECE source category, type of fuel and end user: 1970 – 2006* [online] Available at
http://www.defra.gov.uk/environment/statistics/globatmos/gagccukem.htm [accessed 20/01/08]

Defra (2007c) *UK Biomass Strategy*, London, UK [online] Available at
http://www.defra.gov.uk/Environment/climatechange/uk/energy/renewablefuel/pdf/ukbiomassstrategy-0507.pdf [accessed 20/01/08]

Defra (2007d) *e-Digest Statistics about: Air Quality – Volatile organic compounds* [online] Available at http://www.defra.gov.uk/environment/statistics/airqual/aqvoc.htm [accessed 20/01/08]

Demirbas A, (2001) *Carbonization ranking of selected biomass for charcoal, liquid and gaseous product*, Energy Conversion and Management, 42 pp 1229-1238

Demirbas A and Arin G, (2002) *An Overview of Biomass Pyrolysis,* Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 24 (5) pp 471 - 482

Demirbas A, (2004) *Effects of temperature and particle size on bio-char yield from pyrolysis of agricultural residues,* Journal of Analytical and Applied Pyrolysis, 72 pp. 243-248

Downie A, Klatt P, Downie R, Munroe P (2007) *Slow Pyrolysis: Australian Demonstration Plant Successful on Multi-Feedstocks*, Paper for the Bioenergy 2007 Conference in Finland

DTI (2004) *Environmental Impacts of the extraction of forestry residues*, Cranfield University

EEA (2006) *How much bioenergy can Europe produce without harming the environment?* European Environment Agency, Copenhagen [online] Available at
http://reports.eea.europa.eu/eea_report_2006_7/en/eea_report_7_2006.pdf [accessed 20/01/08]

EPA (1995) *Chapter 10.7 Charcoal*. In: AP 42, Fifth Edition Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources, US Environmental Protection Agency [online] Available at http://www.epa.gov/ttn/chief/ap42/ch10/final/c10s07.pdf [accessed 20/01/08]

Fagbemi L, Khezami L, Capart R, (2001) *Pyrolysis products from different biomasses: application to the thermal cracking of tar*, Applied Energy, 69 pp 293–306

FAO (1985) *Industrial Charcoal Making*, FAO Forestry Paper 63, Rome [online] Available at
http://www.fao.org/docrep/X5555E/X5555E00.htm [accessed 20/01/08]

FAO (1987) *Simple technologies for charcoal making,* FAO Forestry Paper 41, Rome [online] Available at http://www.fao.org/docrep/X5328e/x5328e00.htm [accessed 20/01/08]

FAO (1994) *Integrated energy systems in China - The cold Northeastern region experience* [online] Available at
http://www.fao.org/docrep/T4470E/T4470E00.htm [accessed 20/01/08]

Figueiral I, Mosbrugger V, (2000) *A review of charcoal analysis as a tool for assessing Quaternary and Tertiary environments: achievements and limits.* Palaeogeography, Palaeoclimatology, Palaeoecology, 164 pp 397–407

Forbes MS, Raison R.J. Skjemstad JO, (2006) *Formation, transformation and transport of black carbon (charcoal) in terrestrial and aquatic ecosystems* Science of the Total Environment, 370 pp 190–206

Forestry Commission (2006) *Forestry Facts and Figures 2006* [online] Available at
http://www.forestry.gov.uk/pdf/FCFS206.pdf/$FILE/FCFS206.pdf [accessed 20/01/08]

Fowles M, (2007) *Black carbon sequestration as an alternative to bioenergy,* Biomass and Bioenergy, 31 pp 426-432

Gavin DG, Brubaker LB, Lertsman KP (2003) *Holocene Fire History of a Coastal Temperate Rain Forest based on Soil Charcoal Radiocarbon Dates* Ecology, 84(1), pp. 186–201

Girard P. (2002) *Charcoal production and use in Africa: what future?* Unasylva No. 211 - Wood Energy

Goyal H, Seal D, Saxena RC, (2006) *Bio-fuels from thermochemical conversion of renewable resources: A review.* Renewable and Sustainable Energy Reviews, doi:10.1016/j.rser.2006.07.014

Grace J, (2004) *Understanding and managing the global carbon cycle,* Journal of Ecology, 92 pp 189–202, Blackwell Publishing

Hansen J, Sato M, Ruedy R, Kharecha P, Lacis A, Miller R, Nazarenko L, Lo K, Schmidt G, Russell G, Aleinov I, Bauer S, Baum E, Cairns B, Canuto V, Chandler M, Cheng Y, Cohen A, Del Genio A, Faluvegi G, Fleming E, Friend A, Hall T, Jackman C, Jonas J, Kelley M, Kiang NY, Koch D, Labow G, Lerner J, Menon S, Novakov T, Oinas V, Perlwitz J, Perlwitz J, Rind D, Romanou A, Schmunk R, Shindell D, Stone P, Sun S, Streets D, Tausnev N, Thresher D, Unger N, Yao M and Zhang S, (2007) *Dangerous human-made interference with climate: a GISS modelE study* Atmospheric Chemistry and Physics, 7 pp 2287–2312

Houghton J, (2004) *Global Warming – The Complete Briefing, third edition*, Cambridge University Press

Houghton RA, (2007) *Balancing the Global Carbon Budget,* Annual Review of Earth and Planetary Sciences, 35 pp 313–347

Hulme M, (2003) *Abrupt climate change: can society cope?* Philosopical transactions of the Royal Society, 361 (1810) pp 2001-2021

IPCC (2007) Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jackson J, Li Y, Passant N, Thistlethwaite G, Thomson A, Cardenas L (2007) *Greenhouse Gas Inventories for England, Scotland, Wales and Northern Ireland:1990 – 2005* Report to Department for Environment, Food and Rural Affairs, The Scottish Executive, The Welsh Assembly Government and The Northern Ireland Department of Environment, AEA Energy and Environment

Jacobson MC, Charlson RJ, Rodhe H, Orians GH (2000) *Earth System Science - From Biogeochemical Cycles to Global Change*, Academic Press, London/ California

Karjalainen T, Asikainen A, Ilavsky J, Zamboni R, Hotari K and Röser D, (2004) *Estimation of Energy Wood Potential in Europe* Working Papers of the Finnish Forest Research Institute 6

McKay H, Bijlsma A, Bull G, Coppock R, Duckworth R, Halsall L, Hudson JB, Hudson RJ, Johnson D, Jones B, Lightfoot M, Mackie E, Mason A, Matthews R, Purdy N, Sendros M, Smith S, Ward S (2003a) *Woodfuel Resource in Britain* Forestry Commission and Forestry Contracting Association

McKay H, Hudson JB, Hudson RJ (2003b) *Woodfuel Resource in Britain: Appendices.* Contractor: Forestry Contracting Association (FCA) with Forestry Commission (FC). First published 2003 Forestry Contracting Association

Keith, D.W., Minh Ha-Duong and Stolaroff, J.K., (2006) *Climate Strategy with CO_2 capture from the air* Climatic Change, 74 (1-3) pp 17-45(29)

Kerr RA (2007) *How Urgent is Climate Change*, Science 318 pp 1230-1231

Kirschbaum MUF, (2003) *To sink or burn? A discussion of the potential contributions of forests to greenhouse gas balances through storing carbon or providing biofuels.* Biomass and Bioenergy, 24 pp 297 – 310

Lackner KS, Grimes P and Ziock HJ, (1999) *The Case for Carbon Dioxide Extraction from Air.* SourceBook—The Energy Industry's Journal of Issues, 57 (9) pp 6-10.

Lehmann J, Kern DC, Glaser B, Woods WI, (2004) *Amazonian Dark Earths: Origin, Properties, management*, Kluwer Academic Publishers

Lehmann J, Gaunt J, and Rondon M, (2006) *Bio-char sequestration in terrestrial ecosystems - a review*, Mitigation and Adaptation Strategies for Global Change, 11 pp 403-427

Leifeld J, (2007) *Thermal stability of black carbon characterised byoxidative differential scanning calorimetry* Organic Geochemistry, 38 pp 112–127

Lemieux PM, (2001) *Emissions of Air Toxics from a simulated charcoal kiln equipped with an afterburner*, US Environmental Protection Agency [online] Available at http://www.epa.gov/ORD/NRMRL/pubs/600r01011/600r01011.pdf [accessed 20/01/08)

Liang B, Lehmann J, Solomon D, Kinyangi J, Grossman J, O'Neill B, Skjemstad JO, Thies J, Luiza FJ, Petersen J, Neves EG (2006) *Black Carbon Increases Cation Exchange Capacity in Soils.* Soil science society of America journal 70 pp 1719–1730

Liss P, Chuck, A., Bakker, D., and Turner, S. (2005) *Ocean fertilization with iron: effects on climate and air quality*, Tellus, 57B, pp 269–271

Magin G, (2001) *An introduction to wood waste in the UK*. Fauna & Flora International, Cambridge, UK

Malkow T, (2004) *Novel and innovative pyrolysis and gasification technologies for energy efficient and environmentally sound MSW disposal* Waste Management, 24 pp 53–79

Marland G, Boden TA, and Andres RJ, (2007) *Global, Regional, and National CO2 Emissions. In Trends: A Compendium of Data on Global Change.* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

Maschio G, Koufopanos C, Lucchesi A, (1992) *Pyrolysis, a Promising Route for Biomass Utilization* Bioresource Technology, 42 pp 219-231

Masiello CA, (2004) *New directions in black carbon organic geochemistry* Marine Chemistry, 92 pp 201– 213

Meinshausen M, and Hare B, (2000) *Temporary sinks do not cause permanent climatic benefits - Achieving short-term emission reduction targets at the future's expense.* Greenpeace

Meinshausen M, (2005) *On the Risk of Overshooting 2°C.* Paper presented at Scientific Symposium "Avoiding Dangerous Climate Change", MetOffice, Exeter, 1-3 February

Muti Lin J, (2006) *Development of a high yield and low cycle time biomass char production system* Fuel Processing Technology, 87 pp 487-495

National Statistics (2007) *Mid-year population estimates,* Office for National Statistics, General Register Office for Scotland, Northern Ireland Statistics and Research Agency.

Nikitas C, Boulos S, Shokar P, Leach B (2005) *Reference document on the status of wood waste arisings and management in the UK* The Waste & Resources Action Programme, Banbury, UK

Nishio M, (1996) *Microbial Fertilizers In Japan*, National Institute of Agro-Environmental Sciences, Kannondai 3-1-1, Tsukuba, Ibaraki 305 Japan [online] Available at http://www.agnet.org/library/eb/430/ [accessed 20/01/08)

Pari G, Hendra D, Setiawan D, Mahpudin, Saepuloh, Soleh S, Ali M, Miyakuni K, Ishibashi N, (2004) *Charcoal production for carbon sequestration - Demonstration Study on Carbon Fixing Forest Management in Indonesia*, Japan International Cooperation Agency

Piao S, Ciais P, Friedlingstein P, Peylin P, Reichstein M, Luyssaert S, Margolis H, Fang J, Barr A, Chen A, Grelle A, Hollinger DY, Laurila T, Lindroth A, Richardson AD and Vesala T (2008) *Net carbon dioxide losses of northern ecosystems in response to autumn warming,* Nature 451, 49-52 [online] available at http://www.nature.com/nature/journal/v451/n7174/full/nature06444.html [accessed 22/01/08]

Preston CM, Schmidt MWI, (2006) *Black (pyrogenic) carbon: a synthesis of current knowledge and uncertainties with special consideration of boreal regions* Biogeosciences, 3 pp 397–420

Rondon MA, Molina D, Hurtado M, Ramirez J, Lehmann J, Major J, and Amezquita E (2006) *Enhancing the Productivity of Crops and Grasses while Reducing Greenhouse Gas Emissions through Bio-Char Amendments to Unfertile Tropical Soils*, 18th World Congress of Soil Science July 9-15, 2006 Philadelphia, Pennsylvania, USA

Ryu C, Shari VN, Swithenbank J, (2007) *Waste pyrolysis and generation of storable char*, International Journal of Energy Research, 31 pp 177-191

Sarmiento JL and Gruber N, (2006) *Ocean Biogeochemical Dynamics*, Princeton University Press

Scheffer M, Brovkin V, and Cox PM, (2006) *Positive feedback between global warming and atmospheric CO2 concentration inferred from past climate change*, Geophysical Research Letters, 33, L10702, doi:10.1029/2005GL025044,

Schneider, S.H., S. Semenov, A. Patwardhan, I. Burton, C.H.D. Magadza, M. Oppenheimer, A.B. Pittock, A. Rahman, J.B. Smith, A. Suarez and F. Yamin, (2007) Assessing key vulnerabilities and the risk from climate change. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, pp 779-810.

Shinogi Y, Yoshida H, Koizumi T, Yamaoka M, Saito T (2003) *Basic characteristics of low-temperature carbon products from waste sludge,* Advances in Environmental Research, 7 pp 661–665

Solomon S. Qin D, Manning M, Alley RB, Berntsen T, Bindoff NL, Chen Z, Chidthaisong A, Gregory JM, Hegerl GC, Heimann M, Hewitson B, Hoskins BJ, Joos F, Jouzel J, Kattsov V, Lohmann U, Matsuno T, Molina M, Nicholls N, Overpeck J, Raga G, Ramaswamy V, Ren J, Rusticucci M, Somerville R, Stocker TF, Whetton P, Wood RA and Wratt, (2007): Technical Summary. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Sombroek W, Lourdes Ruivo M de, Fearnside PM, Glaser B, Lehmann J, (2004) *Amazonian Dark Earths as Carbon Stores and Sinks.* In: Lehmann J, Kern DC, Glaser B, Woods WI (2004); *Amazonian Dark Earths: Origin, Properties,* Management, Kluwer Academic Publishers

Stassen HE, (2002) *Developments in charcoal production technology* Unasylva No. 211 - Wood Energy

Strezov V, Patterson M, Zymla V, Fisher K, Evans TJ, Nelson PF, (2007)*Fundamental aspects of biomass carbonization*, Journal of Analytical and Applied Pyrolysis, 79 pp 91-100

Trossero MA, (2002) *Wood energy: the way ahead.* Unasylva 211 Vol. 53

Tryon EH, (1948) *Effect of Charcoal on Certain Physical, Chemical, and Biological Properties of Forest Soils,* Ecological Monographs, 18 (1) pp. 81-115

Ullmann's Encyclopedia of Industrial Chemistry (2000) *Charcoal* Horst-Günter Brocksiepe, Wiley-VCH Verlag GmbH & Co. Horst-Günter Brocksiepe, Degussa AG, Werk Bodenfelde, Federal Republic of Germany.

United Nations (1998) *Kyoto Protocol To The United Nations Framework Convention On Climate Change.* [online] Available at http://unfccc.int/resource/docs/convkp/kpeng.pdf [accessed 19/01/08]

Warnock DD, Lehmann J, Kuyper TW, Rillig MC, (2007) *Mycorrhizal responses to biochar in soil – concepts and mechanisms* Plant Soil, 300 pp 9–20

Welsh Assembly Government (2002) *Wise about waste - the national strategy for Wales*. Cardiff, UK [online] Available at http://www.countryside.wales.gov.uk/fe/master.asp?n1=366&n2=213&n3=368 [accessed November 22, 2007]

Williams PT, Besler S, (1996) The influence of temperature and heating rate on the slow pyrolysis of biomass, Renewable Energy, 7 (3) pp 233-250

Williams RB, Jenkins BM, Nguyen D, (2003) *Solid Waste Conversion: A review and database of current and emerging technologies* FINAL REPORT University of California Davis, Department of Biological and Agricultural Engineering, California Integrated Waste Management Board

Winsley P, (2007) *Biochar and bioenergy production for climate change Mitigation.* New Zealand Science Review, 64(1)

Yaman S, (2004) *Pyrolysis of biomass to produce fuels and chemical feedstocks* Energy Conversion and Management, 45 pp 651–671