Assessing the potential of biochar from crop residues to sequester CO_2: Scenarios to 2100.

By

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The candidate confirms that the work submitted is her own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

Some of the work in Chapter 4, 5 and 7 of the thesis appears in publication as follows:

Windeatt, J.H., A.B. Ross, P.T. Williams, P.M.Forster, M.A. Nahil, S. Singh. 2014. Characteristics of biochars from crop residues: Potential for carbon sequestration and soil amendment. Journal of Environmental Management. **146** (15), pp 189-197.

The candidate, Jayne Windeatt, was responsible for all laboratory analysis, data interpretation and interpretation of the work within the publication. The joint authors had supervisory and advisory roles. Within this thesis Chapter 4 contains some of the published results from the laboratory analysis detailed in the above publication, whilst Chapters 5 and 7 contain some of the same methodology as the publication, although the applications to data are different. This copy has been supplied on the understanding that it is copyright material and that no quotation from the thesis may be published without proper acknowledgement.

Abstract

Amongst the suite of current or developing climate change mitigation tools, biochar is discussed within the literature as a method for long-term carbon sequestration (CS). The biochar field is rapidly developing, though there are uncertainties and limitations for which understanding could be improved.

The aim of this thesis was to assess the potential of biochars from crop residues to sequester carbon, under the land-use pathways of the Representative Concentration Pathways, to 2100. Eight crop residue feedstocks and their biochars were fully characterised to examine the effects of feedstock and process conditions on biochar characteristics. Biochar yield, carbon content and recalcitrance values from this experimental work were utilized in the global modelling of scenarios exploring future carbon sequestration potential.

Biochars produced were Class B or Class C, using the recalcitrance classification of Harvey et al. (2012), and classed as moderately or highly degradable. Recalcitrance increased with increasing pyrolysis temperature. The recalcitrance index of Harvey et al. (2012) may underestimate recalcitrance in high alkali metal content biochars. The carbon sequestration (CS) potential of the biochars was affected by the yield and content of stable carbon content of the biochar and predicted to be between 21.3 % and 32.5 %. The feedstock carbon remaining in the biochars decreased with increasing pyrolysis temperature although carbon stability increased with temperature. Biochar CS potential decreased with increasing pyrolysis temperature, despite increased stability and is due to the decreasing yields observed. A new equation was developed, using feedstock volatile content, as an alternative to the CS equation of Zhao et al. (2013).

The Representative Concentration Pathways (RCPs) were used alongside the experimental results for biochar yield, carbon content and recalcitrance, and secondary data such as future crop yield and crop residue trends to project the CS potential of crop residues from 2005 to 2100. Scenarios of biochar production and carbon storage were developed, built around the RCPs, investigating biochar potential under changing crop land area and exploring parameters such as biochar characteristics and biochar systems. Scenario 1 used the mean or most likely values from experimental data and literature, Scenarios 2 to 7 explored parameter assumptions and Scenarios 8 and 9 explored the impact of climate change on crop yields and subsequent biochar CS potential. Global biochar production in Scenario 1 for the four RCPs over 95 years (2005 to 2100) was: RCP 2.6, 138.4 Gt biochar; RCP 4.5, 132.3 Gt biochar; RCP 6, 173.2 Gt biochar and RCP 8.5, 217.9 Gt biochar. Although the carbon mitigation potential of biochar in the scenarios generally increased from RCP 2.6 to RCP 8.5, the quantity of emissions requiring

mitigation also increased. Scenario 1 saw 49.0, 45.8, 60.9 and 77.2 GtC sequestered over the 95 year period for the four RCPs respectively. These are reductions of 11 %, 5 %, 5 % and 4 % on the RCPs carbon emissions pathways. The maximum and minimum carbon emission mitigation potentials achievable under the assumptions of scenarios 1 to 7 were 22.5 %, 10.8 %, 10.0 %, 8.3 % and 4.7 %, 2.2 %, 1.9 %, 1.5 % for the four RCPs respectively. Climate change generally resulted in a decreasing carbon sequestration potential from RCP 2.6 up to RCP 8.5. This negative impact also increased over time. The maximum impact on mitigation potential in 2100 was - 0.14 GtC yr^{-1} for RCP 2.6, this increased to - 0.72 GtC yr^{-1} for RCP 8.5.

Biochar has the potential to sequester carbon in all of the scenarios explored, however the magnitude of this sequestration potential is dependent on a number of factors of which many are currently subject to large amounts of uncertainty. Reduction in these areas of uncertainty would be a valuable area of further work following this study.

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Contents

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Table of acronyms

BQM	Biochar quality mandate
CDM	Clean Development Mechanism
CDR	Carbon dioxide removal
CEC	Cation exchange capacity
CER	Certified emissions reduction
CFI	Carbon Farming Initiative
CH_4	Methane
CO_2	Carbon dioxide
CS	Carbon sequestration potential
CV	Calorific value
EBC	European biochar certificate
FAO	Food and Agriculture Organisation
FAOSTAT	Food and Agriculture Organisation Statistical Database
FID	Flame ionisation detector
GC	Gas chromatography
GHG	Greenhouse gas
GIS	Geographic Information System
ha	Hectares
hg	Hectograms
HHV	Higher heating value
HI	Harvest index
HTC	Hydrothermal carbonisation
IBI	International Biochar Initiative
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LRTAP	Long-range Transboundary Air Pollution
N_2O	Nitrous oxide
NPP	Net primary production
PAH	Polyaromatic hydrocarbon
RCP	Representative Concentration Pathway
RPR	Residue to product ration
RVC	Recalcitrance from volatile content
SOM	Soil Organic Matter
SRES	Special Report on Emissions Scenarios
SRM	Solar radiation management
SSA	Specific surface area
TCD	Thermal conductivity detector
TCRE	Transient climate response to cumulative carbon emissions
TGA	Thermogravimetric analysis
TPO	Temperature programmed oxidation
UKBRC	UK Biochar Research Centre
UNCCD	United Nations Convention to Combat Desertification
UNFCCC	United Nations Framework Convention on Climate Change
VCS	Verified carbon standard
VER	Voluntary Emission Reduction
WFD	Waste Framework Directive

1 Introduction

Emissions of carbon dioxide (CO_2) into the atmosphere, from sources such as industrial and domestic processes and deforestation, are a key driver of anthropogenic climate change, with CO_2 accounting for 76 % of global anthropogenic greenhouse gas (GHG) emissions in 2010 (IPCC, 2013). Mitigation pathways discussed in the latest IPCC assessment report which aim to keep the increase in global mean surface temperature below 2^{o}C are characterised by substantial reductions in GHG emissions by 2050 which are achieved mainly through changes to energy systems and land-use (IPCC, 2014b). Carbon dioxide removal (CDR) technologies are often employed within these scenarios (typically after 2050 for large scale deployment), relying on technologies including bioenergy with carbon capture and storage (BECCS) (up to -20 $GtCO_2$ eq yr^{-1} in 2100) and afforestation technologies (up to -16 $GtCO_2$ eq yr^{-1} in 2100) to achieve negative emissions. Scenarios with high levels of mitigation without carbon capture and storage (CCS) technologies are projected to be far more costly than those with CCS (IPCC, 2014b). Biochar is one of a number of CDR technologies discussed as a potential methodology for removing CO_2 from the atmosphere and storing it, as a stable form of carbon, for long time periods in soils (Royal Society, 2009). This removal and storage requires a combination of natural and anthropogenic processes. Naturally, CO_2 is removed from the atmosphere through biomass photosynthesis. The biomass retains a large proportion of this carbon, releasing it back to the atmosphere through respiration or decomposition. Biochar systems aim to limit the release through decomposition by the thermal conversion of the biomass to a charcoal like material termed biochar. Thermal conversion processes include pyrolysis, the heating of the biomass without oxygen, or more traditional carbonization methods such as charcoal kilns. Biochar carbon is often much more stable than in the raw biomass, therefore biochar addition to soils may provide a long-term carbon storage sink (Lehmann et al., 2009). Discussion of the potential of biochar to improve agricultural soils exists within historic scientific literature including Retan (1915) and Trimble (1851). Interest in the carbon storage potential of biochar developed from research into high-carbon, highly fertile 'dark-earth' soils such as the *'Terra Preta'* soils of the Amazon (Marris, 2006, Sombroek et al., 2003). Evidence of ancient addition of charcoal to these soils, adding to increased soil fertility, led to the publication of a number of key articles including Glaser et al. (2001), Lehmann et al. (2003), Lehmann and Rondon (2006), Lehmann et al. (2006) and Krull et al. (2008) from which the dedicated, global field of biochar research for carbon sequestration and soil amendment began. Prior to this the term biochar was used mainly in connection with charcoal production, for example by (Demirbas, 2001, Demirbas and Arin, 2002). Biochar literature has expanded in the past decade, to include analysis of production methodologies, biochar characteristics, biochar effects in soils and on vegetation, carbon storage potential, and overarching fields such as economic and life-cycle analysis (Lehmann and Joseph, 2009). This is still a developing field, where many important research contributions can be made. The overarching aim of this thesis is to contribute to the biochar and CDR research fields by providing projections of the long-term carbon sequestration potential of biochar from crop residues under four different land-use scenarios spanning from 2005 to 2100.

1.1 Research objectives

The research has used an interdisciplinary approach to assess the global potential of biochar from crop residues to sequester carbon up to 2100. The methodology aimed to achieve a number of sub-objectives, each contributing to the overarching objective of quantifying the carbon storage potential of biochars from crop residues using the land-use scenarios of the four Representative Concentration Pathways (RCPs). The sub-objectives are:

1. To produce and characterise biochars from eight crop residues under uniform pyrolysis conditions, examining the effect of feedstock characteristics on subsequent biochar characteristics.
2. To characterise biochars from one crop residue, sugarcane bagasse, produced under varied pyrolysis conditions (peak temperature and heating rate), examining the effects of process conditions on subsequent biochar characteristics.
3. To assess the recalcitrance of biochars produced using the R_{50} Index described by Harvey et al. (2012).
4. To examine the potential influence of alkali metal content on biochar degradation, assessing possible conservative recalcitrance estimates in high alkali biochars.
5. The development of scenarios of biochar production using the land-use projections of the four RCPs, exploring the uncertainties and variation in biochar characteristics and biochar systems on these production potentials.
6. Development and evaluation of a new method for estimating long-term carbon storage, based on the CS equation of Zhao et al. (2013) and incorporating the experimental data from biochar characterisation.
7. Assessment of the long-term carbon storage potential of the biochars produced within these scenarios, using the CS methodology of Zhao et al. (2013) and the two-pool methodology of Woolf et al. (2010).

Experimental and modelling techniques were used alongside current biochar literature to develop a number of scenarios exploring aspects of uncertainty and variation in biochar systems.

Experimental work adds to the current knowledge on biochar characteristics, documenting the characteristics of eight crop residue biochars produced under uniform slow pyrolysis conditions. Biochar characteristics, such as biochar yields, recalcitrance and CS potential were used to inform the development of biochar availability scenarios to 2100. Biochar from one crop residue, sugarcane bagasse, was characterised after production under a range of alternative pyrolysis conditions, investigating the effects of temperature and heating rate. The experimental research further investigated the potential of the R_{50} recalcitrance index of Harvey et al. (2012), using temperature programmed oxidation (TPO) to investigate the influence of alkali metals on the thermal degradation of biochar.

Chapters 5 and 7 detail the development of a number of scenarios of biochar production and CS potential from 2005 to 2100. A small number of assessments of the potential for biochar production and CS are detailed within the literature, with a fraction of these studies projecting these figures into the future (see for example Lehmann et al. (2006) and Woolf et al. (2010)). Studies of biochar for carbon sequestration within the literature also do not examine varied pathways of land-use change, projecting mainly biochar potential with current land-use distribution (Harvey et al., 2012). This thesis provides an assessment of biochar CS potential to 2100, looking at the effects of changing land use, crop yields and climate upon factors including feedstock availability, biochar production and CS potential. The RCPs, four emissions scenarios and related socio-economic drivers, were used to project crop residue availability and related biochar production quantities over time. From this, the CS potential of biochar was estimated, using three calculation methods for comparison. Two of these methodologies were taken from the literature (Woolf et al., 2010, Zhao et al., 2013) and one method was developed using the experimentally derived feedstock volatile content, providing an alternative method of estimating the CS potential of biochars.

The thesis is structured as follows: Chapter 2 details the surrounding literature regarding biochar and the RCPs, Chapters 3 and 4 respectively detail the methodology and results of the biochar production and characterisation, Chapters 5 and 6 respectively detail the methodology and results for the development of biochar production scenarios, Chapters 7 and 8 respectively detail the methodology and results for the assessment of the carbon sequestration potential of the biochar scenarios, and Chapter 9 provides an overall summary and discussion.

2 Background literature

2.1 Anthropogenic climate change: A driver for biochar technology?

Anthropogenic climate change is, in large, caused by the increased concentrations of GHGs in the atmosphere which are occurring as a result of actions such as fossil-fuel burning and deforestation (IPCC, 2013). Atmospheric carbon dioxide (CO_2) concentrations have increased by 40 % from pre-industrial levels, reaching 391 ppm in 2011, with CO_2 accounting for 76 % of total anthropogenic GHG emissions in 2010 (IPCC, 2013, IPCC, 2014b). Increased GHG concentrations in the atmosphere affect the Earths radiative balance, with the impacts of GHGs and other natural and anthropogenic climate drivers measured by radiative forcing changes. Radiative forcing, usually measured at the tropopause in W m^{-2}, is the difference in incoming short wave radiation (sunlight) and outgoing long wave radiation and is defined as:

> *'..the change in net (down minus up) irradiance (solar plus longwave in W m^{-2}) at the tropopause after allowing for stratospheric temperatures to adjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values'*
>
> *(Ramaswamy et al., 2001)*

Changes in this radiative balance cause temperature changes in the atmosphere and can cause subsequent changes in other climate systems (Hartmann et al., 2013). Climate change is likely to have impacts which will vary spatially and temporally, and will also be dependent on the manifestation and the magnitude of the changes. The potential impacts of increased GHGs on the climate system are projected, to different levels of certainty and understanding, in the latest report of the Intergovernmental Panel on Climate Change (IPCC) which assesses the current scientific knowledge and evidence on climate change. Warming of the climate has already been detected, with resulting reductions in cover of snow and ice and increased sea-level (IPCC, 2013). The future severity of climate change will depend on the concentrations of greenhouse gases reached, and the sensitivity of the climate to these concentrations. With regard to the sensitivity of the climate to GHG changes, the equilibrium climate sensitivity is a measure of the increase in temperature which would be seen with a doubling of atmospheric CO_2, once the climate had reached equilibrium. Current estimates for the equilibrium climate sensitivity are a global mean surface temperature increase of between 1.5 ^{o}C to 4.5 ^{o}C, with a probability of at least 0.66 (IPCC, 2013). This highlights both the uncertainty in some areas of climate science and a need to further understand and mitigate potential changes (as mentioned previously, atmospheric CO_2 concentrations are now 40 % higher than in 1790). The potential manifestations of climate change, in addition to an increase in global mean surface temperature, include more frequent and more intense extreme weather events (including droughts and storms), increased or decreased precipitation locally and increased variability in weather (IPCC, 2014c). These impacts are expected to vary spatially and temporally with, for example, some regions expected to see impacts such as increased precipitation and other regions facing greater risk of drought. Changes in global mean surface temperature are already impacting food production systems, with, for example, reductions identified in production of wheat and maize in some main production regions. Some positive impacts on crop productions have also been seen in regions of higher latitude such as the United Kingdom and Northeast China (Porter et al., 2014). These positive effects may be attributed to a number or combination of factors, including more favourable temperatures during the crop development cycle and the CO_2 fertilization effect (see below and Section 2.4.3 for further discussion). Any positive effects of climate change which may benefit crop production, for example more favourable growing temperatures, are likely to decline with increasing magnitude of climate change, and with increased frequency and magnitude of extreme events (Porter et al., 2014).

Climate change research now has a number of fields, with areas including diagnostics of climate processes and projections of potential future climate change, mitigation processes to limit emissions of GHG and influence of other climate change drivers, and climate change adaptation which seeks to develop methods of resilience in the face of impending change. There are many complexities within each of these fields, which often include social and economic drivers alongside the physical science aspects. The IPCC acts as an advisory body which aims to provide the most current knowledge on climate change. Alongside its physical science report on climate change, it publishes a volume on the current knowledge of climate change impacts, adaptation and vulnerability, a volume on climate change mitigation and a synthesis report (IPCC, 2014a). The United Nations Framework Convention on Climate Change (UNFCCC) aims to develop international mechanisms to tackle climate change, with 195 parties to the convention. Mechanisms such as the Kyoto Protocol have been developed to achieve international goals such as emissions reductions and the development of adaptation funds (UNFCCC, 2014). There is often a sluggish response to the forecasts of climate scientists with many national and international targets to reduce emissions falling short of the reductions deemed necessary by scientists. In light of the often slow response of governments, businesses and communities to reduce emissions, a number of methods of climate engineering have been proposed and are at varied levels of research and development. There are many important considerations related to the development of these ‘geoengineering’ technologies, beginning with whether such developments may reduce the focus of actors to reduce emissions in the near term. Other considerations include the effectiveness, cost and ease of deployment of these technologies. In terms of the engineering and physical impacts of the geoengineering technologies, they are often divided into two categories; solar radiation management and carbon dioxide removal technologies (Royal Society, 2009). Solar radiation management (SRM) technologies aim to reduce the amount of incoming short wave radiation through various methods including reflectors in space, surface albedo modification and stratospheric aerosol injection. SRM technologies do not reduce the build-up of CO_2 in the atmosphere so other effects such as ocean acidification would still occur, and the SRM technology would need to be continually deployed otherwise an abrupt change in climate may occur. Carbon dioxide removal (CDR) technologies aim to reduce the amount of CO_2 in the atmosphere, through negative emission technologies such as bioenergy with carbon capture and storage (BECCS), biochar, ocean fertilization and enhanced rock weathering. As mentioned previously, these SRM and CDR technologies are in different stages of research and development, with a number of potential regulatory barriers to deployment also existing.

Biochar is one method of CDR which is currently deployed on the small scale, mainly for soil amendment purposes rather than CO_2 removal. The impact on soil and CO_2 sequestration potential of biochar is not currently fully understood with research into areas such as production methods, soil and plant effects, and the potential for larger scale deployment for CS currently dominating the biochar literature. Section 2.2 and 2.3 includes a discussion of the most current biochar literature, from production processes to the projections of CS potential.

2.2 Biochar production, characterisation, uses and environmental impact

2.2.1 What is biochar?

Biochar, a recalcitrant form of carbon made by the thermo-chemical conversion of biomass (Lehmann and Joseph, 2009, Brown, 2009), is defined by the UK Biochar Research Centre (UKBRC) as:

> *‘..a carbon rich solid product of the thermal stabilisation of organic matter, that is safe and potentially beneficial when stored in soil..’*

(UK Biochar Research Centre, 2011)

Biochar is increasingly discussed as a potential tool in areas such as negative emissions technologies, climate change mitigation, soil quality and food security (International Biochar Initiative, 2012d, International Biochar Initiative, 2012a, Lehmann and Joseph, 2009, Sohi et al., 2009). The production and use of biochar as a soil additive may offer an opportunity to tackle a number of these issues simultaneously (Lee et al., 2010).

Biochar can be produced from a number of biomass types including wood, grasses, energy crops, residues and wastes. Currently a number of types of biomass are used for biochar production either commercially or for research purposes, including wood, grasses and energy crops (International Biochar Initiative, 2011b). Production of biochar from materials such as municipal waste and algae is currently less common. Biomass can be processed via a number of thermal conversion routes including pyrolysis, gasification and combustion, amongst other methods (see Figure 2-1) (Bridgewater et al., 2001). Of these processes the production of biochar is normally associated with pyrolysis and gasification technologies which are conducted in conditions of zero or limited oxygen (see Section 2.2.2.2).

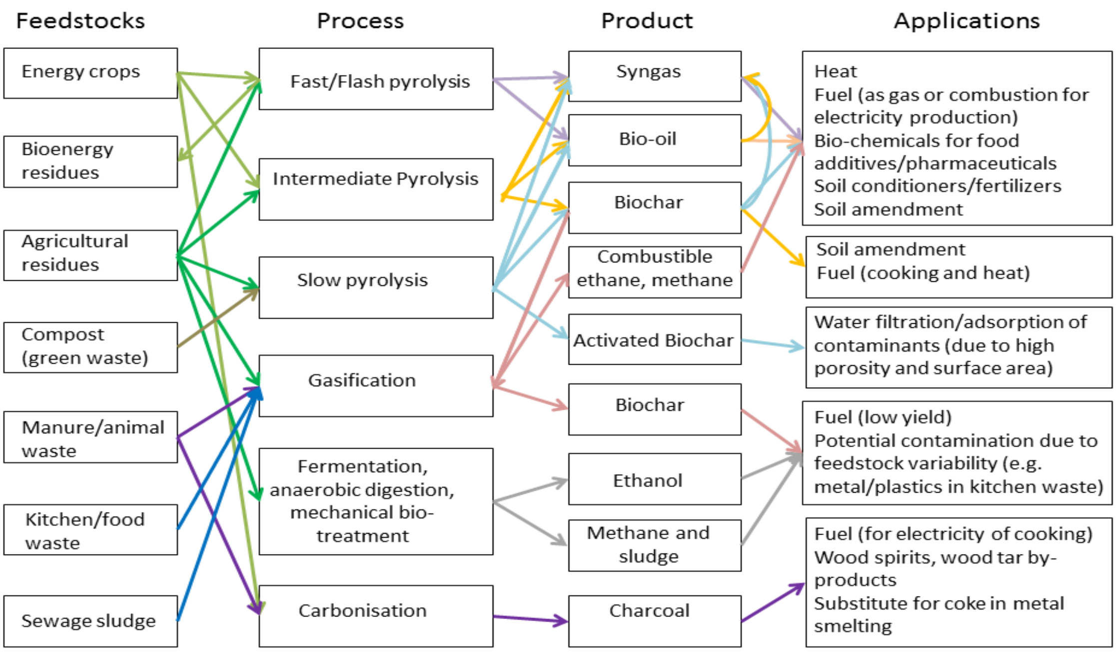

Figure 2-1: Schematic, adapted from Sohi et al. (2009), showing typical biomass feedstocks, biomass thermochemical conversion processes, typical products (including biochar), and product uses. These lists are not exhaustive but give an indication of the range of processes and applications of biomass conversion.

As illustrated by Figure 2-1, each biomass conversion process can have a number of products, for example the production of biochar by pyrolysis also yields oil and gas products which can be used as a renewable energy source (Fagbemi et al., 2001). The yields, quality and composition of these products, including biochars, are influenced by a number of factors including feedstock type, process type and operating conditions. Biochar production processes, and effects on biochar yields and characteristics, are discussed further in Sections 2.2.2 and 2.2.3.

Interest in biochar has been growing, in-part due to its potential to remove carbon dioxide (CO_2) from the atmosphere (see Figure 2-2). Biochar contains an enhanced carbon content compared to the feedstock. A high percentage of this carbon is recalcitrant, meaning it is more resistant to degradation allowing it to remain stable for timescales of hundreds to thousands of years (Lehmann et al., 2009). Due to this high recalcitrance, the long-term storage of carbon from biochar in soil has the potential to create a carbon negative system where CO_2 is removed from the atmosphere and stored (see Section 2.2.5).

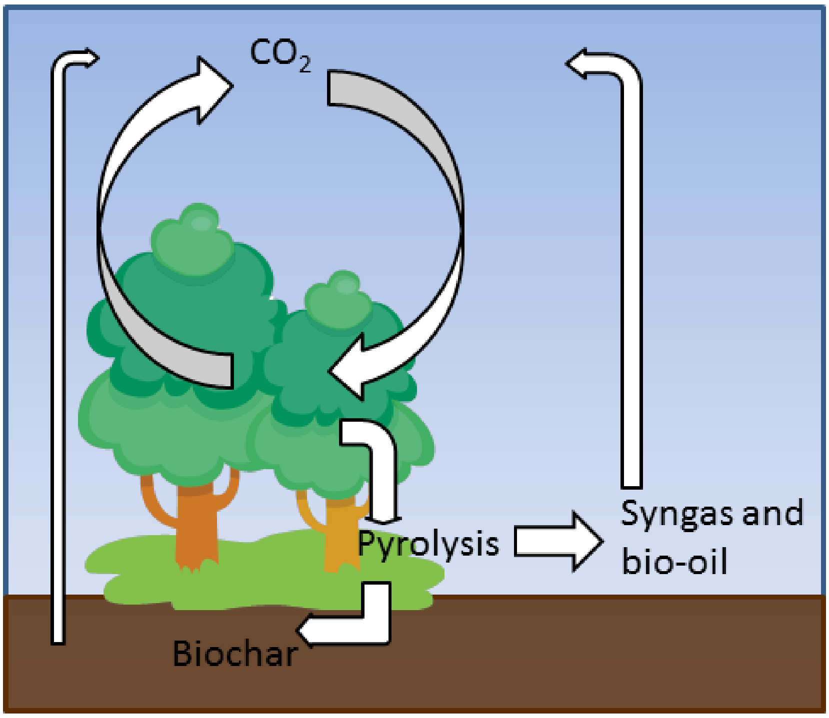

Figure 2-2: Schematic of the negative emissions process which may enable biochar systems to remove CO_2 from the atmosphere and store it in soils for long time periods.

As well as the potential for CO_2 sequestration, there are also other potential benefits of the addition of biochar to soils, such as improvement in the quality of degraded soils resulting in increased crop yields through mechanisms such as reduced nutrient loss, increased water holding capacity, soil pH modification, and soil microbial habitat improvement. There may also be reductions in soil emissions of other greenhouse gas species such as N_2O (International Biochar Initiative, 2012d). The effects of biochar in soil are discussed further in Section 2.2.5.1.

2.2.2 Biochar production: Types of feedstock and production methods

2.2.2.1 Types of feedstock

Biochar can be produced from a number of different biomass feedstock types, with the availability of feedstock, char production process and desired char characteristics all influencing the choice of feedstock. Biochar can be produced from biomass such as agricultural wastes, forestry residues, energy crops, manure and municipal waste (Sohi et al., 2009). Current commercial pyrolysis projects typically use forestry residues, crop residues (including straw, nut and rice residues), switch grass, bagasse (from sugarcane), olive waste, chicken and dairy manure, sewage sludge and paper sludge from the pulp industry (Das et al., 2008, Shinogi et al., 2002, Sohi et al., 2009, Yaman, 2004). Current commercial scale biochar production projects are small in number and often utilize available local waste streams. A number of research-scale projects have experimented with using different types of biomass feedstock to assess variance in biochar characteristics, such as yield and composition of biochar, and to explore research areas such as lifecycle assessments of biochar systems and the impacts of optimizing the pyrolysis process for either energy or biochar production (Gaunt and Lehmann, 2008). When determining the suitability of a biomass feedstock for biochar production, it is important to consider a number of factors including its biochemical content, contaminants, availability of the feedstock, and the economic costs of processing. The lignocellulosic composition (i.e. the cellulose, hemicellulose and lignin content) of the biomass feedstock influences the yield of oils, gas and char from a feedstock, which has implications for the type of biochar system and amount of fossil fuel offset that could be achieved from each biomass type (Antal, 1985).

As discussed previously, biochar can potentially be produced from biomass waste. Questions have been raised about the safety of adding these biochars to soils as well as biochars produced from other potentially contaminated feedstocks such as painted wood. Traces of contaminants, such as heavy metals, may remain in the biochar and be added to soil (International Biochar Initiative, 2012c). Heavy metal contamination is discussed further in Section 2.2.5.3. The use of some feedstocks may also be regulated under waste management regulations, creating a barrier for their use for biochar production. The regulation of biochar, including feedstock choice and addition to soils, is discussed further in Section 2.2.7.

2.2.2.2 Biochar production

Biomass can be converted using a number of thermal processes, such as pyrolysis, gasification, hydrothermal carbonisation. The yields and characteristics of the products of these processes vary greatly, with gasification and combustion products being low in carbon and high in ash and pyrolysis and hydrothermal carbonisation products being high in carbon and low in ash (Capareda, 2011). Biochar technologies span a range of technical complexity and a variety of scales, from individual pyrolysis/gasification cooking stoves to large scale bio-refineries (International Biochar Initiative, 2011a). The main technology currently discussed and used for biochar production is pyrolysis, of which there are again a number of methods. The conditions of pyrolysis can be optimized to favour different products and yields. Systems of energy production, such as gasification can also produce biochar high in ash and low in carbon and typically in smaller yields than pyrolysis. Typical yields for each process are discussed in the following sections.

Due to the optimal yields of biochar being from pyrolysis, this technology is discussed in most detail here, although an overview of all biochar production processes is given.

2.2.2.2.1 Pyrolysis

Pyrolysis is the thermal decomposition of organic matter in the absence of oxygen (Peng et al., 2011). Pyrolysis of biomass degrades the hemicellulose, cellulose, lignin and other organic components, producing products including gas, bio-oil and biochar. A number of different operating conditions can be used, resulting in different yields of these main products (Bridgewater et al., 1999). The operating variables include temperature, residence time, feedstock particle size, heating rate and pressure (DiBlasi, 1996). Of these, the main operating conditions usually controlled in pyrolysis, notably the heating rate and final temperature, have led to the classification of process into either 'fast', 'intermediate' or 'slow' pyrolysis. Typical biochar yields are around 12 %, 25 % and 35 % for fast, intermediate and slow pyrolysis respectively (Table 2-1), although these yields can be highly variable depending on factors such as feedstock type and other process conditions. Pyrolysis is used for a range of commercial applications including production of fuel for transport or storage (densification), as a precursor process to gasification, or for indirect co-firing with conventional fuels (where biomass is converted to gas, bio-oil or char and then co-fired in a traditional combustion chamber). (See Section 2.2.2.2.1 for further discussion of the different types of pyrolysis).

Table 2-1: Approximate yield composition (%) of pyrolysis products by process type (fast, intermediate and slow pyrolysis). Adapted from Sohi et al. (2009).

		Product yield (%)	
Pyrolysis Process	Biochar	Bio-oil	Syngas
Fast	12	75 (25 % water)	13
Intermediate	25	50 (50 % water)	25
Slow	35	30 (70 % water)	35

2.2.2.2.1.1 Pyrolysis chemistry

The three main constituents of biomass, collectively known as lignocellulose, give supporting structure to the roots, leaves and stalks of the biomass material (Figure 2-3). Lignocellulose is composed of cellulose, hemicellulose and lignin, with typically 38-50%, 15-30% and 23-32% composition respectively dependant on biomass type (Society for Biological Engineering, 2011).

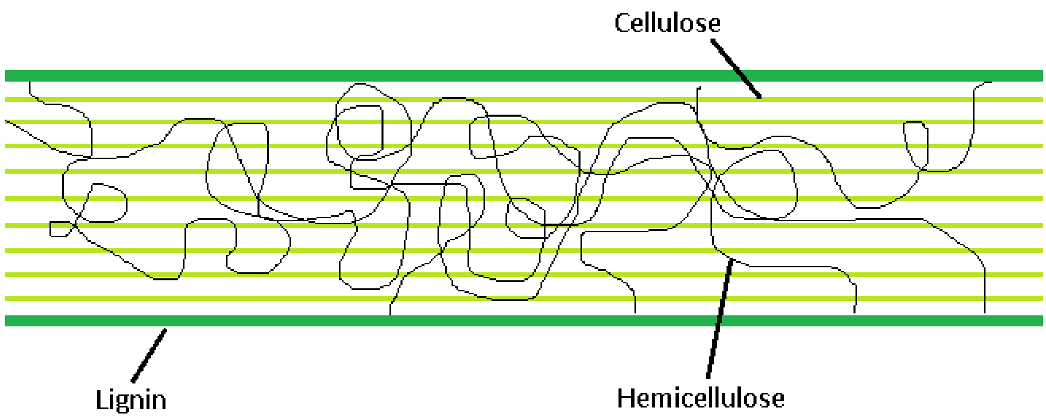

Figure 2-3: Distribution of lignocellulosic components (cellulose, hemicellulose and lignin) in the plant cell wall. Adapted from National Science Foundation (2014).

Cellulose and hemicellulose are both carbohydrate molecules. Cellulose consists of long glucose polymer chains. Hemicellulose consists of shorter polymer chains of 5 carbon sugars such as arabinose, glucose, mannose and xylose (Scheller and Ulvskov, 2010)). Lignin is a non-uniform three dimensional polymer, made from propyl-phenol monomer units which are arranged differently depending on plant type. Structurally, the cellulose and hemicellulose polymers make up fibre like strands called microfibrils, which are arranged into larger groups of macrofibrils. The macrofibrils are surrounded by the lignin polymers which act as a glue and structural support (Lange, 2007).

Pyrolysis of biomass results in a number of parallel and consecutive reactions (Balci et al., 1993). The temperature, residence time, and feedstock composition, influences the types of reactions that take place.

Table 2-2: Approximate temperatures of the different stages of pyrolysis and gasification, and the typical main products of each stage (Preto, 2008).

Temperature (^{o}C)	Process	Main Products
< 200	Drying	H_2O
230 – 250	Depolymerisation	Acetic acid, methanol, CO_2, CO
250 – 280	Torrefaction	Extractives, CO_2, CO
280 – 500	Devolatilization	Organics, Tars, CO_2, CO
500 – 700	Dissociation/Carbonization	CO, H_2
> 700	Gasification	H_2, CO

Low temperature pyrolysis (~300^{o}C) and long residence time favours biochar formation through de-polymerisation of the carbohydrates. Higher temperature pyrolysis (~400 ^{o}C to 700 ^{o}C) favours the production of oil through the release of volatile species. Further increase in pyrolysis temperatures (>700^{o}C) leads to breaking (cracking) of many of the C-C bonds present and the formation of a gas (syngas) (Bridgewater et al., 1999, Lange, 2007). The syngas produced is typically composed of CO, CO_2, H_2 and CH_4 in different concentrations, alongside smaller amounts of other hydrocarbon species, dependent on feedstock and process conditions.

Two phases of biochar formation during pyrolysis are discussed within the literature. Primary biochar formation begins at relatively low pyrolysis temperatures, after moisture is driven off. Depending then, on residence time, further reactions can cause the slow decomposition of the primary biochar and tars to produce a secondary, less reactive, biochar. Neves et al. (2011) reported that the first phase of pyrolysis, termed primary pyrolysis, is completed at temperatures below 500 ^{o}C, with formation of a primary biochar, permanent gas species and tars. Above these temperatures, primary volatiles may undergo secondary reactions, forming secondary products. A number of secondary reactions may take place, including reforming, cracking, oxidation, dehydration, polymerization, gasification and water-gas shift. During the secondary pyrolysis phase the biochar may catalyse the conversion of tarry vapours into both light hydrocarbon gas species and secondary char (through cracking and polymerization reactions respectively). During the secondary pyrolysis phase, biochar may also be converted to gaseous species through gasification reactions. Neves et al. (2011) discuss that the secondary conversion of volatile species occurs at a much faster rate than the secondary conversion of char. For optimization of bio-oil yields, a flash pyrolysis process produces the best results, as the very short residence time does not allow the secondary cracking of semi-volatiles into gaseous species (Demirbas, 2004b).

The proportions of cellulose, hemicellulose and lignin in the biomass feedstock also affect the yields of oil, gas and biochar as this influences the proportion of volatile and semi-volatile compounds which are released from the biomass feedstock to form oil and gas products and the quantities of stable carbon which remains in the solid biochar product (Sohi et al., 2009). Neves et al. (2011) also found that yields of pyrolysis products, including biochar, liquids, water, total gas and individual gas species, are highly dependent on the peak temperature of pyrolysis. They found that the yields and properties of pyrolysis products follow general trends in relation to temperature, despite the variety of biomass types, processes and reactors available.

2.2.2.2.1.2 Fast pyrolysis

Fast pyrolysis is achieved using high peak temperatures and short residence times to optimize production of oil or gas as the end product (Bridgewater et al., 1999). To optimize the process for liquid production, the residence time of product must be short (typically 1 to 5 seconds dependent on reaction temperature) so the further reactions which form gaseous products cannot occur. To maximise the yield of oil or gas products, the aim of fast pyrolysis is to limit exposure of the biomass particles to the lower temperatures that would form biochar (Bridgewater et al., 2001). The process does still yield small quantities of biochar at typically around 12 % (Table 2-1). Fast pyrolysis may, therefore, be more economically viable than slow pyrolysis for biochar production in systems where the production of oil and/or gas is in high demand for energy use (DECC, 2011, International Energy Agency, 2010).

A number of different pyrolysis reactor designs are used for fast pyrolysis, including fluid beds, circulating fluid beds, entrained reactors, rotating cone, ablative reactors and vacuum reactors (Bridgewater et al., 2001, IEA Bioenergy, 2011). The type of reactor used affects the yield and type of products due to differences in heat transfer, residence time and other factors (Bridgewater et al., 1999). In a fluidized bed reactor, the biomass is first dried and ground and then introduced into the reactor where it is passed through a granular material such as sand. The material is introduced at high velocity, which causes it to behave as a fluid. Heat is also added to the system. Fluidized beds crack the polymer chains of the lignocellulosic components, resulting in degradation and the formation of oil, gas and char in varying proportions. Circulating fluidized beds operate on a similar principle but have shorter residence times for gas and vapours. Processing times in a circulating fluidised bed are often shorter than for the basic fluid bed reactor and they can be more effective on materials that are difficult to fluidize (Bridgewater et al., 1999). Ablative pyrolysis uses a hot reactor wall to pyrolyse the biomass. High pressure is used and biomass is fed along the reactor to the reactor wall. A rotating cone reactor involves biomass particles being fed into the bottom of a heated cone. The particles are then swept upwards along the side of the heated cone surface. The close proximity of the particles to the heated cone surface allows for heat transfer to the biomass (BTG, 2011). Vacuum pyrolysis, performed at very low pressure, limits the secondary decomposition reactions of the gaseous products. In a fast vacuum pyrolysis reactor vapour and gases are removed from the reactor by the vacuum pump into the condensers, limiting secondary reactions, and any biochar formed remains in the reactor chamber until the end of the process (Roy et al., 1990). Product yields from vacuum pyrolysis are not currently as high as other methods, and costs of equipment and operation may be currently higher than the other methods as vacuum pyrolysis is in the earlier stages of development than some of the other fast pyrolysis technologies (Bridgewater et al., 1999, Roy et al., 2011).

Biochar produced by fast pyrolysis reactors can typically either be collected for utilization elsewhere (for example as a soil amendment or fuel) or can be recycled and combusted to provide energy for the pyrolysis process (Bridgewater et al., 2001).

2.2.2.2.1.3 Slow pyrolysis

A detailed description of the slow pyrolysis process is given here as this is the process which is used for biochar production in the experimental section of the thesis. Slow pyrolysis occurs at lower temperatures than fast pyrolysis, and with longer residence time of the biomass in the reactor. The lower temperatures, longer heating rates and longer residence times of slow pyrolysis produces higher biochar yields and lower oil and gas yields than fast pyrolysis (Williams and Besler, 1996, Xu et al., 2011). There is still a large amount of variation in the yields and characteristics of biochars produced by slow pyrolysis, dependent on the slow pyrolysis reactor type, process conditions and feedstock type. Examples from the literature of biochar yields from slow pyrolysis are: 25 – 62 % yield using different types of charcoal kiln in research by Antal (2003) and 26 - 63% biochar yield dependent on process peak temperature and residence time by Peng et al. (2011). The lowest yields from Peng et al. (2011) were found at their higher experimental temperatures (450 ^{o}C) and long residence times (8 hours), highest yields were found at lower temperatures (250 °C) and shorter residence times (2 hours). Demirbas (2004b) reported a reduction in yield of biochar (produced from olive husk and corncob respectively) of 56.4 % and 81.4 % when pyrolysis temperature was increased from 177 °C to 977 °C. Williams and Besler (1996) produced biochar yields of between 16.2 % and 60.8 % from the slow pyrolysis of wood at process temperatures ranging from 300 °C to 720 °C and heating rates of between 5 °C min^{-1} and 80 °C min^{-1}. The study found that biochar yields were higher at lower temperatures and with lower heating rates, although the highest biochar yields (produced at 300 °C) may indicate incomplete charring of the biomass. Although it is well documented that increasing temperature results in decreased yield of char, it is also discussed that the quality of char (fixed carbon content and other characteristics) may increase with increasing process temperature. Lange (2007) discuss that depolymerisation of the hemicellulose and cellulose chains begins at low temperatures (< 200 °C) and a residence period of a number of hours is required for this reaction to be completed at these relatively low temperatures. At higher temperatures (~ 300 °C +) dehydration begins and a series of other reactions begin to form unsaturated polymers and biochar. If the process hold time is not sufficient for these reactions to occur fully then the biomass material may not be fully charred.

There are a number of reactor types suitable for the slow pyrolysis process, including fixed bed reactors, multiple hearth kilns, screw kilns, drum kilns and rotary kilns (International Biochar Initiative, 2011a, Williams and Besler, 1996).

In a static batch reactor the feedstock is pyrolysed in batches in a reactor chamber (see Figure 2-4). The process is not continuous.

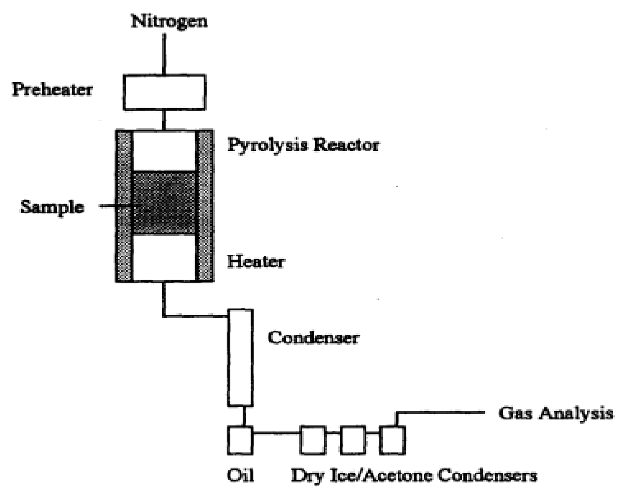

Figure 2-4: Schematic of an example static batch slow pyrolysis reactor from Williams and Besler (1996).

The batch process typically results in long residence times of the biomass and products during the pyrolysis process. In the batch reactor shown in Figure 2-4, biochar is collected from the reaction chamber at the end of the pyrolysis process whilst the volatile and semi-volatile compounds are removed throughout the process with the nitrogen (or other carrier gas) flow. Batch reactors may contain more than one 'hearth'. The feedstock is introduced at the top of the reactor and moved from one hearth down to the next during the pyrolysis process in a continuous process. The rotary kiln slow pyrolysis system consists of a tilted rotating drum which moves feedstock along the kiln during the pyrolysis process through gravity. Research using rotary kilns has found that altering feedstock input rates and/or operating temperature can control production yields of oils and gases whilst keeping the yield of biochar relatively constant at around 20 – 24 % (Klose and Wiest, 1999). The drum kiln reactor also uses a feeding mechanism to allow for continuous operation. The basic drum kiln system is similar in design to the rotary kiln, except a series of paddles inside the kiln move the biomass along the kiln. This allows biomass to be pyrolysed faster than in the batch reactor process, but is still classed as a slow pyrolysis process. The screw kiln pyrolysis mechanism, also similar in design to the rotary and drum kilns, uses a screw mechanism to move the biomass along the kiln. The heat source can be provided externally or by adding a heated substrate such as sand to the kiln to heat the biomass. The screw feeder removes the char at the end of the rotary kiln, again oil and gas products can be collected for use as an energy source. These slow pyrolysis kilns, except for the batch reactor, typically operate with a biomass hopper which can provide a constant flow of feedstock for continuous operation.

2.2.2.2.1.4 Microwave pyrolysis

Microwave pyrolysis uses microwaves to directly heat the feedstock, or to heat carbon that has been added to aid the process, which then transfers heat to the biomass through conduction. Carbon may be added as it has high microwave absorbency, and so can aid the process if the feedstock does not have the desired absorbency. As the biomass begins to carbonize, this increases the microwave absorbency of the materials and microwaves begin to produce reactions within the biomass (Dominguez et al., 2007). Current research focusing on the microwave pyrolysis process, includes improving the efficiency of electricity to microwave conversion and also the optimization of certain microwave pyrolysis products, in particular the yield of H_2 gas within the syngas produced (Dominguez et al., 2007, Zhao et al., 2011).

2.2.2.2.1.5 *Energy intensity of pyrolysis systems*

There are a number of necessary energy inputs for a biomass pyrolysis system. Initially energy may be required to dry biomass. Moisture in biomass is dependent on the biomass type and any pre-treatment, but most types of biomass will need some drying (in some cases natural drying may be sufficient). Example moisture content of some biomass types are 8 – 20 % moisture (wheat straw), 50 – 80 % (rice straw) and 30 – 60 % (wood bark) (Basu, 2010).

The pyrolysis process also requires energy input to provide a heat source for the reactions to occur. This energy may be provided from an external source, or after an initial energy input, may be provided through processing and burning of the secondary products. An energy penalty may apply for upgrading the pyrolysis products, for example, bio-oil is often rich in oxygen, acidic and corrosive and further treatment is often needed which would incur an energy penalty (Beurskens et al., 2000).

2.2.2.2.1.6 *Emissions from pyrolysis*

Pollution that may result from pyrolysis can be placed into three categories, ash, liquid tars and gases (Jauhiainen et al., 2005). In most large scale pyrolysis projects, the gases produced would be captured for energy use, although the further processing of this gas may mean that some fractions are un-used and disposal would therefore be needed. Emissions from the pyrolysis of biomass would depend on both the type of biomass used and the process type and conditions. As a variety of feedstocks can be used, projects would need to be assessed individually to determine the gaseous species which may be released. Examples of emissions from some feedstocks are discussed further here as an illustration. An assessment by Jauhiainen et al. (2005) details emissions of volatile and semi-volatile species from the pyrolysis of olive pomace at temperatures of 750 ^{o}C to 1050 ^{o}C. Emissions of some volatile gas species changed with temperature, whilst others remained relatively constant. They found that with increasing temperature, methane production decreased initially and then increased to return to initial production levels. Ethene emissions decreased with increasing temperatures. Formation of semi-volatile compounds from olive pomace pyrolysis tended to follow a trend of increase with temperature, but the magnitude of production and increase rate for each compound varies with temperature. Increasing temperature of olive pomace pyrolysis increased conversion of biomass to oil and gas. These oil and gas products may be classed as pollutants if not utilized for energy production within the system, or collected and utilized or disposed of properly. Pyrolysis syngas has also been used to replace the N_2 atmosphere once the process is underway, with the N_2 flow reduced proportionally to the inflow of syngas. This would supply direct heat to the process, although the presence of other gases in the reaction chamber can act as co-reactants in the process, altering the reactions occurring (Mante et al., 2012). Pyrolysis on a smaller scale may not have the technical capacity to capture the oil and gases formed and therefore emissions of some pollutants, such as CO and CO_2, would occur (International Biochar Initiative, 2011a).

2.2.2.2.1.7 Scale and efficiency of pyrolysis technologies

Globally, there is a large variation in types of biomass pyrolysis system. In developed countries, the use of large scale pyrolysis systems (bio-refineries) is, and is projected to be, the predominant method of biomass pyrolysis. In developing countries more small scale, localised systems such as farm scale pyrolysis units are currently more likely to be used (Demirbas, 2009, Ramachandra et al., 2000). The efficiency and energy demand of each system type differs and this has implications for the viability and productivity of biochar pyrolysis systems.

The efficiency of larger, industrial scale pyrolysis systems depends on a number of factors. Energy inputs to the system may differ depending on the type and location of the system, biomass may need to be processed by drying and/or grinding into smaller particle sizes (Zafar, 2011) and the harvesting and transport of biomass can add a substantial energy penalty to the life cycle of the whole system (Gaunt, 2012). The use of pyrolysis systems which operate on a smaller scale, for example farm scale, or can be mobilized to travel to a number of farms in a locality have been discussed as a possibility for deployment in some areas, particularly in developing nations or remote locations. Depending on the sophistication of these mid-sized systems, it may be possible to capture the oil and gas products for use within the system or as a fuel for other purposes. The close proximity of the reactor to the biomass source and potentially also to the biochar distribution site would improve the carbon footprint of the overall biochar system by reducing transport energy requirements (Gaunt, 2012).

A large portion of the world's population (over 2 billion people) currently use basic stoves or open fires for cooking and heating requirements which leads to emissions of pollutants which may affect health and climate. A transition to pyrolysis/gasification stoves would improve efficiency and decrease emissions of these pollutants (International Biochar Initiative, 2011a). The efficiency of traditional pyrolysis kilns for charcoal production may still be low compared to their theoretical efficiency, due to issues such as infiltration of O_2 into the reaction zone, where gasification would then convert a large percentage of the biochar to CO and CO_2 (Brown, 2009). This, alongside the pollution and inability to capture oil and gaseous products makes traditional kilns undesirable compared to other more advanced technologies.

Yield of biochar is not the only measure of the effectiveness of a biochar pyrolysis system which must be considered. As detailed in Section 2.2.2.2.1 differences exist in not only the yield of biochar with change in reactor type and process conditions, but in the carbon content and other characteristics of the biochars. Where biochar is being produced for carbon sequestration purposes, the yield, carbon content and recalcitrance of the biochar are all important factors when determining the optimum pyrolysis system and process conditions. These factors highlight that there are many important considerations when determining the most suitable pyrolysis reactor(s) and wider system, including the availability and suitability of feedstocks, energy demands and outputs, potential pollution issues, desired biochar characteristics (if any), and the economic costs and benefits of the system.

2.2.2.2.2 Gasification

The gasification process primarily creates a syngas, mainly consisting of carbon monoxide (CO), hydrogen (H_2) and carbon dioxide (CO_2), with some methane (CH_4). The composition of syngas can be typically around 35 % CO_2, 30 % CO and 20 % H_2 with smaller amounts of other gases present (Haryanto et al., 2009). A number of reaction stages make up the gasification process (Hosoya et al., 2008).

The initial stages of gasification are the same as the pyrolysis reactions which occur at increasing temperatures and include drying, depolymerisation, devolatilization and carbonization (see Table 2-2). Following this, gasification reactions take place in the presence of oxidising agents such as oxygen (O_2), air or steam. The volatiles and a portion of the biochar react with the controlled levels of oxidizing agent added to the reaction chamber to produce CO_2 and some CO. The CO is combusted to provide heat for the gasification reactions, whereas the char is reacted with steam to give carbon monoxide and hydrogen. The reversible water-gas shift reaction can reduce the CO content of the syngas, increasing H_2 content (Biomass Energy Centre, 2014a). Gasification can be classed as low temperature (~700 ^{o}C to 1000 ^{o}C) or high temperature (~1200 ^{o}C to 1600 ^{o}C) gasification. Syngas from low temperature gasification will have more hydrocarbon species present and can be burned directly or further processed to remove tars. Higher temperature syngas will have less hydrocarbon species and more hydrogen and carbon monoxide present. Further upgrading of the high temperature syngas, using the Fischer-Tropsch process can produce a synthetic diesel if the correct proportions of hydrogen to carbon monoxide are present (Biomass Energy Centre, 2014a).

The gasification of biomass, although optimized for syngas production, often yields small amounts of biochar, with yields reported in the region of 10 wt % from sugarcane bagasse, 10.9

wt % from mulberry stems, 12.8 wt % using cassava stems and 13.7 wt % using coconut shells (Rodriguez et al., 2009). 5 to 10 wt % yield of biochar from the gasification of switchgrass and corn stover was reported by Brewer et al. (2009). As with pyrolysis, the technology required for gasification can operate on a small scale or a large scale, ranging from cooking stoves to industrial scale bio-refineries (biochar.org, 2011).

2.2.2.2.3 Hydrothermal carbonization

Hydrothermal carbonization (HTC) is a process in which wet biomass is heated to between 170 and 250 ^{o}C, and subjected to increased pressure, in a closed chamber. The residence time of biomass within the chamber can range from hours to days. A number of conversion reactions take place during HTC, resulting a solid hydrochar, and process water containing nutrients and polar organics (Schneider et al., 2011). One of the main advantages of this process is that the biomass feedstock does not need to be dried before the subsequent carbonisation process, and is therefore particularly suitable for feedstocks with very high moisture content. Using this process, Schneider et al. (2011) produced a yield of 45 % biochar from bamboo biomass. Hydrochars produced by hydrothermal carbonization often have a high carbon content, but the recalcitrance of this carbon is often far lower than pyrolysis biochars (Schimmelpfennig and Glaser, 2012). Some studies have suggested hydrochars have an increased eco-toxicity when added soils due to adsorbed tars, for example Wagner and Kaupenjohann (2014) found that plant biomass growth was reduced in soils which had been amended with hydrochars.

2.2.2.2.4 Traditional carbonisation methods

Carbonisation is a general term used for a number of pyrolysis processes which resemble traditional charcoal manufacturing methods. Auto-thermal carbonisation is a group of simple processes used for small scale charcoal production and is widely used in rural communities. Kilns for charcoal production may be made from materials such as tin drums, concrete pipes or bricks, which provide an affordable, simple method of charcoal production (Okimori et al., 2003). Kilns designed in this way usually admit a small amount of oxygen to the process, in order to burn some of the biomass to supply the required process heat, therefore may more closely resemble a gasification process than pyrolysis (Brown, 2009). Yields of biochar produced using traditional kiln methods with forestry waste feedstock were found to typically produce 24 % biochar with a 76 % carbon content at 400 - 500 ^{o}C and 28 % char with 89 % carbon content at 600^{o}C (Okimori et al., 2003).

2.2.3 Characteristics of biochar

Biochar characteristics can vary greatly and are affected by both the feedstock used and the process conditions. Within the literature there are still a number of uncertainties in the properties of biochar, the causal factors of some biochar properties, and also in the effects of biochar application to soil. Further research to examine these biochar characteristics and the effects of biochar application to soil is pivotal to assessing how much CO_2 could be removed from the atmosphere and stored using biochar systems. Sections 2.2.3 to 2.2.5 discuss the characteristics of biochars, the effects of biochar addition to soil and the potential feedback effects within the carbon cycle that may be seen from this addition. As pyrolysis is the main method currently used for biochar production the characteristics of biochars from pyrolysis are the main focus here, some notable effects on biochar characteristics and effects caused by other production processes are discussed where relevant.

2.2.3.1 Biochar properties

Different feedstocks and pyrolysis processes lead to different characteristics in biochars, such as yield, carbon content, elemental composition, structure, surface area, porosity and pore volume, pH and calorific value. Both the physical and chemical characteristics of biochars may be important depending on the end use of the biochar. Physical properties are discussed in Section 2.2.3.1.1 and chemical properties are discussed in Section 2.2.3.1.2.

A number of biochar properties can potentially be used to classify biochars including pH, volatile content, ash content, water holding capacity, density, pore volume and specific surface area (Kuwagaki and Tamura, 1990). Efforts to design a biochar classification system have been undertaken by a number of groups in order to enable biochar systems to be considered for large scale agronomic and carbon storage purposes. These classification systems are discussed further in Section 2.2.7. Chapters 3 and 4 further explore the production of, and variability in, biochars from different feedstocks and slow pyrolysis conditions through experimental research.

2.2.3.1.1 Physical characteristics of biochar

Biochar yield is influenced by the feedstock characteristics, with high lignin feedstocks producing higher biochar yields due to the increased thermal stability of lignin in comparison to hemicellulose and cellulose (Brown, 2009, Sohi et al., 2010). The physical characteristics of biochars are important as when biochar is added to soils, they may affect the soil properties such as soil structure, water holding capacity and also the microbial communities present in the soil. Characteristics such as the biochar structure, pore volume, surface area and water holding capacity can be affected by both the feedstock properties and pyrolysis conditions. The chemical transformations that occur during biochar formation occur along a temperature gradient, where biomass is converted to partly charred matter, biochar and then soot (Table 2-2).

Biochar structure tends to be more stable than the structure of its feedstock. During the pyrolysis process some restructuring of the elemental composition occurs, generally reducing the ratios of hydrogen (H) to carbon (C) (H/C) and oxygen (O) to carbon (O/C) highlighting increased aromaticity. This aromatic structure indicates an increased stability in structure (Downie et al., 2009). The research of Peng et al. (2011) found that both H/C and O/C ratios decrease with increasing pyrolysis temperature, indicating an increase in aromatic structure and a related increase in structural stability with increasing temperature (University of East Anglia, 2011). The composition and structure of biochar and other products may have been found to change with pyrolysis conditions such as heating rate and residence time (Asadullah et al., 2010, Peng et al., 2011). Research by Asadullah et al. (2010) discusses the effect of heating rate on yield composition, finding that higher pyrolysis heating rates typically yield more volatiles than lower heating rates. Williams and Besler (1996) examined the calorific value (CV) of biochar, finding that CV was not affected by the heating rate of the pyrolysis process. The average CV for biochar in the study was 32 MJ kg^{-1}. A number of studies within the literature discuss an increase in both fixed carbon and corresponding calorific value with increased peak pyrolysis temperature (Demirbas, 2004a, Peters, 2011). Surface area of biochars is influenced by both both feedstock and process conditions. Surface area is generally increased, from that of the feedstock, during pyrolysis with tars being removed and increasing porosity. Graber et al. (2012) reported a range of specific surface areas for biochars, from 3.6 m^2 g^{-1} up to 242 m^2 g^{-1}. The initial feedstock structure (i.e. cellular and capillary structure of biomass) is often retained in the resulting biochar, with a high surface area feedstock typically producing a high surface area biochar. Process conditions also influence biochar surface area, with surface area generally increasing with temperature (Downie et al., 2009). Maximum biochar surface areas were identified by Uchimiya et al. (2011) at production temperatures between 500 ^oC and 900 ^oC. Further increases in surface area can be achieved by including a further activation process, for example steam activation, resulting in an activated carbon. At higher temperatures (~> 900 ^oC) pore structure may begin to break down resulting in reduced surface area.

Biochar may, when added to soils, alter the physical structure of the soil due to the biochars porosity and surface area characteristics. This can offer improved habitat to soil micro-organisms. Warnock et al. (2007) discuss that many species of bacteria and fungi may be protected from predators within the pore space of biochars. Microorganisms in soil perform a variety of functions relating to both soil properties and plant function. These functions include the decomposition of organic matter, nutrient cycling, removal of contaminants and the increase and decrease of greenhouse gas emissions from soil. The surface area and porosity characteristics of biochars can also make them useful adsorbents, where they can be used to immobilize chemicals and toxins whilst also potentially preventing the leaching of nutrients from soil thus increasing nutrient availability to plants (Warnock et al., 2007, Zheng et al., 2010). This could also, in some circumstances, be a detrimental feature as toxins and undesired species could accumulate in soils due to their immobilization by biochar. Herbicides can also, in some cases, be rendered ineffective by their adsorption to biochars (Graber et al., 2012). Biochar colour is another physical property which could be of potential import when added to soils. Biochar is typically a very dark coloured material which has the potential to modify the land surface colour if added to soils in large quantities and where vegetation cover is not constant. A number of studies have begun to examine the potential albedo effect of biochar. Meyer et al. (2012) determined a reduction of 13 – 22 % in the overall climate mitigation potential of a biochar system where albedo is incorporated into the calculation. Genesio et al. (2012) determined a reduction in surface albedo of 20 – 26 % when biochar from durum wheat was added to soils. They determined that a large decrease in this effect was seen in year 2 after application.

2.2.3.1.2 Chemical and nutrient characteristics of biochar

A number of biochar characteristics are chemical in nature, including the biochar composition, pH, calorific value and effect on soil nutrients. The chemical composition of biochars is dependent on the feedstock material and also process conditions (Krull et al., 2009). Sohi et al. (2009) discuss that the elemental composition of the feedstock has a large influence on the composition of the resulting biochar. Biochar elemental composition is also affected by pyrolysis conditions. Krull et al. (2009) discuss that one common feature of biochars produced at different temperatures is a high aromatic carbon content, but that composition and the uniformity of the biochar structure can vary greatly with process conditions.

Ultimate analysis of biochars gives information about the C, H, N, S and O content of biochars. From this, the ratio of hydrogen to carbon (H/C) and oxygen to carbon (O/C) is often calculated to give an indication of the aromaticity present. H/C and O/C ratios tend to decrease with increasing process temperature and increased periods of heating, resulting in a more aromatic structure. A literature review by Downie et al. (2009) of H/C and O/C ratios between various biomass feedstock and biochars detailed increasing aromaticity during biochar production.

The yield of carbon in biochar is affected by both feedstock composition and pyrolysis conditions. With relation to feedstock effects, carbon yield is related to the concentration of carbon in the feedstock and also the ash content. Feedstock with lower ash content tends to have higher biochar carbon content. Increasing pyrolysis temperature also increases carbon content, for example Tanaka (1963) saw a reduction in biochar yield of 41 wt % whilst carbon content was increased by 37 wt % when peak pyrolysis temperature was increased from 300 ^{o}C to 800 ^{o}C. Sohi et al. (2009) note that, generally, the carbon content of a biochar is inversely related to the biochar yield.

Biochar is also known within the literature for providing nutrient benefits to plants (Sohi et al., 2009, Yin Chan and Zhihong, 2009). These effects may be either through the direct supply of nutrients or via indirect attraction of nutrients and retention on the biochar surface resulting in reduced fertilizer loss. Chan and Xu (2009) discuss that nutrient content of biochars can be highly variable, reporting concentrations of total nitrogen (N) of 1.8 g kg^{-1} to 56.4 g kg^{-1}, total phosphorus (P) of 2.7 g kg^{-1} to 480 g kg^{-1} and total potassium (K) of 1.0 g kg^{-1} to 58 g kg^{-1}. Biochar nutrient concentrations are, again, dependent on both feedstock composition and process conditions. Different feedstocks naturally have large variation in nutrient concentrations, for example animal manures are high in total P and sewage sludge biochars tend to be high in total N. Although the total concentration of a nutrient may be high within a biochar, much of this content may be inaccessible to the plant. Potassium, an important macro-nutrient, has often been found to be in high plant available concentrations in biochars, resulting in increased uptake by plants after biochar addition to soils (Yin Chan and Zhihong, 2009). Chan and Xu (2009) analysed biochar content of both total and available P, finding a range of 0.2 to 73 g kg^{-1} total P and 15 to 11,600 mg kg^{-1} available P. The biochar with 0.2 g kg^{-1} total P had 15 mg kg^{-1} available P, and the biochar with 25.2 g kg^{-1} total P had 11,600 mg kg^{-1}, indicating that available P increases with total P, although the limited reporting of either total P and/or available P makes trend determination difficult.

Biochar has also been seen to improve plant nutrient uptake by increasing the cation exchange capacity (CEC) of soils, improving the nutrient retention capacity of the soil. The effects of process conditions on biochar nutrient properties have been seen, for example, to alter biochar surface charges through increased process temperature. This would affect the CEC of the biochar, having implications for its nutrient retention effectiveness (Yin Chan and Zhihong, 2009). Biochars may also contain heavy metal species, retaining heavy metal species if present in the feedstock, or may act as an adsorbent due to this CEC mechanism creating a build-up of heavy metals in soils. This may cause toxicity to soils and plants if the biochar is added to soils, depending on the metal species and concentration. The risk of heavy metal presence in biochars is increased by using feedstocks, such as sewage sludge or painted wood, which may be contaminated. Conversely, evidence shows that biochar added to contaminated soil may immobilize heavy metals and other toxins therefore being a potential substrate for soil remediation (Afionis, 2011). Biochars may also act as a carrier to provide nutrients to plants, after being added onto the biochar through a separate process.

Other indirect nutrient effects, relating to changes in soil structure and function, involve the removal of constraints to plant growth by mechanisms such as improving water holding capacity and increasing soil pH. Biochar pH has been linked to increased plant growth due to the increase or maintenance of soil pH levels (Hoshi, 2001, Van Zweiten et al., 2007, Yin Chan and Zhihong, 2009). Alkaline biochars have the potential to buffer excess soil acidity. Application of biochar to soil has been found to have an overall liming effect, increasing soil pH (Biederman and Harpole, 2013), although knowledge of the initial pH of both biochar and soil is necessary to amend soil pH using biochar. The liming effect of adding alkaline biochars to soils can help to raise pH and overcome potentially toxic effects of acidic soils on plants. The addition of alkaline biochars to neutral or already alkaline soil may have a negative effect by suppressing nutrient availability to plants (Yin Chan and Zhihong, 2009). Increasing the pH of acidic soils has been seen to increase microbial activity, increasing soil organic matter mineralization and increasing nutrient availability to plants. This may, in some circumstances, cause a priming effect resulting in the increased emission of CO_2 from soils and may also have only a short term effect on microbial activity (Sohi et al., 2009). Previous literature reports biochar pH values (without further processing of the chars) of between pH 4 and pH 12, with typical values being above pH 7. Zhao et al. (2013) determined a biochar pH range of between 8.8 and 10.8, dependent on feedstock type. They also reported that the pH of biochars increases with increasing pyrolysis temperature due to the enrichment of ash as the temperature increases.

With regards to carbon storage, the variability of biochar properties has implications for estimating the amount of carbon that could be stored using biochar systems, and also for the accounting and monitoring systems that would be necessary to validate incentives for carbon storage using biochar, such as carbon credits traded within either the compliance market, for example Certified Emissions Reductions (CERs) or within the voluntary market, for example to

Verified Carbon Standard (VCS) credit) (see Section 2.2.7.2 for further discussion of biochar in carbon credit schemes). Sohi et al. (2009) discuss that the biogeochemical characterisation of biochar, alongside techniques to measure and track biochar in soil, will be necessary to enable large scale application and use, and to develop economic incentives such as incorporation into carbon trading schemes.

2.2.4 Biochar uses

The focus of biochar utilization within this study is for carbon sequestration. Financial or regulatory incentives for carbon removal and storage would help to drive scenarios where biochar is produced for carbon sequestration. Such incentives are currently limited by factors such as the need to develop accurate accounting methods for long term retention of biochar carbon in soils (see Section 2.2.7.2 for further discussion). Alongside CS and utilization as a soil improver there are a number of other commercial or theoretical uses and storage options for biochar. The suitability of biochars to be used, as produced or after upgrading, as an activated carbon or an adsorbent have been noted in the literature (Mohan et al., 2011). Utilization as an additive to construction materials has also been proposed (Okimori et al., 2003) and in some regions is current practice (Phonphuak and Thiansem, 2012). Biochar can be burnt to fuel the pyrolysis/gasification process or transported and used to fuel other processes (Williams, 2013). In future scenarios which are reliant on biofuels the use of biochar to fuel bio-oil and/or syngas production may be desirable. Biochar produced in excess of that which can be safely/technically applied to soils could be buried or stored (Shackley et al., 2010). Storing biochar, in disused mines for example, would allow the biochar to be utilized at a later date. This would add to the cost of the biochar system and is unlikely as no immediate economic benefit would be gained.

2.2.5 Biochar addition to soil

2.2.5.1 The effects of biochar in soil

Biochar, when added to soil, forms part of the soil organic carbon (SOC) pool. Soil organic carbon is the largest component of soil organic matter (SOM) and is mainly formed through the decomposition of plant and animal material, ranging from freshly deposited to highly decomposed material (Schumacher, 2002).

The addition of biochar to soils enables carbon from biomass to be stored in the soil carbon pool with more recalcitrance than carbon from un-charred material (see Sections 2.2.3.1.1 and 2.2.5.2 for further discussion of biochar stability). The biochar may also have a number of benefits to both soil quality and plant growth (Sohi et al., 2009). Adding biochar to soil can have co-benefits by improving soil quality by mechanisms such as improving microorganism habitat, improved nutrient retention and cycling, and increased water retention. A number of studies have suggested that these improvements in soil quality and function, as well as the potential improvement in efficiency of fertilizer use, may lead to some increase in crop yields (see Figure 2-5) (Atkinson et al., 2010 , Major et al., 2010, Van Zweiten et al., 2010). The variability of biochar properties, soil properties, environmental and climatic conditions, and plant requirements means that a uniform effect does not occur when biochar is added to soil.

Figure 2-5: Field trial where the effects of biochar on crop yield is tested. Crop yield is shown with no biochar (top left) and with high biochar content soil (top right). Soil profiles are also shown for each test plot with an untreated oxisol (bottom left), and Terra Preta de Indio soil (bottom right). The two samples were taken in close proximity in the Amazon Basin (Glaser et al., 2001, International Biochar Initiative, 2014).

As discussed further in Section 2.2.5.2, historical analogues for the addition of biochar to soil are seen in natural and anthropogenic additions of black carbon and biochar to soils. The Terra Preta anthrosols of the Amazon show increased fertility when compared with the fertility of surrounding untreated soils (Glaser et al., 2001). Characteristics of the Terra Preta soil are often higher SOM, phosphorus content, pH and CEC than surrounding soils. The Terra Preta soils can support a more diverse array of crop and plant variety and have also been seen to increase crop yield in some, but not all, studies (Cornell University, 2006). The Terra Preta analogue can only indicate the effects of charcoal addition to soils. The production methods of Terra Preta soils are somewhat unknown, with a number of theories about their formation, but conclusive evidence is lacking. Research suggests that other additives, such as mineral residues and decomposed organic material, were often used alongside biochar to supplement soils (Woods, 2003). The original soil type and climatic conditions of the Terra Preta soils may have unique effects on the formation and evolution of Terra Preta soils, their effects on plant growth, and carbon storage potential. These effects may not be directly transferable to other soil types and climatic conditions.

Any differences in the effects of adding char to soils of different types and climatic conditions are currently not well researched and documented due to a limited number of studies undertaken, therefore transposing the available data to situations with different combinations of soil type, climate and biochar type is problematic and further studies to broaden this knowledge would be beneficial (Verheijen et al., 2010). A meta-analysis of current data by Verheijen et al. (2010) determined that there is an overall trend of increasing plant productivity with biochar addition, with the magnitude of this increase varying between soil and cultivar type, and with no impact or negative change seen in some cases. Acidic soils saw the greatest crop yield increase, potentially due to increase in soil pH from biochar addition, whilst a number of other soil types saw little or no increase. The meta-analysis showed a trend of increasing productivity as pH increased with biochar addition. This is described by Verheijen et al. (2010) as a possible liming effect. A liming value of approximately 30 % $CaCO_3$ was seen in a study where biochar produced from paper mill waste was added to soils by Van Zweiten (2012). This liming effect was attributed to Calcium mineral formation. The magnitude and longevity of this effect is currently unknown, and the effect of liming on alkaline soils may be detrimental to plant growth by increasing pH past the threshold for healthy plant growth. Further investigation into these effects could enable biochar addition to be targeted in areas where the greatest benefits would be seen, such as acidic soils or used with particular crop types and cultivars.

The removal of biomass for biochar production would mean that less SOC is formed through the natural decomposition of this biomass. The formation of SOC in this way is an important part of the carbon cycle and this reduction may have adverse effects that should be further identified before large scale residue removal should occur. The removal of plant material from soils may also remove nutrients that would otherwise have been returned to the soil through decomposition. As discussed by Lindstrom (1986), a conservative estimate of 70 % residue is required to remain in situ for soil health and nutrient recycling and has been applied here for these in-field residues. This is a highly generalised figure. Acceptable levels of biomass removal must be identified to ensure that enough biomass remains to add essential nutrients and SOC to the soil in a sustainable manner. Evidence from preliminary research has also shown that the addition of biochar to soils may lead to an increased rate of decomposition in existing soil organic matter (SOM), potentially affecting emissions of greenhouse gases such as CO_2 and N_2O from soils (Verheijen et al., 2010).

2.2.5.2 Lifetime of biochar carbon in soil

Biochar carbon is often more recalcitrant than that of un-charred biomass due to the more stable structure of the biochar in relation to that of the raw biomass (see Section 2.2.3.1.1). The charring process tends to increase the aromaticity of carbon in biochar, making it more resistant to degradation, with the extent of this being dependent on both feedstock composition and structure, and pyrolysis conditions (Downie et al., 2009). The stability of biochar is also dependent on external factors such as aggregation within soil, soil type and climate (Foereid et al., 2011). A number of mechanisms can remove or degrade biochars in soil. Abiotic and biological degradation play a large role in the degradation of biochar in soils, but this degradation is thought to occur at a far slower rate than degradation of non-charred material (Verheijen et al., 2010). Examples of abiotic degradation include chemical oxidation, photo-oxidation and solubilisation whilst biological degradation examples include microbial incorporation or the respiration of carbon by organisms (Zimmerman, 2010). Biochar can also be eroded and/or washed out of soils, where it would still have carbon sequestration potential but may not have soil improvement qualities. Figure 2-6 is an example of the remaining carbon from un-charred and charred biomass over a five year period.

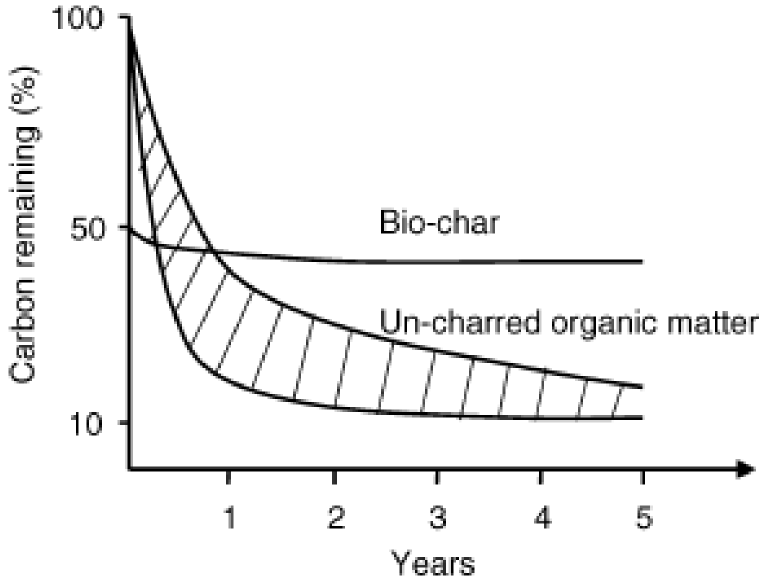

Figure 2-6: Example of typical biomass and biochar degradation. Figure shows the amount of carbon remaining, over time, in biochar and un-charred organic matter after addition to soil. The schematic is a generalisation of the recalcitrance of these materials, for illustrative purposes (Lehmann et al., 2006).

Although the un-charred biomass initially contains 100 % of the original biomass carbon remaining, compared with ~ 50 % for the biochar (with ~ 50 % lost as volatile and semi-volatile matter during the production process), the rate of decomposition of the biochar carbon is much slower than that of the un-charred biomass. Soil organic matter has a mean residence time of 50 years, whereas biochar may have a mean residence time of 1000+ years (Hammond et al., 2011). Much variation still exists in the estimates of biochar lifetime in soils within the literature. A number of studies have attempted to determine the longevity of biochars in soil, with particular focus on the lifetime of the biochar carbon. Determining these long timescales has obvious difficulties due to the long timeframes of any assessment period. A number of different methods have been applied to determine or estimate the longevity of biochar in soil using analogues, proxies, short scale laboratory tests, field experiments and modelling techniques (International Biochar Initiative, 2010). Due to the timescales required for long term carbon sequestration purposes it is not possible to undertake laboratory or field studies which span the full timescales considered. A standardised method of observing and accounting biochar ageing in soils does not yet exist and the difficulties in observing and simulating very long term changes has contributed to the uncertainties regarding the potential of biochar to sequester carbon in the long-term.

Historical analogues used to infer the lifetime of biochar carbon in soil include studies of soils where biochar has been added either anthropogenically or naturally in the past. This includes the study of the *Terra Preta de Indio* ('dark earth') soils of the Amazon and the *Terra Preta Australis* anthrosols of Australia (Glaser et al., 2001). These soils, having a very high carbon content compared to that of neighbouring soils, were anthropogenically altered by the addition of substances including biochar up to several thousand years ago. Carbon dating techniques have indicated that biochar in these soils may be stable for thousands of years (Kuzyakov et al., 2009). Amazonian Terra Preta soils have been dated to 6,850 years old (Acutuba, Brazil), 9,000 years old (Jaguariuna, Brazil), 1,775 ± 325 years old (Santarém, Brazil) and 740 to 2460 years old (Colombia and Venezuela respectively) (Appenzeller, 1998, Glaser et al., 2001, Lee et al., 2010, Saldarriaga and West, 1986). Australian Terra Preta soils contained biochar dated to around 650 and 1609 years old (Downie et al., 2011). The extrapolation of biochar lifetime in soils from research on the Terra Preta soils of South America and Australia, although useful, requires an air of caution. As the soils were often altered by the addition of other substances alongside the biochar addition, and soil and climate properties may influence the lifetime, these studies may not be representative of biochar addition to soils under different circumstances (Glaser et al., 2001). Natural historical analogues of biochar residues or 'black carbon' from forest fires have been found to date back 1000's to 10,000 years (Saldarriaga and West, 1986, Schmidt et al., 2002). Zimmerman (2010) calculated a lifetime of 266 to 1600 years, with 80 Gt of black carbon present in soils today and a rate of accumulation, from natural biomass burning events, of 0.05 to 0.3 GtC year^{-1}. This gives a half-life for black carbon from natural burning events of approximately 100 to 1000 years. (Zimmerman, 2010) also inferred from the amount of black carbon found in soils today, compared with that which should have been produced from natural burning events over time, that some losses of black carbon must be occurring.

As well as observing analogues for biochar degradation rates, researchers have also looked to simulate long term degradation over shorter time periods in laboratory incubation experiments and field experiments. Biochar degradation rates are often classified into two pools, looking at degradation of the labile (easily degraded) fraction and the recalcitrant (more stable) fraction separately (Foereid et al., 2011). The labile fraction of biochar will often degrade relatively quickly, giving an initial impression of fast decay. After this initial period the degradation of the recalcitrant fraction is thought to occur over much longer timescales (Cheng et al., 2008). Within the literature, short term degradation experiments have been used to determine the rates of decay for the labile and recalcitrant biochar fractions, which have then been used to project the lifetime of the biochar (Lehmann et al., 2009). A number of studies have carried out short term incubations at fixed temperature, in different mediums, to determine degradation rates. A range of results have been seen within the literature for these incubation tests. For example, one study by Hamer et al. (2004) saw 0.3 % and 0.8 % carbon loss for two biochars, which were produced at 800 ^oC and 350 ^oC respectively, over 60 days when incubated at 20 ^oC. Cheng et al. (2008) saw mineralization of 0.4 % of biochar carbon in a 50 day incubation experiment. Incubation for 48 days, of biochars pyrolysed at 350 ^oC and 400 ^oC, saw mineralization of 0.5 % to 4 % of biochar (Hilscher et al., 2009). Some longer term experiments have also been conducted, looking at the mineralization of biochar over periods of months to a few years. Although biochar properties due to feedstock characteristics cause variation in the effects of biochar in soils (see Section 2.2.3.1.1), it is discussed by Zimmerman (2010) that the conditions of pyrolysis are most important for the short term stability of biochar in soil. The study discussed that the rate of mineralization of biochar carbon slowed with increasing pyrolysis temperature. The carbon loss over 100 year period, extrapolated from the short term study, was 3 % to 26 %. The half-lives of the biochars assessed were determined to range from 10^2 to 10^7 years. Forestry experiments, where biochar was buried in porous bags, has also revealed large variation in carbon mineralization, from no mass loss to between 16 % and 51 % mass loss over ten years and two years respectively. Lehmann et al. (2009) discuss that these variations may be due, in large, to different analytical techniques as well as the inherent variation in biochars from different feedstocks and process conditions. This supports the theory that the labile fraction of biochar may decompose quickly, with degradation then slowing as the recalcitrant fraction remains (Lehmann et al., 2009). Harvey et al. (2012) used thermogravimetric analysis (TGA) to classify biochars by their stability in relation to that of graphite. They developed the R_{50} index which classifies biochars by the temperature of degradation, using the temperature at which 50 % of the biochar remains and the temperature at which 50 % of a graphite sample remains (see Section 3.2.3.4, Equation 3-1). Comparison of R_{50} values with carbon mineralization rates led Harvey et al. (2012) to classify biochars, by their degradation potential, into three classes: $R_{50} \geq 0.7$, most recalcitrant; $0.5 \leq R_{50} < 0.7$, minimal degradation; $R_{50} < 0.5$, more degradable. The R_{50} index does not give a quantity of carbon that will remain stable, or a timeframe for this stability. Further to the work by Harvey et al. (2012), the R_{50} index was used by Zhao et al. (2013) to develop a method of calculating the long-term carbon sequestration (CS) potential of a biochar (See Section 3.2.3.5, Equation 3-2). The CS potential equation determines the amount of carbon, from that of the original feedstock, which will remain stable for long time periods. The length of this storage period is not detailed in the literature regarding the CS potential, which is an area of potential further research.

Other methods of projecting the stability of biochar use modelling techniques, which may draw on data from the analogues and short-term studies discussed above. Efforts to model the lifetime of biochars in soils often use two mineralization rates, one for each of the labile and recalcitrant fractions. Woolf et al. (2010) used this two pool method to calculate the carbon storage potential of biochars, assuming a range of labile and recalcitrant fraction sizes and half-lives (See Section 7.2.2.3, Equation 7-4). This method enables a time frame to be determined for the carbon storage potential of the biochars. Further research to reduce the uncertainty of the size of the two pools, and rate of decay of each pool would improve the accuracy of prediction using this method. Cheng et al. (2008) discuss that stability of biochar in soils reduces as mean annual temperature increases. They calculated a half-life of 80 years for biochar incubated at the temperature and moisture contents optimum for promoting degradation. They propose, therefore, that degradation in the natural environment would be slower (estimated at half-life of 925 years with a mean annual temperature of 10^{o}C) than in their laboratory experiment, due to less than optimum conditions for degradation. Foereid et al. (2011), using a two-pool model to assess the lifetime of biochar in soils, determined that 9.8 %, 11.7% and 20.7 % of biochar would decompose within 2, 100 and 2000 years respectively. They also determined that 0.02 %, 0.13 % and 0.52 % would be lost due to movement down the soil profile and 49.1 %, 76.1 % and 74.8 % would be lost due to runoff over the same time periods (2, 100 and 2000 years). In total 58.9 %, 87.9 % and 96.0 % of biochar was degraded or removed from its position over 2, 100 and 2000 years respectively. These results highlight the importance of the erosion mechanisms in the lifetime of biochar. The method of application of biochar may also have a large impact on the rate of erosion from the point of deposition. The variation in biochar characteristics, combined with variation in soil types and climate makes the assessment of biochar carbon stability complex. Individual biochar systems could be assessed on a case to case basis, but for the purposes of large scale estimations of biochar stability and carbon storage some generalisations and assumptions about the characteristics of the biochars and the environment of biochar addition must be made.

2.2.5.3 Environmental impacts

2.2.5.3.1 Possible toxicity of biochars

There is some evidence that the type of feedstock or process type used for producing biochar can lead to toxins being present in the biochar and thus added to soils. Contaminants such as heavy metals that may be present in some feedstock types, such as some processed and waste feedstocks, may remain in the biochar upon conversion. There is also some evidence that some types and conditions of thermochemical process used for biochar production can lead to formation of toxic substances such as dioxins, furans and polyaromatic hydrocarbons (PAHs). PAHs are a range of organic compounds, of which a number are highly carcinogenic. Dioxins and furans can be present in soils, air and water. They can become concentrated along the food chain and may cause adverse health effects such as cancers and changes in hormone production in the body (DECC, 2011). Evidence of biochar toxicity in soils has been seen in some studies (Kookana et al., 2011). Freddo et al. (2012) studied the potential for toxic elements in biochars to exceed regulatory thresholds in soils and found that, for the biochars tested, levels were not likely to be exceeded with a biochar application rate of < 100 t ha^{-1}. Some studies also suggest that earthworm activity may be affected by the addition of biochar to soils, dependent on biochar type and application rate (Liesch et al., 2010). In a number of cases, earthworm activity has been seen to increase in biochar soils, but this is not true of all studies (Verheijen et al., 2010).

A number of standards for biochar classification have been developed by different biochar groups, including the Biochar Quality Mandate (BQM) of the British Biochar Foundation, the IBI Biochar Standards of the International Biochar Initiative and the European Biochar Certificate (EBC) of the European Biochar Foundation (British Biochar Foundation, 2013, European Biochar Foundation, 2013, International Biochar Initiative, 2012e). The guidelines developed for standardising biochar are often designed to ensure safe use of biochar, for example setting thresholds for permitted heavy metal contents. Guidance is given on suitable feedstocks, production methods and recording, and the laboratory testing of biochars. Biochar properties including the total and fixed carbon content, molar H/C and O/C ratios, volatile organic compound (VOC) content, major nutrient content (N, P, K, Mg and Ca), heavy metal content, pH, bulk density, moisture and ash content, and specific surface area must be reported and must adhere to the thresholds set for the biochar to gain certification. The requirements for assessment and reporting of positive biochar characteristics, such as nutrient content, are often optional, and where they are a requirement are generally specified as a declaration not within thresholds. Guidance is also set for when testing should occur.

2.2.5.3.2 Effects on emissions of greenhouse gas emissions

The addition of biochar to soils, as well as storing carbon away from the atmosphere, may affect emissions of CO_2 and other greenhouse gases (GHGs) from soils. Research is currently being undertaken to develop further understanding of the effects of biochar on direct emissions of GHGs such as methane (CH_4) and nitrous oxide (N_2O). Current research, although limited, has shown a reduction in emissions of N_2O from soils and an increase in CH_4 uptake by soils (Rondon et al., 2006, Yanai et al., 2007). Maximum emissions of N_2O were seen to decrease by 90 % compared to a control soil, in a seven day incubation study, and by 85 % when large amounts of biochar were added to soil by Yanai et al. (2007) Emissions of N_2O were reduced by between 21 % and 51 % following the addition of 40 t ha^{-1} wheat straw biochar to a rice paddy. Rondon et al. (2006) determined that biochar properties play a large role in the effects on emissions of N_2O, with high temperature biochars significantly reducing emissions of N_2O but low temperature biochars increasing N_2O emission by >100 % from that of the control soil. Proposed mechanisms for the reduction of N_2O emissions through biochar addition to soil include the reduction of anaerobic sites suitable for N_2O production through nitrification, changes in the de-nitrifier species composition and/or a reduction in N_2O from de-nitrification due to increases in soil pH (Van Zweiten et al., 2009).

Emissions of CH_4 from soils were found to be completely suppressed with applications of biochar produced from Calliandra, of the pea family, at 15 g kg^{-1} and 30 g kg^{-1} by Rondon et al. (2006). Conversely, Zhang et al. (2010) found that application of 40 t ha^{-1} wheat straw biochar to a rice paddy increased CH_4 emissions by 34 % to 41 %. Proposed mechanisms for the reduction of CH_4 emissions and potential increased uptake to soils are the reduction of anaerobic zones suitable for the production of CH_4 by methanogenic bacteria and the stimulation of CH_4 uptake into soils through physical soil changes.

The literature also highlights a potential for emissions reductions through the improved efficiency of fertilizer use when added with biochar. Gaunt and Lehmann (2008) discuss that the reduction in N_2O emissions often seen with the addition of biochar to soils indicates an increased efficiency of fertilizer use by plants. As discussed in Section 2.2.3.1.2, the improved efficiency of plant fertilizer use is related to the improvement of soil cation exchange capacity through biochar addition. Scenarios within their research explore 50 %, 10 % and 0 % reduction in fertilizer requirement to maintain current yields. Schulz and Glaser (2012) found a significant increase in plant growth when biochar and fertilizer where added together, when compared to the yield increases of fertilizer addition alone. This suggests a potential for indirect reductions in GHG emissions due to the potential increase in the efficiency of fertilizers with biochar addition, meaning less fertilizer addition may be required for plant growth. Less energy would therefore be needed for the production and transport of fertilizers. Emissions associated with these processes, and also with the application of fertilizer to soils, would be reduced if a reduced fertilizer application rate is required with biochar (Lehmann et al., 2009). This effect on fertilizer efficiency may also be a key economic benefit to the use of biochar as a soil additive.

2.2.5.3.3 Climate effects of biochar use

The previous discussion has detailed a number of possible effects on soils and vegetation that may result from the production of biochar and its addition to soils. These biochar systems, if large enough in scale, may have wider influence on the climate.

The introduction of large scale biochar systems could lead to either an increase or decrease in GHG concentrations, depending on the design and sustainability of the system, and this may affect the climate through changes in radiative forcing. The initial production of biochar would see a removal of CO_2 from the atmosphere through plant photosynthesis and the subsequent conversion of this plant biomass to biochar (see Figure 2-2). Without conversion to biochar much of the CO_2 would be released back into the atmosphere during plant respiration and decomposition, and so carbon storage in biochar results in a net removal from the atmosphere. Depending on the type of biochar system (i.e. slow pyrolysis, fast pyrolysis, gasification) some of the original biomass carbon will be stored temporarily in the bio-oil and syngas products and released back to the atmosphere upon combustion. Transportation of the biomass and/or biochar within the system will lead to some emission of CO_2 and other GHGs depending on the type and distance travelled from the source of biomass, and production and end use of biochar.

A number of possible indirect effects regarding the addition of biochar to soils have been discussed in the literature. The addition of biochar to soil is reported to result in increased biomass production, through increased crop yields or through the re-use of degraded or abandoned land (Sohi et al., 2009) If this were to occur, this would result in an increase in the net removal of CO_2 from the atmosphere. As discussed in Section 2.2.5.3.2, the literature also discusses the possible effects of biochar on direct emissions of GHGs from soils, such as CO_2, CH_4 and N_2O. These effects are not currently well understood. More research is needed on the effects of biochar on different soil and plant types growing under different conditions, to reduce uncertainty and to improve the generalizations required to make meaningful projections. As discussed in Section 2.2.5.3.2, the possible increased efficiency of nutrient uptake and reduced fertilizer loss with addition of biochar may result in reductions in emissions, for instance, of N_2O (Gaunt and Lehmann, 2008). Studies quantifying these effects are limited in number, with generalizations often required to incorporate these systems and processes into large scale studies.

One of the main benefits of biochar systems is the potential for them to be carbon negative, resulting in a net removal of CO_2 from the atmosphere. There are circumstances where the biochar system may not be carbon negative. This, for example, would be in cases where the carbon input (for example energy requirements for growing biomass, the pyrolysis process or to transport the biomass or biochar) to the system is larger than the amount of carbon sequestered by the system. Considerations made when designing a biochar system must include factors such as the energy intensity of feedstock production, of the pyrolysis system (including the amount and quality of oil and gas produced as fossil fuel offset), and the distance and mode of transport of both biomass and biochar. The energy demand of feedstock may not be a factor if the feedstock is a waste or residue product of a biomass grown for other purposes.

An example of biochar system assessments, where some systems have been carbon negative and others carbon positive, is the life cycle assessment study conducted by Roberts et al. (2010). The study showed occasions where the carbon balance of a switch grass biochar system was either carbon positive or negative depending on how land use was accounted in the study. As long as a biochar system has been properly designed by assessing the full life cycle of the process then it is feasible that the system can result in a net reduction in atmospheric CO_2 (Glaser et al., 2009). Figure 2-7 shows an overview of a biochar system, showing the different stages, inputs, processes and impacts on emissions involved. A number of different inputs and process scales can be applied, resulting in potentially very different impacts on the emissions balance of the system. This indicates that the net effect of biochar on atmospheric concentrations of greenhouses gases will, therefore, be dependent on a number of factors including the type and scale of system, the effects of biochar on crop yields and on soil and plant processes such as N_2O and CH_4 emission and fertilizer uptake efficiency. A further consideration of the impact on radiative forcing of biochar systems may be a decrease in surface albedo through the darkening of surfaces due the addition of biochar to soils (Meyer et al., 2012).

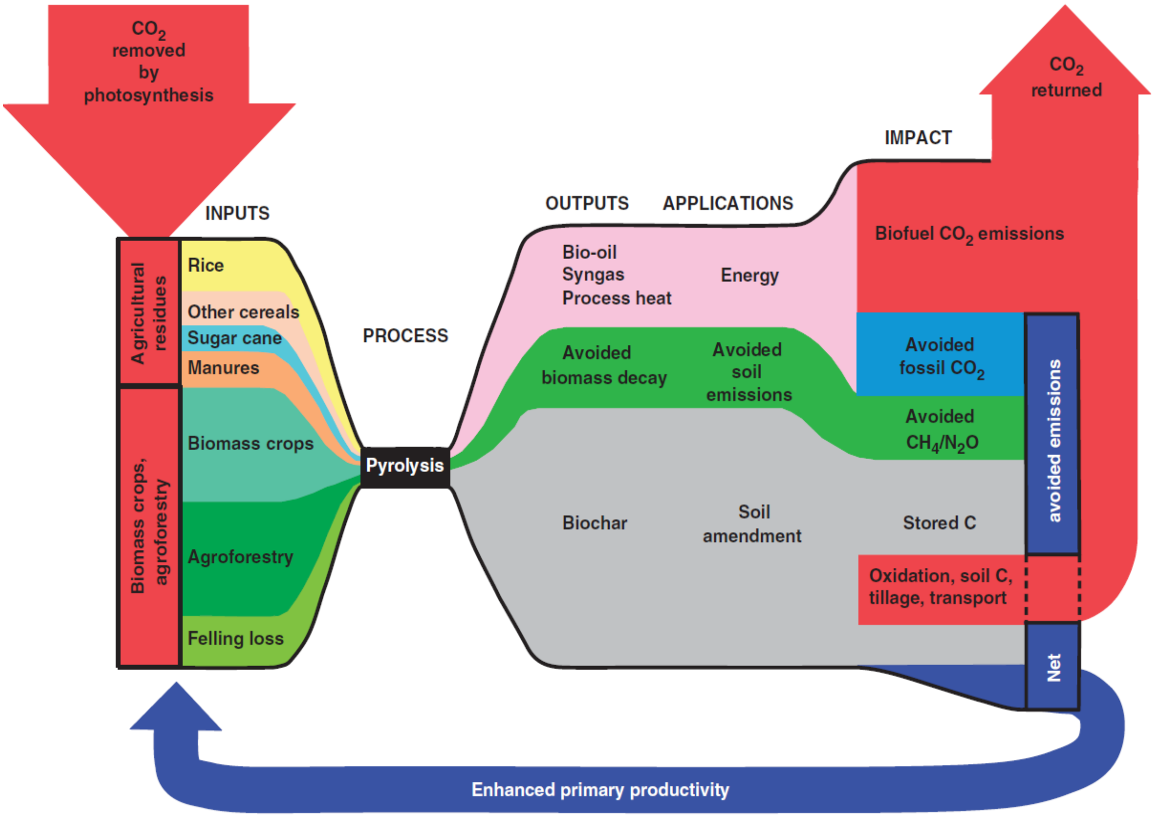

Figure 2-7: Overview of biochar carbon sequestration showing the process inputs and outputs. The schematic also shows possible factors within the biochar system which may affect climate, such as changes in emissions of GHGs including transport emissions, biofuel emissions, avoided fossil fuel emissions, and increased net primary production (NPP) (Woolf et al., 2010).

2.2.6 Sustainable biochar systems

The amount of carbon that can be sequestered by a biochar system is not the only consideration necessary for its design. The long-term sustainability of the system must also be considered in order to ensure no unforeseen damage to the environment, societal systems, or economic systems occur. Issues relating to the sustainability of the system that must be considered include the sustainability of the biochar feedstock supply, competition for land use, competition with food supply and the economic viability of the system (International Biochar Initiative, 2012a). Different scales of biochar system may encounter different sustainability issues, for example a large pyrolysis plant may be more energy efficient than a small or medium unit but may have a larger impact on the biomass resource, or larger emissions from transport demands than the smaller plants as the latter would tend to be located closer to the biomass supply and/or biochar distribution location. A number of the biochar guidance reports discuss issues of sustainability within the biochar system and hold this as a key assessment criterion (see Section 2.2.7.1).

A number of studies of biochar systems do not include traditional carbonization methods used currently in many developing nations to produce charcoal due to the emissions of black carbon and other pollutants to the atmosphere which are often associated with their operation. The development of sustainability criteria to introduce safer, cleaner small scale pyrolysis units in these areas could increase the potential of biochar to sequester carbon in a sustainable way on a more localized scale. This could be an important step towards sustainable development goals such as those in the Rio Declaration as it would also provide opportunities to increase food and energy security for those in developing nations whilst also potentially improving health through the improvement of localised air quality (United Nations Environment Programme, 1992).

2.2.7 Regulation of biochar production and deployment

2.2.7.1 Environmental and sustainability regulation

There are a number of regulatory considerations required when designing and operating a biochar system. Depending on the biochar feedstock and production method, and how current waste regulation is interpreted, biochar may be classified as a waste and regulated by legislation such as the European Union's (EU's) Waste Framework Directive (WFD) (Directive 2008/98/EC) (European Commission, 2011b). Also, the classification and regulation of biochar systems is important to ensure that they are operated in a sustainable manner. Regulation and monitoring is important to ensure that the feedstocks and processes used do not produce harmful toxins that may enter the soil or atmosphere. In order for the sequestration of carbon to be monitored, and perhaps incentivised, then further regulation and monitoring techniques need to be developed to allow this. Section 2.2.7, here, discusses the current regulation which may manage biochar systems, and then moves on to discuss gaps in regulation and how these could be approached as necessary.

Under current legislation, biochar from some systems may be classed as a waste product, and would therefore be subject to strict regulation on handling and disposal. This could inhibit the use of biochar from some systems as a soil amendment. If biochar is classed as a waste product then in would need to be managed in accordance with waste regulations such as the EU's WFD or the US's Resource Conservation or Recovery Act 1976 (RCRA) (Zhang, 2011). The wording of these legislations can be open to interpretation over whether biochar would, or would not, be classified as a waste. The EU has an inclusive list of wastes, listing those which are regulated, and the US has an exclusive list of wastes, listing substances which are not regulated. An example of how biochar may be classed as a waste under EU law is the inclusion of *'..wastes from incineration or from pyrolysis of wastes'*, which leaves the question of whether biochar is a waste product of pyrolysis. If pyrolysis is conducted for the production of biochar then it is not a waste, but pyrolysis for the production of energy would yield biochar as a waste product, and current pyrolysis systems operate mainly for the latter purpose. If biochar is classified as a waste product under these guidelines then further consideration is needed to determine whether biochar could, subsequently, be re-classified from a waste to a desired end product of the process. Van den bergh, (2009) suggests that four further questions must then be considered for this reclassification: Will biochar be commonly used for a specific purpose? Does a market exist for biochar? Does biochar conform to existing technical and legislative requirements? Would the addition of biochar to soil cause adverse environmental or health impacts? In many cases it seems that a case could be easily made for biochar as a viable product rather than a waste, but the variation seen between biochar systems, inputs and outputs would mean that detailed assessment of cases may be required. A biochar system using virgin biomass material, and where biochar is a main product should not encounter these difficulties. As biochar systems evolve, and if biochar is recognised as a product of pyrolysis and not a waste, these problems of waste regulation may recede.

Another consideration regarding biochar as a waste is whether certain biochars would be classed as hazardous wastes. Certain feedstocks or production conditions may lead to the presence of toxins within the biochar, which could pose issues for soil, water or air contamination upon application to soils (see Section 2.2.5.3.1). Any biochar containing toxic substances such as PAHs would be regulated under legislation such as the Hazardous Waste Directive (Directive 91/689/EEC) (European Commission, 2011b). As this is dependent on feedstock and process type the IBI propose standards for testing of biochars from pyrolysis plants on a basis of feedstock type, feedstock throughput volume and/or annual testing to ensure that safe levels are maintained (International Biochar Initiative, 2012e). Due to the scientific and regulatory barriers, biochar testing regimes and updated regulation would be needed if feedstocks such as municipal wastes or sewage sludge were to be used to create biochar for addition to soils due to the increased risk of contaminants entering the system. The regulation of sustainable feedstock supplies for each biochar system will depend on the type of feedstock used. Some mechanisms may currently allow for the regulation of sustainable use, for example, feedstocks from forestry waste may be regulated by guidelines such as the Forest Stewardship Council's standards for forest management (Forest Stewardship Council, 2014).

There are, to date, no legally binding environmental or sustainability regulations specifically for biochar systems. Examples of aspects of biochar systems which may be regulated by existing legislation are air and water quality requirements. The Sustainability Protocols designed by the US Biochar Initiative (2011) highlight a number of areas where existing regulation may be able to provide some guidance, discussing that biochar systems should adhere to the following principles:

> *'..biochar production does not contaminate water and utilizes water resources efficiently.'*
>
> *and*
>
> *'..biochar production and use improves air quality and does not lead to increased air pollution as compared to fossil fuels.'*

(US Biochar Initiative, 2011)

A number of environmental and sustainability principles may, therefore, be regulated by existing wider guidance and legislation at either national or international level. For example, water pollution is regulated nationally and multi-nationally in many regions, and air pollution is regulated both nationally and internationally through a number of mechanisms such as the UKs Clean Air Act (Crown, 1993), the Montreal Protocol (UNEP, 2012), the Kyoto Protocol (UNFCCC, 2012) and the Geneva Convention on Long-range Transboundary Air Pollution (LRTAP Convention) (United Nations Economic Commission for Europe, 1979). These regulatory systems may apply to different points of the biochar systems, with, for example, air quality regulation likely to apply to the biochar production process and water quality regulation more likely to apply to factors surrounding the addition of biochar to soils. Any potential environmental impacts of a proposed biochar system must be considered and necessary regulatory guidance taken into consideration.

As discussed above, a range of environmental and social aspects of biochar systems may be regulated by existing regulation. There may be regional issues where some nations do not have adequate regulation or enforcement procedures in place to ensure that biochar systems are conducted in a sustainable manner. Where national, rather than international, regulation will guide the biochar system there may also be some differences between these national guidelines leading to regional differences in standards for biochar systems.

2.2.7.2 Incorporation into carbon credit/reduction schemes

In order to optimise the viability of biochar systems, there is a need for mechanisms to support and incentivise these systems. There are three main options to develop the economic viability of these systems: compliance market carbon credits, voluntary market carbon credits or adding economic value through soil benefits. One example of this is inclusion into emissions reduction or carbon removal and storage mechanisms such as the United Nations Framework Convention on Climate Change's (UNFCCC's) Clean Development Mechanism (CDM). A number of nations have requested to the UNFCCC that biochar is included into such mechanisms to incentivise CO_2 removal and carbon storage. In order for biochar to be successfully incorporated into schemes such as carbon credit schemes there needs to be further development of the monitoring schemes and quantification techniques of biochar over time to determine how much carbon is being stored in each system. This would involve analysing the carbon content of biochars, monitoring rates and location of addition to soils, and further research into quantifying the lifetime of biochar carbon in soils. The variation seen in biochar characteristics from different feedstocks and processes also adds another layer of complexity to this. Such monitoring schemes could potentially incorporate quantification of emission reductions from reduced fertilizer requirements and soil greenhouse gas emission changes. Any fossil fuel offset achieved by the system could also be credited, along with the negative emissions from the photosynthetic removal of CO_2 from the atmosphere. These additions to carbon credit calculations would further incentivise the use of biochar systems. There remain a number of challenges to the development of the monitoring techniques necessary for a robust, accurate methodology to be installed. A 'sister' framework convention to the UNFCCC, the United Nations Convention to Combat Desertification (UNCCD), has set goals for the development of biochar technologies and stated its support for inclusion of biochar into future climate mitigation agreements. To reach these goals, the UNCCD recognises that classification of biochar within the UNFCCC's definitions such as additionality, permanence and leakage are necessary (International Biochar Initiative, 2012b, UNCCD, 2009). Determining the permanence of biochar carbon, when added to soils, involves a number of uncertainties and assumptions. The various methods currently used to determine the lifetime of biochar are discussed in Section 2.2.5.2. Calculations of the permanence of biochar under schemes such as the UNCCD would also require the determination of biochar lifetime under a changed climate, which is currently an area of scant literature. Determining the additionality of biochar systems, that is the extra impact the system has on carbon storage which would not have otherwise occurred, may also be very difficult to document. Steiner (2010) details that the addition of biochar to soils leads to the addition of carbon to the inactive carbon pool, rather than the active pool which is currently the main focus of similar projects (including afforestation and reforestation) for the UNCCD. He discussed, therefore, that these issues of addition, leakage and permanence may not be of such high priority.

The voluntary market currently includes schemes such as the Verified Carbon Standard (VCS) which has been developed by a number of partners including the World Economic Forum and The Climate Group (VCS, 2014). The VCS scheme allows businesses and schemes which are able to sequester carbon (which would not otherwise have been sequestered) to gain carbon credits for each tonne of carbon stored. These credits can then be sold to other businesses or interested parties who wish to reduce the carbon emissions footprint of their activities. These systems operate on a voluntary participation basis. A number of other voluntary trading schemes exist including the Gold Standard Voluntary Emission Reduction (VER) credits (Gold Standard, 2014). Currently methodologies for the assessment of biochar systems within voluntary carbon schemes are rare. The VCS and VER schemes detailed above do not yet have approved methodologies for biochar systems to be accountable. One example of a carbon reduction scheme which has incorporated a biochar methodology into its potential project portfolio is the Carbon Farming Initiative (CFI) in Australia (Australian Government, 2014).

2.3 Scenarios of future biochar production and use

2.3.1 Biomass potential

The biochar literature details a limited number of assessments which have been conducted into different aspects of biochar potential. These include assessing the sustainable availability of biomass to produce biochar, the carbon storage potential of biochar under particular economic and physical constraints and the comparison of biochar systems with other types of energy production scenario. The assessments of biomass availability range from a localised assessment of a particular project, to a large scale assessment of one or more biomass types regionally or globally. The assessments of the potential biomass resource can be allocated into two categories, demand driven and resource focused assessments. Demand driven assessments are used to estimate the amount of biomass that would be needed to fulfil a particular requirement, such as a biofuels obligation, or to analyse the competitiveness of different biomass based fuels or processes. Resource based studies focus on the available resource (Berndes et al., 2003, Ericsson and Nilsson, 2006). A review of studies of biomass potential, both demand driven and resource based, for the potential bio-energy production was undertaken by Berndes et al. (2003) and shows estimates ranging from 47 EJ yr^{-1} to 450 EJ yr^{-1}. Although these studies are focused on biomass for bio-energy, the methodology used is also applicable to biomass resource for biochar production. The literature study relates the large variation in estimates of biomass potential to differences in the methodologies and the assumptions made, including assumptions of land availability and crop yields.

Resource based methods will be the focus of further discussion here, as an assessment of the available crop residue resource for biochar production is a key aim of this study. An example of a small scale resource based study assessed the available biomass resource for a number of power plants in the Tennessee area of the US (Noon and Daly, 1996). The study used a Geographic Information System (GIS) platform to develop a map of the biomass resource available to the Tennessee plants. This GIS platform then provided economic data for biomass supply, related to factors such as the biomass type, location of source and end use of biomass and related infrastructure (e.g. transport). This kind of methodology would be useful to assess the feasibility of individual biochar projects or pyrolysis plants, with regard to factors such as sustainability and economic viability of supply. An example of using a global scale methodology to assess biomass resource would be to assess the available land that is, or could be, utilized for biomass production, and then applying biomass productivity for different biomass types relating to this available land area (Hoogwijk et al., 2009, Hoogwijk et al., 2005, Lehmann, 2007). This methodology has been used to estimate the current global biomass resource, and could also be used to project scenarios for the available biomass resource in the future. As discussed in Section 2.2.6, when assessing biomass potential, the criteria used must apply sustainability principles throughout biomass production and utilization (Rogulska and Kunikowski, 2006). This means finding a good balance between environmental, economic and societal issues, which in practice may be very difficult and is often ill-defined. In order to address these issues of sustainability within biochar scenarios, a number of factors should be considered when making assessments of available biomass. A key issue is that such an assessment must account for competition for the resource, such as for manufacturing, food production, bio-energy production, forestry and other land uses (De Meester et al., 2011). The level of inclusion and detail of these factors will affect the accuracy of biomass resource estimates (Berndes et al., 2003). Factors such as land area for production and distribution, crop yields and resource competition, particularly for future scenarios, are also often difficult to project and quantify. Assumptions and generalisations made regarding these parameters can add significant uncertainty to the projection and are often a main cause of differences between studies (Slade et al., 2011). Other variations between studies may arise from differences in the foci of the studies. Studies to assess the potential of biochar have often focused on one feedstock or one type of feedstocks (e.g. forestry waste), or a particular location, to make an assessment. This often makes the assessment more manageable, but comparability and transparency between studies is often difficult due to the different considerations within the studies. A number of previous studies began by assessing the full biomass resource, and then subsequently applying the limiting factors such as competition for the resource. Hoogwijk et al. (2005) made an assessment of the global biomass resource after identifying gaps and issues with previous assessments, which they attempted to address. They discussed that previous assessments had a mainly regional aggregation, which may have led to oversights in the spatial distribution of biomass. This could have had implications for the economic viability assessment of the biochar systems as a large proportion of the cost is often transportation costs (McCarl et al., 2009). Hoogwijk et al. (2005) also discussed that the inclusion of land use competition is an important factor in the assessment. The work used an assessment of land use scenarios (adapted from the IPCC SRES scenarios (IPCC, 2000)) to determine the geographical potential of the biomass resource globally. They use a method of 'five categories of potentials' to assess the availability of biomass (for bio-energy production) by including assumptions at different levels, including economic and social factors. The five categories of potentials used for the assessment were:

I. *The theoretical potential*

   This is the theoretical upper limit for total Net Primary Productivity (NPP) of biomass at the earth's surface produced by photosynthesis.

II. *The geographical potential*

   This is the potential land that is available for the production of biomass. A 'land claim exclusion factor' was applied at grid cell level to estimate the land that would be available for biomass production.

III. *The technical potential*

   The technical potential accounts for efficiency losses during the conversion of primary biomass to product (energy/stored carbon).

IV. *The economic potential*

   The economic potential assesses the technical potential that can be utilised whilst maintaining profitability.

V. *The implementation potential*

   The implementation potential uses the economic potential and applies factors to account for the timescale of implementation, for example incorporating governance barriers and incentives.

Making an assessment using all five levels of potential is a very detailed, lengthy task, but the number of steps included in an assessment could greatly influence the resulting amount of biomass predicted within the scenario. The Hoogwijk et al., (2005) study went to level 3, the technical potential.

Projecting biomass scenarios into the future is possible using the same methodology as the Hoogwijk et al. (2005) 'categories of potential' assessment, but complex and often uncertain factors such as the effects of future land use change and future policy implementation must be estimate and incorporated. An example of this is the Rogulska and Kunikowski (2006) study of EU energy crop potential to 2030. The study made assumptions about future environmental regulation and obligations, future market development and future regulation such as agricultural and renewable energy legislation. One of their main findings was that much of the land available for future bio-fuel production could come from a reform of the EUs Common Agricultural Policy (CAP) (European Commission, 2011a). The necessity for assumptions made during the scenario development make the research more a projection of a possible future that a prediction of the likelihood of a certain outcome. The inherent assumptions related to making future projections make producing projections of global resources difficult as socio-economics, regulation and environmental constraint will change both spatially and temporally. The further into the future the projection timescale, the more difficulty and uncertainty arises in projecting what changes will take place.

2.3.2 Estimation of carbon storage/emissions reductions through biochar use

Estimations have been made within the literature, using various methodologies, for the potential of biochar to reduce emissions of CO_2 and other GHGs. The research which, using resource based approaches, provides projections of emissions reductions using biochar systems and shows a great deal of variation in results dependent on the methodology, assumptions and uncertainties of each assessment.

One assessment, which focussed on the sustainability of biochar systems and accounted issues such as food security and soil conservation, estimated a maximum total net emissions reduction of 1.8 Pg CO_2-C_e yr^{-1} and a 130 Pg CO_2-C_e over 100 years. The study included emissions of CO_2, CH_4 and N_2O, was global in scale and included a number of feedback affects in the analysis (Woolf et al., 2010). The research involved the development of an assessment framework incorporating the effects of a number of processes, but did not include factors such as biochar under future climate change, land use change, technological development or population changes. A study of biochar potential by Lehmann et al. (2006) included the potential of biochar to sequester carbon from charcoal production wastes, bio-fuel production, agricultural wastes, forestry croppings and alterations to current shifting cultivation practices. They calculated that

0.56 Pg C yr^{-1} could be produced from these feedstocks currently, with 0.16 Pg C yr^{-1} current storage potential from agricultural waste biochars. The agricultural feedstocks considered are forest and mill residues, rice husks, groundnut shells, and urban waste (i.e. garden wastes). A number of crop residues are not considered within the study due to them being deemed as unsuitable for biochar production due to lower lignin content. Exceptions to this are rice husks, sugarcane bagasse and nut shells. Experimental research undertaken for this study and detailed in Chapter 6 discusses how many of the excluded crop wastes are in fact suitable for biochar production, storing a similar amount of carbon, and having a similar recalcitrance in soils, to rice husk biochar. The projections by Lehmann et al. (2006) also look at conversion of current biofuel production to pyrolysis systems, with biochar as a by-product which they projected could sequester 0.18 Pg C yr^{-1}. This could increase to between 5.5 and 9.5 Pg C yr^{-1} if biofuel production, up to the year 2100, is met using pyrolysis (using biofuel projections from literature). With regards to the rate of addition of biochar to soils the research estimates that sequestering 140 Mg C ha^{-1} in the 1,600 Mha of global cropland would achieve 224 Pg C stored, and 175 Pg C could be stored in the 1,250 M ha of temperate grassland available. The rate of application is discussed by Lehmann et al (2006) as a very high application rate, but one which has not seen detrimental effects on soil and plant health in their experimentation. They highlight that some studies within the literature have seen detrimental effects at lower rates of application. The Lehmann et al. (2006) study has also come under some scrutiny, for example by Paul et al. (2009), for the large amount of land use change which is assumed within the scenarios, as incentives which promote land-use change from food production to biofuels production may impact on the long-term sustainability of food production and the integrity of vital ecosystems within the scenario. Another biochar study by Matovic (2011) projected that the conversion of 10 % of global net primary productivity (NPP) to biochar, with 50 % biochar yield and 30 % oil and gas yield for energy use, would sequester 4.8 Pg C yr^{-1}. The 50 % assumption of biochar yield may be an overestimation of potential biochar yields on such a scale. Biochar yields from within the literature from experimental data are discussed further in Sections 2.2.3 and 4.3.1 respectively. The study by Matovic (2011) also does not include estimations of feedback effects such as potential increases in NPP or reduced fertilizer requirements. Lenton and Vaughan (2009) used the radiative forcing change relating to the reduction in atmospheric CO_2 to calculate the climate cooling potential of a number of different methods of climate engineering. They discuss biochar production potential from a number of different studies, including a projection of 15 Pg C storage potential by 2035, increasing to 52 Pg C by 2060 from an unpublished study by Reid (2009), discussed in the published work of Reid (2008). The Reid

(2008) study does not focus on the use of crop residues, as is the main focus of the research detailed in Chapters 3 to 8 here, instead assessing the potential of producing biochar from dedicated timber/bio-energy plantations, mostly on non-arable land. Lenton and Vaughan (2009) use the values from the Reid and Parshotam (2008) study to calculate a C removal from the atmosphere of 11 Pg C in 2030 and 31 Pg C in 2060. The quantity of atmospheric carbon removed is lower, in comparison to the carbon stored in the biochar, due to the reaction of the other land and ocean sinks which may respond by releasing larger amounts of CO_2 into the atmosphere. They discuss that, for small removals of atmospheric CO_2, 92 % would be still be removed after 1 year, 64 % after 10 years, and 34 % would still be removed from the atmosphere after 100 years. Lenton and Vaughan (2009) summarised that the long term global carbon storage capacity of cropland, using biochar, is 224 Pg C, and of temperate grasslands is 175 Pg C. This carbon storage would result in a reduction in atmospheric CO_2 of 34 ppm resulting in a radiative forcing of -0.52 W m^{-2}. This projection assumes that the biochar carbon stocks stored in soils is replenished as it decays.

On a UK scale, Shackley et al. (2010), using life cycle assessment (LCA) methodology, concluded that available virgin biomass in the UK could abate between 3.59 - 11.15 Mt CO_2eq yr^{-1} (between 0.00359-0.01115Pg CO_2eq yr^{-1}). The scope of an LCA is defined as ensuring;

> *'..that all environmental burdens connected with a product or service have to be assessed, back to the raw materials and down to waste removal.'*
>
> (Kloppfer, 1997)

LCAs are very specific to the product or service assessed and highly sensitive to the parameters chosen. Changes in the depth and/or breadth of the assessment parameters can alter the results dramatically. The UK Biochar Research Centre (UKBRC) conducted LCAs of a number of scenarios of biochar production from various feedstocks, incorporating factors such as the energy requirements of feedstock production and transport and looking at both 'large' and 'small' scale production (Shackley et al., 2010).

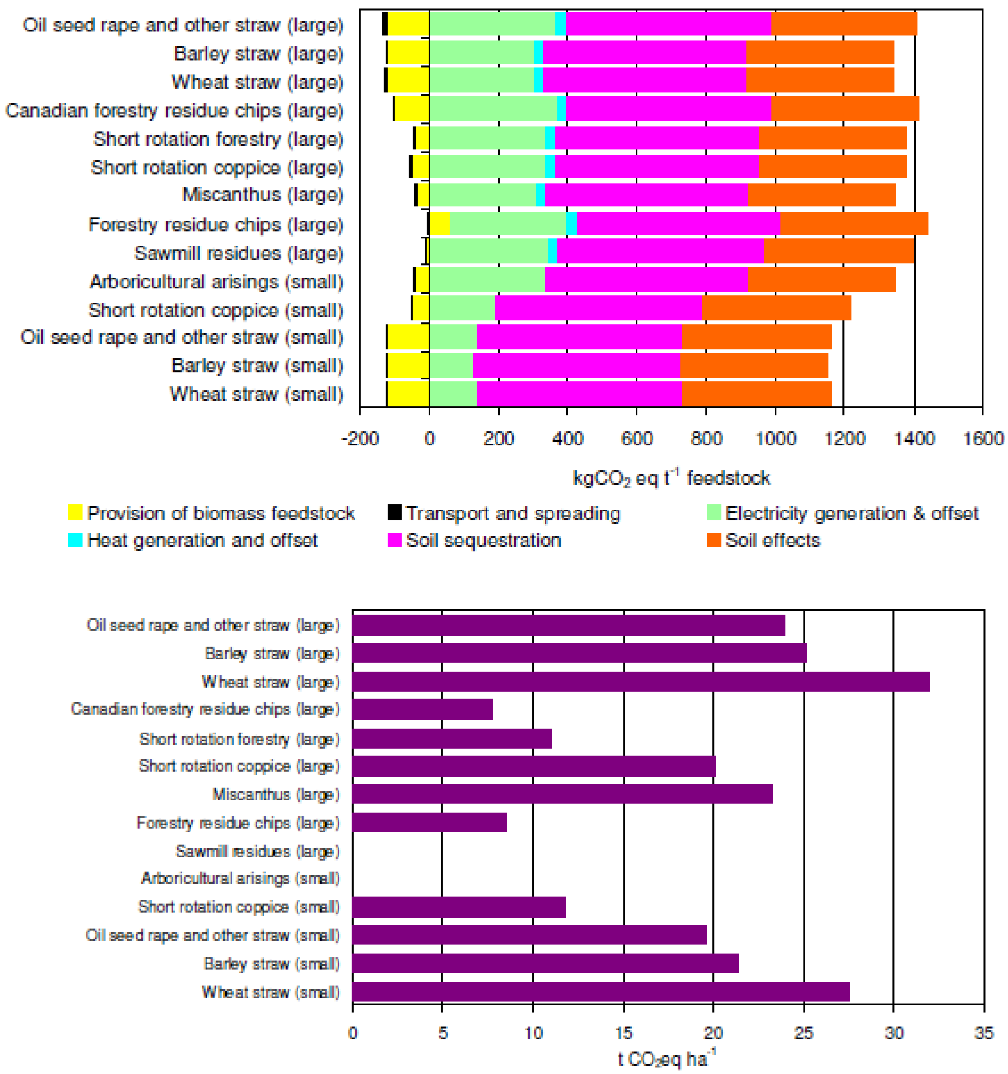

Figure 2-8: Life cycle assessment for carbon abatement of a number of biomass systems. Top panel shows the abatement potential (kg CO_2 eq) per tonne of feedstock. Bottom panel shows Life cycle assessment of carbon abatement (t CO_2 eq) per hectare. 'Large' and 'small' relates to large and small scale production facilities respectively (Shackley et al., 2010).

The study assessed a number of feedstocks and estimated that approximately 7 – 30 t CO_2eq ha^{-1} yr^{-1} could be abated using biochar systems. Brownsort (2009) concluded that within the LCA analysis, the largest portion of the carbon abatement was achieved through the storage of carbon in soils through biochar addition. Other relatively large abatement factors were the indirect effects of biochar addition to soil, for instance reduced GHG emissions from soil, and the offset of fossil fuel emissions (Hammond et al., 2011). A similar LCA conducted for biochar produced from corn stover, yard waste and switch grass determined a carbon abatement of 864 kg CO_2 eq t^{-1} and 885 kg CO_2 eq t^{-1} for corn stover and yard waste respectively (Roberts et al., 2010). Adverse carbon abatement potential, where CO_2 emissions were increased due to the system, was found in some cases for the switch grass biochar system depending on the methods of accounting used for land use change. The assessment of carbon abatement by hectare by Shackley et al. (2010) (see Figure 2-8 (bottom)) shows that even under the LCA assumptions of one study there can be large variation (~ 30 t CO_2 eq ha^{-1}) between the carbon abatement potential of biochar systems using different feedstocks and processes. Shackley et al. (2010) also conducted an assessment of potential carbon abatement from biochar production of non-virgin biomass feedstocks (see Figure 2-9). The assessment resulted in estimates of abatement potential of between 300 kg CO_2eq per tonne of feedstock and over 1700 kg CO_2eq per tonne of feedstock, dependent on feedstock choice. The abatement potentials calculated for garden and green waste, food waste and wood waste are higher than the estimates for virgin biomass.

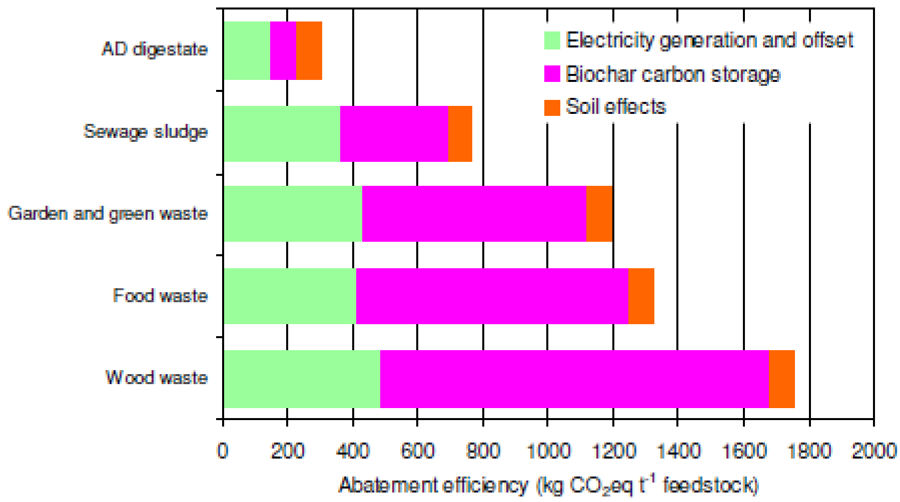

Figure 2-9: Carbon abatement efficiency of waste biomass feedstocks as calculated using LCA (Shackley et al., 2010).

The scenario uncertainties, which are dependent on feedstock and process type assumptions amongst other factors, are increased for the non-virgin biomass. The LCAs carried out in the Shackley et al. (2010) study were designed with a focus on carbon abatement potential of systems within the UK and therefore have assumptions such as production type, transport methods, available biomass types and quantities, and types of energy to be offset which may not be applicable to other systems internationally. The carbon abatement values discussed by Roberts et al. (2010) are lower than those of Shackley et al. (2010). This is likely to be due to differences in the accounting methods and assumptions made within the development of each LCA. This highlights that LCA analysis is difficult, if not often impossible, to apply to other cases due to the very complex network and interactions of the system assumptions. The highly specific and sensitive nature of LCAs, to the assumptions made and parameters chosen, means that an LCA conducted for another area or system is likely to produce different results. However, the values in the two LCA studies indicate well the potential of individual scenarios to abate carbon emissions and the contributions of individual factors to the total abatement. They also help to give a general impression of how biochar may be used to abate CO_2 emissions.

2.4 Future projections of climate change

The climate modelling community have developed a number of projections of future climate change. These projections have, generally, improved over time as understanding of the climate system and drivers of climate change also improves. The IPCC have used a range of future scenarios in their previous assessments. In 2000 the IPCC published their Special Report in Emissions Scenarios (SRES) which detailed a number of future emissions pathways developed by the IPCC to guide future research and to assist in the harmonization of other research (IPCC, 2000). The SRES emissions pathways were used in the 2007 IPCC report to direct discussion of potential climate change (IPCC, 2007). The most recent IPCC report uses future emissions scenarios developed by modelling communities, including physical science and socio-economic groups, to assess potential future climate change. These scenarios are the Representative Concentration Pathways (RCPs).

2.4.1 The representative concentration pathways (RCPs)

The RCPs are four scenarios of future emissions, each resulting in a different radiative forcing change in 2100 (van Vuuren et al., 2011a). The four radiative forcing end-points explored are 2.6 W m^{-2}, 4.5 W m^{-2}, 6 W m^{-2} and 8.5 W m^{-2}, and the RCPs are named after their respective radiative forcing targets: RCP2.6; RCP4.5; RCP6; RCP8.5. Each RCP, designed by a different climate modelling group, aims to give one example of how the radiative forcing could be achieved in 2100. The radiative forcing levels covered by the four RCPs encompass the range seen within the climate change literature. Each pathway is designed around an underlying socio-economic scenario and comprises of datasets for the evolution of emissions of well-mixed greenhouse gases, other species important to radiative forcing, land-use changes, radiative forcing and atmospheric concentrations. The research detailed in Chapters 3 to 8 uses the land-use projections for each RCP to investigate how much biochar could be produced from crop residues within each scenario. Section 2.4.1 outlines the main assumptions of each RCP and Chapter 3 details how the assumptions of each RCP were used to develop the biochar pathways.

2.4.1.1 RCP 2.6

RCP 2.6 was designed by the IMAGE modelling team and is a 'peak and decline' scenario where radiative forcing peaks at around 3 W m^{-2} mid-century and then declines to the target of 2.6 W m^{-2} in 2100. It was designed to represent those scenarios within the literature which have very ambitious radiative forcing targets, as a representation of scenarios which aim to limit global mean temperature increase to 2 ^{o}C. Van Vuuren et al. (2011a) detailed that the scenario involves the reduction of cumulative emissions by 70 % from 2010 to 2100, and emissions reduction of 95 % by 2100 when compared to the 2100 emissions of the baseline scenario. The RCP 2.6 scenario relies heavily on bio-energy and reforestation to achieve these objectives. Emissions of CO_2 from the energy sector are negative by 2100, with the use of nuclear energy and renewable energy technologies (solar PV and wind) and carbon capture and storage on both fossil-fuel and biomass energy production. Emissions of CO_2 from land are increased, relative to the baseline, due to the large increases in biofuel production. Emissions of other species (e.g. N_2O, CH_4) mostly decrease in RCP 2.6, relative to the baseline, although within this some sectors where emissions reductions are difficult, see increases (e.g. livestock production).

The RCP scenario was developed using an integrated assessment model, from a baseline scenario of medium development (using population, income, energy and land use as indicators). Agricultural production within RCP2.6 is based on assumptions of demand and trade, then calculated using the input of production data taken from the Adapting Mosaic scenario of the Millennium Ecosystem Assessment (2005). The initial distribution of agricultural land is taken from the History Database of the Global Environment (HYDE) (Klein Goldewijk et al., 2011). The changing distribution of agricultural land is then calculated using data on agricultural productivity, proximity of existing agriculture, proximity to water sources and urban areas, and a random factor. Van Vuuren et al. (2011a) discuss that crop land for food production increases moderately to 2050, levelling off after this period. The increase in agricultural land projected for RCP 2.6, relative to the baseline scenario, is attributed to increased use of bio-energy and a reduced CO_2 fertilization effect. The increase in agricultural productivity projected is achieved mainly through increases in crop yields. Van Vuuren et al. (2011a) also note a shift in agricultural production from regions of high income to regions of low income, with biofuel production occurring near areas of current agricultural production and in particular in the regions abandoned in high income areas.

2.4.1.2 RCP 4.5

The RCP 4.5 scenario was developed by the Global Change Assessment Model (GCAM) group at the Joint Global Change Research Institute (2013) and details a pathway which reaches a radiative forcing of 4.5 W m^{-2} in 2080 which then remains constant to 2100. Thomson et al. (2011) discuss that this relates to atmospheric concentrations of approximately 650 ppm CO_2-equivalent, with 526 ppm atmospheric CO_2 in 2100, compared with 792 ppm CO_2 by 2100 in the reference scenario (Clarke et al., 2007). Descriptions of scenario development are detailed in Wise et al. (2009) and Thomson et al. (2011). Global greenhouse gas emission pricing is used within the scenario to prompt reductions in emissions, with agriculture and land-use emissions included in the system. The scenario assumes that efforts are made in unison, globally, to achieve emissions reductions through the pricing scheme. In terms of energy systems, the scenario sees deployment of carbon capture and storage (for both fossil and biofuels), as well as a general shift towards electricity and low emissions technologies for energy production as well as energy efficiency measures. Thomson et al. (2010) detail the changing use of land within RCP 4.5 across the period, with decreasing crop and pasture land and increasing biofuel and forest cover. A reduction in pasture land is seen within the scenario due to a shift away from beef consumption. Afforestation occurs due to the inclusion of carbon storage in land sinks, and of reduced emissions from land-use change, into the carbon pricing scheme.

2.4.1.3 RCP 6

RCP 6 reaches a radiative forcing of 6 W m^{-2} in 2100. The scenario, developed by the Asia-Pacific Integrated Model (AIM) team, includes a global market for emissions credits resulting in limits on emissions, achieving 13 GtC per year by the end of the century, with emissions peaking around 2060 and declining to 2100. The scenario is projected to reach atmospheric CO_2-equivalent concentrations of 855ppm. Cumulative CO_2 reductions are 463 GtC lower in RCP 6 than the reference scenario (Masui et al., 2011). No climate intervention policies are assumed in the reference scenario, which sees emissions increase to 27.7 GtC yr^{-1} and reaches a radiative forcing of 7.0 W m^{-2} in 2100 (Masui et al., 2011). The baseline scenario for RCP 6 is based upon the SRES B2 scenario which assumes intermediate levels of economic development and technological change (Nakicenovic et al., 2000). RCP 6 sees an increase in renewable energy production and in electricity use compared with other final energy types. A shift from coal to gas and nuclear power is also seen for electricity production. The use of non-fossil sources for electricity production and the increased use of carbon capture and storage see a decrease in CO_2 emissions from electricity generation from 2060 onwards. Crop land is seen to increase by 26 % over time due to increased demand for food and energy crops within the scenario (Masui et al., 2011).

2.4.1.4 RCP 8.5

RCP 8.5, reaching a radiative forcing of 8.5 W m^{-2} in 2100, was developed by the MESSAGE modelling team using the IIASA Integrated Modelling Framework (Riahi et al., 2011). This RCP is also used by modelling communities as the baseline climate scenario as it does not include any specific climate mitigation actions although some air pollutants are regulated for air quality rather than climate purposes. As such there is no baseline scenario to the RCP against which emissions reductions are made, as has been seen with the other RCPs. A number of the main drivers and assumptions for RCP 8.5 were derived from a revised version of the SRES A2 scenario, named the A2r scenario (Nakicenovic et al., 2000, Riahi et al., 2007). The main revision of the A2 scenario, to A2r, was the replacement of future demographic projections with more current data, including a decrease in projected population from 15 billion down to 12 billion in 2100. Riahi et al. (2011) discuss that, of the literature regarding business as usual scenarios, RCP 8.5 is a conservative projection of future development, with high population, low incomes and high energy demand. RCP 8.5 assumes some reduction in emissions intensity after 2030 due to the assumed link between welfare and environmental conditions, as shown with the Environmental Kuznets Curve theory (Riahi et al., 2011, Stern, 2004). Fossil fuels, predominantly coal, are the most economically viable and dominant energy source within the scenario, with unconventional fossil fuel sources also being utilised. The share of nuclear and hydro energy also increases towards the end of the scenario. Riahi et al. (2011) discuss that much of the potential for increased agricultural land exists in South America and Africa, with some other regions, notably Asia, seeing constraints in the amount of expansion possible. They project that agricultural land in developed nations will decline over the period, whilst net increases will be seen in the developing nations. Increased yields and intensification of agricultural production are projected to provide most of the increase in agricultural production, with crop land expansion making a smaller contribution.

2.4.2 Global mean temperature and the RCPs

Within the literature projections of changes in future temperature with climate change and the impacts of climate change on crops, within each of the RCPs and wider climate change scenarios, are determined using climate models and their associated inputs. Working Group I of the IPCC has collated and summarised current knowledge of the physical science of climate change, including projections of future temperature change under the RCP emissions scenarios (Collins et al., 2013, IPCC, 2013, Kirtman et al., 2013). There are many uncertainties and challenges involved in the projection of future climate, including natural variability, non-linear response to drivers, future emissions pathways (of the many species which can influence radiative forcing, for example of emissions of short lived pollutants such as sulphate, nitrate and black carbon aerosols and carbon monoxide (CO) and methane (CH_4)), and the climate response to these forcings. Despite these uncertainties, climate model projections are becoming more robust and are among the best indicators, currently, of the changes in climate which may manifest in the future due to anthropological emissions.

Near term projections of the 5 to 95 % range for changes in global mean surface air temperature for 2016-2035 (from the 1986-2005 reference period) are 0.47 ^{o}C to 1.0 ^{o}C using CMIP5 (climate model intercomparison project 5) projections (Kirtman et al., 2013). Kirtman et al. (2013) discuss that, between 2016 – 2035, global mean surface temperature is likely to be more than 1^{o}C above the 1850-1900 mean, but not likely to be more than 1.5^{o}C above this mean. Using the Allen, Stott and Kettleborough (ASK) method of weighting models in relation to their quality by considering the accuracy of previous model predictions to observations, the 5 % to 95 % range for the same period is 0.39 ^{o}C to 0.87 ^{o}C. The lower projections of the ASK method are mainly attributed to the weighting towards models which agree more closely with the temperature hiatus seen in recent observations (Kirtman et al., 2013). Collins et al. (2013) detail the longer term projections for changes in annual mean surface temperature which are summarised in **Table 2-3**.

Table 2-3: Projected changes in annual mean surface temperature (^{o}C) from the 1986-2005 reference period for the four RCPs in different spatial and temporal regions (global 2046-2065, global 2081-2100, land and tropics). Adapted from Table 12.2 in Collins et al. (2013). Values shown are the multi-model mean, ± 1 standard deviation and, in brackets, the 5 and 95 % ranges of the distribution.

		RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
		ΔT in ^{o}C			
Global	2046-2065	1.0±0.3(0.4,1.6)	1.4±0.3(0.9,2.0)	1.3±0.3(0.8,1.8)	2.0±0.4(1.4,2.6)
Global	2081-2100	1.0±0.4(0.3,1.7)	1.8±0.5(1.1,2.6)	2.2±0.5(1.4,3.1)	3.7±0.7(2.6,4.8)
Land	2081-2100	1.2±0.6(0.3,2.2)	2.4±0.6(1.3,3.4)	3.0±0.7(1.8,4.1)	4.8±0.9(3.4,6.2)
Tropics	2081-2100	0.9±0.3(0.3,1.4)	1.6±0.4(0.9,2.3)	2.0±0.4(1.3,2.7)	3.3±0.6(2.2,4.4)

2.4.3 Crop yield impacts of RCP projected climate change

As each RCP pathway would be expected to induce different levels of climate change, due to the different radiative forcings of each scenario, the changes in climate induced by each RCP would be expected to affect crop yields differently. A number, if not all, of the impacts of climate change may affect the potential for biochar production and subsequent carbon sequestration within the scenarios discussed in the previous sections. The impacts of climate change on crop yields and residue production is one of the main effects which may impact biochar potential within the scenarios, and may occur due to a number of climate impacts. Impacts may be due to changes in temperature, precipitation, extreme events such as drought or flooding, and other factors. For example, many plants and crops have thresholds for water and/or temperature stress for all or part of their development and maturation cycles, which, if not achieved or exceeded, may limit development of the crop (Porter et al., 2014). From this, it would be expected that crops growing within the RCP scenarios with higher projected global mean surface temperatures (e.g. RCP 8.5) may suffer more from temperature stress than those crops in scenarios of lower projected global mean temperature change (e.g. RCP 2.6). Countering this effect, to some extent, may be the influence of increased atmospheric CO_2 concentrations on crop yields, where some research has found increased crop yields with increased atmospheric CO_2 (Lobell and Field, 2008). RCP 2.6 has a lower atmospheric CO_2 concentration pathway than RCP 8.5, meaning that any increases in crop yield through the CO_2 fertilization effect are likely to be lower in RCP 2.6 than RCP 8.5. The results of studies into this CO_2 fertilization effect are highly variable. The CO_2 fertilization effect has often been found to be stronger in the C_3 crops, such as wheat, rice and cotton, than C_4 crops due to the increased responsiveness of the C_3 photosynthetic pathway to increased CO_2 concentrations (Leakey, 2009, Porter et al., 2014). Laboratory and enclosed CO_2 fertilization experiments often see greater increases in crop yields than open air experiments (termed Free Air Concentration Enrichment (FACE) studies), potentially due to a number of factors including temporal fluctuations in CO_2 or difficulty in controlling other experimental variables (Porter et al., 2014). Although high uncertainty exists around the potential effect of CO_2 fertilization on crop production, Lobell and Field (2008) determined an average effect on the C_3 crops rice, wheat and maize of 0.1 % yield increase for each 1 ppm CO_2 increase. Porter et al. (2014) summarise that, with CO_2 fertilization effects and without adaptation, negative impacts will be seen for all crop yields with a temperature increase above 3^{o}C. Projections of many climate change impacts in the near-term (to 2035) are very similar for the four RCPs. For this reason, the projections discussed within the literature mainly focus on the impacts of RCP 4.5 as this is an intermediate scenario (Kirtman et al., 2013). In the longer term the projected impacts become increasingly divergent, and so longer term projections discuss the RCPs separately (Collins et al., 2013).

A summary of the current literature regarding projections of the impacts of increasing temperatures on crop yields is detailed in the most recent IPCC Working Group II report (Porter et al., 2014). The report details projections, from a review of the available literature, of the impacts of temperature increases between 1 ^{o}C and 5 ^{o}C on three major crops: maize, wheat and rice. The projections include yield changes with and without adaptation for both tropical and temperate regions. The specific methods of adaptation are not discussed by Porter et al. (2014) in relation to the figure, but are described as methods of 'simple agronomic adaptation'.

Kyle et al. (2014) detailed the change in crop yield which may occur due to the temperature change projected for each RCP, relative to the projected change without temperature change, for corn, wheat, rice, fibre, sugar and bioenergy crops. The data in Kyle et al. (2014) is given for every tenth year from 2015 to 2095 for most species, both with no adaptation, and with some relocation of species to more suitable land as climate change progresses. The study uses the GCAM model, used for the development of RCP 4.5, and a crop growth model to assess the impacts of each RCP pathway on crops. They discuss that including the potential effects of climate change into assessment of the RCP could significantly change the evolution of the RCP pathways. The Kyle et al. (2014) study determined decadal average changes in crop yields for each RCP including climate change effects, relative to baseline crop yields. The baseline crop yield data, representing a 'present climate', was sourced from the FAO and so is compatible with the baseline data used in Scenario 1. The study summarised that climate impacts were, on average, negative for all crops except sugar and dedicated bioenergy crops. The lowest yields of cereals, including rice and wheat, were seen towards the end of the assessment period (2100) and under the highest emission scenarios. The study discussed that re-distribution of crop-types across available land would be likely to mitigate, to some extent, the reduction in crop yield from that expected with no change in crop distribution.

3 Characterisation of biochars from crop residues: Methodology

3.1 Introduction

Biochar characteristics including carbon content, surface area, ash content, nutrient content, pH and cation exchange capacity (CEC) vary due to both feedstock properties (Manya, 2012) and process conditions including temperature, residence time and pyrolysis atmosphere (Demirbas, 2004b, Zhao et al., 2013). The extent to which these factors influence biochar characteristics is not fully understood, with the drivers of variation in biochar characteristics requiring further investigation (Lehmann and Joseph, 2009).

The thermal decomposition of biomass into biochar can be achieved using a number of processes including (slow, intermediate or fast) pyrolysis, gasification, hydrothermal carbonisation (HTC), torrefaction and traditional carbonisation methods (Bridgwater, 2003) (see Section 2.2.2.2). Slow pyrolysis generally produces higher biochar yields relative to the other processes, and therefore is considered further here for biochar production. During pyrolysis the biomass feedstock is heated in the absence of oxygen so that full combustion does not occur. Volatiles and semi-volatiles are released from the biomass, as oil and gas products, leaving the biochar product (Antal, 2003).

Various feedstocks exist for biochar production including agricultural and forestry residues, municipal wastes, animal manures and purpose grown biomass. A number of factors such as desired biochar characteristics, sustainability requirements, possible toxicity effects and desired biochar end-use must be considered when determining the suitability of particular feedstocks (Joseph et al., 2009). One prominent focus for biochar use is the addition of biochar to soils, which may have both agronomic and climate change mitigation benefits, enabling the removal and storage of atmospheric carbon whilst potentially acting as a soil improver with benefits such as increased plant growth (Biederman and Harpole, 2013, Lehmann and Joseph, 2009, UK Biochar Research Centre, 2011).

Many of the investigations reported within the literature, for biochar production from the pyrolysis of biomass, have used uniform pyrolysis conditions and focus only on one or a small number of biomass types (Chan et al., 2008, Cheah et al., 2014, Das et al., 2008, Hossain et al., 2011, Kim et al., 2012, Peng et al., 2011). Production conditions and feedstock details are also often not reported fully. These factors often make comparison between biochar studies difficult. Improving knowledge of biochar characteristics and their relationship to feedstock characteristics and process conditions will enable further understanding of soils and vegetation effects, and of biochar for carbon sequestration. This study adds insight to the current biochar characterisation literature through documenting biochars produced from eight agricultural crop residues using a fixed-bed slow pyrolysis reactor, exploring the effects of feedstock characteristics on biochar yield and characteristics. The biochars were documented by yield, carbon content and recalcitrance, pH, nutrient content, surface area and porosity, elemental composition, moisture, ash, fixed carbon and volatile matter content, and calorific value. Sugarcane bagasse biochars produced under different pyrolysis temperatures and heating rates also gave insight into how the conditions of pyrolysis affect biochar characteristics. Yields and calorific values of oils and gases were also documented, alongside identification of individual gas species present.

3.2 Materials and methods

3.2.1 Feedstock selection

Agricultural crop residues are an often underutilized resource which, if large scale conversion to biochar and co-products was achieved, have the potential to offer both agronomic and carbon sequestration functions. Eight globally predominant agricultural residue types were selected for analysis using crop production quantities from the Food and Agriculture Organisation's (FAO) statistical database FAOSTAT (FAO, 2013a). Residue to product ratio (RPR) values, indicating the amount of residue produced alongside the commodity production detailed by the FAO data, were calculated from averages from literature (ARNAB, 1989, Lal, 2005, Penn State College of Agricultural Sciences, 2012, US National Research Council Board on Agriculture, 1983). Crops with high regional production quantities and high RPRs were chosen for analysis, the eight residues being: coconut fibre, coconut shell, cotton stalk, olive pomace, palm shell, rice husk, sugarcane bagasse, and wheat straw. Wheat straw and rice husk samples were sourced from fields in the Faisalabad District, Punjab province, Pakistan (31 21 N, 72 59 E), Sugarcane bagasse was sourced from Samundri, Pakistan (30 48 N, 71 52 E). Samples were transported in plastic bags and, on receipt, ground and sieved to 1.4 to 2.8 mm particle size. Coconut husk and shell, and palm kernel shells were sourced from the waste streams of coconut and palm kernel oil processing in the western region of Ghana. The coconut and palm kernel shells, as received, ranged from 3.35 to 10 mm particles. Cotton stalks were sourced from Northern Syria. Olive pomace was received in powdered form, with particle size < 2mm. All samples were stored in air tight containers after grinding, prior to pyrolysis.

3.2.2 Slow pyrolysis

A laboratory scale fixed-bed slow pyrolysis reactor was used to pyrolyse the feedstocks (Figure 3-1). The reactor, 250 mm in length by 30 mm internal diameter, was externally heated by a 1.2 kW tube furnace. The furnace was controlled to produce the desired heating rate, final temperature and residence time at peak temperature. A stainless steel crucible was used to hold 6 g of each biomass sample.

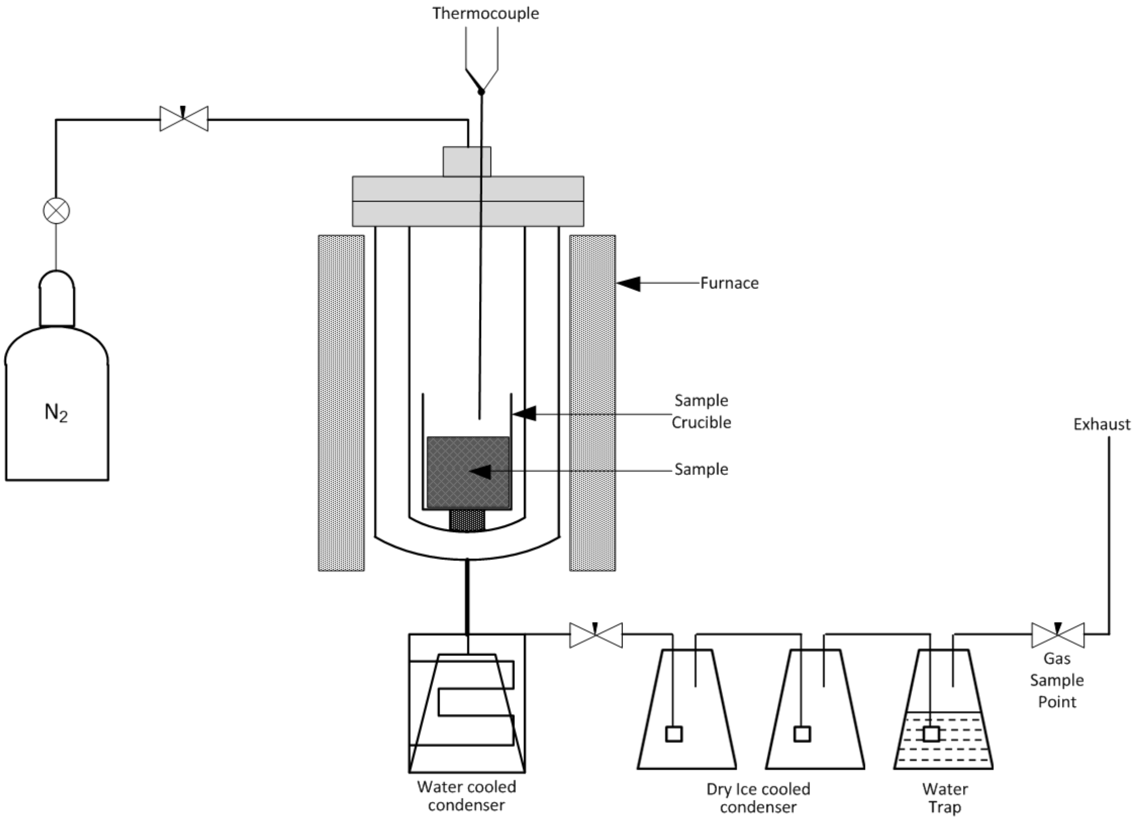

Figure 3-1: Schematic of the slow pyrolysis reactor (Windeatt et al., 2014).

To isolate and investigate relationships between feedstock and biochar characteristics, the conditions of pyrolysis were kept uniform. From this point these are termed the 'standard conditions'.

Under standard conditions the eight biomass types were pyrolysed with a heating rate of 5 ^{o}C min^{-1} and final temperature of 600 ^{o}C which was held constant for one hour. The sugarcane bagasse feedstock was also pyrolysed under alternative conditions, exploring the effects of pyrolysis temperature and heating rate on biochar characteristics (Table 3-1 summarises the temperature and heating rate conditions used).

Table 3-1: Experimental conditions: final temperature and gas collection period. The table shows the standard conditions used for all feedstocks (top) and those of altered final temperature (middle) and heating rate (bottom) used in experiments on the sugarcane bagasse feedstock.

Final Temperature (°C)	Heating Rate (°C min^{-1})	Gas collection start (x min after experiment start)	Gas collection period after final temperature hold time (x min)
Standard Conditions (all feedstocks)			
600	5	30	15
Conditions with altered final temperature (sugarcane bagasse only)			
400	5	30	15
800	5	30	15
Conditions with altered heating rate (sugarcane bagasse only)			
600	20	10	15
600	50	10	15

Pyrolysis was undertaken in a nitrogen (N_2) atmosphere with a flow rate of 200 ml min^{-1} at 20°C and 1 bar pressure. The N_2 carrier gas was introduced 10 minutes before heating commenced to purge oxygen from the system. Oil was collected using a three condenser system, with glass wool used to remove uncondensed semi-volatiles from the gas stream.

The crucible and condenser system were weighed before and after each experiment to calculate mass balance of the feedstocks and products. Biochar and oil yields were determined by weight. Product gases were collected in a tedlar bag and analysed off-line by gas chromatography (see 3.2.3.12).

3.2.3 Analytical methodology

3.2.3.1 Moisture, carbon, volatile and ash content

Proximate analysis, used to determine the moisture, fixed carbon, volatile matter and ash content of the raw feedstocks and biochars was conducted using a muffle furnace method. Samples, in a ceramic crucible with lid, were dried in an oven at 105 °C for 2 hours, then heated to 550 °C, and held for 4 hours. The lids were then removed and the samples held at 550°C for 1 hour to combust the fixed carbon, leaving the residual ash. Moisture, volatiles and ash were calculated by direct weight loss and fixed carbon content calculated by difference.

3.2.3.2 Elemental composition

Carbon, hydrogen, nitrogen, sulphur and oxygen (C, H, N, S, O) content of the feedstocks and biochars was determined by ultimate analysis methodology using a Flash 2000 organic element analyser with thermal conductivity detector. 3mg of each sample was analysed, in duplicate, with vanadium pentoxide (V_2O_5) to aid combustion. During ultimate analysis the samples, combusted in oxygen, produce N_2, H_2O, CO_2 and SO_2, which is quantified using chromatography to give the elemental composition. Oxygen was calculated by difference. Carbon yield, defined here as the carbon retained from the original biomass carbon, was calculated from the ultimate analysis.

3.2.3.3 Metal and nutrient content

Metal and nutrient content of the feedstocks and biochars was analysed using inductively coupled plasma mass spectrometry (ICP-MS). 0.2 g of either feedstock or biochar was added to 8 ml of nitric acid and heated, in either a microwave reactor or using a sand bath, to aid sample digestion. Concentrations of phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) were determined as these are key macro-nutrients for healthy plant growth and soil quality (Maathuis and Diatloff, 2013).

3.2.3.4 Biochar recalcitrance

There are a number of methods of estimating the recalcitrance of biochar carbon including using analogues and laboratory enhanced weathering methods. Section 2.2.5.2 discusses the methods currently used to estimate the stability of biochar carbon in more detail. One method of estimating biochar recalcitrance is the R_{50} index developed by Harvey et al. (2012) which assesses the recalcitrance of a biochar in relation to that of graphite and is described in equation 3-1.

$$R_{50,x} = T_{50,x}/T_{50,graphite} \qquad (3\text{-}1)$$

Where $T_{50\,x}$ and $T_{50\,graphite}$ are the temperatures at which 50 % of the material was oxidized for biochar and graphite respectively. $T_{50\,x}$ was determined by Temperature Programmed Oxidation (TPO), conducted by thermogravimetric analysis (TGA) using a Mettler Toledo TGA/DSC1 analyser with alumina crucible and Al lid. 5 mg of sample was heated in air to 900 ^{o}C at 10 ^{o}C min^{-1}. R_{50} values were calculated from the TPO data using equation 3-1 (Harvey et al., 2012). A value of 886 ^{o}C for $T_{50\,graphite}$, as reported by Harvey et al. (2012), was used here. The R_{50} index only gives a measure of the recalcitrance of the biochar in relation to that of other biochars and graphite, it does not give a timescale or rate of degradation. Methodology for using the R_{50} index to indicate a timescale for degradation is discussed in Section 3.2.3.5.

We hypothesised that high concentrations of alkali metals, such as potassium (K), in biochars may influence the oxidation temperature during TPO, due to this effect being reported for other materials such as raw biomass (Jiang et al., 2013). Alkali metals are likely to be rapidly leached from biochars upon addition to soil (Lindstrom, 1986) which, if high alkali content catalyses the oxidation of biochars, as hypothesised, the R_{50} value for that biochar would be conservative. The biochar may have a higher stability in soil than predicted due to this rapid leaching. To test this hypothesis a wheat straw biochar (high in alkali content) was washed in deionised water at 80 ^{o}C for 2 hours, removing the majority of the alkali metals present. TPO was performed as described above, in duplicate, on the washed and unwashed biochars for comparison.

3.2.3.5 Carbon sequestration potential

The carbon sequestration (CS) potential of a biochar is defined by Zhao et al. (2013) as a measure of the amount of feedstock carbon that would be retained in the soil long-term upon addition as biochar. The CS potential methodology, as detailed in equation 3-2, was developed by Zhao et al. (2013) and is calculated as:

$$CS\ (\%) = (M \times Ch \times C_{Ch} \times R_{50}) / M \times C_F \qquad (3\text{-}2)$$

Where, M is the mass of feedstock (g), Ch is the yield of biochar (%), C_{Ch} is the carbon content of the biochar (%), R_{50} is the recalcitrance and C_F is the carbon content of the feedstock (%). The CS potential was calculated for each of our biochars. The methodology described by Zhao et al. (2013) does not detail the timeframe of 'long-term' sequestration, but does discuss that biochar may be recalcitrant for <100 to >1000's of years. The CS potential is therefore assumed here to be estimate long-term storage above the 95 year period of the biochar scenarios within this thesis (see Chapter 5).

3.2.3.6 Surface area and pore volume

Biochar surface area and pore volume was determined using a Quantasorb continuous flow gas adsorption unit with N_2 adsorbate. Vacuum outgassing was conducted at 200 ^{o}C for 3 hours. Surface area was determined using the BET method of isotherm analysis (Brunauer et al., 1938, Osborne, 2004). Combined micropore and mesopore volume was determined using the BJH cumulative adsorption method (Ceram, 2013).

3.2.3.7 Calorific value

Calorific value, determined as the heating value (HV), of the biochars was determined using a PARR 6200 bomb calorimeter, determining the energy contained within the sample by detecting a temperature rise in surrounding water (University of Waterloo, 2012). Some samples required the addition of kerosene to aid burning, with the calorific value of the accelerant factored into the calculations. Calorific value was also calculated for the raw feedstocks and biochars using the Dulong equation:

$$HV\ (kJ/kg) = 33{,}800 * C + 144{,}000 * (H_2 - O_2/8) + 9{,}270 * S \qquad (3\text{-}3)$$

(Capareda, 2011)

Where C, H, O and S are elemental mass fractions from the ultimate analysis (Section 3.2.3.2).

3.2.3.8 pH

pH was determined using a pH meter, following the method described by Yao et al. (2010). A solution of 1:20 biochar to deionised water was shaken for 30 minutes then left to stand for 10 minutes before testing.

3.2.3.9 Lignocellulosic content

Typical cellulose, hemicellulose and lignin content were determined for each feedstock as an average of the values available from literature (Table 4-1).

3.2.3.10 Statistical analysis

Correlation and regression analysis was used to determine significant relationships between characteristics of the raw feedstock and biochars, and also between the different biochar characteristics. The data was analysed using Microsoft Excel correlation and regression tools and a confidence level of 95% was used.

3.2.3.11 Oil analysis

Oil yields were calculated by weight. Calorific value of the oil products was analysed using the same method as for biochars which is discussed in Section 3.2.3.7.

3.2.3.12 Gas analysis

Gas collection are summarised in Table 3-1. The gases were collected into a gas tedlar bag throughout the experiment and then analysed offline by gas chromatography. The initial gas flow was not collected as volatile formation does not begin until around 300 ^{o}C, therefore this initial flow was assumed to be the N_2 carrier gas. A 'flushing period' at the end of the pyrolysis hold time was maintained to ensure collection of any remaining gases.

Gas chromatography (GC) was used for the analysis of gas species type and concentration. Three gas chromatographs were used to separately determine CO_2, permanent gases (H_2 and CO) and hydrocarbon gases (CH_4, C_2H_4, C_2H_6, C_3H_6, C_3H_8, C_4H_8, C_4H_6, C_4H_{10}). A 1 ml glass syringe was used for all gas injections. The CO_2 and permanent gas chromatographs used thermal conductivity detectors (GC/TCD), with argon as the carrier gas. The column oven temperature was 30 ^{o}C, injector and detector temperature was 120 ^{o}C and the filament temperature was 160 ^{o}C. The hydrocarbon chromatograph used a flame ionisation detector (GC/FID) with nitrogen gas carrier. The initial temperature was 60 ^{o}C for 3 minutes, increased by 10 ^{o}C min^{-1} to 100 ^{o}C and held for 3 minutes, then increased by 20 ^{o}C min^{-1} to 120 ^{o}C and held for 3 minutes. The injector temperature was 150 ^{o}C and detector temperature was 200 ^{o}C.

The calorific value of each gas species was calculated and multiplied by the mole fraction in the gas using:

$$CV = \sum (x_1 * CV_1 + x_2 * CV_2 +_{\dots} x_n * CV_n) \quad \textbf{(3-4)}$$

The compression factor (Z) was applied to modify the ideal gas law for the behaviour of real gas, giving the volume of the gas at given pressure and temperature divided by the volume under the same conditions under the ideal gas law.

$$Z = \frac{p}{\rho R_{specific} T} \quad \textbf{(3-5)}$$

Where ρ is the gas density, $R_{specific}$ = R/M (specific gas constant where R is the molar gas constant and M is the molar mass) and T is temperature. The final calorific value, corrected to 15 ^{o}C and 1 atmosphere of pressure, is then given by:

$$CV = \frac{CV}{Z} \quad \textbf{(3-6)}$$

This methodology is detailed further in Ulbig and Hoburg (2002).

3.3 Summary

Methodologies for the production and characterisation of biochar, bio-oil and syngas have been detailed in Sections 3.2.2 to 3.2.3.12. Characterisation of biochars from eight crop residues under uniform pyrolysis conditions enabled relationships between feedstock and biochar characteristics to be analysed. Sugarcane bagasse biochars produced under alternative pyrolysis conditions enabled relationships between pyrolysis conditions and biochar characteristics to be determined. Feedstock characterisation was by elemental composition, moisture, volatile, carbon and ash content, H/C and O/C content and calorific value. This provides valuable documentation of biochar feedstock properties, as in-depth reporting of feedstock characteristics is often under-reported within the literature and the analysis here will both add to the limited literature (Downie et al., 2009). Biochar characterisation included the same methodologies as for the raw feedstocks, with the addition of pH, pore volume, surface area, stored carbon, recalcitrance (R_{50} index) and the carbon sequestration (CS) potential. These characterisations gave a well-rounded documentation of the biochars, enabling analysis of relationships between feedstocks, biochar characteristics and process conditions. Analysis to determine whether the degradation of some biochars is catalysed by high alkali metal content, potentially making the R_{50} classifications of these biochars conservative, was also undertaken through TPO of washed and unwashed biochars. Biochar yield, carbon content, R_{50} and CS potential data was fed into the later work assessing the global potential of biochar for carbon sequestration (see Chapter 5 onwards).

4 Characterisation of biochars from crop residues: Results and discussion

4.1 Introduction

Pyrolysis of eight crop residue types (see Table 4-1), under the standard pyrolysis conditions of 5 $^{o}C\ min^{-1}$ heating rate, to 600 ^{o}C and 1 hour hold time, was used to produce biochars, bio-oils and syngas for analysis. Sugarcane bagasse was pyrolysed under alternative conditions, with peak temperatures of 400 ^{o}C and 800 ^{o}C and heating rates of 20 $^{o}C\ min^{-1}$ and 50 $^{o}C\ min^{-1}$, to examine the effects of alternate pyrolysis conditions of the characteristics of pyrolysis products.

The feedstocks and biochars were assessed for elemental composition and moisture, volatile, fixed carbon and ash content by ultimate and proximate analysis respectively. The H/C and O/C ratios of the feedstocks and biochars were determined from the ultimate analysis. The Dulong equation was used to determine the calorific value of the feedstocks and biochars, alongside bomb calorimetry of the biochars and bio-oils. Biochars were also characterised by pore volume and surface area using a gas adsorption method using N_2 adsorbate, and pH determined using a pH meter. ICP-MS was used to determine the macro-nutrient content of the feedstocks and biochars, in particular the P, K, Ca and Mg content. Syngas species composition, concentration and calorific value was determined using gas chromatography (GC). The carbon retained in the biochar from that of the feedstock, R_{50} values and the (long-term) carbon sequestration (CS) potentials were calculated for the biochars. Temperature programmed oxidation of washed and unwashed wheat straw biochars was conducted to determine whether high alkali metal content influences the degradation temperature of a biochar. These analysis techniques, excluding TPO on washed biochar, were conducted on the alternate conditions biochars to examine any effects these conditions have on biochar characteristics.

4.2 Feedstock composition

The typical lignocellulosic composition of the feedstocks is listed in Table 4-1, illustrating that the composition of biomass feedstocks are often very different in their basic composition.

Feedstock characteristics are detailed in Table 4.2. Feedstock carbon content was highest in the palm shell feedstock (53.1 wt %) and lowest in the rice husk feedstock (42.5 wt %). The rice husk feedstock had correspondingly high ash content at 19.6 wt %. The lowest ash content was seen in the coconut shell raw feedstock (0.6 wt %) which had the second highest carbon content (52.6 wt %), palm shell had the second lowest ash content (2.0 %).

Table 4-1: Typical cellulose, hemicellulose and lignin content of raw feedstocks (%).

	Cellulose (%)	Hemicellulose (%)	Lignin (%)	References
Palm shell	30	18	53	(Daud and Ali, 2004, Okoroigwe and Saffron, 2012)
Sugarcane bagasse	39	26	24	(Aguilar et al., 2002, Pandey et al., 2000)
Rice husk	38	18	22	(Kadam et al., 2000, Nguyen et al., 2010)
Coconut shell	20	49	30	(Daud and Ali, 2004)
Wheat straw	35	25	19	(Kaparju et al., 2009, Kristensen et al., 2007, McKendry, 2002)
Cotton stalk	35	39	21	(Akpinar et al., 2007, Goksu et al., 2007, Kang et al., 2012, Ververis et al., 2004)
Olive pomace	34	15	20	(Ayrilmis and Buyuksari, 2010)
Coconut fibre	46	15	33	(Justiz-Smith et al., 2008, Khedari et al., 2004, Tomczak et al., 2007)

Regression analysis showed some significant relationship between carbon content and ash content (r^2 = 0.53, p = 0.04). A significant correlation was seen between the typical feedstock cellulose content and feedstock carbon content (r^2 = 0.64, p = 0.02), with the cellulose content declining with increasing carbon content (Figure 3-1). No significant correlation was seen between typical hemicellulose or lignin content and carbon content. The lignocellulose values used were typical values from the literature. Analysis of the lignocellulosic composition of the actual feedstocks assessed here would provide more accurate representation of correlation between these factors. This was not possible here due to time constraints, but would be a useful area for further study.

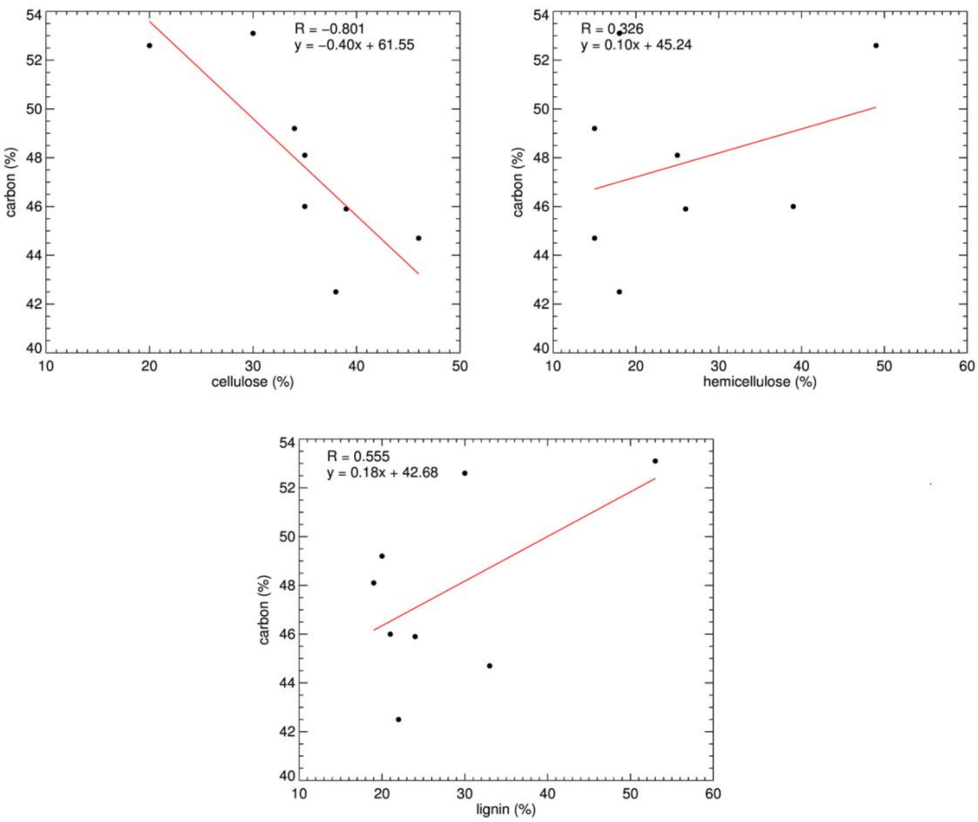

Figure 4-1: Correlation analysis of the typical feedstock lignocellulosic composition (%) (cellulose (top left), hemicellulose (top right) and lignin (bottom)) and the feedstock carbon content (%).

The main macro-nutrient content (P, K, Ca and Mg) of the feedstocks are shown in Figure 4-6 alongside the macro-nutrient content of the biochars, showing the effects of pyrolysis on macro-nutrient content. Table I-1 in Annexe I shows the data values for macro-nutrient concentration. The coconut shell feedstock had very low concentrations of the nutrients assessed, relative to most of the other feedstocks. Wheat straw also had relatively low concentrations of P, Ca and Mg, though concentrations of K were relatively high when compared with other feedstocks except olive pomace. A significant correlation was seen between the P and Mg content of feedstocks (r^2 = 0.77, p = 0.01), where, if concentrations of P are high then concentrations of Mg tend to be correspondingly high (Figure 4-2).

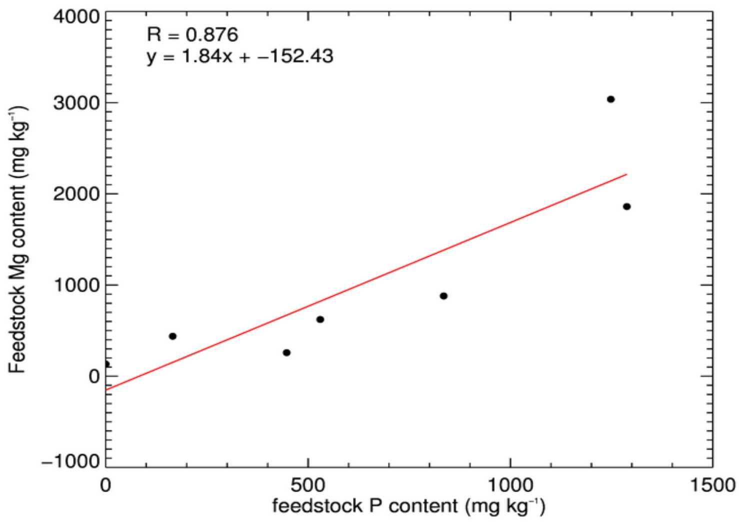

Figure 4-2: The relationship between phosphorus (P) and magnesium (Mg) content (mg kg^{-1}) of the feedstocks.

No other significant correlations were seen between the different macro-nutrient species in the feedstocks.

4.3 Biochar yields and characteristics

The proximate analysis, ultimate analysis and calorific value of the feedstocks and biochars (produced under standard conditions) are listed in Table 4.2 together with the pH, calorific value, surface area, pore volume, stored carbon, R_{50} values and carbon sequestration (CS) potential of the standard biochars. The characteristics of biochars produced under altered conditions are detailed in Section 4.6.

Table 4-2: Characteristics of raw feedstocks (top) and biochars (bottom) produced under standard conditions.

Raw materials	units	palm shell	sugar cane bagasse	rice husk	coconut shell	wheat straw	cotton stalk	olive pomace	coconut fibre
Ultimate Analysis									
C (ar)	%	53.1	45.9	42.5	52.6	48.1	46.0	49.2	44.7
H (ar)	%	7.1	6.7	6.5	6.2	6.8	7.6	6.8	7.5
N (ar)	%	0.7	0.9	1.3	2.0	1.8	5.6	2.0	0.8
S (ar)	%	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0
O (by diff)	%	46.8	59.2	46.0	53.1	49.0	54.5	45.8	61.8
H/C		1.6	1.7	1.8	1.4	1.7	2.0	1.6	2.0
O/C		0.7	1.0	0.8	0.8	0.8	0.9	0.7	1.0
Proximate Analysis									
Moisture	%	3.0	5.8	5.7	5.7	5.6	6.1	5.7	7.5
Volatiles (daf)	%	74.1	85.3	80.9	77.2	85.9	93.1	80.5	85.3
Fixed Carbon (daf)	%	25.9	14.7	19.1	22.8	14.1	6.9	19.5	14.7
Ash (db)	%	2.0	4.4	19.6	0.6	7.9	4.2	4.5	5.3
HHV	MJ kg^{-1}	19.9	14.6	15.5	17.2	17.3	16.8	18.2	14.9

Chars	units	palm shell	sugar cane bagasse	rice husk	coconut shell	wheat straw	cotton stalk	olive pomace	coconut fibre
Product Yields									
Char	%	31.8	27.7	39.0	28.2	30.3	28.0	30.5	30.8
Oil	%	50.3	50.3	33.5	43.7	50.0	53.6	44.8	47.8
Gas	%	17.9	23.6	21.8	28.1	17.6	18.4	29.2	25.1
Ultimate Analysis									
C (ar)	%	90.6	88.6	54.5	93.9	75.3	83.2	71.8	82.6
H (ar)	%	2.8	2.8	2.1	3.0	2.6	3.2	2.8	2.7
N (ar)	%	0.9	1.3	1.1	0.4	1.0	4.8	1.9	2.4
S (ar)	%	0.0	0.1	0.0	0.0	0.2	0.1	0.0	0.0
O (by diff)	%	7.9	13.7	5.4	2.6	4.5	14.2	11.6	12.8
H/C		0.4	0.4	0.5	0.4	0.4	0.5	0.5	0.4
O/C		0.1	0.1	0.1	0.02	0.04	0.1	0.1	0.1
Proximate Analysis									
Moisture	%	2.2	3.7	5.7	7.1	8.1	8.5	10.0	10.4
Volatiles (db)	%	11.5	30.1	13.9	8.1	21.2	28.8	20.9	25.1
Fixed Carbon (daf)	%	88.5	69.9	86.1	91.9	78.8	71.2	79.1	74.9
Ash (db)	%	6.7	13.0	47.0	4.1	23.4	9.5	18.1	13.5
Other Characteristics									
HHV	$MJkg^{-1}$	33.6	30.1	19.3	33.7	26.5	31.4	24.1	26.6
Total pore volume	cc g^{-1}	0.16	0.18	0.10	0.15	0.01	0.05	0.00	0.04
Surface Area (BET)	M^2 g^{-1}	220.0	149.1	114.9	222.5	6.3	121.2	1.2	23.2
pH		6.1	8.6	9.9	8.5	11.6	10.3	10.5	9.6
stored carbon (db)	%	54.3	53.5	50.0	50.3	47.4	50.6	44.5	56.9
R_{50}		0.61	0.53	0.54	0.59	0.46	0.50	0.58	0.49
CS (sequestration potential)	%	32.5	27.3	26	28.7	21.3	23.8	24.5	26.8

(ar) = as received, (db) = dry basis, (daf) = dry ash free, HHV = higher heating value

4.3.1 *Biochar yields*

Biochar yields, when produced under the standard conditions, ranged from 27.7 wt % (sugarcane bagasse) to 39 wt % (rice husk) showing that feedstock characteristics can have a large influence on biochar yield. Correlation between biochar yield and biochar carbon content (r^2 = 0.67, p = 0.01).

4.3.2 *Ultimate analysis*

Biochar carbon content varied from 55 wt % (rice husk) to 94 wt % (coconut shell). Between 45 wt % and 57 % of the original feedstock carbon was contained in the biochar after pyrolysis, with an average value of 51 %, comparing well with values of 49 % from Woolf et al. (2010) and 50% from Xu et al. (2012).

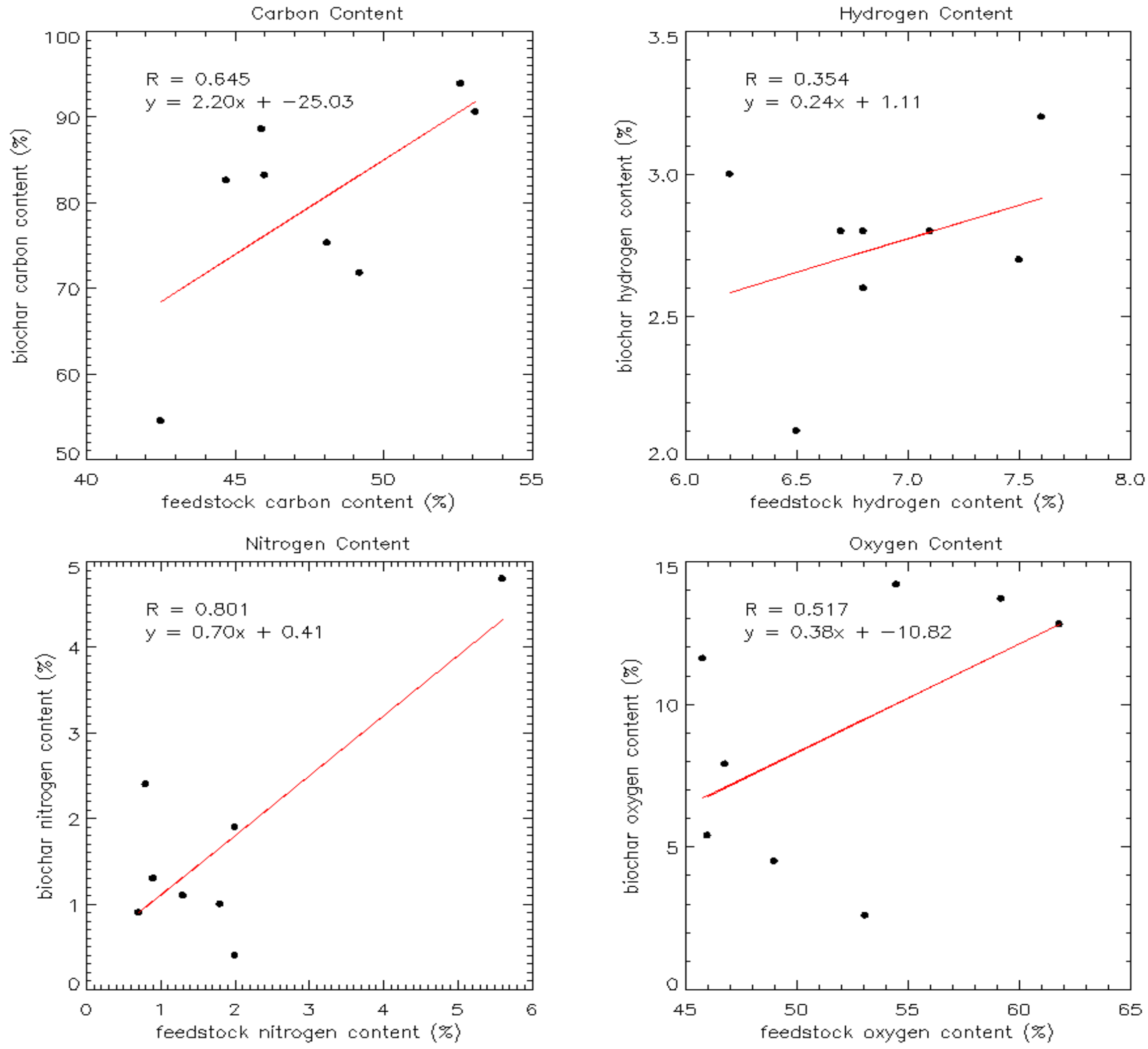

Figure 4-3: Correlation analysis of feedstock C (top left), H (top right), N (bottom left) and O (bottom right) content and corresponding biochar content.

Correlation analysis of the ultimate analysis results for the feedstocks and biochars (Figure 4-3) highlighted strong correlation between the nitrogen content of feedstocks and biochars (r^2 = 0.64, p = 0.02). Correlation between feedstocks and biochar content for carbon, hydrogen and oxygen was low, showing no significance.

4.3.3 Proximate analysis

Biochar volatile content was from 8 wt % to 30 wt %. Good correlation was found between the proximate analysis results of the feedstocks (moisture, volatiles, fixed carbon and ash) and the corresponding characteristic in the biochars (Figure 4-4). Ash content of the biochars had a large range, from 4.1 wt % (coconut shell) to 47 wt % (rice husk).

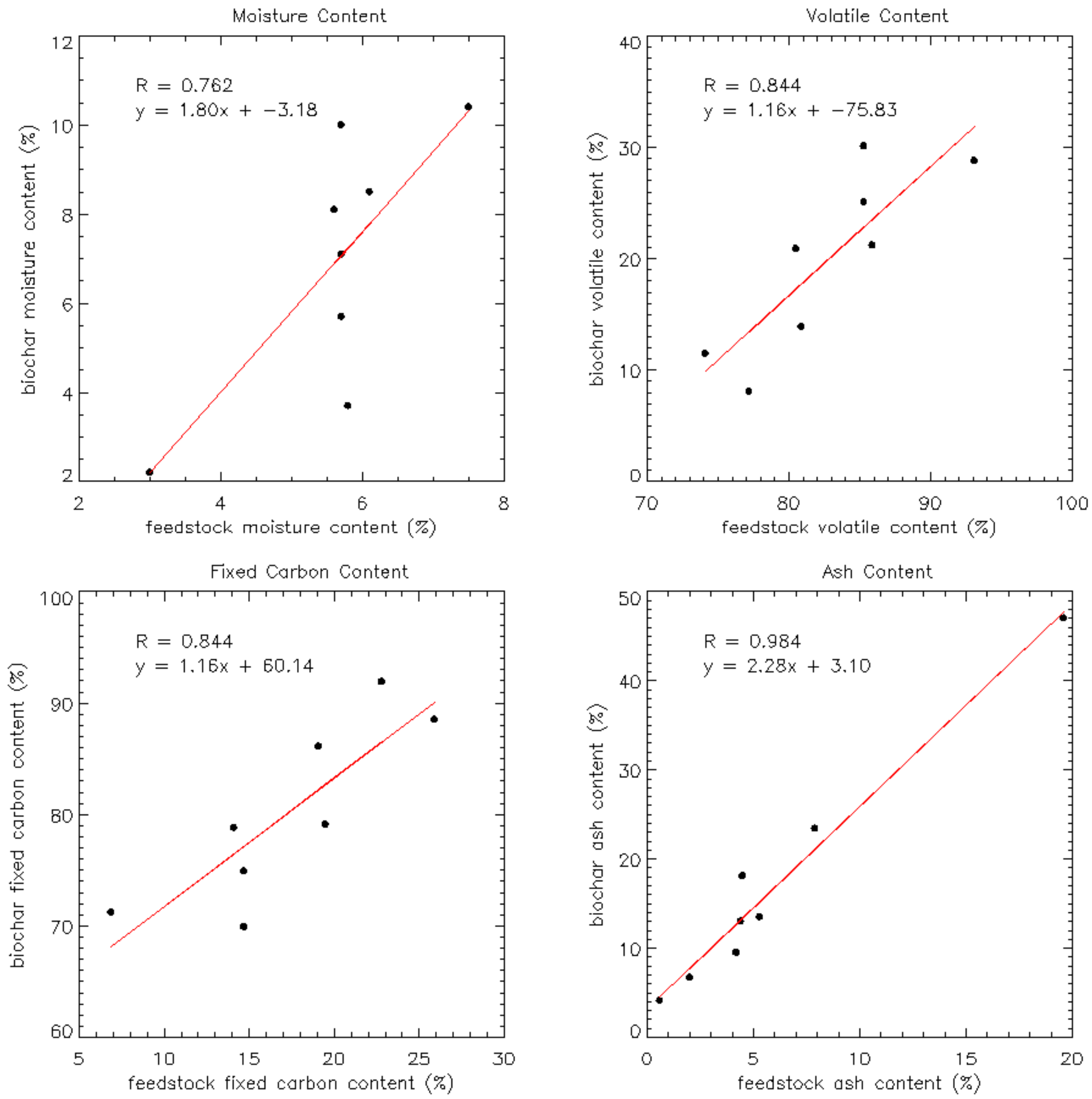

Figure 4-4: Correlation analysis of feedstock moisture (top left), volatile (top right), fixed carbon (bottom left) and ash content (bottom right) (%) with corresponding biochar content.

Correlation between feedstock and biochar moisture content was $r^2 = 0.58$, $p = 0.03$. Feedstock and biochar volatile content ($r^2 = 0.71$, $p = 0.01$) and feedstock and biochar fixed carbon content ($r^2 = 0.71$, $p = 0.01$) were strongly correlated. Feedstocks with high ash content tended to result in lower biochar yields ($r^2 = 0.76$, $p = 0.005$), and also in biochars with higher ash content ($r^2 = 0.97$, $p = 0.0001$). Coconut shell biochar had both the highest carbon content and lowest ash content. Enders et al (2012) suggested that feedstocks with high ash content produce biochars with lower fixed carbon, which they attribute to the high ash content inhibiting the formation of aromatic carbon structures. Clearly there is a shift from high volatile, low fixed carbon content in the raw biomass to low volatile, high fixed carbon for the product biochars. Enders et al. (2012) reported ash, volatile and fixed carbon contents for a range of biochars from the literature, confirming these trends for a number of other biochars. There was also variation in the proportions of volatiles, fixed carbon and ash in the resulting biochars, some of which could be attributed to feedstock characteristics and some of which may be related to process conditions (see Section 4.6).

4.3.4 Hydrogen to carbon (H/C) and oxygen to carbon (O/C) ratios

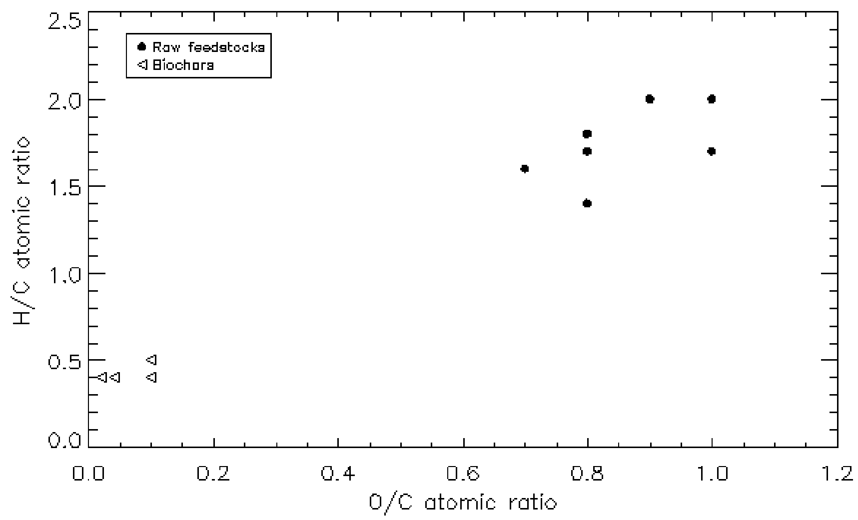

Figure 4-5: Van Krevelen Diagram of O/C and H/C ratios of raw feedstocks and biochars. Eight feedstocks and biochars are presented, although some values are overlying.

The H/C atomic ratios plotted against the O/C atomic ratios for the feedstocks and biochars are shown by van Krevelen diagram in Figure 4-5. H/C and O/C ratios decreased in all biochars when compared with their feedstocks. This decrease is related to the removal of H and O during pyrolysis and indicates increased aromatic structure. Figure 4-5 clearly indicates the loss of volatile hydrocarbon and oxygenated hydrocarbon species and increasing carbon content during pyrolysis.

Krull et al. (2009) reported that a decreasing biochar H/C ratio indicates increasing aromatic structure in the biochar potentially increasing the stability of the biochar and the recalcitrance of carbon. Increased carbon content also relates to an increased calorific value of the material. Kim et al. (2012) reported H/C and O/C ratios for biochars produced from the fast pyrolysis of pitch pine at 500 °C which were similar to those reported found here using slow pyrolysis at 600 °C. Lee et al. (2013) also reported a decrease in H/C and O/C ratios upon slow pyrolysis of Miscanthus to 500 °C.

4.3.5 Calorific value

Biochar may also be utilised as a solid fuel. Biochar calorific value (CV) followed the expected trend with the higher carbon, lower ash biochars having the highest CVs. The lowest CV was for rice husk biochar at 19 MJ kg^{-1}, and the highest for coconut shell biochar at 34 MJ kg^{-1}. Feedstocks with higher hemicellulose and lignin contents also tended to have higher CV. The biochar CVs ranging between 26-34 MJ kg^{-1} are in a similar range to bituminous-anthracite grade coal and may therefore be a useful solid fuel commodity. Biochars with a lower CV are unlikely to be a commercially competitive solid fuel source but could potentially be used for household fuel use (i.e. cooking or heating).

4.3.6 Surface area and porosity

Biochar surface area ranged from 1.2 m^2 g^{-1} for olive pomace biochar to 223 m^2 g^{-1} for coconut shell biochar. Total pore volume of the biochars ranged from negligible for olive pomace biochar to 0.18 cc g^{-1} for sugarcane bagasse biochar. Significant correlation was seen between biochar surface area and total pore volume (r^2 = 0.80, p = 0.003). Lee et al. (2013) reported a surface area of 293 m^2 g^{-1} for biochar produced from Miscanthus at a pyrolysis temperature of 600 °C. This is higher than, but within a similar range to, the highest surface areas seen in this study. The surface area and porosity properties of biochars can influence biochar effects in soil. The physical properties of soil, such as structure, water holding capacity and soil biology, such as microbial communities and earthworm presence, may be altered by biochar application (Biederman and Harpole, 2013, UK Biochar Research Centre, 2010). The high surface areas and porosities found in some biochar here, for example coconut shell biochar, indicate that the biochar may have positive soil impacts, such as increasing water holding capacity and providing habitat for microbial communities. Biochars may also be subjected to a further processing stage, for example chemical or steam activation, to further increase the surface area and produce activated carbons (Wu et al., 2012). Azargohar and Dalai (2006) increased the internal surface area of a biochar by 50 times through potassium hydroxide chemical activation.

4.3.7 Macro-nutrient concentrations

Biochars have been noted to contain varying concentrations of nutrient species (Chan and Xu, 2009). The macro-nutrient contents of the feedstocks and biochars assessed in this study are shown in Figure 4-6. P, K, Ca and Mg contents were assessed due to their importance for healthy plant growth (Maathuis and Diatloff, 2013). Nitrogen (N) content, which is another important macronutrient, was also examined by ultimate analysis (see Table 4.2), and is discussed further within this section.

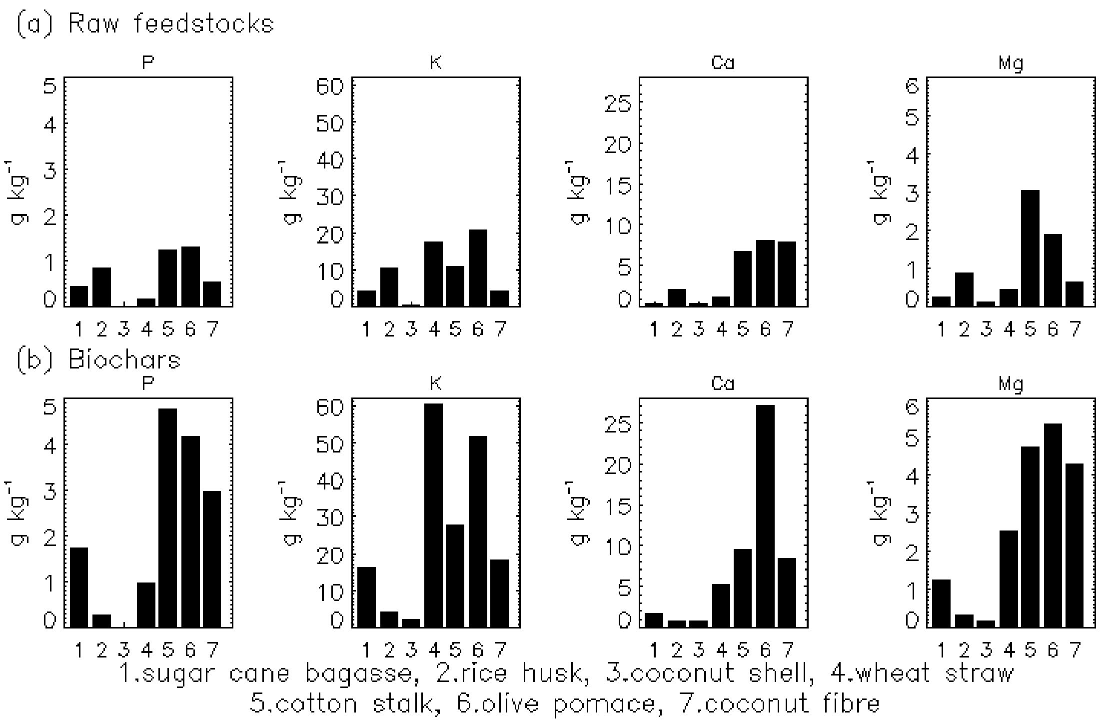

Figure 4-6: Macro-nutrient content (g kg^{-1}) (dry basis (db)) of (a) raw feedstocks and (b) biochars. Species, from left to right, are phosphorus (P), potassium (K), calcium (Ca) and Magnesium (Mg). N.B. Scales vary between different nutrient species.

Large variations in some nutrient concentrations were found between the different raw feedstocks and also between the different biochars. A number of the nutrient species examined were concentrated within the biochar during the pyrolysis process. Those feedstocks with lower macro-nutrient concentrations had relatively lower concentrations when converted to biochar. Total biochar N content ranged from 4.3 g kg^{-1} for coconut shell to 47.8 g kg^{-1} for cotton stalk. Total P content of the biochars was between 0 g kg^{-1} for palm shell and coconut shell to 4.2 g kg^{-1}

for olive pomace. Total biochar K ranged from 0.6 g kg^{-1} for palm shell to 60 g kg^{-1} for wheat straw. Total N and P concentrations of the biochars were low compared to some values found in literature (Chan and Xu, 2009). This may be due to the types of biomass used for biochar production, for example manure biochars used by Chan and Xu (2009) are known to have relatively high nutrient content when compared to the woody biomass biochars used here. The literature on biochar nutrients details that biochar total nitrogen (N), phosphorus (P) and potassium (K) concentrations are often under-reported, though a large range exists within those values available. For example, Chan and Xu (2009), in a meta-analysis of the current literature, reported concentrations of total N of 1.8 to 56.4g kg^{-1}, total P of 2.7 to 480g kg^{-1} and total K of 1.0 to 58g kg^{-1}. Total N and total K contents are fairly well matched with those determined within this study. Biochar P content was over 100 times greater than the highest values of P content determined here. These high concentrations of P are attributed by Chan and Xu (2009) to feedstocks of animal origin such as sewage sludge, broiler litter and manures, rather than from plant based feedstocks as used in this study. The values reported both here and by Chan and Xu (2009) are for total N, P and K concentrations. N, P and K can be present in different forms, only some of which may be available for uptake and use by plants. N is taken up as NO_3^-, NH_4^+, and N_2 in gas from the atmosphere or ions from soil solution; P is taken up as phosphates from soil solution; K, Ca and Mg are taken up as ions from soil solution (Kirkby, 2012). Although total N, P and K concentrations may be high in some biochars, this does not always correlate with high plant available N, P and K concentrations. Often, concentrations of mineral N are low even where total N is high, as in biochars produced from poultry manures, conversely where total K is high, available K is often also high (Chan et al., 2007). Chan et al. (2007) detailed both total and available P for a number of biochars, finding a range of 0.2 to 73 g kg^{-1} total P and 15 to 11,600 mg kg^{-1} available P. The biochar containing 0.2 g kg^{-1} total P had 15 mg kg^{-1} available P, and the biochar containing 25.2 g kg^{-1} total P had 11,600 mg kg^{-1}. This indicates that plant available P may increase with total P, though available P concentrations remain much lower than total P concentrations. The limited reporting of total and/or available nutrient concentrations for biochars makes it difficult to determine trends between the two. Despite these limitations it appears that the highest concentrations of both total and available N, P and K are often seen in biochars from nutrient rich feedstocks such as poultry manures and sewage sludge (Chan et al., 2007).

The nutrients required for optimal plant growth are dependent on factors including soil type, soil nutrient concentrations and plant specific requirements. In some soils an excess of nutrient may already exist. Knowledge of the nutrient content of biochars from different feedstocks would assist the tailoring of biochar production, complimenting efforts to achieve soil optimum nutrient concentrations (Roberts et al., 2010). Methods of biochar application to soils include adding biochar to organic fertilizers such as composts, during and after the composting process, and anaerobic digestate (Lehmann et al., 2009, Schulz et al., 2013). Such processing of biochar, before addition to soil, aims to increase the nutrient content of biochars to encourage optimum plant growth. The use of biochar to manage nutrient concentrations within soils could potentially reduce mineral and organic fertilizer requirements due to the addition of nutrients, increased fertilizer efficiency and reduce fertilizer run-off with biochar addition (Lehmann, 2007). As the production of mineral fertilizer is both energy and resource intensive, and its over-use can be damaging to the environment, any reduction in mineral fertilizer use could be environmentally and economically beneficial (Brentrup et al., 2004).

As well as the potential beneficial effects on soil nutrients, biochar addition to soil can also have detrimental effects such as the introduction of toxic metals and organic contaminants. Contaminants may be introduced to biochar from the feedstock or through the production process (McHenry, 2009). As with macronutrient species some heavy metal species, if present in the feedstock, may be concentrated within the biochar during the pyrolysis process. Some biochars may carry these toxic metal species into soils and potentially into vegetation through plant uptake mechanisms (Kirkby, 2012). None of the biochars tested here were above the thresholds for heavy metal species specified in the IBI Biochar Standards (International Biochar Initiative, 2012e).

4.3.8 Biochar pH

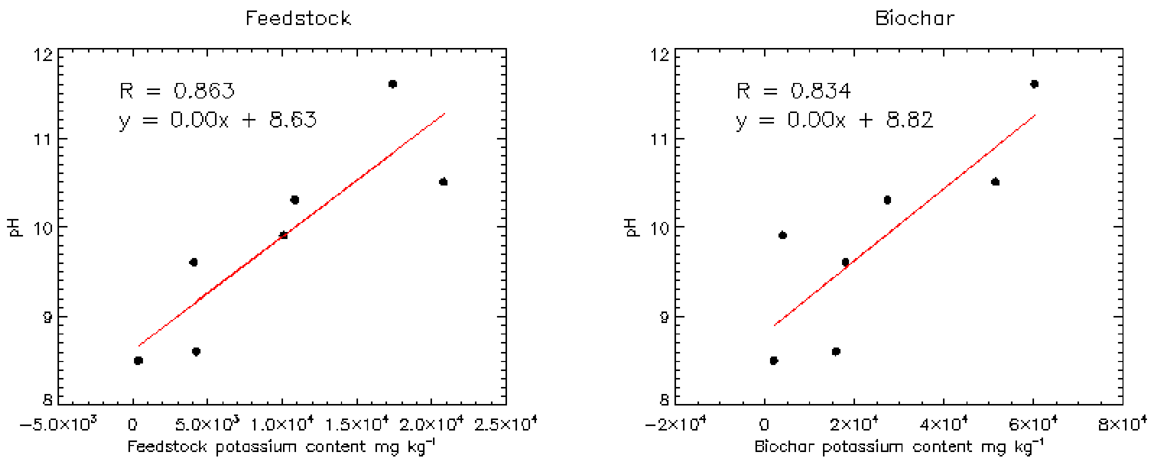

Figure 4-7: Correlation analysis between biochar pH and feedstock potassium content (left) and biochar potassium content (right).

Biochar pH ranged from pH 6.1 for palm shell biochar to pH 11.6 for wheat straw biochar, with the majority of biochars being slightly alkaline. Higher concentrations of alkali metals (P, K, Ca, Mg) generally corresponded to higher pH of the biochar. Biochar pH correlated well with feedstock (r^2 = 0.74, p = 0.01) and biochar (r^2 = 0.70, p = 0.02) potassium content.

No other correlations were found between feedstock or biochar alkali content and biochar pH. Palm shell produced slightly acidic biochar and was found to be low in alkali metals and high in lignin content. The thermal degradation of lignin produces phenolic compounds which may contribute to the acidity of biochars (Nonier et al., 2006). Previous literature reports biochar pH values (without further processing of the biochars) of between pH 4 and pH 12, with values normally found to be above pH 7 (Lehmann and Joseph, 2009). All of the biochars produced here were within this range. Zhao et al. (2013) detailed biochar pH of 8.8 to 10.8 depending on biomass feedstock type. They reported increasing biochar pH with increasing pyrolysis temperature. The maximum temperature of 600 °C used in the standard conditions here may, therefore, promote biochar alkalinity. The application of biochar to soils has been reported in some cases to produce a liming effect, increasing soil pH (Biederman and Harpole, 2013). The UK Biochar Research Centre (2010) reported that alkaline biochars have the potential to buffer excess soil acidity. Increasing the pH of acidic soils has been seen to increase microbial activity, increasing soil organic matter mineralization and increasing nutrient availability to plants. This mineralization may result in the emission of more CO_2 from soils, termed a priming effect. Some of the biochars characterised here may have potential for reducing soil acidity, including the rice husk, wheat straw, cotton stalk and olive pomace biochars. Knowledge of the initial pH of both biochar and soil would be necessary to amend soil pH effectively using biochar, due to the potential ranges of both biochar and soil pH which may be encountered, and the relationship may involve other factors and could by highly complex. Due to the uncertainties of using biochar to alter soil pH, further large scale and scenario specific (i.e. particular biochar/soil combinations) analysis should be undertaken before large scale application to soils for this purpose.

4.3.9 Biochar recalcitrance

Temperature programmed oxidation (TPO) to determine the R_{50} recalcitrance index of each biochar showed a range of degradation profiles (Figure 4-8). 50 % weight loss was achieved between 400 ^oC and 560 ^oC. Biochars produced from physically hard feedstocks, such as palm shell and coconut shell, tended to have higher oxidation temperatures than biochars from feedstocks which were not as physically hard, for example wheat straw and coconut fibre.

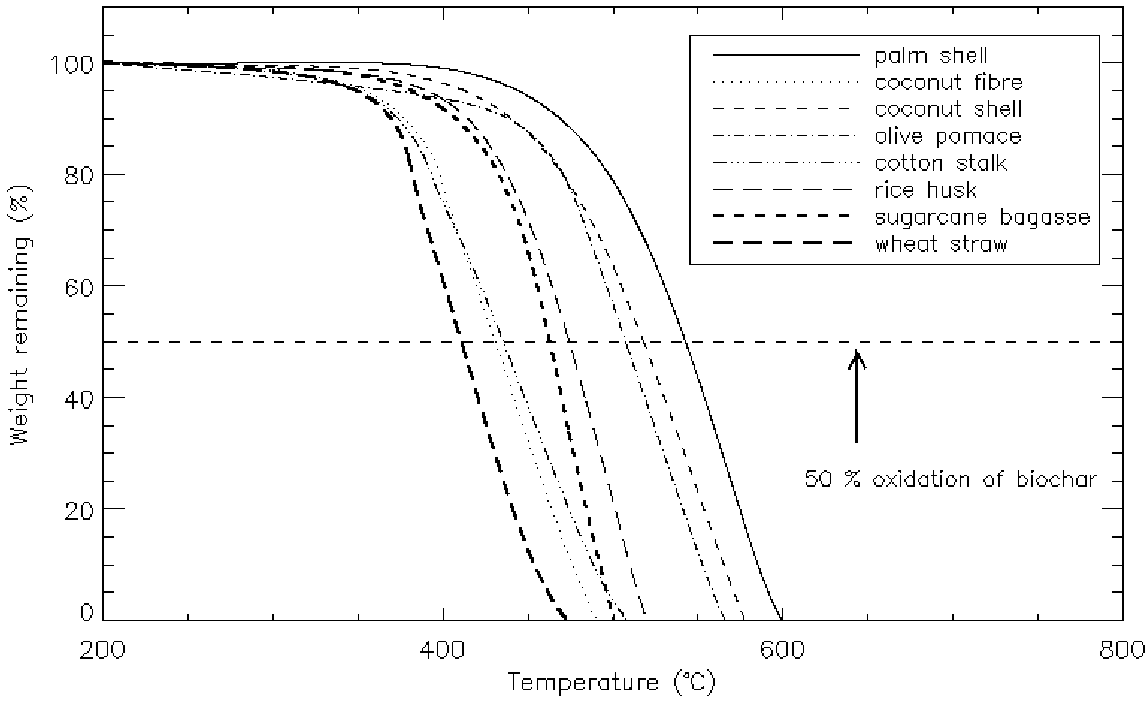

Figure 4-8: Temperature programmed oxidation (TPO) profiles for biochars showing the weight loss (%) of each biochar with increasing temperature (^oC). (Thermograms have been corrected for moisture and ash content following the method of Harvey et al. (2012)).

The TPO profiles of Figure 4-8 were used to calculate the recalcitrance index (R_{50} values) of each biochar following the method of Harvey et al. (2012). Comparison of R_{50} values with carbon mineralization rates led Harvey et al. (2012) to classify biochars, by their degradation potential, into three classes where: $R_{50} \geq 0.7$ = Class A: most recalcitrant biochar; $0.5 \leq R_{50} < 0.7$ = Class B: minimal degradation; $R_{50} < 0.5$ = Class C: more degradable biochar. Using the same classification system two of our biochars were Class C biochars ('more degradable') and six biochars were Class B ('minimal degradation'). None of the biochars were class A biochars (most recalcitrant). Palm shell biochar (R_{50} = 0.60) would be most resistant to degradation and wheat straw biochar (R_{50} = 0.45) would be least resistant. The R_{50} recalcitrance index was developed by comparison of R_{50} values with rates of microbial degradation for 12 biochars (Harvey et al., 2012). Their comparison of these two characteristics showed that, over an incubation period of 1 year, Class A biochars experienced negligible amounts of carbon mineralisation, Class B biochars experienced between 0.2 % and 1.3 % carbon mineralisation and Class C biochars experienced between 0.8 % and 3 % carbon mineralisation. The biochars classified by Harvey et al. (2012) as Class C were all produced at temperatures below 400 ^oC, which was not the case in our study. Our R_{50} analysis indicated that biochars produced at 600^oC can also exhibit Class C degradation rates, with both wheat straw and coconut fibre residues producing Class C biochars within this study. Zhao et al. (2013) calculated a range of R_{50} values of 0.54 to 0.83 for wheat straw and shrimp hull respectively whilst examining a number of biochars produced at 500 ^{o}C from various biomass types including agricultural residues, manures and algae. Wheat straw, which is the only comparable feedstock between the two studies, had a R_{50} value of 0.46 within this study, which is lower than the value of 0.54 found by Zhao et al. (2013). The wheat straw biochar was classified here as a Class 3 biochar, but achieved Class 2 in the Zhao et al. (2013) study. This highlights that variability may be seen between biochars from the same feedstock type as factors such as geographical location and growing conditions may affect biomass characteristics. Such variation may also be caused by pyrolysis conditions. Zhao et al. (2013) used a faster heating rate, and the Zhao et al. (2013) and Harvey et al. (2012) studies both used longer residence times at peak temperature than the standard pyrolysis conditions used here. The higher R_{50} values seen by Zhao et al. (2013) and Harvey et al. (2012) may be related to the longer residence time of the biochars within those studies, allowing for longer exposure of the feedstock, perhaps allowing the charring process, including formation of aromatic structure, to develop further. This is investigated further in Section 4.6.

4.3.10 Catalysis of biochar degradation by alkali metal content

Some inorganic metal species including potassium, calcium and magnesium have been reported to lower the degradation temperature of biomass during thermogravimetric analysis (TGA). Nowakowski et al. (2007) discuss that biomass samples prepared with high concentrations of potassium had lower degradation temperatures than samples which had been demineralised by an acid washing pre-treatment. In-Yong et al. (2011) also reported this behaviour in biomass samples pyrolysed using TGA. A number of the biomass samples in the latter study were washed with water rather than acid, suggesting that the metals and salts can be easily removed by water and that more complex pre-treatment is not needed to see the effect of metal removal on oxidation temperature. Major et al. (2009) observed the leaching of nutrients from soils as water percolation caused nutrient displacement to areas outside the rooting zone, removing them from areas of potential plant uptake. They discuss that cations such as K, Ca and Mg are easily leached. Our analysis of thermograms from washed and unwashed wheat straw biochars showed that high alkali metal concentrations may reduce the oxidation temperature of biochars, and washing may remove sufficient alkali metal content to remove or reduce this effect. This has implications for the recalcitrance index (R_{50}) values calculated for the biochars in this study (Table 4.2), where the biochars may have high alkali content.

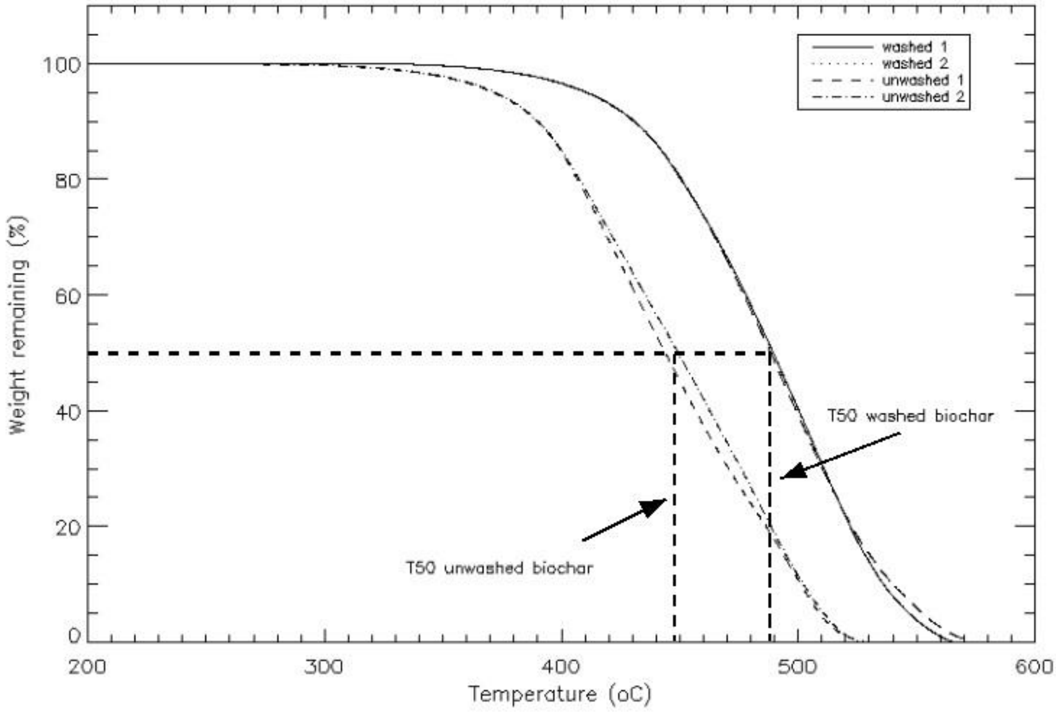

Figure 4-9: Thermograms indicating the oxidation temperatures of washed and unwashed wheat straw biochar samples, showing weight loss (%) of each biochar with increasing temperature. Thermograms have been corrected for moisture and ash content following the method of Harvey et al. (2012).

The washed biochar had 92 % lower potassium (K) content than the unwashed biochar, at 0.2 g kg^{-1} and 2.2 g kg^{-1} respectively. The oxidation temperature of the washed biochar was increased in relation to that of the unwashed biochar (Figure 4-9). The R_{50} value of wheat straw biochar was increased from 0.46 to 0.55 by the washing pre-treatment to reduce alkali content. This reclassified the wheat straw biochar as a Class B biochar (minimum degradation) where previously it was Class C (most susceptible to degradation). As leaching is likely to occur quickly when biochars are added to soils there is likely to be a significant reduction in the concentration of alkali metal species in the biochars in a short time-frame, potentially reducing the degradation potential of some biochars in soils. R_{50} values determined by TPO for unwashed biochars with high alkali content may therefore provide a conservative estimate of recalcitrance, with stability increased soon after addition to soil.

4.3.11 Carbon sequestration (CS) potential

The carbon sequestration (CS) potentials of the biochars indicate that between 21.3 % and 32.5 % of the feedstock carbon would be retained in soil long term upon conversion to biochar and addition to soil. Zhao et al. (2013), investigating the production of biochars from 12 different biomass feedstocks, reported CS potentials from 21.1 % to 47.1 %. The CS potential of the biochars studied here are within the same range as those biochars assessed by Zhao et al. (2013), but tend to be towards the lower end of their range. There are also caveats to be considered when applying this method to biochar analysis. Firstly, the method and definition for carbon sequestration potential described by Zhao et al. (2013) does not define a time frame for the 'long-term' carbon storage. As the Harvey et al (2012) study, which developed the R_{50} index, discussed, the lifetime of biochar in soils can range from under a century to several millennia, therefore it is assumed throughout the rest of this study that the carbon retained would be stored for a period of longer than 100 years. This is an acceptable assumption as 100 years is at the very bottom end of the lifetime range discussed in Harvey et al. (2012). Secondly, as discussed in Section 2.2.5.2, there is no single favoured method of estimating the recalcitrance or carbon storage potential of biochars. Harvey et al. (2012) and Zhao et al. (2013) used thermal degradation to indicate a biochars stability, other methods include chemical enhancement of degradation or estimates of degradation using proxies such as charcoal from natural forest fires. The thermal degradation method of Harvey et al. (2012), incorporated into the assessment of carbon sequestration potential by Zhao et al. (2013) is used here due to a number of factors including the relatively short timescale of carbon storage required for the scenarios of Chapters 5 to 8 (95 years), the ease of comparison and ranking of biochar stability, and the relative simplicity of the assessment which made analysis possible within the study timeframe and constraints.

4.4 Oil yields and characteristics

The highest product yield for all feedstocks was oil, achieving between 33.5 % and 53.6 % yield under standard pyrolysis conditions. Oil CV was between 9 and 15 MJ kg^{-1} which is low compared to that of, for example, conventional oil at 42.5 MJ kg^{-1} (Biomass Energy Centre, 2014b). Higher heating values (HHVs) of 20 MJ kg^{-1} are reported by Qi et al. (2007) for pyrolysis oils from wood and agricultural residues. They also detail that a number of characteristics including high oxygen content, high water content, high acidity, low HHV and variable viscosity often make pyrolysis oils a poor substitute for conventional hydrocarbon fuels. Upgrading to reduce oxygen content and address other problems such as water content can make them a more suitable fuel source. Oils produced from the process could, therefore, be used as a fuel for the process or for other energy needs after upgrading, although this would add an energy penalty and further technological complexity to the system. After processing, energy from the pyrolysis oils could be utilized with the pyrolysis system or as a renewable replacement within other fossil fuel systems.

4.5 Gas characteristics

Syngas yield ranged from 17.6 % to 29.2 %, from wheat straw and olive pomace residues respectively. The CV and composition of each syngas are detailed in Table I-2, Annexe I. The syngas produced had an average CV of 12.4 MJ m^{-3} which is lower than the average 40 MJ m^{-3} of natural gas (Demirbas and Arin, 2002, National Grid, 2013). The syngas of lowest CV was from coconut shell, at 10.2 MJ m^{-3}, whilst the highest CV, at 15.0 MJ m^{-3}, was seen in syngas from rice husk. The dominant gas species produced from all feedstocks under standard pyrolysis conditions was CO_2 which constituted between 42.4 % and 54.8 % of the total syngas (these values are from palm shell and cotton stalk pyrolysis respectively). The other dominant gas species produced from all feedstocks were carbon monoxide (CO), methane (CH_4) and (H_2). Small concentrations of other hydrocarbon (HC) species were present in varying quantities. All of these gases, except CO_2, can be used as a fossil fuel offset source either at the pyrolysis plant or elsewhere, although some upgrading may be required to increase the CV per unit of gas which would incur an energy penalty.

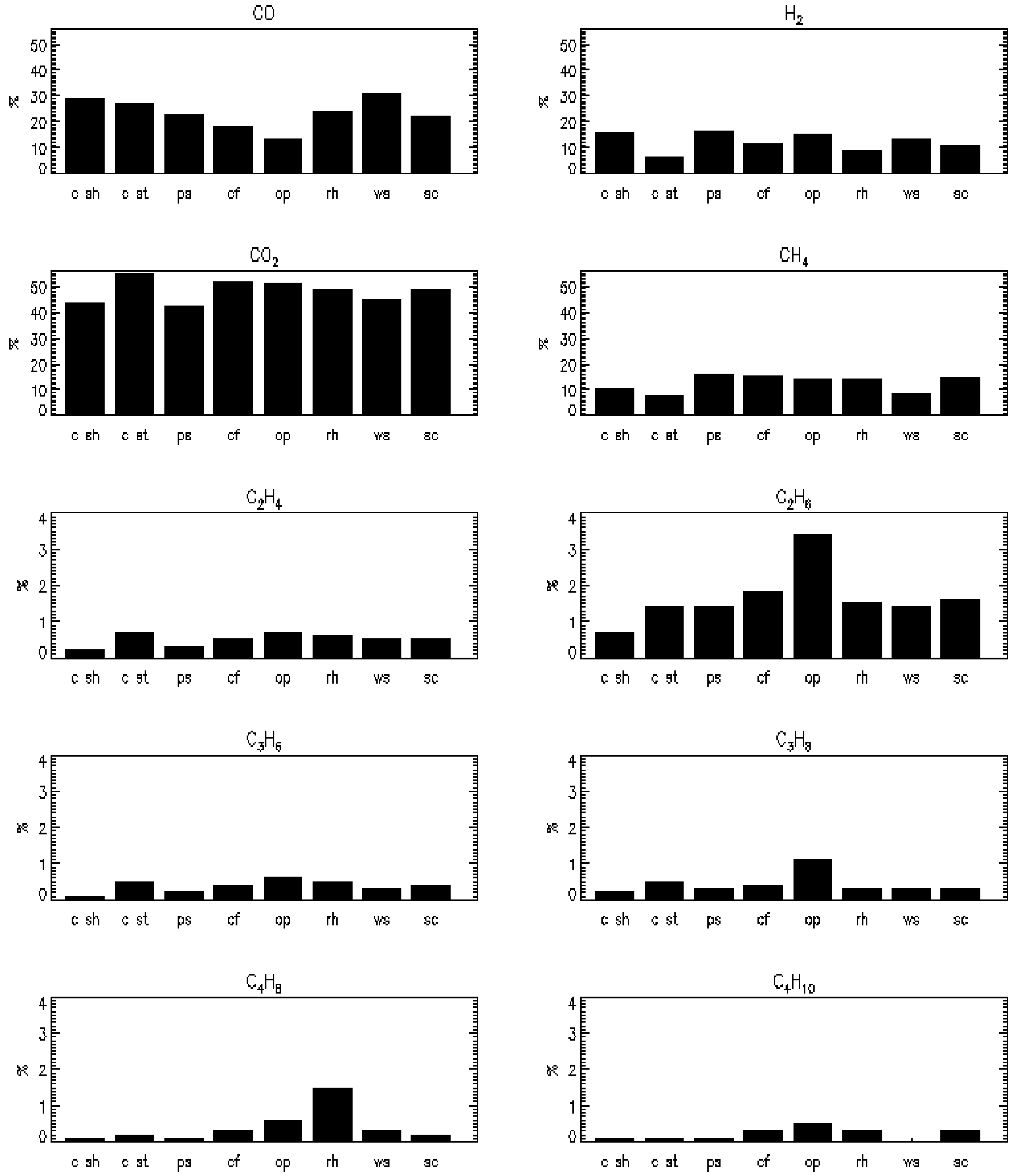

Figure 4-10: Gas species concentration (%) for the syngas produced from each feedstock. Gas species detrmined are carbon dioxide (CO_2); permanent gases: hydrogen (H_2) and carbon monoxide (CO); and hydrocarbon gases: methane (CH_4), ethene (C_2H_4), ethane (C_2H_6), propene (C_3H_6),propane (C_3H_8), butene (C_4H_8), butane (C_4H_{10})). Feedstocks are: coconut shell (c sh), cotton stalk (c st), palm shell (ps), coconut fibre (cf), olive pomace (op), rice husk (rh), wheat straw (ws) and sugarcane bagasse (sc). N.B. Scales vary: some species are displayed on a 0 - 50 % scales, whilst others are displayed on a 0 – 4 %.

4.6 The effects of pyrolysis conditions on product yields and characteristics

The standard pyrolysis conditions used to explore the effect of feedstock on biochar yields and characteristics were varied to examine the effects of alternative pyrolysis conditions, particularly peak temperature and heating rate. One feedstock type, sugarcane bagasse, was pyrolysed under final temperatures of 400 ^{o}C, 600 ^{o}C and 800 ^{o}C, and heating rates of 5 ^{o}C min^{-1}, 20 ^{o}C min^{-1} and 50 ^{o}C min^{-1}. These alternative pyrolysis conditions used are discussed in more detail in Section 3.2.2 and Table 3-1.

Table 4-3: Characteristics of biochars produced from the slow pyrolysis of sugarcane bagasse under different pyrolysis temperature and heating rate regimes. The results attained at 600 ^{o}C and 5 ^{o}C min^{-1} are those determined under standard conditions to allow for comparison of the effects of altered conditions against the standard conditions.

		Final temperature (^{o}C)			**Heating rate (^{o}C min^{-1})**		
Characteristics	Units	400	600	800	5	20	50
Product Yields							
biochar	%	34.0	27.7	23.0	27.7	23.3	22.8
oil	%	49.0	50.3	44.0	50.3	59.5	56.2
gas	%	21.8	20.9	24.0	20.9	25.5	19.2
Ultimate Analysis							
C	%	85.0	87.0	81.9	87.0	82.2	81.7
H	%	0.9	2.1	1.0	2.1	2.2	2.2
N	%	0.5	1.3	0.5	1.3	0.6	0.8
S	%	0.1	0.1	0.0	0.1	0.1	0.1
O *(by diff)*	%	17.8	13.2	20.9	13.2	18.5	18.8
H/C		0.1	0.3	0.1	0.3	0.3	0.3
O/C		0.2	0.1	0.2	0.1	0.2	0.2
Proximate Analysis							
moisture	%	4.1	3.7	4.1	3.7	3.6	3.5
volatiles *(daf)*	%	28.1	30.1	17.2	30.1	29.3	18.0
carbon *(daf)*	%	71.9	69.9	82.8	69.9	70.7	82.0
ash *(db)*	%	14.5	15.5	16.5	17.5	18.5	19.5
Other Characteristics							
HHV	MJ kg^{-1}	30.0	30.1	31.1	30.1	32.5	30.8
Total pore volume	cc g^{-1}	0.0	0.2	0.0	0.2	0.0	0.1
Surface Area (BET)	M_2 g^{-1}	2.8	149.1	15.7	149.1	77.6	110.4
pH		6.9	8.6	10.6	8.6	9.2	9.2
stored carbon	%	63.0	53.5	41.0	53.5	41.8	40.6
R_{50}		0.47	0.51	0.56	0.51	0.52	0.51
CS (sequestration potential)	%	29.6	27.3	23.0	27.3	21.7	20.7

4.6.1 Product yields

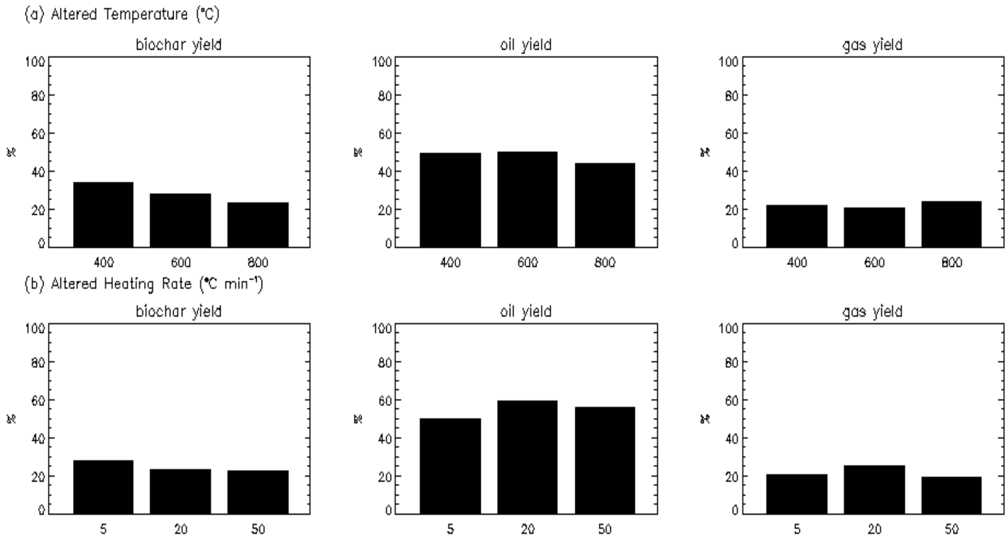

Figure 4-11: Yields of biochar (left), bio-oil (centre) and syngas (right) from the pyrolysis of sugarcane bagasse at (a) temperatures of 400 °C, 600 °C and 800 °C and (b) heating rates of 5 °C min^{-1}, 20 °C min^{-1} and 50 °C min^{-1} at 600 °C.

Biochar yields decreased with increasing temperature, with a clear trend seen in Figure 4-11. This can be linked to the evolution of more semi-volatile and volatile material from the biochar at increasing temperatures. Biochars produced at 400 °C may not be fully charred (Williams and Besler, 1996), potentially leading to higher degradation rates, upon addition to soil, than fully charred material. Biochar yield also decreased slightly with increasing heating rate, although this effect was not as pronounced as that of peak temperature. Bio-oil production increased slightly as temperature increased from 400 °C to 600 °C indicating the evolution of higher-molecular weight hydrocarbon species from the biomass, occurring at ~ 500 °C (Neves et al., 2011). 600 °C is not sufficient to convert many of these hydrocarbons to gaseous species. 50.3 % bio-oil yield was achieved from pyrolysis of sugarcane bagasse at peak temperature of 600 °C, with 49 % and 44 % yields achieved at 400 °C and 800 °C respectively. Oil yields decreased at 800 °C indicating the presence of secondary reactions at higher pyrolysis temperatures, for example the increased breakdown of the high-molecular weight species into lower molecular weight gaseous species. A heating rate of 20 °C min^{-1} increased oil yields by almost 10 % to 59.5 %. Further increase to 50 °C min^{-1} caused a reduction in yields. Gas yields followed the opposite trend, seeing a slight yield decrease when peak temperature was increased from 400 °C to 600 °C, and a yield increase when peak temperature was increased to 800 °C. Again, this is due to the higher pyrolysis temperatures breaking down more higher-molecular weight species into gaseous products. Gas production was highest at the heating rate of 20 °C min^{-1} and lowest at 50 °C min^{-1}. A pyrolysis heating rate of 20 °C min^{-1} was optimal for both oil and gas yields. In addition to impacts on yields, biochar, oil and gas characteristics may also vary with pyrolysis conditions. Sections 4.6.2 to 4.6.7 examine variance in biochar conditions with pyrolysis conditions. Effects on the composition syngas are discussed in Section 4.6.8.

4.6.2 Proximate analysis

Proximate analysis determined the moisture, volatile, fixed carbon and ash content of the biochars from sugarcane bagasse.

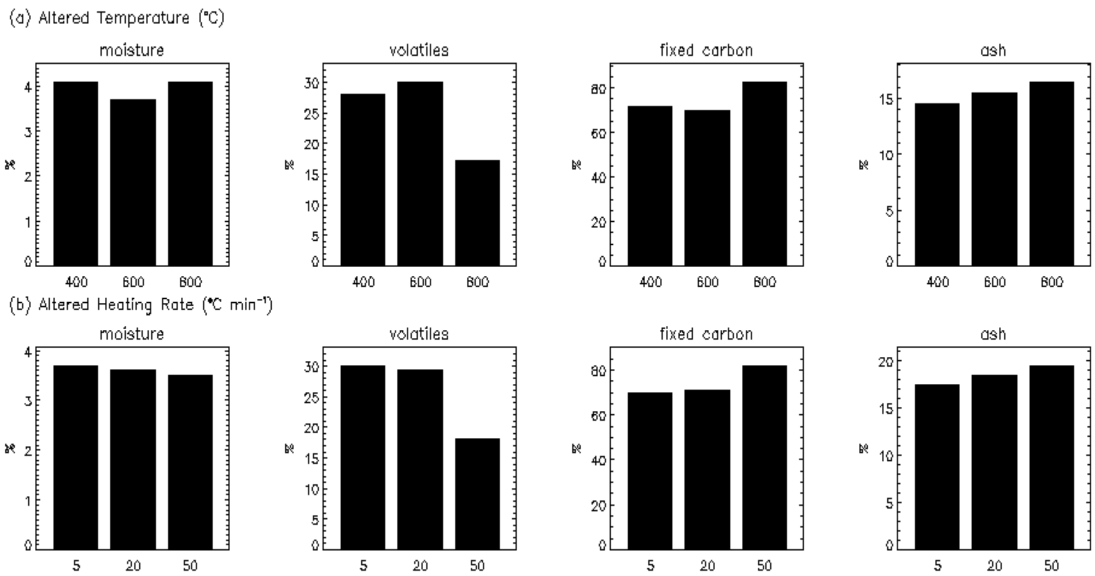

Figure 4-12: Proximate analysis (moisture, volatiles, fixed carbon and ash content (left to right)) of (a) biochars produced from the pyrolysis of sugarcane bagasse at temperatures of 400 °C, 600 °C and 800 °C (top) and (b) heating rates of 5 °C min^{-1}, 20 °C min^{-1} and 50 °C min^{-1} (bottom) at 600 °C. N.B. Scales vary between characteristics.

Biochar moisture content was initially reduced as peak temperature was increased from 400 °C to 600 °C, and then increased at 800 °C. It was also reduced by increasing heating rate. There was a slight increase in biochar volatile concentration at 600 °C, relative to that of 400 °C, and then a marked decrease in volatile content at 800 °C. This may be explained by the secondary pyrolysis processes discussed by Neves et al. (2011) and discussed in Section 4.6.1. As temperatures are raised above ~ 500 °C secondary processes including polymerisation may cause volatiles to be reformed on the biochar. As temperature is increased further the likelihood of cracking and the evolution of volatile species from the biochar increases, resulting in the lower volatile content seen at 800 ^{o}C. Fixed carbon content was initially reduced very marginally (-2 %) by the increase peak temperature to 600 ^{o}C then increased by a further 12.7 % at 800 ^{o}C. This indicates the removal of other species from the biochar and the increased aromaticity of the biochar structure at higher temperatures. Although biochar yields were reduced at 800^{o}C , the fixed carbon proportion of this biochar increased. Ash content increased with both increased peak temperature and heating rate, with a range of 2 % between biochars produced at the highest and lowest of each pyrolysis condition tested. This indicates that ash is concentrated within the biochar as other species, such as volatiles, are evolved from the biochar with both increasing temperature and heating rate.

4.6.3 Ultimate analysis

Ultimate analysis determined the carbon, hydrogen, nitrogen, sulphur and oxygen content of the sugarcane bagasse biochars.

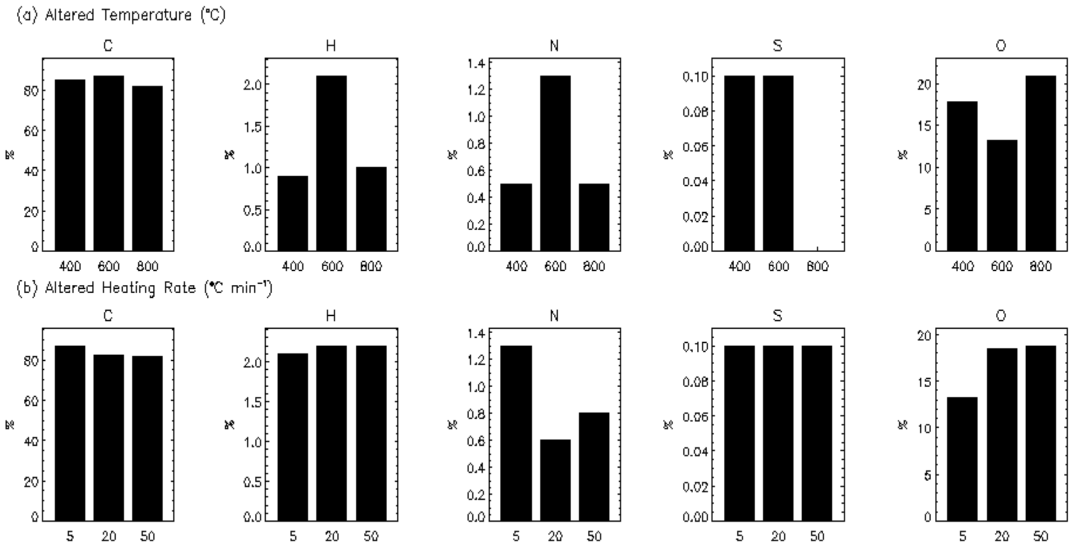

Figure 4-13: Elemental composition (carbon (C), hydrogen (H), nitrogen (N), sulphur (S) and oxygen (O) content (%) (left to right)) of biochars produced from the pyrolysis of sugarcane bagasse at peak final temperatures of 400 ^{o}C, 600 ^{o}C and 800 ^{o}C (top) and heating rates of 5 ^{o}C min^{-1}, 20 ^{o}C min^{-1} and 50 ^{o}C min^{-1} (bottom). N.B. scales vary between elemental species.

A slight increase of 2 % was seen in carbon content with increasing peak temperature from 400 ^{o}C to 600 ^{o}C. Further increase to 800 ^{o}C decreased elemental carbon by 5.1 %. This is different from the trend seen by proximate analysis for fixed carbon content (Figure 4-12). It was expected that elemental carbon content would continue to increase with increasing temperature, therefore further investigation of sugarcane bagasse biochar produced at different temperatures would be beneficial, but was not possible within the timescale of this study. Elemental hydrogen and nitrogen concentrations increased markedly as peak temperature was increased from 400 ^{o}C to 600 ^{o}C, reducing to near 400 ^{o}C concentrations as peak temperature was increased further to 800 ^{o}C. Again this may correlate with the increased volatile content of biochars produced at 600 ^{o}C (Figure 4-12). Oxygen content of the biochars was reduced and then increased as peak pyrolysis temperature was increased from 400 ^{o}C to 600 ^{o}C and 800 ^{o}C, at 17.8 %, 13.2 % and 20.9 % respectively. High oxygen content in the biochar produced at 800 ^{o}C may be attributable to inorganic oxygen content in ash (Brewer et al., 2009). Sulphur concentration was 0.1 % for biochars produced at both 400 ^{o}C and 600 ^{o}C, reducing to 0 % at 800 ^{o}C. The sulphur contents were low, in comparison to that of coal, potentially making biochar a suitable low sulphur fuel. Removal of the sulphur at peak temperature between 600 ^{o}C and 800 ^{o}C can be related to the evolution of sulphur as hydrogen sulphide (H_2S) in syngas with increasing temperature (Cheah et al., 2014).

Increasing the pyrolysis heating rate resulted in a small reduction in elemental carbon content, with a reduction of 3.1 % seen between carbon in biochars produced at the lowest and highest heating rates. The carbon reduction with increased heating rate follows the same trend as the reduction in biochar yield. This may mean that slightly more elemental carbon is removed from the feedstock as volatile matter during pyrolysis with increasing heating rate. Hydrogen and sulphur contents were largely unaffected by heating rate. Nitrogen content reduced from 1.3 % to 0.6 % when heating rate was increased from 5 ^{o}C min^{-1} to 20 ^{o}C min^{-1}, then increased slightly to 0.8 %, at 50 ^{o}C min^{-1}. Oxygen content was increased with increasing heating rate, from 5 ^{o}C min^{-1} to 20 ^{o}C min^{-1} and then remained unaffected with a further increase in heating rate to 50 ^{o}C min^{-1}.

Where peak pyrolysis temperature was increased from 400 ^{o}C to 600 ^{o}C the ratio of H/C was increased from 0.1 to 0.3 and then reduced again to 0.1 at 800 ^{o}C.

4.6.4 pH

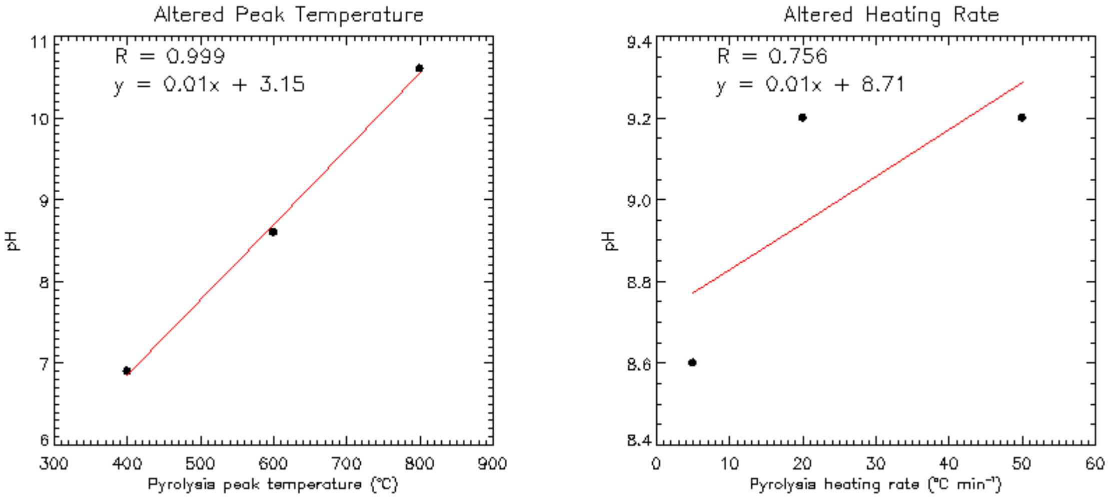

Figure 4-14: Biochar pH in biochars produced from sugarcane bagasse at the different peak pyrolysis temperatures (left) and heating rates (right).

Biochar pH increased from 6.9 to 10.6 in the biochars produced at peak temperatures of 400 °C and 800 °C respectively. The r^2 value of 0.997 ($p = 0.03$) indicates an almost perfect correlation between pyrolysis temperature and biochar pH. The significance of this correlation analysis would benefit from a larger sample size. The increase in pH of 3.7 seen across the range of peak pyrolysis temperatures (400 °C) indicates that each 10 °C increase in pyrolysis temperature would result in an increase in biochar pH of 0.09. Biochar pH showed a smaller increase with increasing heating rate, being pH 8.6 and 9.2 in the biochars produced at 5 °C min^{-1} and 50 °C min^{-1} respectively. The increase in pH seen with temperature may be related to the increasing ash and alkali species content in the higher temperature biochars (Figure 4-12, Figure 4-16 and Section 4.3.8). The increasing ash content and pH of biochars with increasing peak temperature and heating rate was consistent with the discussion of Enders et al. (2012) who reported a relationship of increasing biochar ash content and pH. They did not find correlation with any individual alkali metal or alkali earth metal species. The rate of increase in pH seen here with increasing temperature, in relation to that of increased hearing rate, could be explained by the larger increases seen in potassium, magnesium and calcium seen with increasing temperature than with increases in heating rate (Section 4.6.7). When examining the effects of feedstock characteristics on biochar pH in Section 4.3.8, biochar pH was positively correlated with concentrations of potassium in the eight different feedstock types and resulting biochars. These correlations between the potassium content and pH of biochars from different feedstocks indicate that the increased potassium content seen with increasing pyrolysis temperature, and to a lesser extent with increasing heating rate, may be related to the increased pH values seen here.

4.6.5 Surface area

Surface area increased markedly, from 2.8 m^2 g^{-1} to 149 m^2 g^{-1} when final pyrolysis temperature was increased from 400 ^oC to 600 ^oC. Pagnanelli et al. (2008) discuss the temperature dependent evolution of volatile matter from pore spaces, causing an increase of biochar surface area through unblocking of the pore spaces. Increasing peak temperature further to 800 ^oC reduced surface area to 15.7 m^2 g^{-1}. The reduction seen at 800 ^oC may be related to a breakdown of structure at high temperatures. Uchimiya et al. (2011) reported a breakdown in biochar structure at higher temperatures, resulting in a drastically lowered surface area. The breakdown of biochar structure was related to the lignin content of biochars, with the structure of lower lignin biochars degrading at lower temperatures. They reported this effect at temperatures above ~ 900 ^oC. The results here indicate that this effect may occur at lower temperatures (~800 ^oC) for some biochars. Sugarcane bagasse has typically low lignin content, when compared to feedstocks such as palm shell (Table 4-1). Future research into the magnitude of this effect in other feedstocks, and at a wider range of peak pyrolysis temperatures would be beneficial. Surface area was reduced from 149 m^2 g^{-1} to 77.6 m^2 g^{-1} by an increase in heating rate to 20 ^oC min^{-1}. Surface area was increased again, to 110.4 m^2 g^{-1} with a heating rate of 50 ^oC min^{-1}. These results imply that heating rate may have some effect on biochar surface area, though these effects were not as marked as those seen with increasing temperature.

4.6.6 Biochar recalcitrance

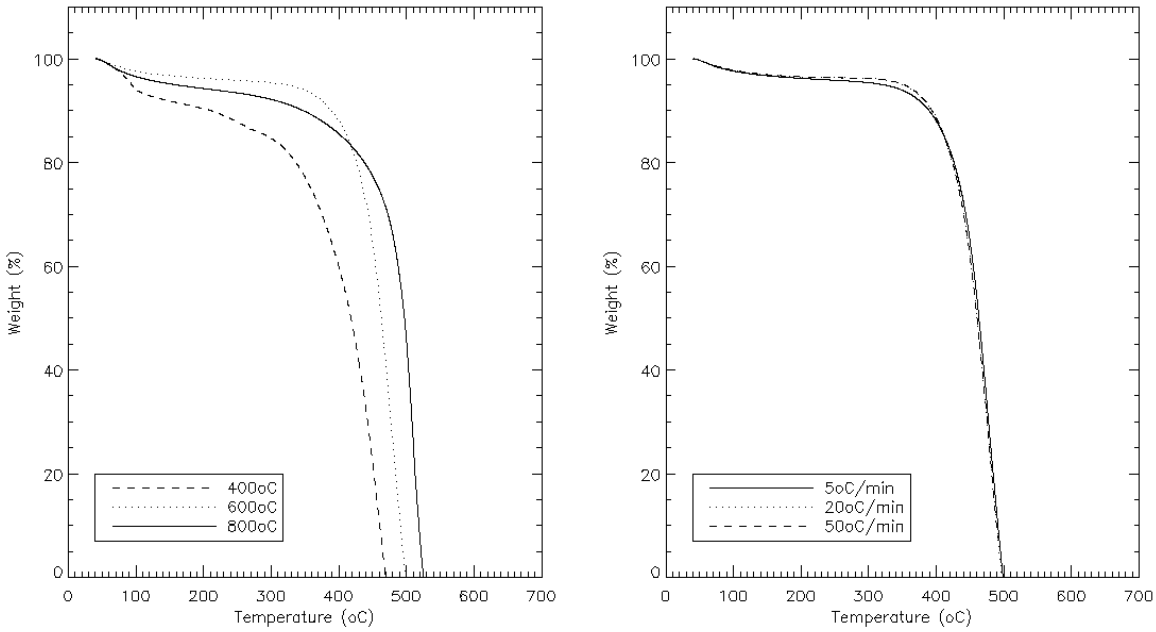

Figure 4-15: Temperature programmed oxidation (TPO) profiles of biochars produced from (a) sugarcane bagasse at pyrolysis temperatures of 400 °C, 600 °C and 800 °C (left) and (b) heating rates of 5 °C min^{-1}, 20 °C min^{-1} and 50 °C min^{-1} (right). Thermograms were corrected for moisture and ash following the method of Harvey et al. (2012).

Biochars produced from sugarcane bagasse at higher peak pyrolysis temperatures showed increased oxidation temperatures (Figure 4-15). This was reflected in the recalcitrance index R_{50} values of the biochars, which increased from 0.47 to 0.56 for biochars produced at 400 °C and 800 °C respectively. This reclassified the sugarcane bagasse biochar from Class C of the R_{50} classification index where the biochar is 'most susceptible to degradation', to Class B with 'some susceptibility to degradation' (Harvey et al., 2012). This increase in oxidation temperature and subsequent R_{50} may be indicative of increased aromaticity with increasing peak pyrolysis temperature. Heating rate did not have an effect on the oxidation temperature of the sugarcane bagasse biochars, indicating that heating rate does not significantly affect the aromaticity or stability of the biochars. The R_{50} values were very similar for all three biochars produced at different heating rates.

The carbon sequestration (CS) potential of the biochars did not exhibit the same relationship with peak pyrolysis temperature as seen between biochar R_{50} and pyrolysis temperature (Table 4-3). CS potential is also related to biochar yield and carbon retained from that of the original feedstock. Although the biochars produced at higher temperatures may have higher R_{50} values, containing carbon which is more stable, the production of larger quantities of biochar at lower pyrolysis temperatures and slower heating rates resulted in biochars with higher CS potentials. The biochar produced at 5 ^{o}C min^{-1} heating rate had the highest CS potential of the three biochars assessed due to higher biochar yield combined with higher carbon content.

Harvey et al. (2012), through examining the R_{50} value of a number of biochars and the amount of carbon mineralization which has occurred after 1 year, determined that between 0.8 % and 3 % of a Class C biochar would be mineralized after 1 year, compared with 0.2 % to 1.3 % of a Class B biochar. This indicates that although increasing the temperature of pyrolysis would reduce the amount of carbon added to soil in biochar, this would also reduce the carbon mineralised over time after soil addition. Discussion regarding mineralization rates of biochar by Cheng et al. (2008) and Foereid et al. (2011) indicates that the degradation of biochar may occur at two rates, which is often modelled as a ‘two pool’ method (Section 2.2.5.2). Degradation initially occurs at a fast initial rate until any labile fraction is degraded, and the remaining recalcitrant fraction then degrades over much longer timescales. Foereid et al. (2011), for example, determined that carbon mineralization over timescales of 2, 100 and 2000 years would see 9.8 %, 11.7 % and 20.7 % of biochar degraded respectively. This highlights rapid initial degradation, followed by a marked reduction in degradation rate over time. This implies that, where biochars are produced solely for carbon storage purposes, the required timescale for carbon storage must be considered when determining which pyrolysis conditions should be used. Where a storage period of decades to hundreds of years is required then a Class C biochar produced at 400 ^{o}C may be sufficient, whereas if carbon storage of thousands of years is required then higher pyrolysis temperatures, resulting in lower initial carbon quantities, may be necessary.

4.6.7 Macro-nutrient content

Pyrolysis peak temperature and heating rate affected the concentrations of some macro-nutrient species in biochars produced from sugarcane bagasse, whilst having little or no effect on other species.

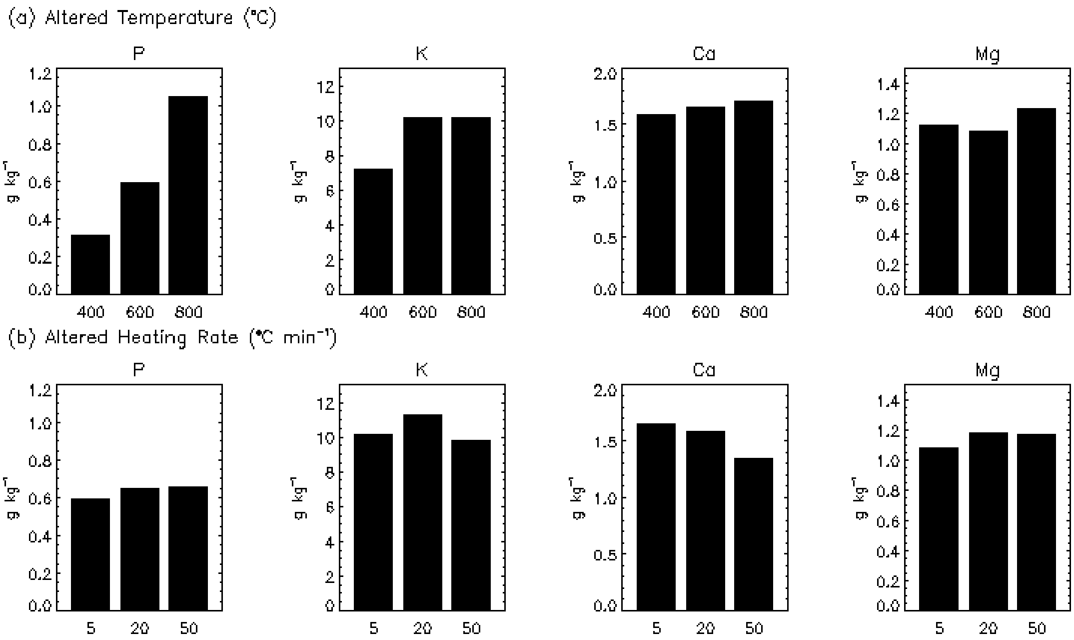

Figure 4-16: Macro-nutrient content (g kg^{-1}) (dry basis) of sugarcane bagasse biochars produced under (a) different pyrolysis temperature regimes and (b) different pyrolysis heating rate regimes. Macro-nutrient species shown (left to right) are phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg). N.B. Scales vary between nutrient species.

Most notably, biochar phosphorus concentration was increased with increasing pyrolysis temperature. Hossain et al. (2011) related increasing phosphorus content and pyrolysis temperature to the inorganic nature of the phosphorus contained within the feedstock, meaning phosphorus is retained and concentrated with pyrolysis. A similar but smaller trend was seen with calcium concentration. Potassium content increased as peak temperature was increased from 400 °C to 600 °C, but no further increase was seen at 800 °C, perhaps due to the onset of volatilisation. A small decrease in calcium concentration was seen with increasing heating rate which may indicate that calcium is increasingly evolved from the biochar at faster pyrolysis heating rates.

4.6.8 Gas characteristics

As well as affecting yields, changing the peak temperature of the pyrolysis process also affected the composition of the syngas produced. Calorific value of the syngas from sugarcane bagasse increased with increasing peak pyrolysis temperature from 6.6 MJ m^{-3} at 400 °C, to 14.5 m^{-3} at 800 °C. This was attributed to reductions in CO and CO_2 production and increases in production of H_2, CH_4 and other hydrocarbon species.

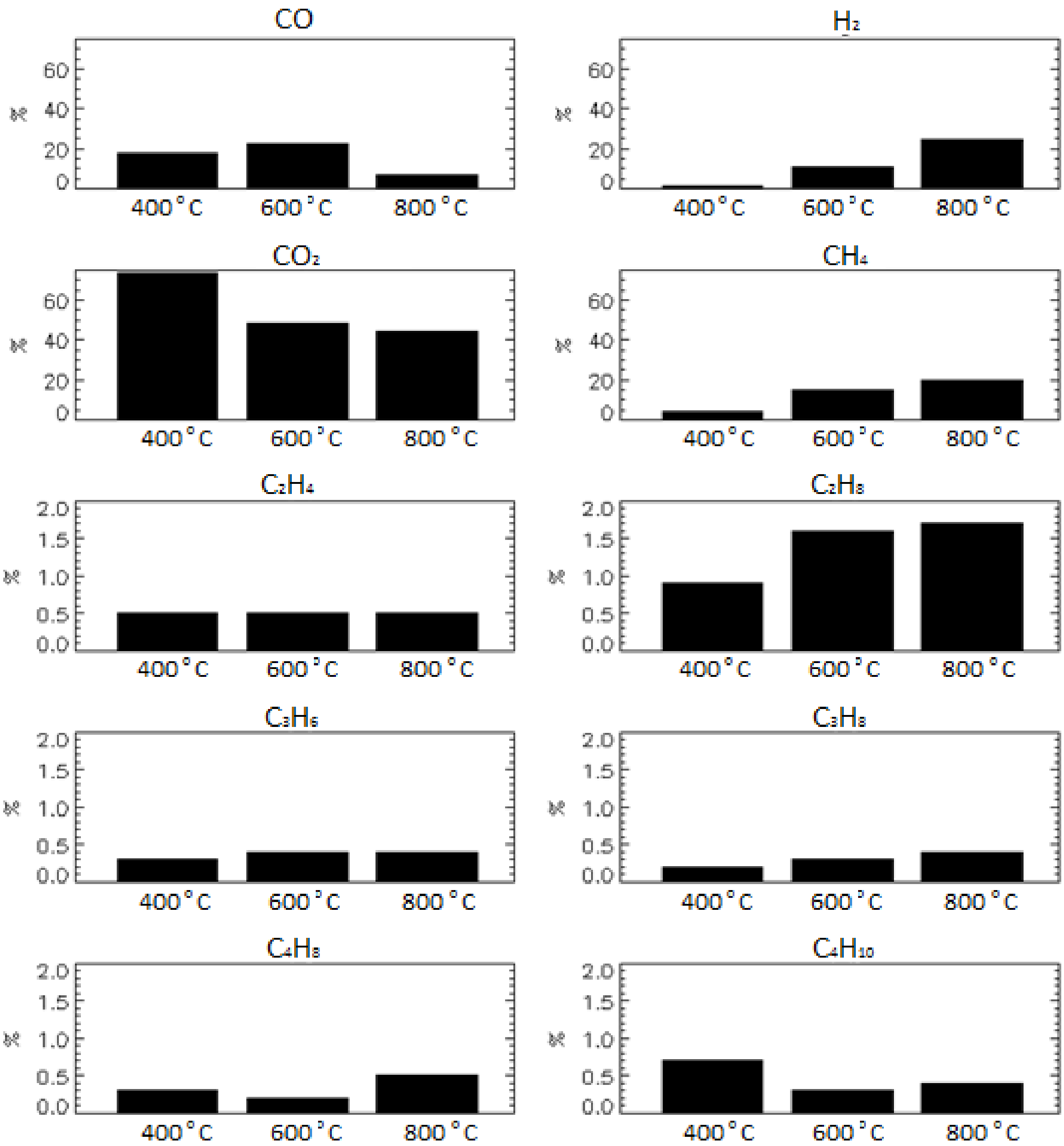

Figure 4-17: Syngas composition (%) from the pyrolysis of sugarcane bagasse at different pyrolysis peak temperatures of 400 °C, 600 °C and 800 °C. Gas species determined are carbon dioxide (CO_2); permanent gases: hydrogen (H_2) and carbon monoxide (CO); and hydrocarbon gases: methane (CH_4), ethene (C_2H_4), ethane (C_2H_6), propene (C_3H_6), propane (C_3H_8), butene (C_4H_8), butane (C_4H_{10})). N.B. Scales vary between gas species.

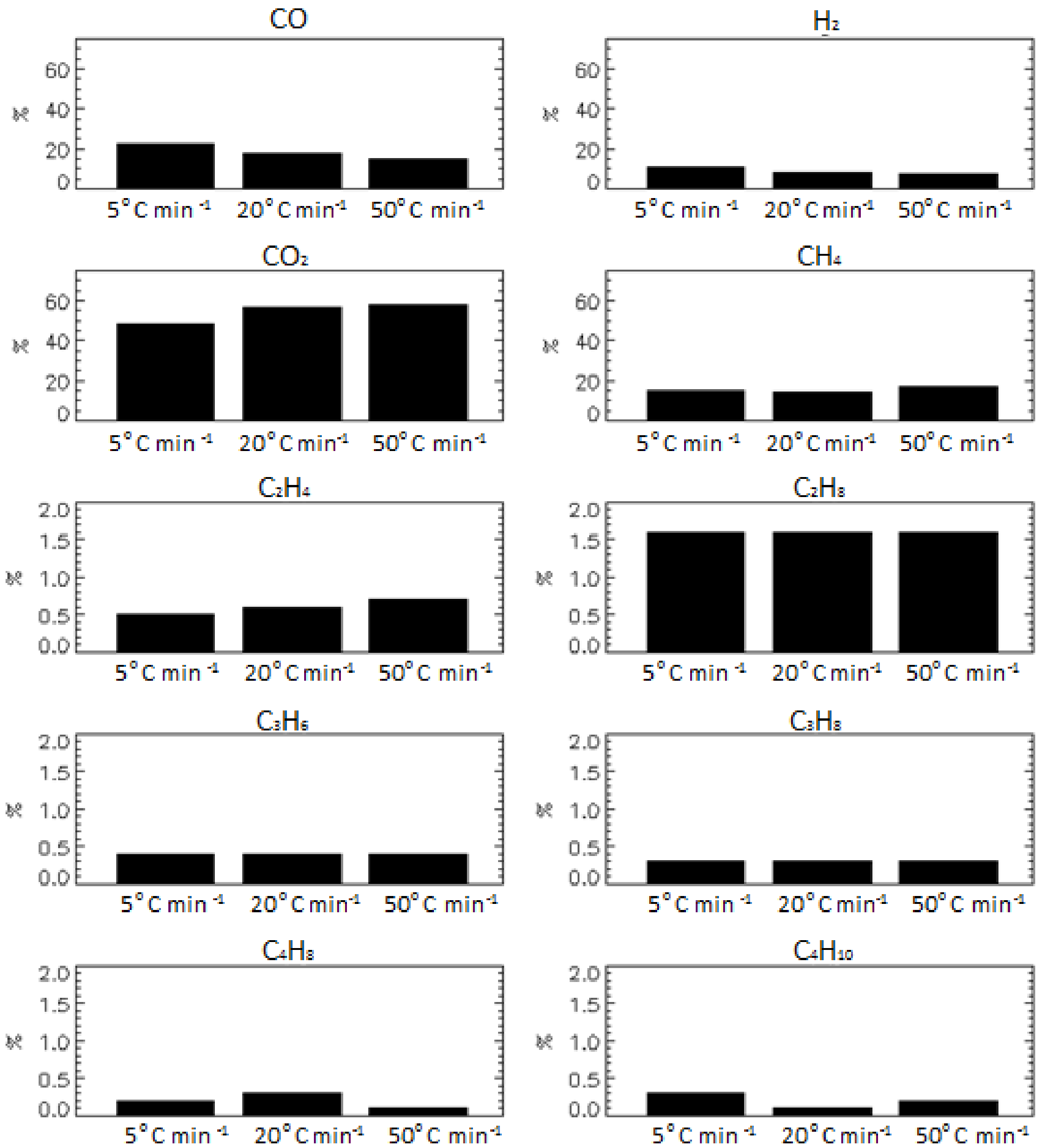

Figure 4-18: Syngas composition (%) from the pyrolysis of sugarcane bagasse at different pyrolysis heating rates of 5 °C min^{-1}, 20 °C min^{-1}, and 50 °C min^{-1}. Gas species determined are carbon dioxide (CO_2); permanent gases: hydrogen (H_2) and carbon monoxide (CO); and hydrocarbon gases: methane (CH_4), ethene (C_2H_4), ethane (C_2H_6), propene (C_3H_6), propane (C_3H_8), butene (C_4H_8), butane (C_4H_{10})). N.B. Scales vary between gas species.

Increasing the peak temperature of pyrolysis increased the production of hydrogen (H_2), methane (CH_4), ethane (C_2H_6) and propane (C_3H_8) within the syngas. Production of carbon dioxide (CO_2) was reduced with increasing peak temperature, with a large decrease of 25 % seen as peak temperature increased from 400 °C to 600 °C and a further decrease of 3.8 % at 800 °C. Carbon monoxide (CO) production increased slightly as peak temperature was increased from

400 ^{o}C to 600 ^{o}C, but was then reduced by 15.5 % as peak temperature increased to 800 ^{o}C.Increasing heating rate led to increased CO_2 production and reduced production of CO and H_2. CH_4 production was increased at 50 ^{o}C min^{-1} after an initial reduction when conditions were altered from 5 ^{o}C min^{-1} to 20 ^{o}C min^{-1}. A number of hydrocarbon species were not affected by changing heating rate, including C_2H_6, C_3H_6 and C_3H_8. Due to the minimal increase seen in CH_4 production combined with the increase in CO_2 and slight decreases seen in CO and H_2, the optimum heating rate for production of a gas useful for energy utilization, of those assessed here, was 5 ^{o}C min^{-1}.

4.7 Limitations and opportunities for further work

The nature of experimental work carries a risk of human or technical error introducing error into the results. Mass balances were calculated for each pyrolysis experiment in order to reduce the potential for experimental error, with a ± 5 % allowance made. Any experiments having a mass balance outside this were discarded and repeated. A wood chip feedstock was pyrolysed three times under standard conditions to check that variation between results was acceptable. Other experimental methodology was conducted using tested methodology which was, where possible, peer reviewed. All experimental equipment, such as gas chromatographs and pH meters were calibrated before use. All results were considered against trends and the wider literature, with anomalous results scrutinised to determine whether experimental or data reporting error was the causal factor.

The study assessed the characteristics of agricultural residues and their resulting biochars. This was due to the later focus of this research on the global potential of crop residue biochars to sequester carbon. The biochar characterisations made here are not, therefore, representative of biochar characteristics produced from other biomass feedstocks such as animal or municipal wastes. The results detailed here have been discussed in the context of the wider literature where possible, including that of biochars produced from other feedstocks. Analysis of other feedstock types using the methodology detailed in Chapter 3 would further add to the literature.

This research also offers insight into the effects of pyrolysis conditions on pyrolysis yields and conditions, but could be expanded in a number of areas to offer further insight. The alternative pyrolysis conditions were applied here to one feedstock type, sugarcane bagasse. This, whilst offering insight into the effects of pyrolysis conditions, may not be representative of the behaviour of other feedstocks under the alternative pyrolysis conditions. This could be explored in future research, to supplement the current literature, by assessing a number of other feedstocks under the different pyrolysis conditions used here. Three variations were explored within this research for each of the pyrolysis conditions explored. It would be useful to widen the ranges of pyrolysis conditions explored outside those examined here. Determining any threshold temperatures which may have large impacts on a particular characteristic, for example determining whether a threshold peak temperature exists for the breakdown of biochar structure would also be a useful addition to this research. The limited number of pyrolysis conditions explored (i.e. three peak pyrolysis temperatures and three heating rates on one feedstock type) makes inference of correlations between experimental variables and product characteristics difficult, although the results here are indicative of relationships which could be further investigated. Whilst correlation analysis has been used to suggest potential relationships, an increase in sample size would help to further define these relationships.

4.8 Summary and conclusions

Biochars from eight crop residues exhibited variation in a number of characteristics. Under the standard pyrolysis conditions biochar yields were 28 wt % to 39 wt %, with relationships seen between biochar yield and ash content of both feedstock and biochar. Overall, the nutrient contents of the feedstocks and biochars were low, with the majority of nutrient species being concentrated during pyrolysis. Biochar pH range (pH 6.1 to pH 11.6) showed the majority of biochars were slightly alkaline, with relationships seen between K content and pH. A strong correlation indicated a relationship between increased peak pyrolysis temperature and increased biochar pH. The average carbon quantity retained in biochar from the original feedstock carbon was 51 %. This stored carbon decreased with increasing peak pyrolysis temperature and to a lesser extent with increased heating rate, although recalcitrance of the remaining carbon increased with increasing peak temperature. High lignin feedstocks produced high carbon biochars with high recalcitrance. Feedstock and biochar H/C and O/C ratios indicated increasing aromaticity upon charring. The biochars were either moderately or more highly degradable, with palm shell and wheat straw biochars having the highest and lowest recalcitrance values respectively. None of the biochars were of the most recalcitrant classification. Recalcitrance values for biochars with high alkali content were found to be conservative due to lowering of the oxidation temperature by these alkali species. CS potentials of the biochars were between 21.3 % and 32.5 %, and were affected by the yields of biochar and carbon content, as well as the stability of this carbon. CS potential of the biochars were decreased by increasing both peak pyrolysis temperature and heating rate.

Oil yields were between 33.5 % and 53.6 %. The oil produced would be likely to require upgrading, due to high water and oxygen content, before it would be a useful fuel source.

Syngas yields ranged from 17.6 % to 29.2 %. All of the syngases produced contained some hydrocarbon species alongside CO and H_2 which could all be utilised for energy purposes. The most dominant species in each syngas was CO_2. CO_2 content was decreased by increasing peak pyrolysis temperature, with quantities of H_2 and some hydrocarbon species increasing concurrently. This corresponded to an increase in syngas CV. CVs of the oil and gas products were considerably lower than their fossil-fuel alternatives (fuel oil and natural gas). Their energy could still be utilised as a fuel source, after some upgrading, to fuel the pyrolysis process or fulfil other fuel requirements. Any bio-oil and syngas produced within a biochar system would also represent carbon neutral emissions (disregarding any transport of feedstock or fuel to point of use) which could help to reduce emissions if replacing a fossil-fuel energy source.

In conclusion, much variability is seen in biochars which can be attributed to both feedstock variability and the influence of process conditions. Producing a biochar of particular characteristics requires consideration of both of these factors, though some characteristics may be influenced more by feedstock characteristics or process conditions than others. A number of characterisations were made here which can be used to select feedstocks or process conditions to produce biochars with particular traits. The R_{50} index is a useful tool to estimate the stability of biochar carbon. Knowledge of the alkali content of a biochar would enable assessment of whether its R_{50} value is a conservative estimate for that biochar. The long term CS potential of the biochars is also a useful tool for determining which biochars would be useful in biochar systems designed for carbon storage. The CS potential, dependent on the biochar yields, carbon content and stability can be used in the assessment of biochar scenarios for carbon sequestration, although a number of other considerations such as the availability of feedstock also need to be accounted for.

5 Biochar production potential within the RCPs: Methodology

5.1 Introduction

Chapter 4 discusses the potential yields and characteristics of biochars produced from a number of agricultural residues. This research and literature such as Shackley et al. (2010) and Lehmann et al. (2009) indicates that biochar from crop residues has substantial carbon content and that this carbon may have a high stability over long periods, alongside having other characteristics which may be beneficial to soils and plant growth. Discussion within Chapter 4 highlights that there can be a large amount of variability between different biochars, and often a large element of uncertainty regarding biochar characteristics and the effects of biochars in soils. Chapters 5 and 7 detail the development of a framework for the global assessment of the long-term potential for biochar production to sequester carbon in soils. The framework uses data reported in Chapter 4 alongside other current knowledge of biochar characteristics and behaviour in soils. A number of scenarios were created to explore the effects of current uncertainty and variability in biochar systems on biochar production and carbon storage potential.

Within the literature few projections have been made for the potential of carbon sequestration using biochar. Section 2.3 discusses a number of projections detailed in the literature and discusses the strengths and limitations of these previous studies. One major limitation of the current literature on carbon sequestration using biochar, as a whole, is that the current literature does not investigate in detail the effects of future changes in land use and related socio-economic metrics on biochar potential. Most studies instead use static current scenarios of land-use, or very closely related land distributions. One example of this is the study by Woolf et al. (2010) which estimates a theoretical upper potential of biochar for climate change mitigation under current conditions. Although their study aims to assess a potential for future mitigation, the only land-use conversion considered within the study is of the production of dedicated 'biomass for biochar' crops on currently abandoned or degraded agricultural land. Further to this, their study does not consider the potential impact of changing agricultural land area over time, only looking at the maximum potential under existing land-use regimes. It is highly unlikely that land use will remain unchanged into the future, therefore alternative scenarios must be explored (Alcamo et al., 2008). Efforts to model potential future changes in land-use are reliant on a number of assumptions, both physical and socio-economic in nature, which results in a number of uncertainties within the scenarios. In addition to considering only current land-use, the study by Woolf et al. (2010) does not consider the effect of changing climate on biochar production potential or stability in soils. This is another area which should be investigated as potential manifestations of climate change, including changes in temperature and precipitation, may impact on biochar scenarios.

The Representative Concentration Pathways (RCPs) are one set of projections, developed by the climate modelling community, which provide pathways of how land use may change under different socio-economic drivers from 2005 to 2100 (van Vuuren et al., 2011a). The pathways also have projections of emissions of gas species such as long-lived greenhouse gases and aerosols which, when combined with the emissions and sinks associated with the land-use pathways, results in projections of changes in radiative forcing. Further discussion of the literature surrounding the background and assumptions of each RCP can be found in Section 2.4.1. and Annexe II.b. Sections within this chapter discuss how the RCP land-use and CO_2 emissions projections were used, alongside the biochar literature and experimental data, for the development of the biochar model and scenarios. Chapter 6 details the resulting projections of future biochar production potential from a number of different scenarios, allowing for analysis of the carbon sequestration potential of the scenarios, which is detailed in Chapters 7 and 8.

5.2 Model overview

An overview of the stages of model development is shown in Figure 5-1 and the details and assumptions of each stage are discussed in Sections 5.2 to 5.5.

Key inputs to our biochar assessment model were baseline production values for 2005, projected yield changes to 2100, and the RCP land use scenarios to 2100, all used to determine potential global agricultural production for cereals crops, fibre crops, sugarcane and oil crops. Residue to product ratios (RPRs) and unused residue coefficients were then applied to agricultural residue feedstock availability for biochar production. Biochar literature and primary experimental data, including biochar yield and carbon content, were applied to determine potential yields of biochar, the carbon content of this biochar and related carbon dioxide (CO_2) values for each year from 2005 - 2100.

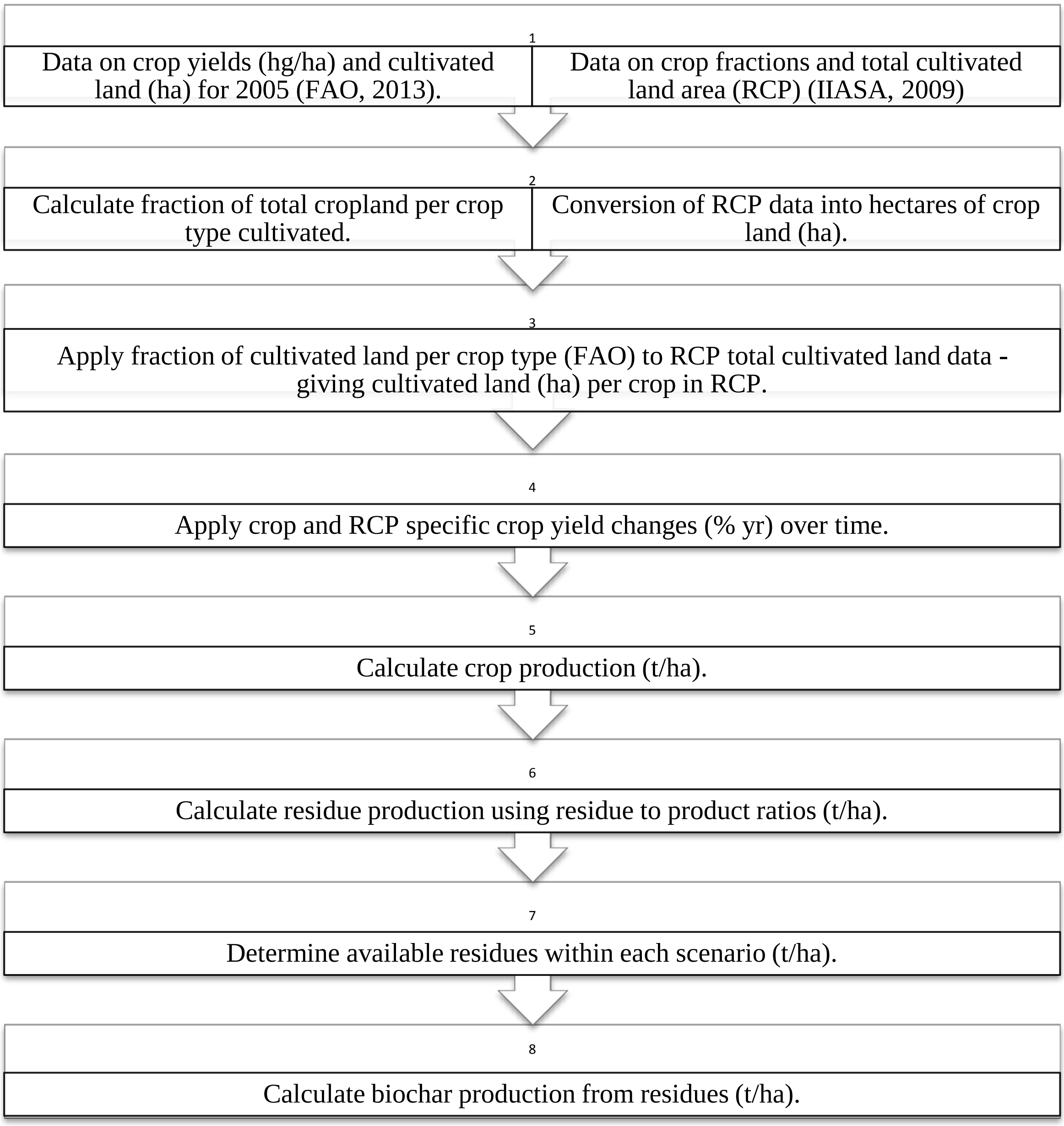

Figure 5-1: Overview of the model stages and inputs used to calculate the biochar production potential for each future scenario. These stages were modified slightly depending on the focus of the sub-scenario under assessment. These modifications are discussed in the relevant summary of individual scenarios.

5.3 Model development

Sections 5.2 to 5.5 detail the model development for the assessment of biochar production potential and carbon content. The subsequent methodology for the assessment of long-term carbon stability within these scenarios is detailed in Chapter 7. The parameters discussed in Sections 5.3.1 to 5.3.8 are those used in Scenario 1 unless otherwise stated. Development of alternative scenario parameters is detailed in Section 5.4.

5.3.1 Dominant crop residues

The first step in model and scenario development involved determining which crops are globally dominant and which, of these dominant crops, produce relatively large quantities of residues which may be used for biochar production. The Food and Agriculture Organisation's (FAO) statistical database (FAOSTAT) was used to analyse commodity production values for different regions of the world (FAO, 2013a).

Table 5-1: The 5 world regions and 22 sub-regions used to determine dominant crop residues, total cropland (ha) and the fraction of this total cropland (where total cropland = 1) cultivated for each crop type. The individual countries within each region are detailed in Annexe II.a.

Region	Sub-region
Africa	Eastern Africa
	Middle Africa
	Northern Africa
	Southern Africa
	Western Africa
Americas	Northern America
	Central America
	Caribbean
	South America
Asia	Central Asia
	Eastern Asia
	Southern Asia
	South-Eastern Asia
	Western Asia
Europe	Eastern Europe
	Northern Europe
	Southern Europe
	Western Europe
Oceania	Australia & New Zealand
	Melanesia
	Micronesia
	Polynesia

A database of crops with high production and high regional importance was constructed to highlight globally dominant crops. Crop yields (in hectograms per hectare (hg ha^{-1})) and the regional land area under crop production, in hectares (ha), were sourced from FAOSTAT for each of the main crop types (FAO, 2013a). The crop yield and production data were both averaged using data for 2004 to 2006 to give an average figure for 2005 excluding any very short term anomalies, for example changes caused by extremes in weather or agronomic conditions, or errors within the statistical collection and reporting system. RPR values were determined from the literature for these crops, determining which crop types yield the largest quantities of residue. Discussion within the literature of global crop residues includes Woolf et al. (2010) who found that 75 % of crop residues in 2001 were from cereal crops and 8 % from sugarcane. Lal (2005) found that 74 % of total residue was cereal residues, 10 % sugar crop residues, and 3 % oil crop residues. Taken together, 87 % of total residue production was from these three crop types. Following this analysis of global residues it was decided to focus on the four crop groups which have the highest potential for global residue production: cereal crops, sugarcane, fibre crops and oil crops. Table 5-2 shows the main crop types within each of the groups examined.

Table 5-2: The five categories of crop groups used within the study and the main crop types within each category, as per FAO (2013b) categorisation.

Crop category	**Main crop types**
Cereals (excluding rice)	Wheat
	Maize
	Sorghum
	Barley
	Rye
	Oats
	Millet
Rice	Rice (paddy)
Sugarcane	Sugarcane
Fibre crops	Cotton
	Jute
Oil crops	Soya beans
	Groundnuts in shells
	Cottonseed
	Linseed
	Mustard seed
	Rape
	Sesame seed
	Sunflower seed
	Olives
	Coconuts (in shell)
	Palm nuts and kernels

Rice, although a cereal crop, was categorised as a separate group due to differences in the requirements for residues left in the field, compared to other cereal crops. This is discussed in more detail in Section 5.3.6.1.

5.3.2 Baseline data

Each biochar scenario was developed using 2005 baseline data of crop production including crop land area, crop type and crop yield. These baseline datasets for 2005 were developed using historical data from FAOSTAT and the baseline 2005 land-use dataset for the RCPs.

Arable land is defined as:

> *'..land under temporary agricultural crops (with multiple-cropped areas counted only once), temporary meadows for mowing or pasture, land under market and kitchen gardens and land temporarily fallow'*
>
> *(FAO, 2013b)*

Permanent crop land is defined as:

> *'..land cultivated with long term crops which do not have to be regularly replanted for several years (such as cocoa and coffee).'*
>
> *(FAO, 2013b)*

Definitions of each crop type are detailed in the glossary section of the FAOSTAT website (FAO, 2013b).

Data was sourced from FAOSTAT detailing, for each of the 22 world regions (Table 5-1) for 2004 to 2006, the total cropland (total arable and permanent crop land) (in hectares (ha)) and the area harvested (ha) for each of the five crop groups. Comparison of FAOSTAT production data with national inventories by Kim and Dale (2004) determined that, although some discrepancies exist, the datasets are mostly consistent. FAOSTAT data was accepted for use here as it is globally representative, consistent with most national inventories and the only official, global data source available. The regional data for total crop land and area harvested per crop type was used to calculate the percentage of the total crop land that was cultivated under each of the five crop types in 2005. Regional variation was retained at the scale of the 22 sub-regional groups. Annexe II.a details the regional crop fractions applied for each crop group. Throughout the biochar scenarios, it was assumed that although total crop land may increase or decrease within a region, the percentage of this total regional cropland dedicated to each crop type remained constant. In reality, the percentage of a region's cropland used to cultivate each crop type would be very likely to change over time due to changes in economic, technological, climatic and social factors. There is a large amount of uncertainty involved in projecting how the contribution of each crop type to total crop production will change over time due to the complex interactions of these drivers of change, and the RCP literature does not discuss this in detail. It is beyond the scope of this research to project how drivers such as demand, climate and economic considerations may change for each crop type, unfolding into the future. The method used here gives a plausible projection of future production, but in reality the fraction of each crop type, as a fraction of total production, may alter.

5.3.3 RCP land-use data

As discussed in detail in Section 2.4, the RCP scenarios are four scenarios of future emissions and land-use pathways which are projected, using current knowledge of radiative forcing potentials and climate sensitivity, to each lead to a different radiative forcing in 2100. Each RCP consists of a number of datasets, for example emissions pathways for different climatically important species and land use datasets. This research used the land-use projections of each RCP to project available residue quantities within the biochar scenarios. Within the land-use data for each RCP there are a number of separate datasets detailing a) the types of land within each grid cell and b) changes between land-use types for each grid cell. The datasets extracted from the wider RCP data for use here were annual gridded data of the fraction of each grid cell used for cropland, for 2005 to 2100, for the four RCPs. The grid format of the data represents 0.5 x 0.5 degree global coverage. The cropped area of each 0.5 x 0.5 degree grid cell was found by computing the total area of each grid cell using cosine weighted latitudes and multiplying by the cropland fraction. The area of total cropland cultivated for each of the five crop groups (see Table 5-2) was determined for each year (2005-2100), for the four RCPs.

5.3.4 Crop production

Crop and scenario specific crop yields, in hectograms per hectare (hg ha^{-1}), were applied to the data of cultivated land area for each crop type, determining annual production quantities for each crop type. These values were converted to tonnes per grid cell, per year. The baseline (2005) regional crop yields (hg ha^{-1} yr^{-1}), taken from FAOSTAT, were the regional average yield for that crop group and whilst crop group specific, were uniform across the four RCP scenarios. Regional crop yields were averaged for the years 2004 to 2006 to eliminate any short term anomalies, resulting in an average regional crop yield per crop group for 2005. This includes all production from cropping systems which operate more than one cropping cycle per year (i.e. dual or multiple harvests per year) as may be seen, for example, with some rice cultivars (Walcott et al., 1977) or where more than one crop is grown on one land area.

The development of the agricultural scenarios within each RCP used scenario drivers such as population, dietary demands and crop yields to project land use requirements and distributions. Crop yields within each RCP are assumed to change over time, simulating influences of factors within the scenario such as technological development or socio-economic factors, with each RCP having different assumptions. The literature surrounding each RCP was examined separately to determine its underlying assumptions affecting crop yields. The assumptions made to project future crop yields in Scenario 1 are based on the assumptions of each individual RCP pathway, and where necessary on the scenario assumptions and background literature underlying each RCP. Other scenarios of crop-yield change were also assessed to examine the effects of alternative crop yield pathways (Sections 5.4.1 and 5.4.7). Detailed analysis of crop yields within the RCPs can be found in Appendix II.b and a summary of the assumptions found in Table 5-3. Discussion of changes in crop yields within the RCP literature, and yield data derived from the surrounding literature, is often differentiated by the developed or developing status of nations, without explicitly stating these classifications, therefore the current development status of nations was determined. A number of organisations around the world classify the development status of nations. Figure 5-2 shows that many regions of the world are classified by the World Bank as developing, with the exception of North America, Canada, Western Europe, Southern Europe, Japan, Australia, New Zealand, Saudi Arabia and Oman. Those nations currently classed as developing by the World Bank (2011) are detailed in Annexe II.a.

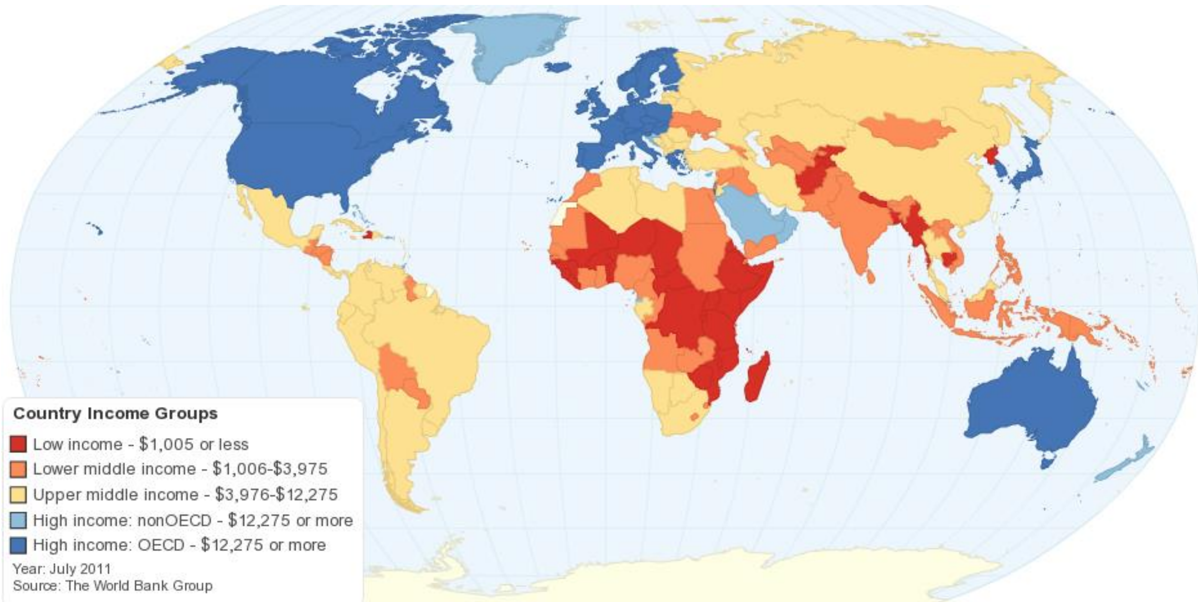

Figure 5-2: Map of average income groups used to classify current developed and developing nations (World Bank, 2011).

The FAO's regional classification data details the developed regions of the world as: Northern America, Canada, Europe, Japan and Australia and New Zealand (United Nations Statistics Division, 2013). This correlates well with the World Bank classifications, with the exception of Saudi Arabia and Oman. Within this research, the development classifications from the more recent FAO classifications were used. Table 5-3 shows the annual crop yield change (% yr^{-1}) for each 10th year from 2010. The values may change in the years between those shown, but the general trends can be seen from the decadal summary.

Table 5-3: Summary of the annual crop yield change (% yr^{-1}), for the four RCPs, for each 10th year. For each RCP, crop yields are differentiated by the developed or developing status of the region.

		Annual crop yield change (% yr^{-1})									
RCP	Development status	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
2.6	developed	0.55	0.55	0.55	0.55	0.55	0.36	0.36	0.36	0.36	0.36
2.6	developing	0.55	0.55	0.55	0.55	0.55	0.36	0.36	0.36	0.36	0.36
4.5	developed	0.9	0.9	0.9	0.81	0.71	0.62	0.53	0.44	0.34	0.25
4.5	developing	1.1	1.1	1.1	0.98	0.86	0.74	0.61	0.49	0.37	0.25
6	developed	1	1	1	1	1	1	1	1	1	1
6	developing	1	1	1	1	1	1	1	1	1	1
8.5	developed	1	1	1	1	1	1	1	1	1	1
8.5	developing	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5

The RCP scenarios do not include the potential impacts of climate change on crop yields therefore the crop yields used in biochar Scenario 1 (Table 5-3) also do not include climate change impacts. In reality, as the climate changes there may be a number of related impacts on crops. A set of alternative crop yield scenarios exploring the effects of different crop yield assumptions (without climate change impacts) and the related effects on biochar production are detailed in Section 5.4.1. Scenarios exploring the effects of climate change related crop yield impacts are detailed in Section 5.4.7.

5.3.5 Crop residues

The crop production quantities calculated represent the marketable commodity of the crop excluding the residues and losses during harvest (FAO, 2013b). The total residue from each crop group is therefore a related factor and was calculated from the production quantities using residue factors from the literature. Jolli and Giljum (2005) discuss two methods for estimating residue quantities from agricultural production, the first method calculating total (gross) residues and the second method calculating total unused residues. The first method involves applying a coefficient for the unused proportion of crop to that of the calculated commodity. This coefficient may be a harvest index (HI) which is defined within the literature as the ratio of grain yield to the total above ground biomass (Equation 5-1) or may be the related residue to product ratio (RPR), also known as the straw to grain ratio (Equation 5-3).

$$HI = \frac{X}{Y} = \frac{X}{X+S} \quad (5\text{-}1)$$

(Huehn, 1993)

Where X is grain yield, Y is the above ground biomass at harvest/maturity and S is the straw (residue) weight at crop maturity.

The grain to straw ratio (GSR), also called the crop to residue ratio is the ratio of harvested product to residue (Perlack et al., 2005).

$$GSR = \frac{X}{S} = \frac{X}{Y-X} \quad (5\text{-}2)$$

(Huehn, 1993)

Related to the GSR is the residue to product ratio (RPR), also called the residue to crop, straw to grain, or residue to grain ratio.

$$RPR = \frac{S}{X} = \frac{Y-X}{X} \quad (5\text{-}3)$$

(Huehn, 1993)

The terms HI and RPR are related, although differences between the methodologies used to take measurements and calculate the two values, such as the amount of plant harvested and height of stubble, can mean that the values are often not easily interchangeable (Huehn, 1993). Explicit detail of the calculation methodology is required for the RPR to be properly calculated from the HI and vice versa. The second method discussed by Jolli and Giljum (2005) directly applies a coefficient of unused crop residue to the harvest area. The 'unused crop' coefficient is determined using the HI of crops and the amount of crop which is not used for other purposes (technical availability). This unused crop coefficient is then applied directly to the land area, giving an amount of unused residue per area. Within our study the availability of residues for biochar production, within each scenario, is dependent on a number of factors including the amount of residue produced relative to commodity, the requirements for residues to remain in situ for soil nutrient purposes, and competing uses for the resource such as for fodder and biofuel production. The first method detailed by Jolli and Giljum (2005), applying a coefficient to calculate total (gross) residue, was used in our study to enable the total residue quantity and unused residue factors to be considered as separate parameters within the biochar model.

Within the literature on crop residues, a number of RPR values for different crop types are discussed. These values are often average figures and actual values may vary with crop strain and growing conditions (Smil, 1999). Projection of future changes in RPR within the literature range from decreasing to increasing RPRs (Hoogwijk et al., 2003). A decrease in RPR may be seen, for example, in scenarios where crops types with increased yields but current or reduced residue quantities in relation to the grain yield are utilised. An increase in RPR may be seen, for example, where crop varieties which obtain similar yields to present but produce more residue are utilized. This could be within a heavily biofuels or biochar focussed scenario, where crop residue production is desirable. Potential future changes in RPR are explored in Section 5.4.3.

To determine residue quantities for Scenario 1 RPR values were used to determine how much crop residue would be produced alongside the commodity values calculated. Ranges of RPR values from the literature were collated for each of the crop types.

Table 5-4: Average residue to product ratio (RPR) values used Scenario 1 and other scenarios unless specified. Rice residues were separated into rice straw and rice husk, sugarcane residues were separated into sugarcane leaf and sugarcane bagasse due to the very different RPR values for these residues. Averaging over these residues for the crop group would result in an unacceptable skewing of the RPR value that could be easily avoided due to the separate crop group categories for rice crops and for sugarcane crops throughout the model.

Crop group	Average residue to product ratio (RPR)
Cereals	1.22
Rice (straw)	1.41
Rice (husk)	0.27
Fibre crops	0.2
Oil crops	1.64
Sugarcane (leaf)	0.1
Sugarcane (bagasse)	0.4

Although RPRs are specific to each crop, cultivar and growing conditions (for example: region, climate, environmental stresses), it was beyond the scope of this study to apply each specific crop RPR and therefore some generalisations were assumed. The values used, for Scenario 1 and other scenarios unless specified, were averages across the crop group (Table 5-4). Some exceptions were made, for example separate RPR values were applied to rice straw and rice husk due to the very different RPR values, and primary experimental knowledge on biochar properties from these two residue types (see Chapter 4).

Smil (1999) discussed that some RPR values within literature do not account for stubble left in the field. This extra stubble was not accounted for here due to often poor reporting within the literature, often not detailing whether field stubble was included in the RPR value. It has been assumed here, therefore, that all RPR values are inclusive of field stubble. This may lead to a larger quantity of residue produced than that determined here. This assumption ensures that sufficient residues remain in the field for soil quality purposes but may, in some cases, lead to more residues remaining in the field than necessary. This was deemed to be an acceptable method of dealing with this uncertainty, avoiding the risk of developing a scenario which removes too much residue from the field.

5.3.6 Competition for crop residues

A number of sources of competition exist for agricultural residues, including for the maintenance of soil quality by leaving some residues in situ, use as fuel, fodder and within manufacturing processes. The following discussion details these sources of competition for crop residues and how they are addressed within this study.

5.3.6.1 Residues left in-situ

Some crop residue is often required to remain on soils after harvest to avoid wind and water erosion and to maintain soil organic matter, nutrients and soil structure. Residues may also be later returned to the field for nutrient recycling by mulching or after incorporation into substrates such as animal wastes or compost. The amount of in-situ residue necessary to maintain healthy soils varies from system to system, for example rice paddy agriculture does not require any residue to remain, whereas other systems may need up to 50 – 70 % of the residue to remain (Andrews, 2006, Perlack et al., 2005). Safe levels of residue removal are highly dependent on soil type, yield and management practices, with complex relationships existing between the quality of residues, climate, soil type, topography and soil management practices such as tillage and the addition of nitrogen fertilizers (Andrews, 2006). Lindstrom (1986) found that adverse effects of residue removal from corn (maize) systems decreased with decreasing residue removal, but this effect plateaued at 30 % residue removal and below. This indicates that 30 % of residues could be removed without a detrimental effect on soils. Lal (2005) also reported evidence that 20 - 40 % of residues can be safely removed from fields. Woolf et al. (2010) discuss a range of safe removal rates within the literature, from < 25 % for soils prone to erosion, to 70 % in a no till system. Their biochar assessment used three levels of residue removal, at 25 %, 35 % and 45 % extraction, whilst noting that the higher removal rates may require changes in soil management practices to retain soil quality. The exact conditions of each system within this assessment, particularly into the future, are not currently known and therefore assumptions are made in order to generalise system types. Average values from the literature regarding the amount of residue required to remain in situ for a generalized system are used.

5.3.6.2 Residues burnt in the field

Within some agricultural systems crop residues are burnt in the field. This is common in rice-growing systems, where residues are not required to provide cover from erosion, but the practice does occur in other growing systems (Kroeze et al., 1996). Burning may take place for a number of reasons, including to reduce the risk of pests and diseases remaining in soils between harvests, and to reduce the difficulties of preparing and planting a new crop with previous residues remaining in situ (Smil, 1999). The United Nations Environment Program (UNEP) estimated that approximately 25 % and 10 % of total crop residue is burnt in field for developing and developed nations respectively. These figures are conservative estimates as they do not include any residues burnt as fuel. The minimum estimates including residues burnt as fuel are 33 % and 15 %, and maximum estimates are 45 % and 25 % of residues burnt in developing and developed nations respectively (UNEP, 1995). In Scenario 1 crop residues usually burnt in the field were assumed instead to be collected for biochar production using the average values from the UNEP (1995) analysis.

5.3.6.3 Competing uses for crop residues

Apart from residues which must remain in situ and those burnt in the field, a number of other uses currently exist for agricultural crop residues. These uses vary regionally, with some residue types being utilised in some areas and not in others. Crop residues are commonly converted to biofuels, burnt as fuel, used as animal feed, building materials, pulp materials, as a mushroom cultivation substrate and for chemical extraction (Smil, 1999, Sud et al., 2008). For each RCP scenario a residue availability factor for each crop category was applied to the gross residue production quantities determining how much residue may be available, within each scenario, for biochar production.

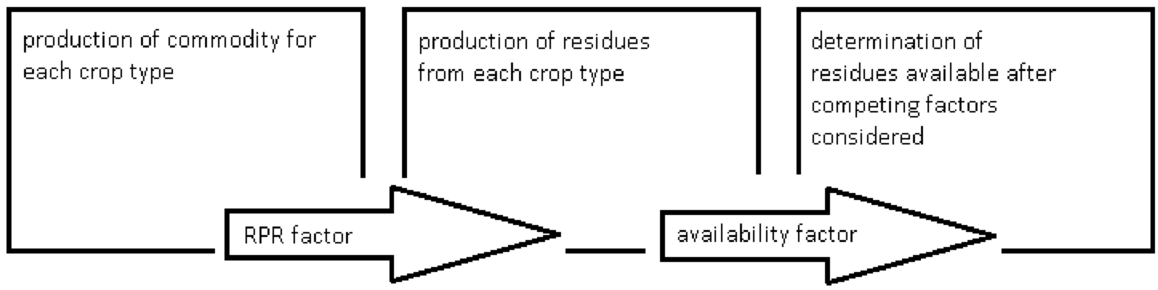

Figure 5-3: Schematic showing the calculation stages of residue availability within the framework model.

Each residue availability factor is crop category specific, accounting for specialised uses. The utilization of crop residues will, in reality, vary spatially within the crop categories used here. It is beyond the scope of this study to project this spatial variation in crop residue utilisation with average values assumed here aggregated at the scale of developed and developing countries. Residue availability assumptions for the main biochar scenario (Scenario 1) are summarised in Table 5-5. Annexe II.c details the residue availability assumptions of Scenario 1 regarding residue availability, for the different crop categories.

Table 5-5: Residue availability assumptions for Scenario 1 (% of total (gross) residue). Values are differentiated by crop group and regional development status.

	Residue availability (%)						
Scenario	Cereals	Rice (straw)	Rice (husk)	Sugarcane (bagasse)	Sugarcane (trash)	Oil crops	Fibre crops
Developing	55	70	100	100	50	30	30
Developed	40	70	100	100	50	30	30

5.3.7 Biochar production

5.3.7.1 Yields of biochar

The biochar scenarios assumed a uniform production method for biochar throughout the scenario period (2005 – 2100), with crop specific biochar yields remaining constant both spatially and temporally. The pyrolysis process was assumed to be a modern technological process enabling higher biochar yields alongside oil and gas capture, also enabling good levels of yield and emissions control.

Chapter 2 detailed typical biochar yields from the literature, and also discussed the variation which may be seen in yields of biochar from pyrolysis, due to factors such as feedstock and process conditions. Average biochar yields determined experimentally from the slow pyrolysis process used in Chapter 4 were used to apply a coefficient of biochar yield to the scenarios of residue availability for Scenario 1. Chapter 4 saw a range of biochar yields from 28 % to 39 % for crop residues pyrolysed at 600 ^{o}C with a heating rate of 5 ^{o}C min^{-1}. The experimental results for biochar yield and other characteristics under pyrolysis conditions of 600 ^{o}C and 5 ^{o}C min^{-1} were used to calculate the values used within biochar Scenario 1 and all other scenarios unless stated otherwise. Although higher values were determined for biochar fixed carbon content at peak pyrolysis temperatures of 800 ^{o}C, the consideration of other factors such as increased biochar yield and surface area of biochars produced at 600 ^{o}C was seen to justify a potential small forfeit in fixed carbon and recalcitrance (R_{50}). This would most likely optimise the soil amendment properties of the biochars, making the biochar product more desirable and economically competitive. Biochar yields of 30 % for cereal residues (excluding rice) and oil crop residues, 28 % for fibre crops and sugarcane residues, and 39 % for rice residues were assumed for Scenario 1.

5.3.8 Biochar carbon content

For Scenario 1 the experimental values for total elemental carbon content of 75.3 % for cereal biochars (excluding rice), 84.7 % for oil crop residue biochars, 54.5 % for rice residue biochars, 83.2 % for fibre crop residue biochars and 88.6 % for sugarcane residue biochars were used (See Section 4.3.2). Using the total elemental carbon content, from ultimate analysis, gives results for the total carbon that would enter the soil with the biochar, including any volatile material, whereas use of the total fixed carbon, from proximate analysis results, would disregard this volatile carbon content and therefor lead to an incorrect value for carbon entering the soil.

Following the calculation of the carbon content of the biochars, the related quantity of CO_2 was calculated. A conversion factor of 3.67 was applied to the carbon values, as one molecule of CO_2 is roughly 3.67 times the mass of one molecule of carbon (C). It must be noted that the CO_2 values are related to the carbon content of the biochars before addition to soils. Some of the biochar carbon may be released over time, as CO_2, upon degradation of the biochar after addition to soil. The net carbon storage potential of the biochars, after addition to soil, and related CO_2 quantities are discussed in Chapter 7.

5.4 Alternative scenario drivers and assumptions

In addition to Scenario 1, a number of other scenarios were designed to explore the sensitivity of results to the assumptions of the main scenario. The parameters explored, and the related sub-scenario group, are detailed in Table 5-6. Further detail of each alternative scenario can be found in Sections 5.4.1 to 5.4.7. Within the alternative scenarios all assumptions are the same as for Scenario 1 unless specified.

Table 5-6: Summary of biochar scenario groups indicating the parameters explored within each sub-scenario set.

Scenario	Scenario driver	Assumptions
Main Scenario		
1	Main/mean scenario assumptions	See Section 5.3
Crop yields		
2a	No crop yield change	0 % yr^{-1}
2b	Optimistic crop yield	Scenario 1 + 50 % yr^{-1}
2c	Alternative convergence point of crop yield to 0.25 % yr^{-1} for RCP 4.5	0.25 % yr^{-1} in 2050 for RCP 4.5
Land-use change		
3a	No land-use change	2005 land use distribution kept constant
3b	RCP crop land without dedicated biofuels	Subtraction of biofuel land from total cropland for RCPs 2.6, 4.5 and 6
Residue to product ratio		
4a1	Small RPR decrease	RPR of 0.75 (2005) to 0.71 (2100)
4a2	Large RPR decrease	RPR of 0.75 (2005) to 0.14 (2100)
4b	Increasing RPR	RPR of 0.75 (2005) to 1.28 (2100)
Crop residue availability		
5a	Low availability	25 % availability
5b	Medium availability	50 % availability
5c	High availability	75 % availability
5d	Conservative Woolf et al (2010)	See Table 5-7
5e	Optimistic Woolf et al (2010)	See Table 5-7

Biochar yield		
6a	Low yield	25 %
6b	High yield	63 %
Biochar carbon content		
7a	Low carbon content	60.2 %
7b	Medium carbon content	72.5 %
7c	High carbon content	89.0 %
Climate change impacts		
8a	Min temp change, mean yields	See Section 5.4.7
8b	Mean temp change, mean yields	
8c	Max temp change, mean yields	
8d1	Min temp, min yields	
8d2	Mean temp, min yields	
9d3	Max temp, min yields	
8e1	Min temp, max yields	
8e2	Mean temp, max yields	
8e3	Max temp, max yields	
8f	Assumptions of Kyle et al (2014)	
Climate change with adaptation		
9a	Min temp change, mean yields	See Section 5.4.7
9b	Mean temp change, mean yields	
9c	Max temp change, mean yields	
9d1	Min temp, min yields	
9d2	Mean temp, min yields	
9d3	Max temp, min yields	
9e1	Min temp, max yields	
9e2	Mean temp, max yields	
9e3	Max temp, max yields	

5.4.1 Scenario 2: Crop yields

Each RCP uses a prescribed crop yield and land-use combination to provide the agricultural resources needed to meet demand within the scenario. These projections of crop yields within the RCPs are not certain pathways of how crop yields will change into the future. Scenario 2 looks at the effect of alternative rates of crop yield change over time. This may mean that, used alongside the prescribed land-use of the RCP, the demand for crops and other agricultural produce may not be met within the RCP. The analysis does give an indication of the impact of different rates of crop yields on crop production and subsequent biochar potential. It also indicates how sensitive production within the RCP is to the yield assumptions of the pathway. Three scenarios of alternate crop yields were developed: Scenario 2a, no crop yield increase; Scenario 2b, optimistic crop yield increase; Scenario 2c, alternative convergence period for RCP 4.5. The assumptions of each alternative crop yield scenario are summarised in Sections 5.4.1.1 to 5.4.1.3. These scenarios of alternative crop yields are not intended to simulate the impacts of climate change, which are explored in Scenarios 8 and 9, Section 5.4.5.

5.4.1.1 Scenario 2a: No crop yield increase

Scenario 2a used the baseline yields for 2005 throughout the scenario, keeping them constant to 2100. This determined how much of the biochar production potential of Scenario 1 could be attributed to the assumed crop yield increase over time.

5.4.1.2 Scenario 2b: Optimistic crop yield increase

Scenario 2b used rates of crop yield increase which are higher than those projected within the RPCs, perhaps due to factors such as new crop cultivars, genetic modification or higher rates of technological development than prescribed within the RCP. Thomson et al. (2011) discussed an optimistic yield scenario where the annual yield increase assumptions are increased by 50 %. For Scenario 2b this assumption of Scenario 1 crop yield increase + 50 % was applied to the rates of crop yield change (see Annexe II.d).

5.4.1.3 Scenario 2c: Convergence rates for RCP 4.5

In Scenario 1, the annual rate of crop yield increase for RCP 4.5 was assumed to converge to 0.25 % yr^{-1} in the year 2100. Due to uncertainty in the RCP scenario literature about when this convergence occurs, Scenario 2c examined an alternative convergence point of 2050. This gave biochar production potential in RCP 4.5 using the earliest and latest potential yield rate convergence points. Convergence to 0.25% yr^{-1} yield increase was implemented using an incremental change every 10 years for consistency with Scenario 1 yield assumptions.

5.4.2 Scenario 3: Land use

5.4.2.1 Scenario 3a: No change in land use

Scenario 3 applied the crop land distribution of 2005 to the entire biochar scenario period, from 2005 to 2100. The assumption that land-use will not change over time is unlikely to manifest in reality. However, the use of a static land-use scenario was used to determine how much of the biochar production potential of Scenario 1 could be attributed to the changing agricultural land area projected within each of the RCPs.

5.4.2.2 Scenario 3b: Biofuels land

Scenario 3b examined the impact which subscribed biofuels land has on the biochar production potential of Scenario 1. Biofuels produced from crops (either purpose grown energy crops or crop residues) are considered as an energy source within all of the RCP scenarios. They are categorised in different ways within the development and datasets of each RCP scenario. Within RCP 2.6, RCP 4.5 and RCP 6 biofuels are categorised as crops and, as such, are included in the datasets of total crop fraction provided by the RCP modelling team and used here for scenario development. RCP 2.6 and RCP 6 treat biofuels as a number of different crop types, RCP 4.5 treats biofuel crops as herbaceous crop species. RCP 8.5 considers biofuels to be part of the wood harvest, which is not included in the dataset for total crop land fraction. Separate biofuels datasets of the gridded fraction of land used for biofuel cultivation are provided by the RCP modelling teams for RCPs 2.6, RCP 4.5 and RCP 6. The RCP 8.5 biofuels dataset is comprised of the wood harvest for fuel within the scenario. This was adapted by Hurtt et al. (2009) into a dataset of the carbon content of the wood harvested for energy production within RCP 8.5.

Whilst the main biochar scenario set (Scenario 1) uses the fraction of total cropland datasets as provided by the RCP development teams, Scenario 3b subtracts the biofuels land area from the total cropland area for RCPs 2.6, 4.5 and 6. The cropland dataset for RCP 8.5 is not altered in Scenario 3b as biofuels are not included in the original cropland datasets by the RCP 8.5 team.

5.4.3 Scenario 4: Residue to product ratio (RPR)

Scenario 4 examined the effect of alternative RPRs on the biochar production potential. Historically, a high crop RPR was desirable due to the high economic value of straw. More recently the economic value of grain has increased in comparison to that of straw, leading to a desire to produce crops with higher grain yields relative to straw yield (Reddy et al., 2003, Sinclair, 1998). This change in RPR has occurred through crop and cultivar selection alongside other management techniques (Reddy et al., 2003). Imhoff et al. (2004) discuss that RPRs of 0.14, 0.71 and 1.28 are low, intermediate and high estimations of generalised RPR. These RPR values are generalised across a number of crop types and are average values of current RPRs, which may not be representative of the potential RPRs of the future. Future projections of changes in RPR are not discussed widely within the available literature. It is possible that future crop RPRs may continue to decrease or may begin to increase, dependent on factors such as technological improvements, cultivar choice, genetic alteration, and crop management

(Hoogwijk et al., 2003). The future economic potential of residues may be a main driver in the changes of RPRs, meaning that RPRs may increase in a future biochar or biofuels focussed scenario, where residues can be easily utilized for economic gain. In other future scenarios crop residues may become less desirable, for example where the majority of residues are regarded as waste and the main focus is on increasing yield of grain from the crop. Regional differences in RPR are beyond the scope of this work, with potential changes in the global average RPR of the different crop groups being examined within Scenario 4. An initial RPR of 0.75 (in 2005), which is the average value of the RPRs used for all of the crop types in Scenario 1, is assumed for the Scenario 4 sub-sets. For Scenario 1 separate RPR values were assumed for the different crop groups. For Scenario 4 one average RPR value for all crop groups is assumed, due to scant literature regarding projected changes in RPRs. Total rice residue and total sugarcane residue is therefore calculated, where Scenario 1 separates these groups into sub-residue types. Using the relative contribution of each residue type (i.e. rice straw and rice husk) to the total residue quantity for each crop type (i.e. total rice residues) from Scenario 1 enabled the application of availability factors for each residue sub-set to be applied in Scenario 4. The values used for the contribution of each residue type to total residues for their crop group in Scenario 4 were: rice straw, 84 %; rice husk, 16 %; sugarcane leaf, 20 %; sugarcane bagasse 80 %.

5.4.3.1 Scenario 4a: Decreasing RPR

A decrease in RPR over time was examined in Scenario 4a. This represents a continuation of the recent historical trend of decreasing RPR which has been attributed to faster increases in grain yield relative to residue increases (de Leeuw, 1997). The rate of this decrease is not discussed in detail within the literature so we make two assumptions below. The changes in RPR were made incrementally each decade so that the final RPR is reached in 2090 and maintained until 2100. This 10 year increment period is in-keeping with the changes applied to other scenario variables, such as crop yield increase. The initial RPR of 0.75 was reduced over the scenario period to the intermediate RPR of 0.71 discussed by Imhoff et al. (2004). The RPR of 0.75 was reduced over the scenario period to the low RPR of 0.14 discussed by Imhoff et al. (2004).

5.4.3.2 Scenario 4b: Increasing RPR

This scenario is representative of a future pathway where crop residues become more desirable, holding more economic value. The increased desirability of crop residue is not likely to occur at the expense of grain yields, with all parts of the plant expected to gain economic value in such a scenario (Lorenz et al., 2010). Because of this, only marginal increases in RPR would be expected in a future scenario of increasing RPR. The initial RPR of 0.75 was increased over the scenario period to the high RPR value of 1.28 discussed by Imhoff et al. (2004).

5.4.4 Scenario 5: Crop residue availability

Scenario 5 examined the effect of potential changes in the availability of crop residues on biochar production potential. Scenarios 5a to 5c used average residue availability values across all residue types, of 25 %, 50 % and 75 % availability respectively. Although these average values are generalisations of the availability of crop residues, which in reality will vary with crop type and spatial and temporal coverage, these generalisations were used to provide general estimations of crop residue availability under different assumptions. Scenarios 5d and 5e used the conservative and optimistic residue availability assumptions of Woolf et al. (2010) respectively to assess the impact of the assumptions of similar studies on the biochar production potential here. With regards to residue availability Woolf et al. (2010) discussed cereal, rice and sugarcane residues which are relevant to this study. They also discussed the availability of other 'biomass crops' which has been used here to represent oil and fibre crop residues. The values are aggregated to a global scale, rather than by developed and developing region status in Scenario 1 here, due to the global scale of aggregation in Woolf et al. (2010). The largest change in residue availability in Scenario 5d, relative to Scenario 1, was the reduction in cereal residue availability to 8 %. Rice straw, rice husk and sugarcane bagasse residues remained at the level of availability seen in Scenario 1, as this is the same as availability discussed in the conservative scenario of Woolf et al. (2010). Scenario 5e used 'the maximum potential' values from Woolf et al. (2010). The 20 % availability of cereal residues was lower than the values used for cereal residue availability in Scenario 1. Woolf et al. (2010) assume 45 % removal rates from the field of cereal crop residues, 25 % use as animal fodder, leaving 20 % for use in biochar production.

Table 5-7: Summary of crop residue availability (%) for Scenarios 5d and 5e, the conservative and maximum scenarios of residue availability using the assumptions of Woolf et al. (2010).

	Residue availability (%)						
Scenario	Cereals	Rice (straw)	Rice (husk)	Sugarcane (bagasse)	Sugarcane (trash)	Oil crops	Fibre crops
5d	8	70	100	100	25	30	30
5e	20	90	100	100	75	75	75

The cereal residue availability assumptions made in Scenario 1 included the use of residues which are currently burned in the field or used for energy production, which are not considered by Woolf et al. (2010), contributing to the difference in availability factors. Scenarios 5d and 5e highlight the impact which alternative residue availability assumptions have on the biochar production potential of Scenario 1.

5.4.5 Scenario 6: Biochar yield

Scenario 6 explored the assumptions of biochar yield, using the average low biochar yield (25 %) and average high biochar yield (63 %) from the literature to give conservative and optimistic accounts of biochar production potential. The scenarios, termed Scenario 6a and 6b represent low and high biochar yield respectively. In reality variation in biochar yield will occur in biochars produced from different feedstocks, and both spatially and temporally depending on factors such as process type and conditions. The values here were used to give an indication of the variability which may occur around the biochar yield assumptions of Scenario 1.

5.4.6 Scenario 7: Biochar carbon content

Scenario 1 used the experimentally derived values for total elemental carbon content of biochars which are discussed in Section 5.3.8. These values assume that all biochars produced from each residue type will have the same carbon content as those derived experimentally. In reality this is dependent on a number of factors including the provenance of the residue, for example plant strain and growing conditions, and the biochar process type and conditions. To explore the effects that variation in biochar carbon content may have on total biochar carbon content, values representing low and high carbon content values from the literature were used to determine a possible range. Annexe II.e details carbon contents from the literature where biochars were produced between 500 ^{o}C and 600 ^{o}C under slow and fast pyrolysis. These values for total carbon content were used to determine minimum, mean and maximum values of 60.2 %, 72.5 % and 89.0 % which were applied to the biochar quantities for Scenarios 7a, 7 b and 7c respectively.

5.4.7 Scenarios 8 and 9: Climate change impacts (with and without adaptation).

The climate change scenarios (Scenarios 8 and 9) examined the potential effects of climate change impacts on the biochar production potential of Scenario 1. The baseline scenario assumptions, before the effects of climate change, were taken from scenario 1 except where specified. There may be some yield increases with small temperature increases, and some crops may experience yield increases at relatively higher temperatures, though the dominant impact is expected to be decreased yield (Porter et al., 2014). The impact on crop yields is expected to increase with increasing temperature, meaning that impacts are likely to increase in magnitude, from lower to higher, across RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5 respectively.

The work both of Kyle et al. (2014) and Porter et al. (2014) were used to determine changes in crop yield, related to the level of climate change projected for each RCP. These crop yield assumptions were applied within biochar Scenario 8 and 9 scenario sets, where Scenario 8 assessed the impact of climate change induced temperature change, relative to Scenario 1, with no adaptation measures employed and Scenario 9 assessed the impact of climate change induced temperature change, relative to Scenario 1, with simple adaptation measures.

The crop yield impact projections of Porter et al. (2014) contribute to Scenarios 8a-e, and 9a-e. The literature on projected temperature change from the IPCC (2013) report was used to determine projected temperature changes up to 2100 for each of the RCPs. The IPCC literature was then used to apply crop yield impacts relating to these projected temperature changes. Scenario 8f was developed using the work of Kyle et al. (2014) which discusses the effects which climate change may have on the agricultural projections within each RCP. Section 2.4.3 details the discussion of Porter et al. (2014) and Kyle et al. (2014).

5.4.7.1 Scenarios 8a-e and 9a-e

To project the impact on crop yields of temperature change within each RCP the data from Porter et al. (2014) was used. The projected impact on crop yield was determined from Figure 7-4 of the Porter et al. (2014) report, which shows projected change in crop yield (%) from the baseline crop yields, at 1 ^{o}C intervals for a 1 ^{o}C to 5 ^{o}C temperature increase. This data was linearly extrapolated between each 1 ^{o}C temperature interval to give a projected yield change for each 0.1 ^{o}C increase in temperature. Using the 95 % confidence interval values were determined for the lowest, mean and maximum yield projections for crop yield impacts both with and without the ‘simple agronomic’ adaptation measures (this data is displayed in Annexe II.f). These changes in crop yield, relative to the crop yields of Scenario 1, were applied alongside the projected changes in global mean surface temperature projected for each RCP to project the changes in crop yield which may occur with the manifestation of climate change induced temperature change for each RCP pathway. Scenarios using both the non-adaptation and adaptation crop yield impact data were developed (Scenarios 8 and 9 respectively). Scenarios 8a to c and 9a to c assume the mean projections of crop yield impact with the minimum, mean and maximum temperature projection for each RCP (Scenarios a, b and c respectively). Scenarios 8 d and 9 d apply the lowest yield projections with the minimum, mean and max temperature projections (d1, d2 and d3) respectively. Scenarios 8 e and 9 e apply the highest yield projections with the min, mean and max temperature projections (d1, d2 and d3) respectively.

5.4.7.2 Scenario 8f

A similar methodology to that discussed in Section 5.4.7.1 was used to determine the impacts that the crop yield changes projected by Kyle et al. (2014) would have on the potential for biochar production. The data for crop yield impacts with no species relocation was used to determine a percentage change in crop yield for each crop type of the biochar scenarios, relative to the baseline changes of Scenario 1, for each RCP. The crop yield impacts of each RCP scenario were applied to the initial crop yield assumptions of Scenario 1. The decadal data was linearly extrapolated to determine an annual variation from the baseline yield. Projections of changes in corn and wheat yields were averaged for each year to produce a value for cereal crops. Bioenergy crop projections from Kyle et al. (2014) were applied to the yield projections for fibre crops in the biochar scenarios, as no fibre crop category was detailed in Kyle et al. (2014). This data projection set was chosen as a number of herbaceous fibre crops can also be used for bioenergy production, therefore it was deemed to be the closest fit of the crop groups available from Kyle et al. (2014). This was done only for the dataset without adaptation measures from Kyle et al. (2014), resulting in Scenario 8f (no adaptation). The dataset of projected crop yields with crop relocation adaptation measures from Kyle et al. (2014) was not used to project an adaptation scenario here as the land-use projections would then deviate from those of the RCPs.

5.4.7.3 Scenario 9: Climate change with adaptation

Scenarios 9 a-e used the same methodology and data sources as Scenarios 8a-e, as described in Section 5.4.7, except the values for crop yields impacts with adaptation (Annexe II.f) were used alongside the temperature projections for each RCP. This gives insight into how simple crop based adaptation measures may alter the potential of biochar production, relative to both Scenario 1 and Scenarios 8 a-d.

5.5 Scenario limitations and uncertainties

There are a number of limitations which must be considered when assessing and using the data provided by these biochar scenarios. Some of these limitations apply to all of the scenarios and some just to one or two scenarios. Many of the limitations are a result of the assumptions which have been made during the development of each scenario, often incorporating underlying uncertainty. These uncertainties exist in a number of factors such as biochar properties and effects, future radiative forcing pathways and the manifestation of future climate change. Many of these uncertainties are discussed during the sections on scenario development and a number of the main uncertainties are also detailed here in summary. These scenarios should be used as a set of plausible future scenarios, although a number of other potential future scenarios are also possible. Many of the assumptions made during the development of these scenarios have been made to enable large-scale scenario analysis. For example, it has often been necessary to develop average values of spatial data.

It is not possible to determine how future land-use will vary spatially, therefore the RCP pathways have been used as possible pathways, but with no probability of occurrence attached. In reality a number of land-use scenarios could result in the same radiative forcing pathways as the RCPs, and many other land-use scenarios may contribute to a range of other radiative forcing pathways. As the development of the RCP land-use scenarios did not consider climate change, it is feasible that some of the land prescribed as cropland within each RCP scenario may become unsuitable for crop production under a changed climate (Kyle et al., 2014). Concurrently other areas may become more suitable for crop production. Detailed information on how climate change may impact the suitability of agricultural land for particular crop types is not available for the RCP scenarios. The land prescribed as crop land within each RCP is, therefore, not changed in Scenarios 8 and 9, thus giving a representation of the impacts of climate change on crop yields and biochar production without the relocation of crop species beyond the changes originally prescribed in each RCP scenario. The biochar assessment model can also be used to assess further land-use scenarios as uncertainties are reduced. The projections of land use change within each RCP scenario are interlinked with projections of crop yield. Each scenario, dependent on underlying drivers such as population and diet, was developed by the RCP teams around a certain demand for crop production. The RCP land-use development involved the prescription of crop yields and rates of crop yield change, combined with prescribed agricultural land area to satisfy this demand. The fractional contribution of each crop group to the total regional production was kept constant within the scenarios, with the exception of Scenario 3b which explores the prescription of biofuels land within the RCPs. Drivers such as changing socio-economic pathways and/or climate may, in the future, alter the fractional contribution of each crop type to the total crop production within each region of agricultural land area. It is beyond the scope of this study to project how these crop fractions may change over time. The main focus here regarding the effects of climate change on the biochar production potential of Scenario 1 is the effects of temperature changes on crop yields within each RCP. Although changing regional crop distribution due to climate change and changing demand for particular crop types are not explored here, these are both future potential research areas which could offer further insight and development of the biochar scenarios.

The datasets used for Scenario 1 are inclusive of biofuels land, though the fraction of total cropland cultivated by each crop type applied to each region remains the same from 2005. In reality, the biofuel crop fraction will change with time. The crop fraction value has been held constant within the study due to the aforementioned difficulties in projecting changing demand in crop types. The RCP literature does not specify in detail what crop types will be used for biofuels. As the crop fractions applied include cereal crops, oil crops, sugarcane and fibre crops this was assumed here to be inclusive of most biofuel producing species. Further research regarding the assumptions of future changing demand for different crop types, and the impact of this on the contribution of crop types to total crop production, would be beneficial.

The IPCC literature summarises the latest scientific research, projecting how the climate may change with each RCP emissions pathway. This includes, but is not limited to, projections of temperature, precipitation, cloud cover and extreme weather events. Ensembles of climate models, using detailed parameters for a number of Earth processes, are used to make these projections. There are still a number of uncertainties associated with prescribing these model parameters and how the parameters are interlinked to accurately represent the Earth's complex systems. Current climate models are able to reproduce historical large-scale changes in mean surface temperature to a very high confidence (correlation between the historical observations and model reproductions is ~ 0.99). The climate models often have more difficulty making accurate regional or smaller scale projections of observed temperature changes (Flato et al., 2013). Although representation of Earth processes such as the carbon cycle and cryosphere are improving within climate models, some large areas of uncertainty remain. In order to increase the likelihood of an accurate representation of potential future climate change assessment often uses an ensemble of models, creating a range of likely values. Flato et al. (2013) discuss that the simulation of global mean temperature change is mostly good, and is often represented more accurately that other parameters such as regional temperature change and precipitation. The IPCC ranges of potential mean surface temperature change for each RCP are accepted here as representing the most current and accurate projections available. They are used here due to the validation of the projected ranges by the use of an ensemble of models, and also due to the ability of the models in the ensemble to effectively simulate large scale mean historical surface temperature changes. In reality, the temperature changes which may manifest through climate change will vary regionally, dependent on a number of factors. Localised temperature changes are not applied within the biochar scenarios. The ability of climate models to predict localised changes can be limited (Flato et al., 2013), and the application of regional temperature changes to the biochar scenarios is beyond the scope of this study. The average global mean surface temperature change is used when applying temperature changes to the effects of crop yields within the biochar scenarios.

The impact of the projected temperature changes on crop yields also has a number of related assumptions and uncertainties. The impacts on crop yields taken from the literature are related to changes in global mean surface temperature. On a more localised scale changes may be seen in localised surface temperature which may have larger range and variance than the changes in global mean surface temperature. Due to the large scale nature of the scenarios developed here, and the scarcity of localised temperature change projections from the RCPs, changes in the global mean surface temperature was deemed an acceptable aggregate scale for temperature change. The uncertainties in more localised temperature change projections to 2100 would add another layer of uncertainty to the assessment. The biochar assessment model could be used to assess a smaller regional area, with the application of local temperature change projections if required and as uncertainty in the projected data is reduced.

The values for crop yield impacts taken from Porter et al. (2014) are mean values from a review of the literature. A range of values exist around these mean values. In order to address this, the development of scenarios 8a-e and 9a-e used these mean values and also the 5 % and 95 % confidence intervals (as indicators of lowest and highest crop yield impact values), meaning that 95 % of the crop yield impact projections assessed within the IPCC review of literature are encompassed within the scenarios assessed here. All of these yield scenarios are subject to inherent uncertainties related to the prediction of future scenarios and also the generalisation necessary to develop manageable global scenarios. A number of factors other than temperature may also affect crop yields, such as precipitation changes and change in the frequency and/or magnitude of extreme events. The assessment of all of these drivers of change is outside the scope of this study, but would add valuable insight to the scenarios during future assessment. As further literature becomes available regarding the potential impacts of the many drivers of crop yield change, and potential likelihood of the manifestation of these future impacts, new scenarios may be examined.

As discussed in Section 5.4.3, a combination of impacts on crop grain yields and residue production may occur, potentially leading to changes in crop RPR values. Scenario 4 explores future scenario of both increasing and decreasing RPR. A range of maximum, mean and minimum values for the RPR have been used within these scenarios to determine a range of possible outcomes for the total residues within each scenario. In reality RPR values may exhibit more variation than this, with variation possible regionally, temporally and both between and within crop groups and cultivars. It is beyond the scope of this study to examine the RPRs in more detail than has been conducted here. However, the addition of more detailed RPR values, perhaps on a crop type and regional scale, would enable the projection of more accurate results. Sufficient literature on future RPRs and the impacts of climate change on RPRs is not currently available to project how RPR may be change in Scenarios 8 and 9. These scenarios therefore assume the same RPR values as Scenario 1, assuming that they remain constant over time. This simulates a uniform effect of potential changes in global mean temperature on both commodity and residue production, which may be re-assessed as further literature becomes available regarding future projections of RPR.

Assessment of the biochar yield potential of each scenario has relied upon a number of parameter generalisations, such as the RPR values of crops, biochar yields and biochar carbon content. In reality each of the parameter values applied has some variability. It is beyond the scope of this study to apply this variability in its full complexity due to the global nature of the study. As with other studies of this type it has been necessary to make some generalisations about these parameters. Saying this, the potential variability in these parameters has been explored within individual scenarios, exploring the effect which maximum and minimum values derived from experimental work and/or the current literature has on the biochar production potential. The assessment of biochar yield potential also does not account for the impacts of any extreme events such as weather, pest or disease events which may impact land-use, crop or residue production or the ability to collect and convert residues. These extreme events were not included in the scenario analysis here due to the magnitude of current uncertainties. It was not possible to account for these events during the analysis here, though it is possible to say the projections should be seen as maximum potential biochar production scenarios, with the impacts of extreme events likely to affect biochar production in reality.

Many of the caveats addressed in this study are related to either uncertainty within the current knowledge relating to the parameter, or a high level of spatial or temporal complexity which has been generalised during this study due to the global nature of the assessment. Future research developments will allow for the assumptions relating to current uncertainty to be refined, updating the scenarios as new information is disseminated. The biochar assessment model may also be adapted in the future to apply higher levels of complexity to the spatial and temporal variations in parameter values.

5.6 Summary

The assessment of biochar production potential using the RCP land-use pathways incorporated a number of parameters from both experimental research and the surrounding literature. The development of a main scenario (Scenario 1) enabled the assessment of the biochar production potential using the main or most likely assumptions. Due to the high potential variation or uncertainty in a number of the parameters, such as crop yields, residue availability and biochar yields, a number of sub-scenarios were developed, each focussing on the variability of one parameter. The parameter variation or uncertainty assessed within the sub-scenarios looked at the potential variation in: crop yields, land-use change, RPR, residue availability, biochar yield, biochar carbon content and the impacts of climate change related temperature change on crop yields.

6 Biochar production potential within the RCPs: Results and discussion

6.1 Introduction

A number of scenarios which assess the potential for biochar production within the Representative Concentration Pathways (RCPs) (van Vurren et al., 2011) are presented. Scenario 1 explored the main parameter assumptions, using the mean or most likely parameter values throughout the assessment. Sub-scenarios 2 to 9 explored the range of variation and uncertainty surrounding a number of the parameters. Each sub-scenario focused on the variation and uncertainty of one parameter, these parameters being: crop yields, land-use change, RPR, residue availability, biochar yield, biochar carbon content and the impacts of climate change related temperature change on crop yields with and without adaptation measures. The initial results and discussion presented discuss the effectiveness of the biochar model, looking at projections of cropland and spatial accuracy. Following this the biochar production potential of Scenario 1 is discussed, looking in detail at the projections at each model stage. Variance from the projections of Scenario 1 induced by the assumption of alternative parameters are then detailed to outline the uncertainty in the projections of Scenario 1, and the variance in the biochar production quantities and carbon content which may occur.

6.2 Cropland within the RCPs

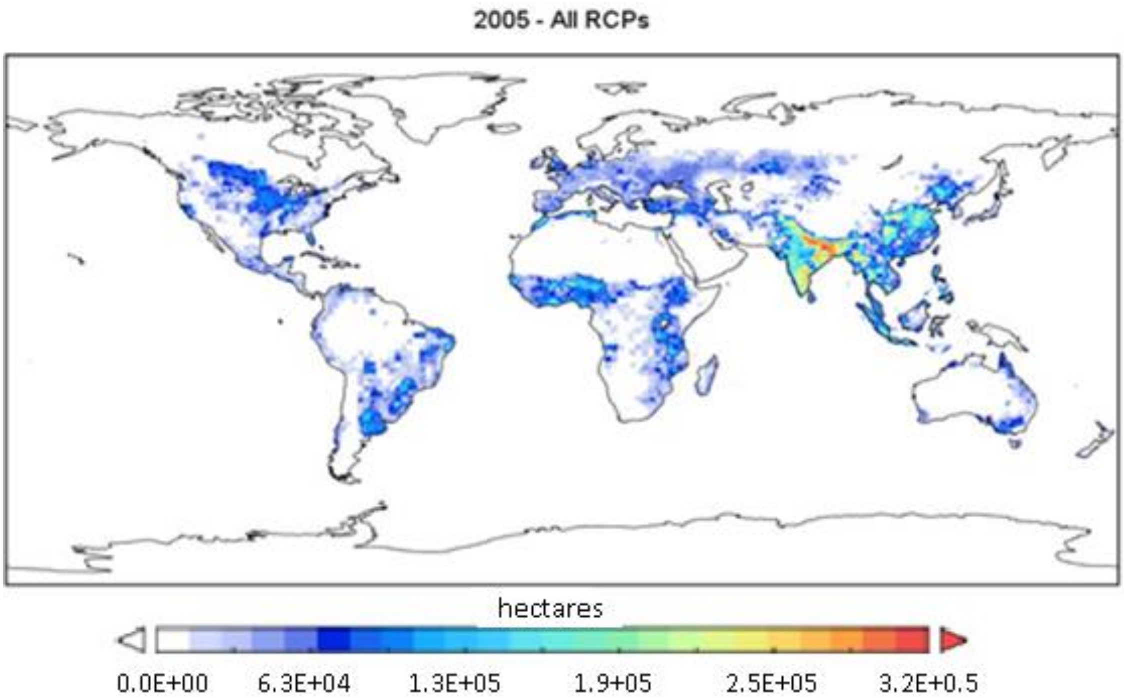

Figure 6-1: Hectares of crop land used globally for crop cultivation in 2005 for all RCPs.

Figure 6-1 shows the distribution of crop land in 2005 for all four RCPs. This is the baseline year for all scenarios, from which the RCPs diverge, along separate pathways of land-use to 2100. The baseline year of 2005 sees 1.56 billion hectares of land under cultivation in each RCP. This corresponds well with data from the FAO database FAOSTAT which details that 1.54 billion hectares of land were under the cultivation of permanent of arable crops in 2005 (FAO, 2014).

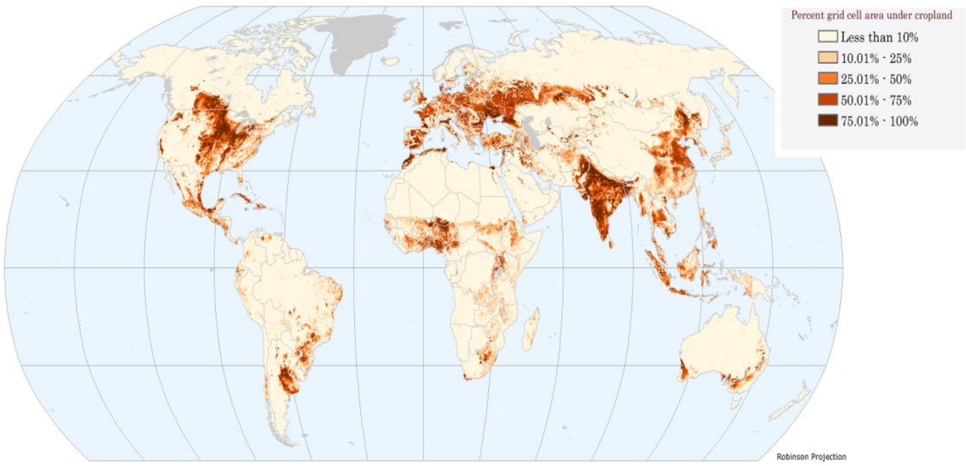

Figure 6-2: Percentage grid cell area under cropland in 2000. Adapted from SEDAC (2014) under the creative commons 3.0 Attribution Licence (http://creativecommons.org/licenses/by/3.0/legalcode).

When compared with data from NASA's Socioeconomic Data and Applications Centre (SEDAC) (Figure 6-2) (SEDAC, 2014) and data from a study of global cropland coverage in 2000 by Ramankutty et al. (2008) the spatial coverage of cropland is reproduced well in the RCP datasets for 2005. Small discrepancies can be seen between the datasets, for example the RCP dataset has more prescribed land coverage in North Eastern Australia than is detailed in the SEDAC (2014) and Ramankutty et al. (2008) datasets, but generally agricultural land use coverage is a good match between the datasets. Figure 6-3 below shows how the total global cropland area (Mha) changes over time within each RCP.

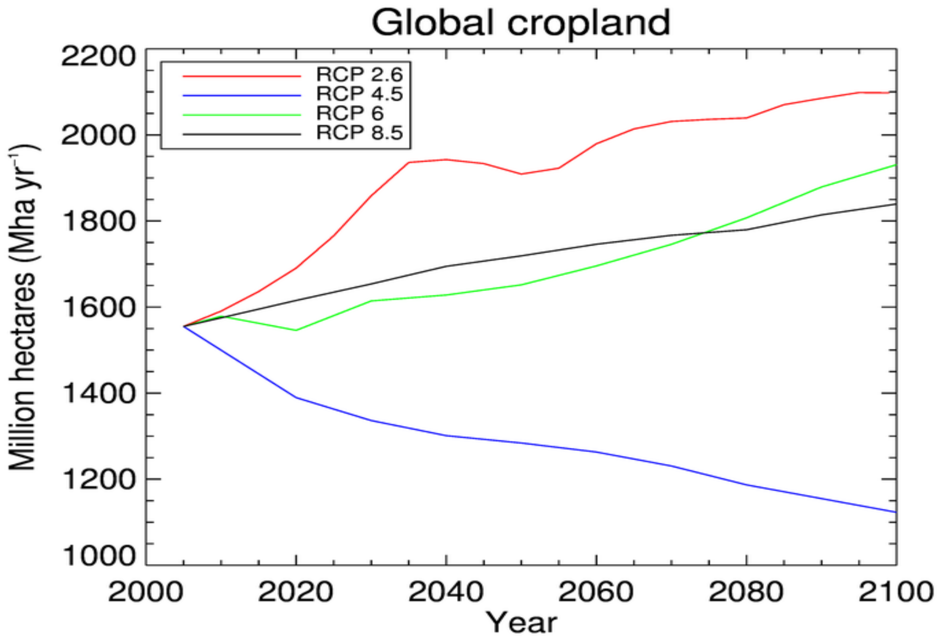

Figure 6-3: Total global cropland (Mha yr^{-1}) for the four RCPs over the scenario period of 2005 to 2100.

From the initial 1.56 billion hectares in 2005, the cropland area in 2100 is 2.10, 1.12, 1.93 and 1.84 billion hectares (B ha) for RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5 respectively. RCP 4.5 consistently has the smallest area of land under crop cultivation of the four RCPs. It is the only scenario which sees a major and sustained decline in cropland area, resulting in less land used for crop cultivation in 2100 than in the baseline year of 2005. This is attributed to the scenario drivers of RCP 4.5, including afforestation measures and dietary changes (Thomson et al., 2011). RCP 6 and RCP 8.5 have similar crop land area pathways throughout the period, with RCP 6 overtaking RCP 8.5 in around 2075. RCP 6 has around 91.4 Mha of cropland more than RCP 8.5 in 2100. RCP 2.6 consistently has the largest land area under crop cultivation throughout the time period. RCP 2.6 sees 975 Mha yr^{-1} more cropland under cultivation than RCP 4.5 in 2100. Figure 6-4 shows the distribution of cropland in 2100 for RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5 respectively.

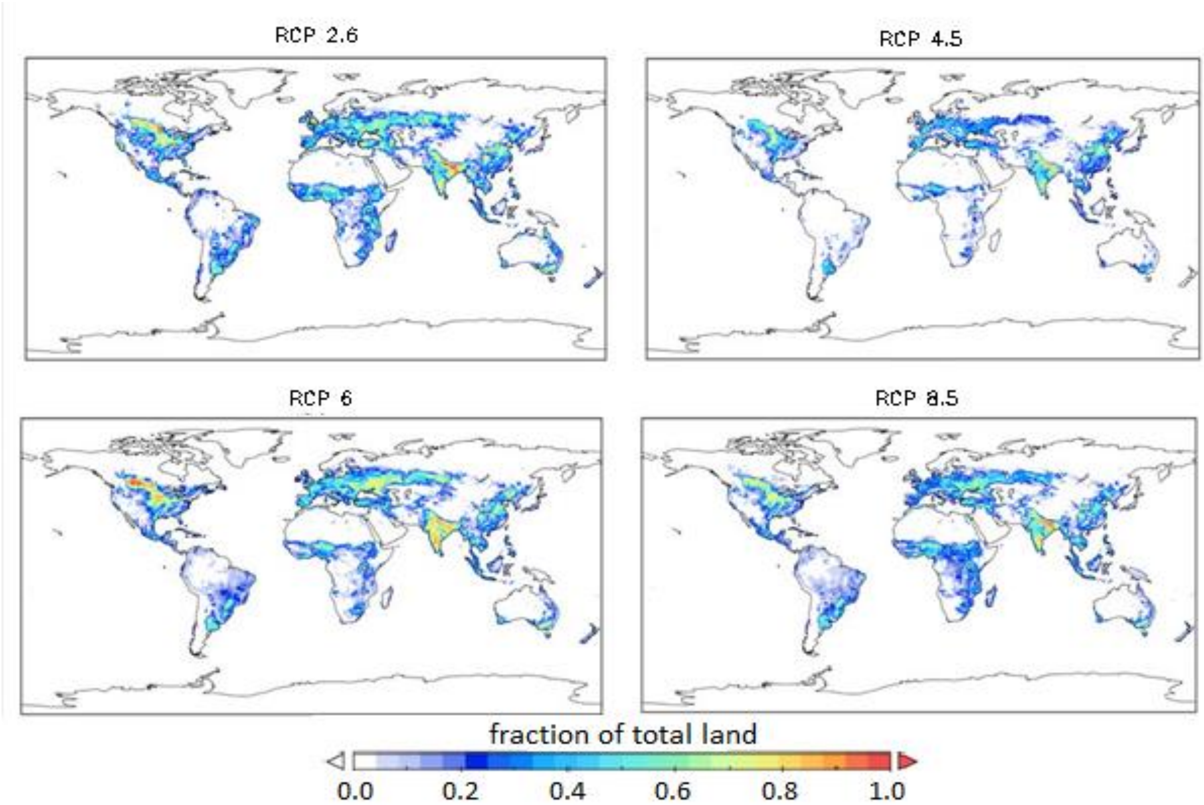

Figure 6-4: Fraction of land area used as cropland in 2100 for RCP 2.6 (top left), RCP 4.5 (top right), RCP 6 (bottom left), RCP 8.5 (bottom right).

The large-scale regional distribution of land used for crop production is similar in the four RCPs in 2100 (Figure 6-4). Within each region there is often large variation in the more localised areas of cultivation, with some RCPs utilising much more cropland than others. In all regions, RCP 4.5 appears to utilise the smallest area of cropland in 2100, with cropland area in South America and Africa particularly reduced in comparison to the other RCPs. In 2100, in a number of regions, RCP 6 has the second lowest area of cropland, with, in particular, less crop land under cultivation in Africa and South America than in RCP 2.6 and RCP 8.5. In other regions RCP 6 has more land under crop production in 2100 than the other three RCPs. Some areas of India have more land under crop cultivation in 2100 in RCP 6 than in RCP 2.6 or RCP 8.5.

The total land under cultivation of the crop groups assessed within this study (see Table 5-2) in 2005 is 1.16 Gha, this is 74 % of the total permanent and arable cropland prescribed for the RCPs in 2005. The total cropland area in each RCP for the years 2005, 2025, 2050, 2075 and 2100 is detailed in Annexe III.

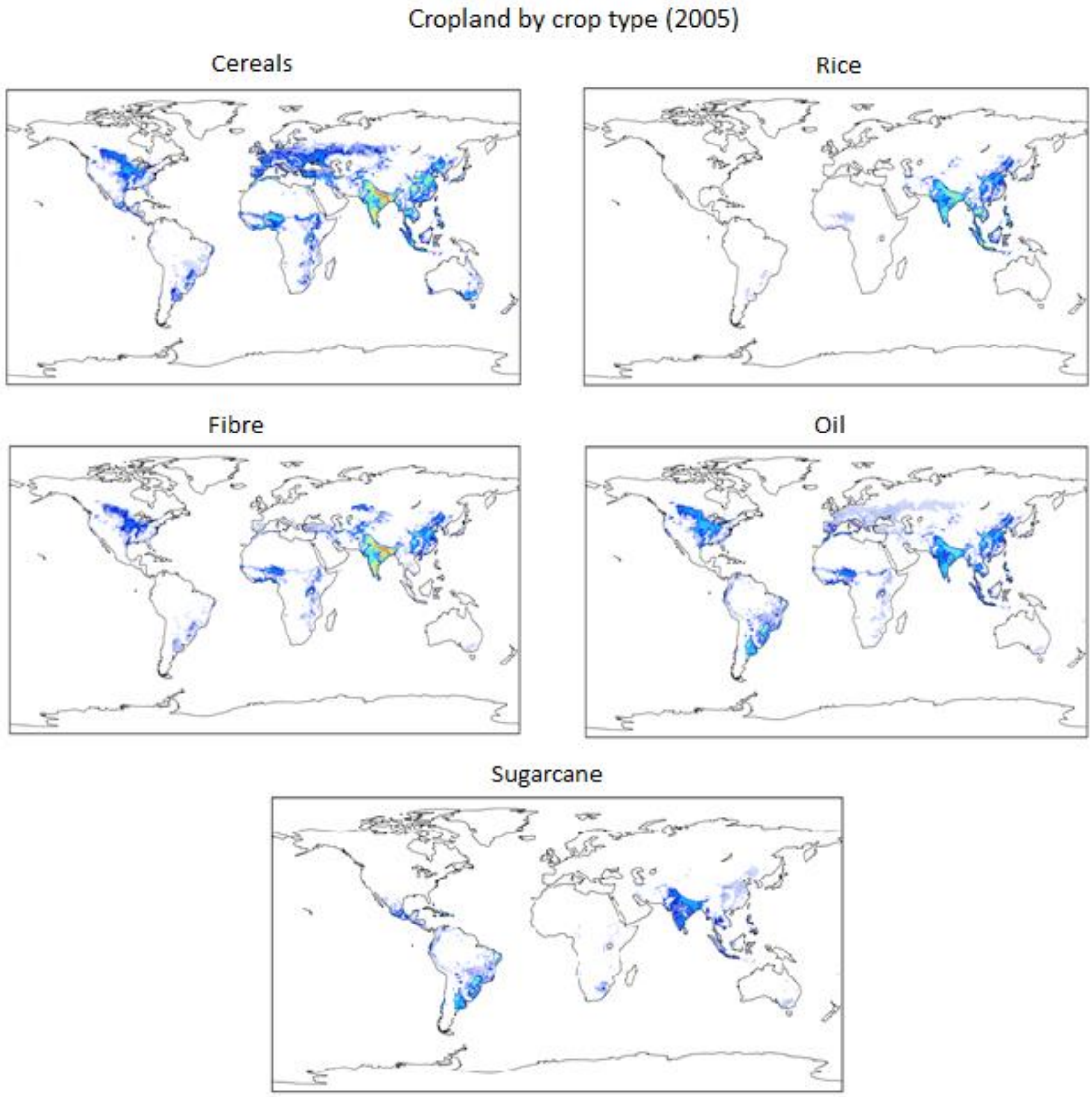

Figure 6-5: Distribution of the different crop types by crop category in 2005. Plots show distribution of cereal crops (top left), rice crops (top right), fibre crops (mid-left), oil crops (mid-right) and sugarcane (bottom). This represents the baseline distribution of crops for the four RCPs.

The distribution of crop types generated by the biochar model for 2005 is illustrated in Figure 6-5. The spatial variation in crop groups simulated by the model, using RCP cropland data and calculated crop fractions is representative of the distribution of these crop types in reality.

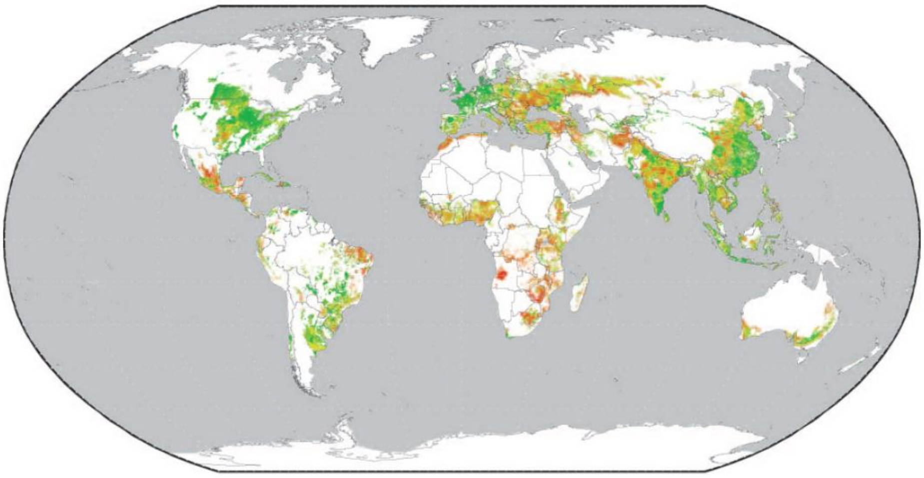

Figure 6-6: Plot detailing progress towards peak cereal crop yields, taken from Mueller et al. (2012). The plot illustrates the current global distribution of cereal crop cultivation land, for comparison with cereal cropland generated by the biochar model (Figure 6-5, top left panel). See Annexe V for licencing details for use of this figure.

Comparison of current cereal cultivation land (Figure 6-6) with the model distribution of cereal land (Figure 6-5, top left panel) shows that the model recreates cereal land distribution well. There are a few small areas which may not be prescribed as crop land within the model, for example the North Eastern region of Brazil and Angola (South Western Africa), but overall the fit of cereal crop land in the model is seen to be good.

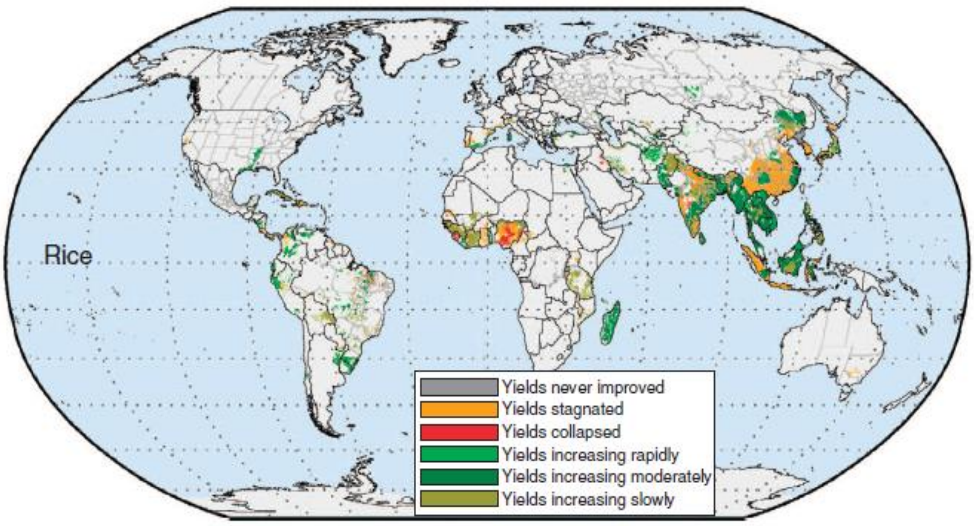

Figure 6-7: Plot detailing progress towards achieving maximum rice yields, taken from Ray et al. (2012). The plot illustrates the current global distribution of rice cultivation land. See Annexe V for licencing details for use of this figure.

Comparison of current rice cultivation land (Figure 6-7) with the model distribution of cereal land (Figure 6-5, top right panel) shows that the model also recreates rice cultivation land distribution well. The main rice cultivation areas are defined in the model, though the model misses some small areas of rice cultivation, for example Madagascar and the North American states of Arkansas, Louisiana and Texas are not prescribed as rice producing regions within the model. This is due to the aggregation of production data from the FAO into regional data, meaning that the small levels of production in these areas are overlooked due to the larger scale of the data (for example production was determined from FAOSTAT for the North American region, of which the vast majority is not rice producing). The oversight of these rice producing areas was deemed to be acceptable for the assessment here as the main rice producing regions of the world were prescribed well by the model (Asia currently produces over 90 % of the world's rice (FAO, 2000)). In 2007, the countries Brazil, India and China contributed more than 60 % of global sugarcane production, with other countries such as Mexico, Thailand and the Philippines also making important contributions (Fischer et al., 2008). The distribution of sugarcane crops projected by the model was, therefore, deemed to be representative of current distribution as the main areas of sugarcane production within the model are representative of these regions (Figure 6-5, bottom panel). The various types of oil crop, for example oil palm and rapeseed (see Table 5-2), are produced in different regions of the world, with one or more oil crop types being grown in almost every agricultural region (Oregon State University, 2004). For this reason, the representation of oil crops produced by the model was accepted here due to the good fit with global agricultural land. The representation of crop group distribution in 2005 simulated by the model was a good fit to the actual distribution.

Table 6-1: Comparison of the model prescribed cropland area (Mha) (left) and FAO data for the total area of cultivated cropland in 2005 (Mha) (right) for each crop group.

Crop group	Area cultivated in 2005 (model projection) (Mha)	Area cultivated in 2005 (FAO data) (Mha)
cereals	694	691
rice	154	155
oil	252	253
fibre	38	38
sugarcane	19	20

Table 6-1 details a comparison of the total cropland area (Mha) prescribed to each crop group within the biochar assessment model, and data for the actual area of cultivated cropland (Mha) for each crop group in 2005, taken from FAOSTAT. Analysis of the cultivated area prescribed within the model, in comparison to the data from FAOSTAT shows very good correlation between the two sets of values. Total cropland cultivated for these crop groups is the same for both datasets. The area of cropland prescribed for cereal land within the model is 3 Mha more than the dataset from the FAO. This is the largest discrepancy between the two, at 0.4 % larger than the actual cultivated area, with rice, oil and sugarcane cropland all being prescribed 1 Mha less in the model than in FAOSTAT. Fibre crops are prescribed the same amount of land for cultivation within both datasets. The model prescribed values were therefore determined to be a close fit to the actual data, allowing further use of the model to project the biochar scenarios from a realistic baseline.

The amount of land cultivated for each crop group differs within each RCP, spatially and temporally. Figure 6-8 shows the trends of cultivation area (Mha) for each crop group within each RCP. The differences seen in trends over time between the crop groups indicate the spatial differences in total cultivation land area between the RCPs. An example of this can be seen clearly in the cultivation areas of the different crop groups in RCP 4.5. To differing extents, the land area under cultivation of cereals (excluding rice), fibre, oil crops and sugarcane sees a decline to 2020, before an increase in cultivation area begins. This initial decline is not seen in the area of land under rice cultivation, indicating that the changes in total cropland area in RCP 4.5 affect areas where rice is cultivated in a different way to land under cultivation of the other crop groups. Figure 6-8 shows a number of such differences, indicating changing regional cropland areas over time, thus affecting the production of each crop category over time. Figure 6-8 also demonstrates the large differences seen in cultivation area, within each crop category, between the RCPs. RCP 2.6 consistently has the largest area of land under cultivation for all of the crop groups, although RCPs 6 and 8.5 are beginning to converge on the RCP 2.5 values in 2100 for some crop types (notably rice and sugarcane). RCP 4.5 has consistently declining cropland for all crop groups across the scenario period, with some variation in rates of decline seen temporally and between crop groups.

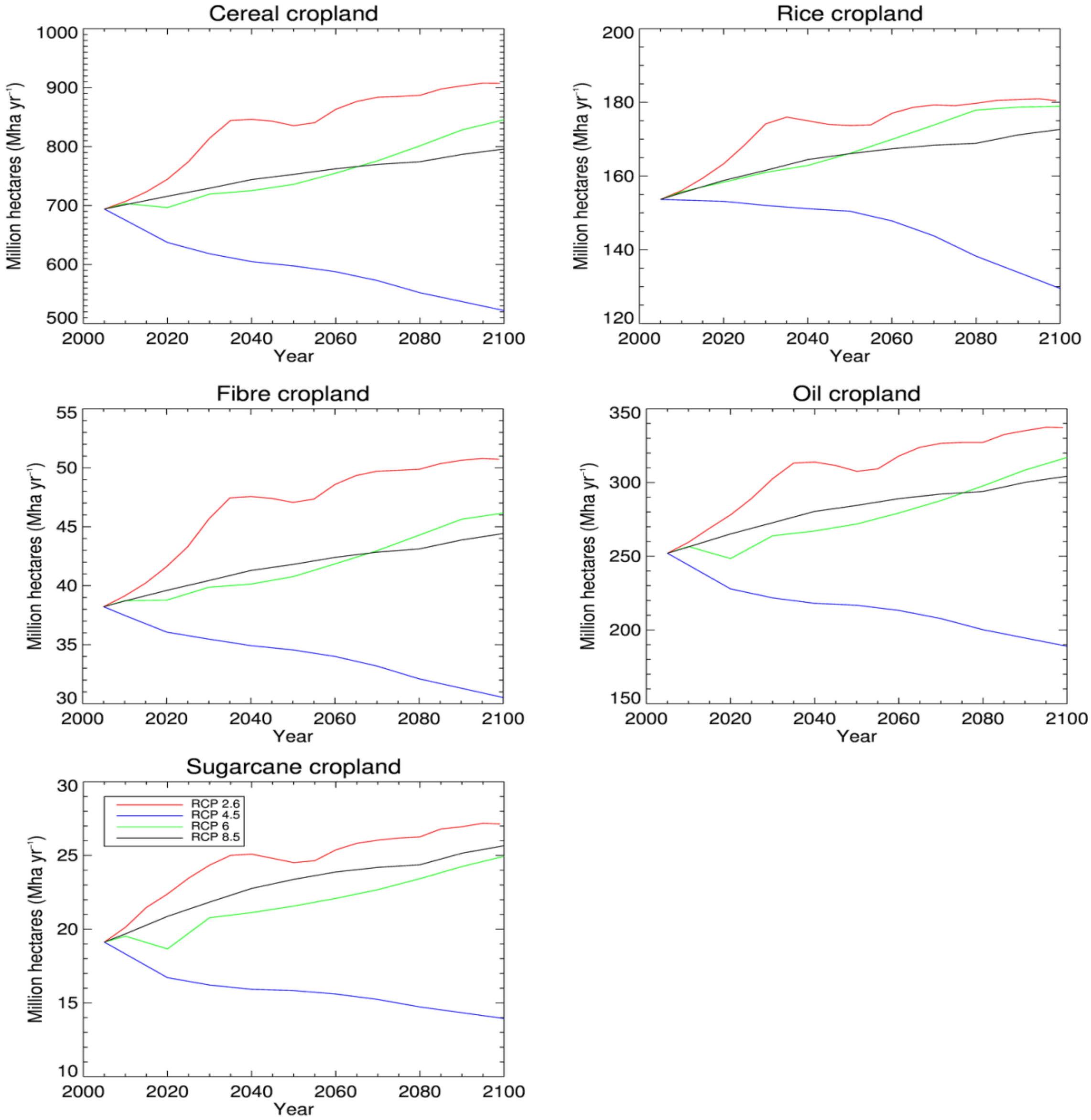

Figure 6-8: Global cropland (Mha yr^{-1}), by crop group, for the four RCPs over the 95 year assessment period. N.B. Scales vary between crop groups.

6.3 Scenario 1

Section 6.2 has detailed the land prescription for the production of each crop type for the biochar model. Sections 6.3.1 to 6.3.4 detail the model outputs at each stage of assessment of Scenario 1 which is the main scenario, using the most likely or average values for the parameters prescribed within the model. Variations in these parameters are discussed in Sections 6.4 to 6.11.

6.3.1 Commodity production

Using the crop land area prescribed for each RCP and the crop yield projections for each RCP resulted in commodity production quantities for each RCP. Figure 6-9 shows total annual commodity production (Gt yr^{-1}) for the four RCPs and Figure 6-10 details the distribution of total commodity production in 2100 for each RCP.

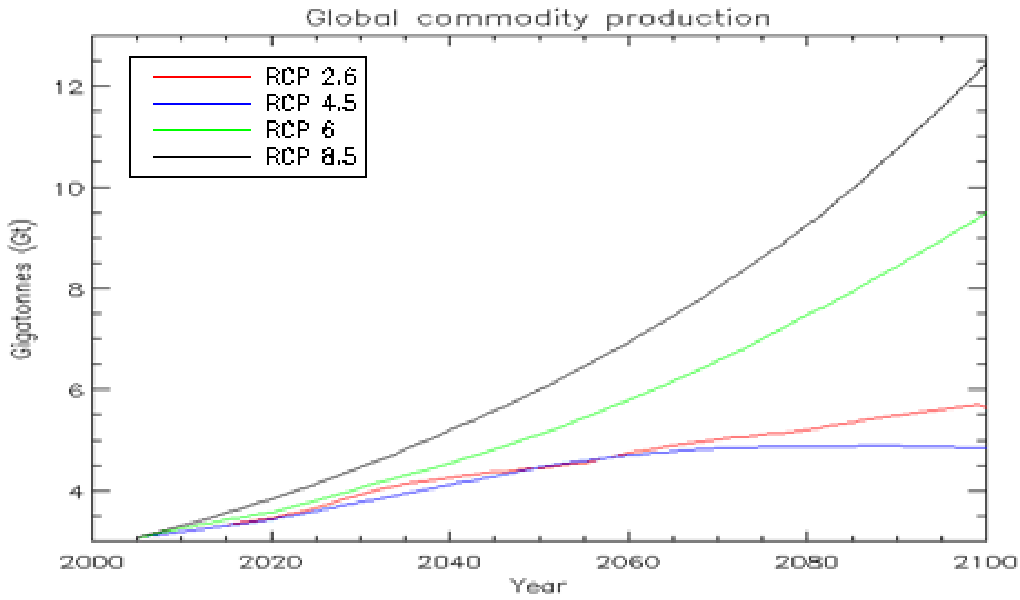

Figure 6-9: Total global commodity production (Gt yr^{-1}) for the four RCPs over the 95 year time period.

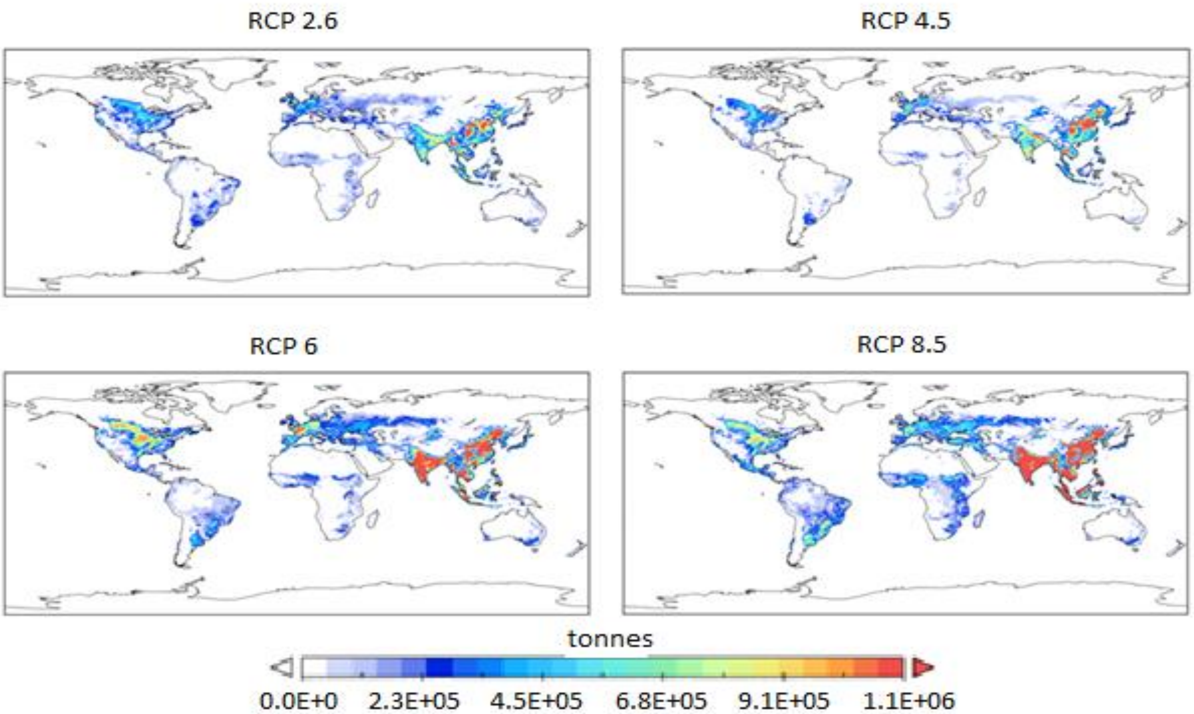

Figure 6-10: Total commodity production (tonnes) in 2100 for all crop categories for RCP 2.6 (top left), RCP 4.5 (top right), RCP 6 (bottom left) and RCP 8.5 (bottom right).

Commodity production quantities within the RCPs do not follow the same trends as cropland area due to the different crop yield assumptions of each RCP (Figure 6-9). Although RCP 2.6 has a higher area of land under cultivation for all of the crop groups, RCP 6 and RCP 8.5 both produce more commodity due to the larger crop yield increases assumed within those RCPs.

A large quantity of the total commodity production in each RCP is produced in Asia. RCP 2.6 and RCP 4.5 have production hotspots in China, with large quantities of commodity produced there. RCP 6 and RCP 8.5 see these large production quantities in the wider Asian region, including India. The Corn Belt region of North America is also an area of consistent production throughout the four RCPs, with RCP 6 seeing the largest production quantities, of the four RCPs, for this region in 2100. Figure 6-10 shows that production in other regions of the world is highly variable, for example total commodity production in Africa is relatively low in RCP 2.6 and RCP 4.5 compared to that of RCP 6 and RCP 8.5. Total commodity production over the 95 year period was 430 Gt, 411 Gt, 541 Gt and 646 Gt for RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5 respectively. Annexe III details the total commodity production in each RCP for the years 2005, 2025, 2050, 2075 and 2100.

6.3.2 Residue production and availability

Combined with the crop specific RPR values the total commodity quantity produced within each RCP would produce the residue quantities shown in Figure 6-11.

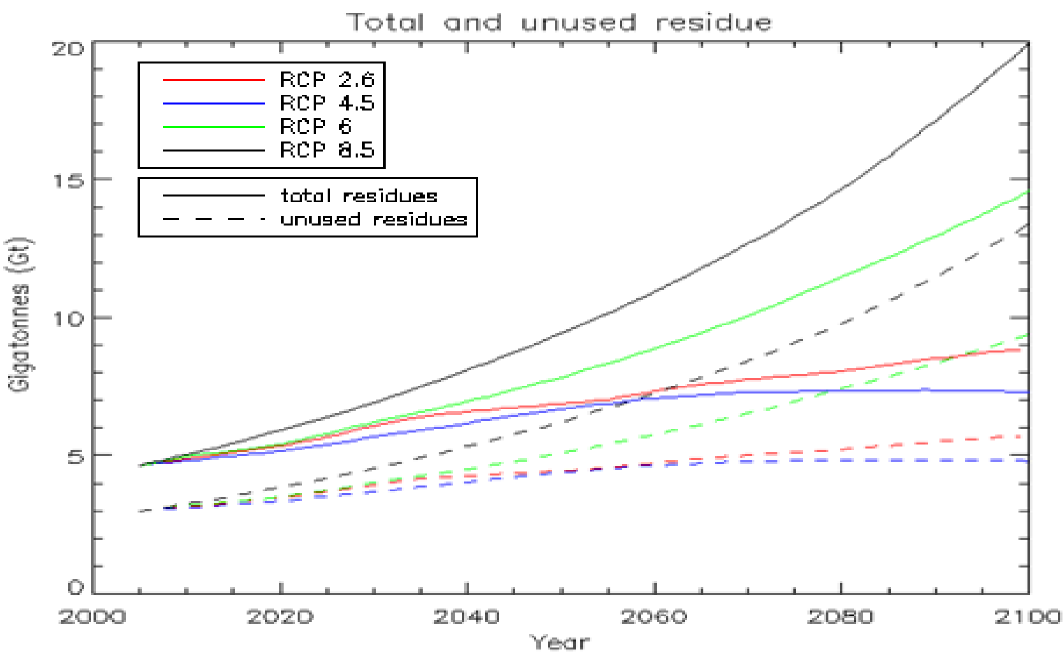

Figure 6-11: Global annual crop residue yield (Gt yr^{-1}) (solid line) and unused residue (Gt yr^{-1}) (dashed line) for the four RCPs over the 95 year time period for Scenario 1.

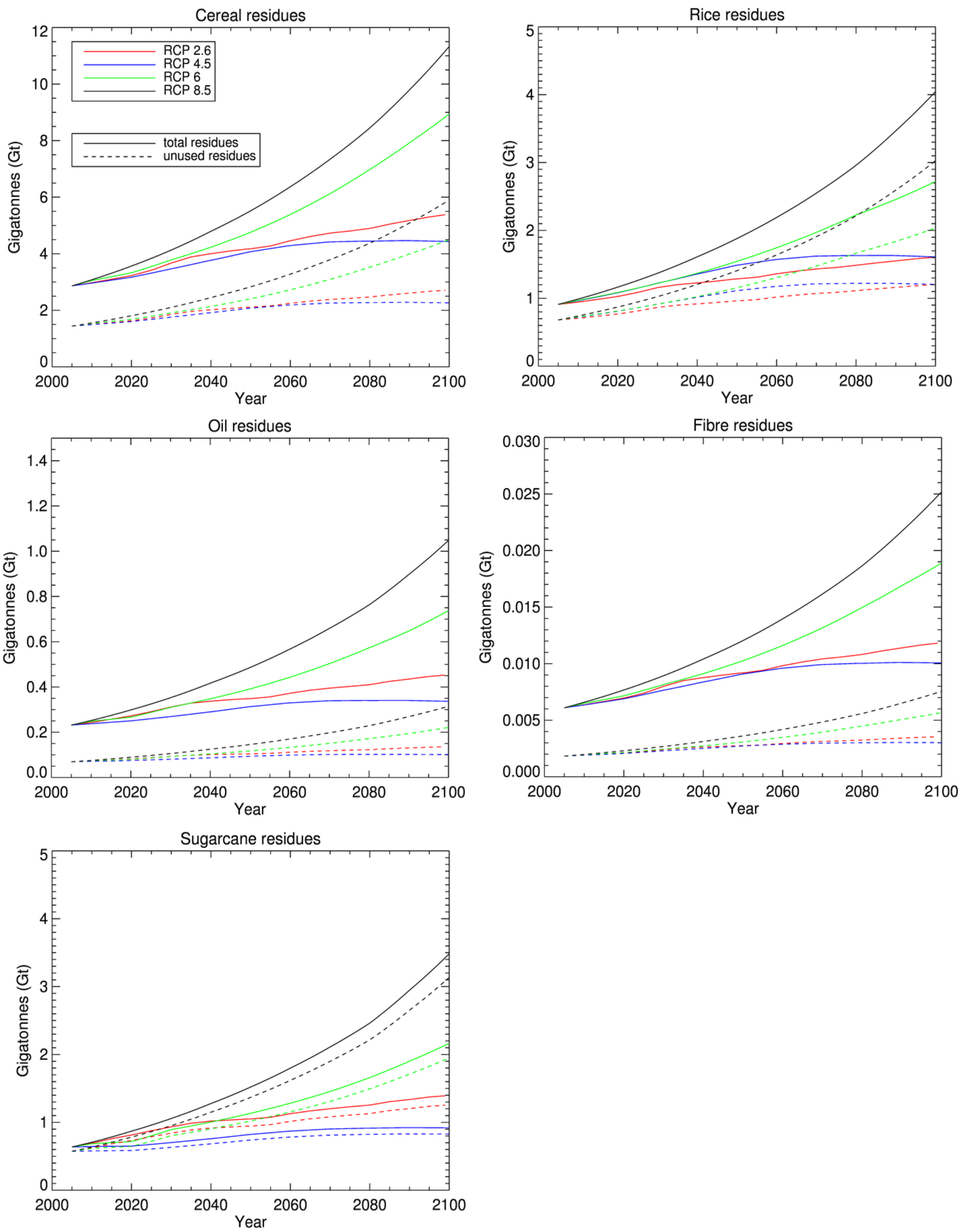

Figure 6-12: Global annual residue and unused residue quantities by crop group for each RCP. Plots show: Cereal residues, top left; rice residues, top right; oil residues, mid left; fibre crop residues, mid right; sugarcane residues, bottom left. Each plot shows total residues (Gt) (solid line) and total unused residues (Gt) (dashed line), by crop category under the assumptions of Scenario 1. N.B. Scales vary between crop groups.

The trends for total commodity and residue production are very similar across the period, as are the trends in total and unused residue quantities (Figure 6-11). Figure 6-11 also shows the total unused residue quantities for under the assumptions of biochar scenario 1. Total residues and unused residues are 4.65 Gt yr^{-1} and 3.0 Gt yr^{-1} respectively in 2005. Figure 6-12 shows the total residue production from each crop group for each RCP, alongside the unused portion of each residue type.

The trends in the production of residues are seen to differ between the crop groups, particularly in the production of crops in RCP 2.6 and RCP 4.5. The majority of crop groups loosely follow the trend of total residue production see in Figure 6-11. Rice residues in RCP 4.5 are one exception to this, with residue quantities from rice production increasing above those of RCP 2.6 after 2030, then declining to similar levels as RCP 2.6 at the end of the century. The variation seen in production trends between the different crop groups for RCP 2.6 and RCP 4.5 indicates that changing land-use has a dominant effect on these RCPs, which is not the case for RCP 6 and RCP 8.5. The crop yield increase assumptions of RCP 6 and RCP 8.5 appears to be the dominant factor in commodity production and residue trends for these two RCPs. This is explored further in Sections 5.4.1, 5.4.2 and 5.4.7.

Figure 6-13 details the distribution of total crop residues (left panels) and unused crop residues (right panels) in 2100 for the four RCPs. Some differences in the distribution of unused crop residues are seen, when compared to the total production of residues. For example, much of the residue produced in Europe becomes unavailable for conversion to biochar within the model, although much of the total residue produced in Asia is still available as unused residue. These differences in regional availability between total and unused residues are attributable to the different spatial distributions and availability of the different crop residue types. Within all RCPs the largest quantities of both total residues and available residues are in Asia. South America is consistently the second largest region of available residues. The potential of these residues for biochar production depends on a number of other factors such as biochar yield, biochar carbon content and other properties.

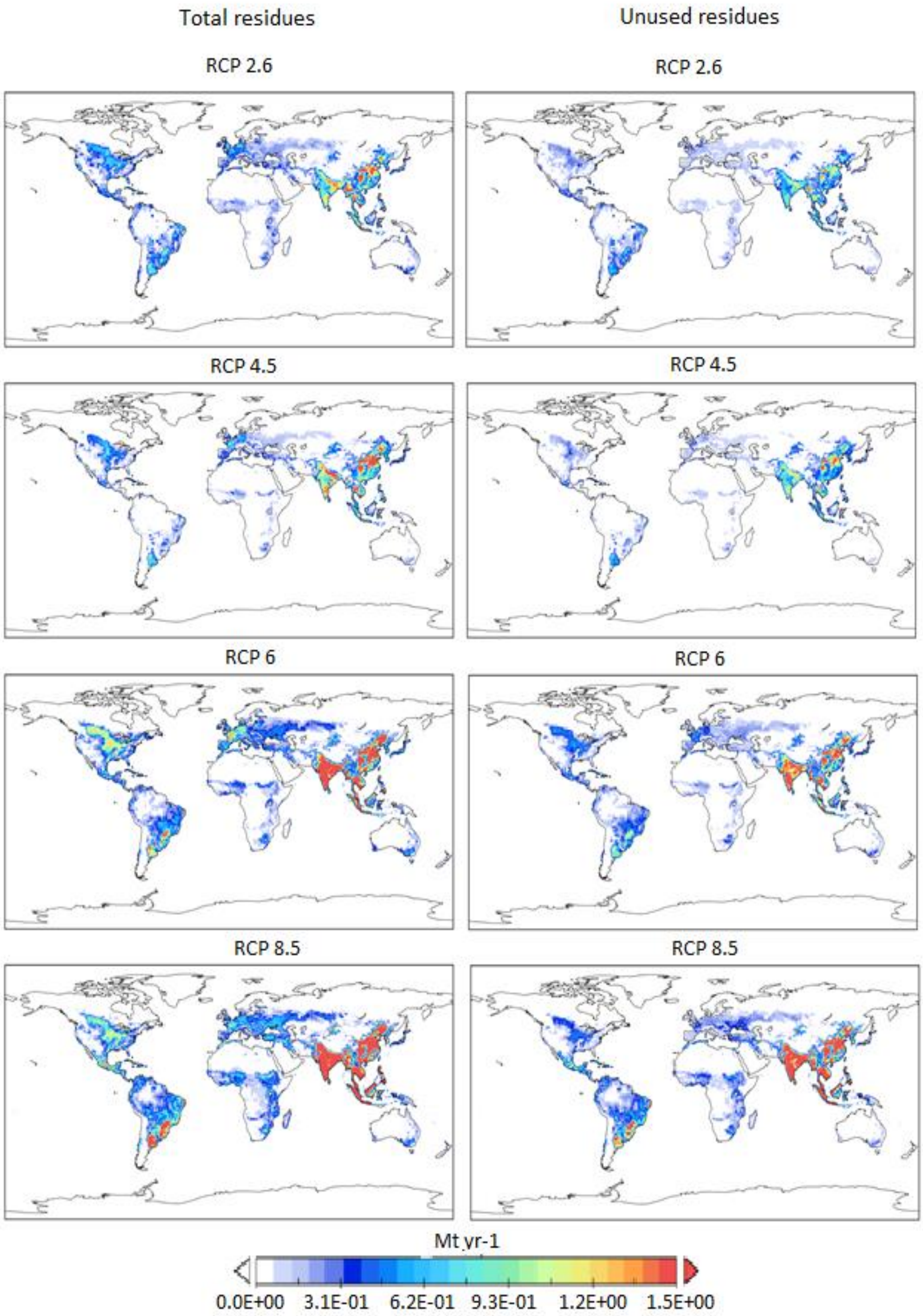

Figure 6-13: Spatial distribution of total crop residues (Mt yr^{-1}) in 2100 for each RCP (left panels) and total unused crop residues (Mt yr^{-1}) in 2100 for each RCP (right panels).

6.3.3 Yield of biochar

6.3.3.1 Total biochar yield (all crop categories)

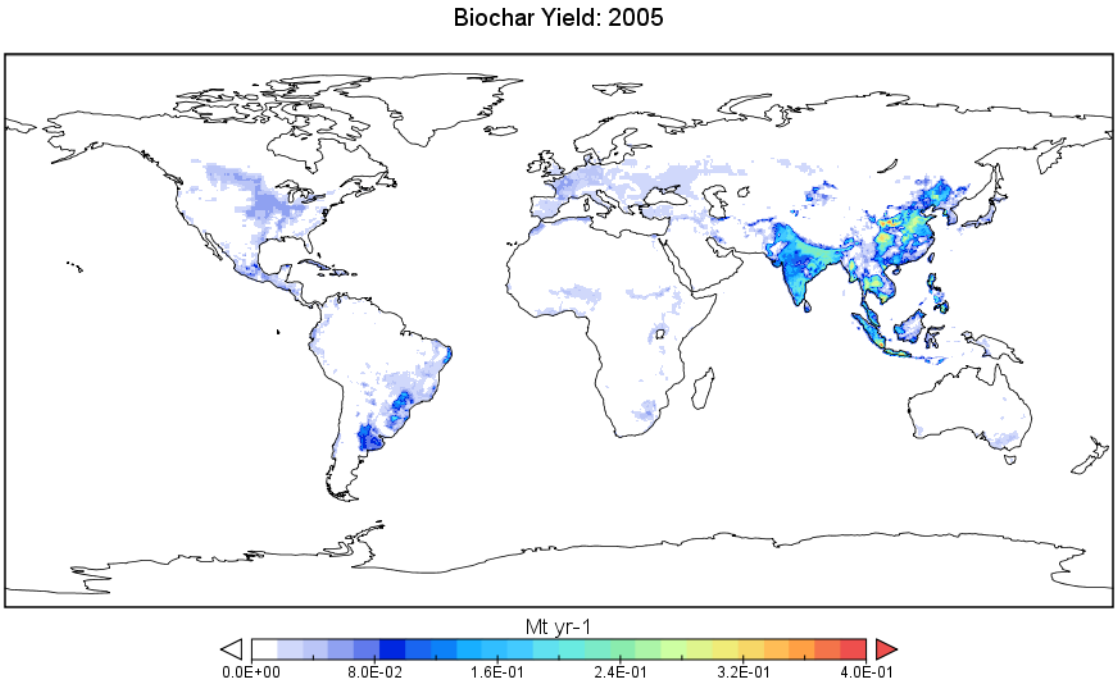

Figure 6-14: Total biochar yield (Mt yr^{-1}) from all crop residue types assessed for the baseline year (2005) of all RCP scenarios for Scenario 1.

Biochar yield in 2005, under the assumptions of Scenario 1, is the same for each of the RCPs due to the baseline conditions being the same for each scenario. The total amount of biochar produced globally in 2005, within Scenario 1, is 932.28 million tonnes (Mt). As can be seen in Figure 6-14 the distribution of biochar varies regionally. As with residue availability, much of the biochar production is concentrated in Asia, particularly in India, China, and Indonesia. The maximum regional average production potential, per hectare, in 2005 is in Asia, at 1.7 t ha^{-1} yr^{-1}. Central and South America (particularly Brazil and Argentina) also have some more intense regions of biochar production potential, producing an average of 0.8 t ha^{-1} yr^{-1} in 2005. Other regions, such as the Corn Belt of the USA and Europe also have some biochar production potential, although the quantities are lower than the regions discussed previously. The potential for biochar production within each RCP changes over time under the assumptions of Scenario 1.

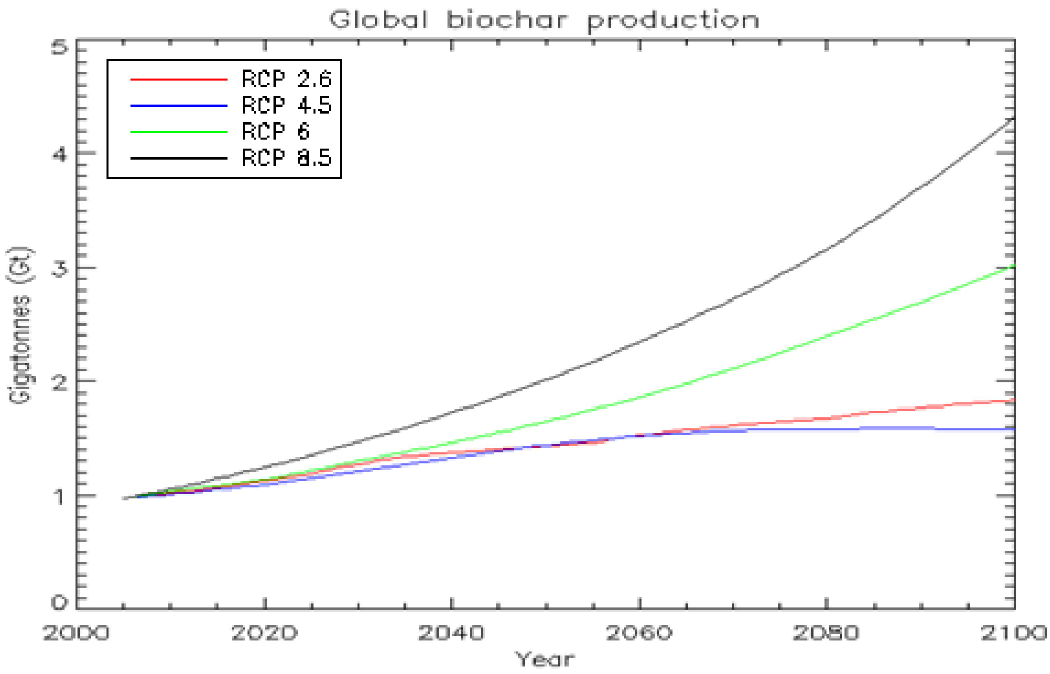

Figure 6-15: Global annual biochar yield (Gt yr^{-1}) for the four RCPs as assessed under Scenario 1.

RCP 8.5 consistently has the largest global potential for biochar production under the assessment of biochar Scenario 1. RCP 4.5 has the lowest potential for biochar production for the majority of the assessment period, with one period (2050 to 2060) where biochar production potential in RCP 2.6 drops below that of RCP 4.5. RCPs 2.6 and 6 follow a very similar trajectory for global biochar production potential to around 2035, where divergence begins and RCP 6 then demonstrates a larger production potential throughout the rest of the assessment. As with commodity production, the crop yield increase assumptions of RCPs 6 and 8.5 appear to be the dominant factors in the biochar production trends for these two RCPs. The increased fluctuation in the trends of RCP 2.6 and RCP 4.5 indicate that other influences, such as land-use change, are more dominant in the biochar production potential of these two pathways.

Figure 6-16 shows the spatial potential for biochar production in 2100 for the four RCPs. RCP 4.5 generally manifests the lowest potential for total biochar production in many regions. There are a few small regions where biochar production may be greater in RCP 4.5 than RCP 2.6 (see, for example, the difference in the magnitude of biochar production in Eastern China and Southern India, where more biochar is produced in RCP 4.5 than in RCP 2.6). Although there are some regions of higher biochar production potential, per hectare, in RCP 4.5, there area of biochar production potential is more widespread in RCP 2.6 and the other RCPs.

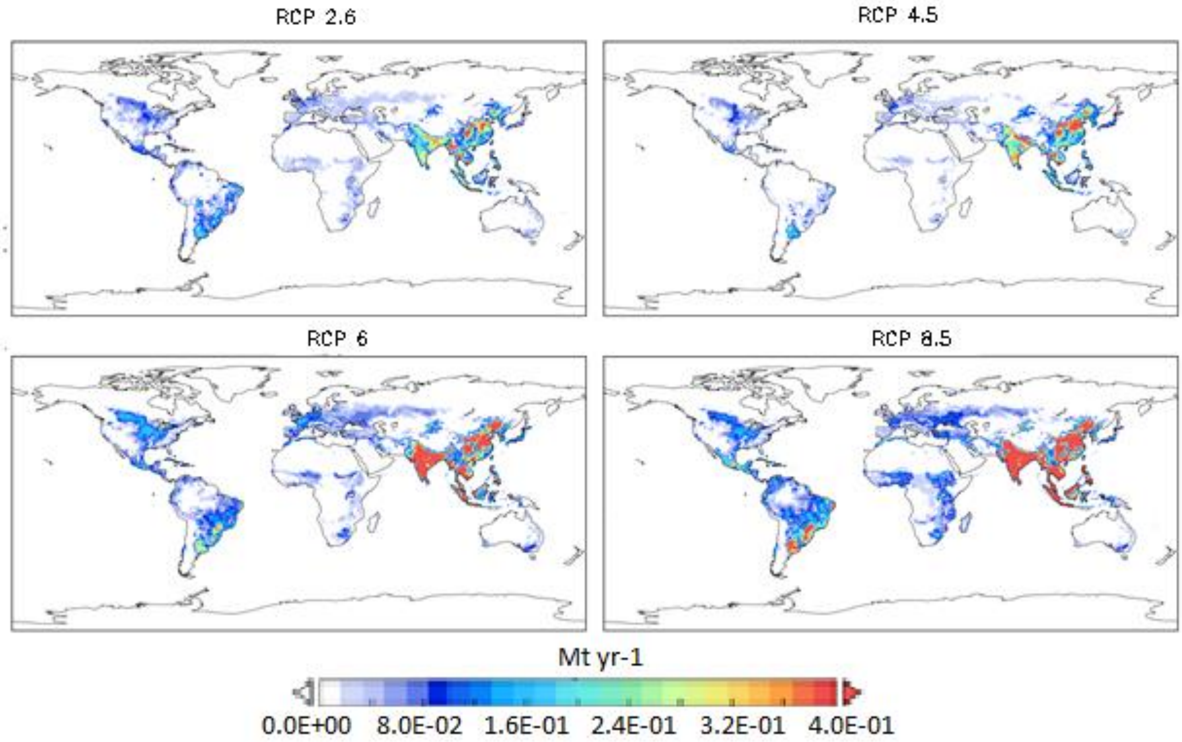

Figure 6-16: Regional biochar yield (Mt yr^{-1}) from all crop residues in 2100, under the assumptions of Scenario 1, for the different RCPs. Biochar production is shown for RCP 2.6 (top left), RCP 4.5 (top right), RCP 6 (bottom left) and RCP 8.5 (bottom right).

The spatial distribution of total biochar yield within the RCPs in 2100 is closely matched with the distribution of total available residues (Figure 6-11), indicating that the dominant available crop residues are likely to produce the majority of biochar. Figure 6-17 to Figure 6-22 examines the contribution of each crop group to the biochar production potential of each RCP, highlighting in particular the different magnitudes of production potential between some crop groups.

6.3.3.2 *Contribution of different crop categories to biochar production*

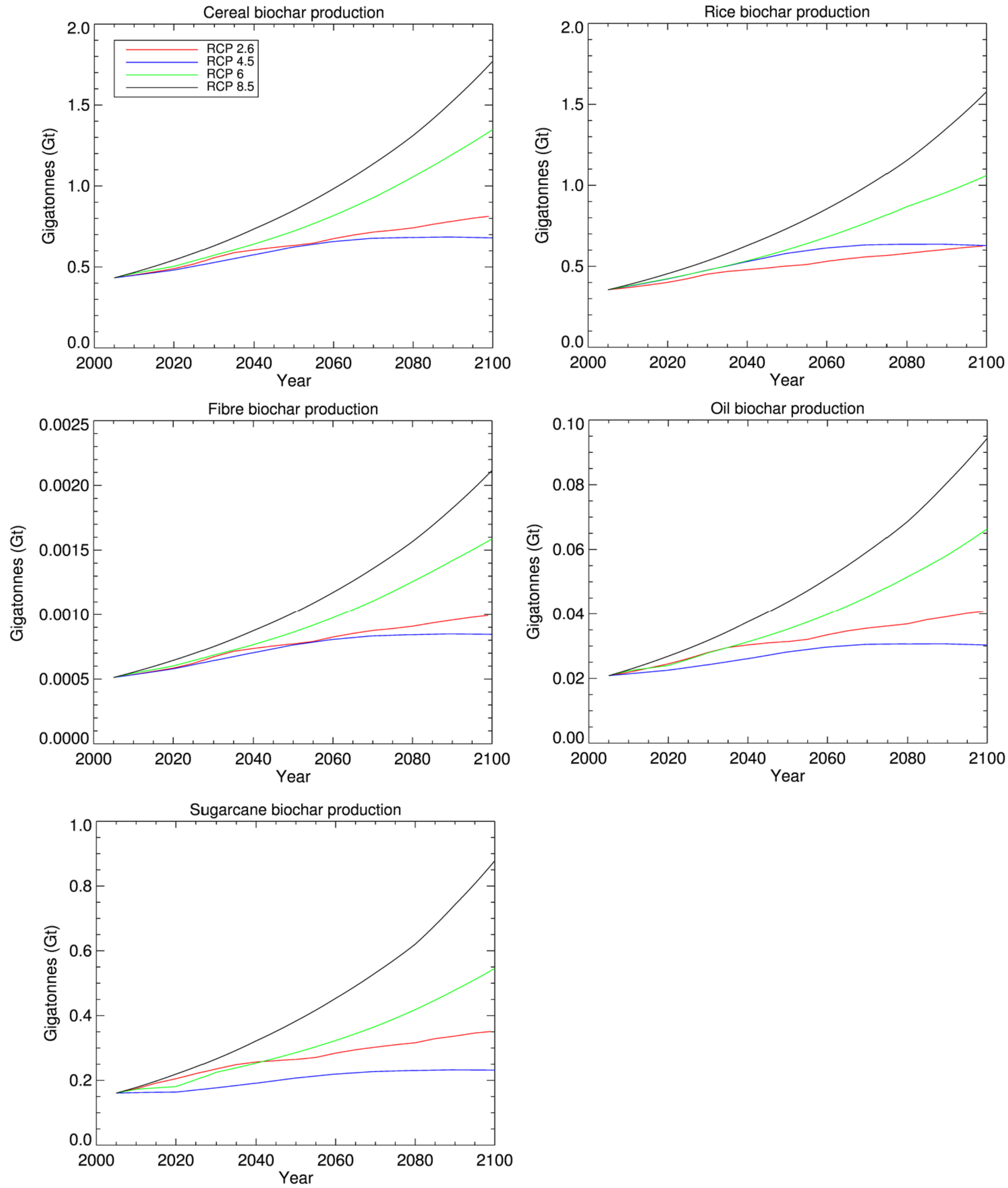

Figure 6-17: Global biochar production potential (Gt yr^{-1}), differentiated by crop category, over time for the four RCPs under the assumptions of Scenario 1. Plot shows biochar from cereal residues (top left), rice residues (top right), fibre residues (mid-left), oil residues (mid-right) and sugarcane residues (bottom). N.B. Scales vary between biochar quantities from different crop residue types.

The different crop categories offer varied contributions to the total quantity of biochar which could potentially be produced within each RCP (see variation in scales in Figure 6-17). For all RCPs the largest contribution comes from cereal crops, producing 0.43 Gt yr^{-1} of biochar in 2005. The other crop groups with relatively high biochar production potential in 2005 are rice and sugarcane crops at 0.35 Gt and 0.16 Gt of biochar respectively. Oil crops and fibre crops are projected to produce 0.02 Gt and 0.5 Mt each respectively in 2005. The large quantities and widespread distribution of biochar produced from cereal crops indicates that this biochar may be of high global significance for carbon sequestration. Although large quantities of biochar may be produced from some crop types, it does not always follow that this is the feedstock of highest importance and potential regionally. For example, biochar from rice residues would be mostly produced in Asia (see Figure 6-19) therefore the location of the addition to soil must also be considered. See Section 2.2.5 and Chapter 7 for further discussion on biochar addition to soil and carbon sequestration potential. The regional significance of the crop groups for biochar production may also change temporally. This regional analysis of each crop group is beyond the scope of this study but would offer important insight into biochar production potential as the product of further research.

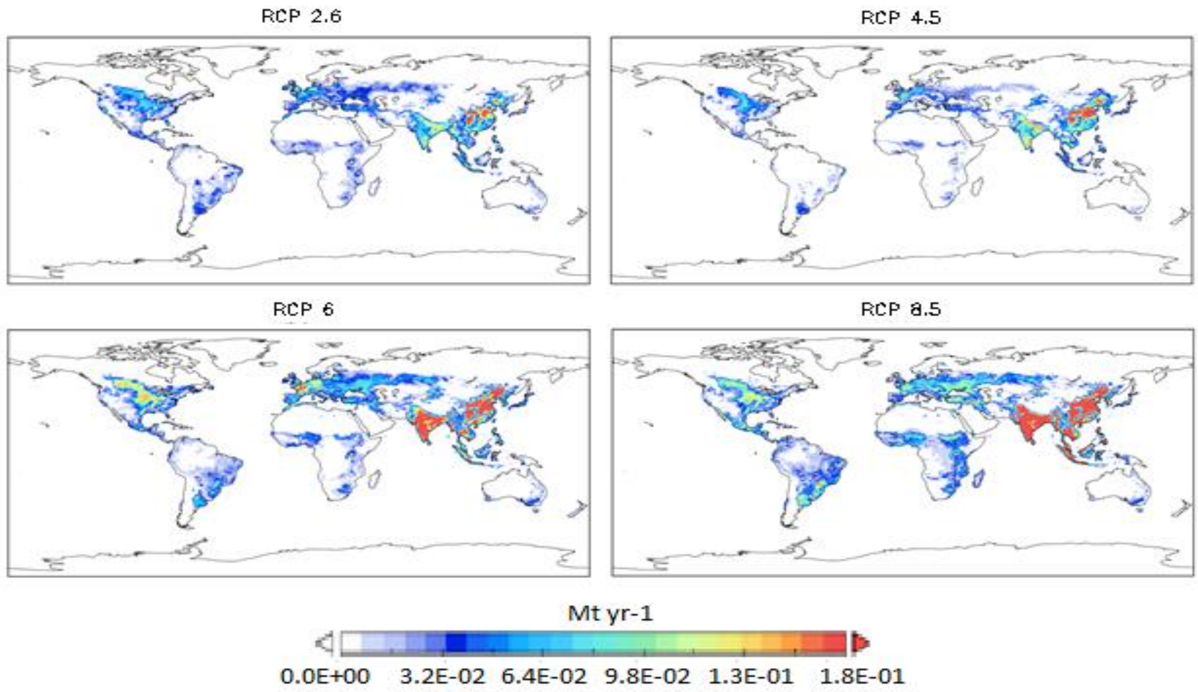

Figure 6-18: Regional biochar yield (Mt yr^{-1}) from cereal crop residues (excluding rice) in 2100 for the four RCPs under the assumptions of Scenario 1. The panels show RCP 2.6 (top left), RCP 4.5 (top right), RCP 6 (bottom left) and RCP 8.5 (bottom right).

The biochar produced from cereal crop residues in Africa and South and Central America in RCP 8.5 covers a far wider geographical area than in these regions for the other RCPs. Many regions also see more biochar produced per hectare, from cereal crops, in RCP 8.5 than the other three RCPs. Regardless of this larger total geographical area of biochar production in RCP 8.5, and generally higher intensity of production, there are still some regions in the other RCPs where more biochar is produced from cereal residues than in the same region in RCP 8.5 due to higher utilization of cropland within the particular region. Examples of this are the North American and Western European regions in RCP 6, which produce more biochar in certain area due to a higher fraction of land used for crop production in these areas (see Figure 6-4). RCP 4.5 has the smallest geographical area of biochar production from cereal crop residues in 2100, at 522 Mha, but does have some areas of increased biochar production per hectare, when compared to RCP 2.6. This is particularly noticeable in China and India.

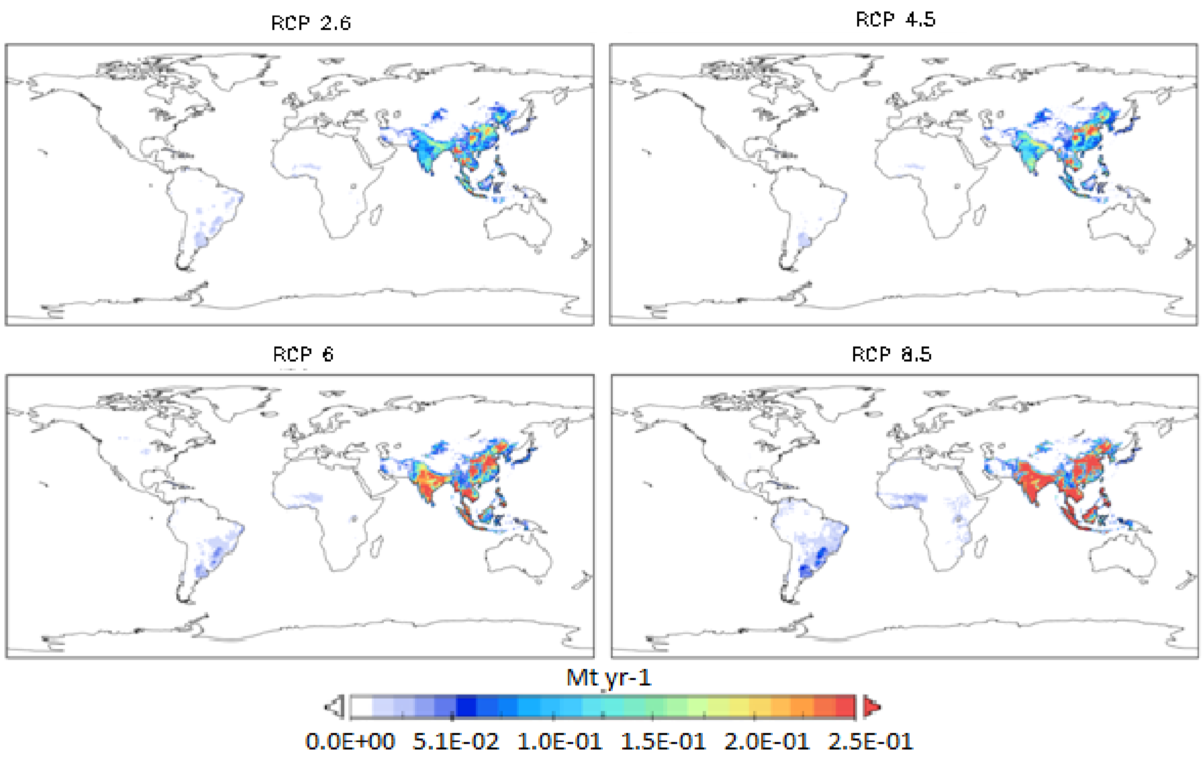

Figure 6-19: Biochar yield (Mt yr^{-1}) from rice crop residues in 2100 for the four RCPs under the assumptions of Scenario 1. The panels show RCP 2.6 (top left), RCP 4.5 (top right), RCP 6 (bottom left) and RCP 8.5 (bottom right).

Biochar production from rice residues is mainly concentrated in Asia, with some potential also in South America and Western Africa. Total production potential is larger in RCP 4.5 than RCP 2.6, at 52.6 Gt and 48 Gt respectively, as production per hectare in Asia is higher in RCP 4.5.

Production potential from rice residues in the alternative production regions of Africa and South America is lowest in RCP 4.5, with increased geographical coverage in RCPs 2.6, 6 and 8.5 respectively.

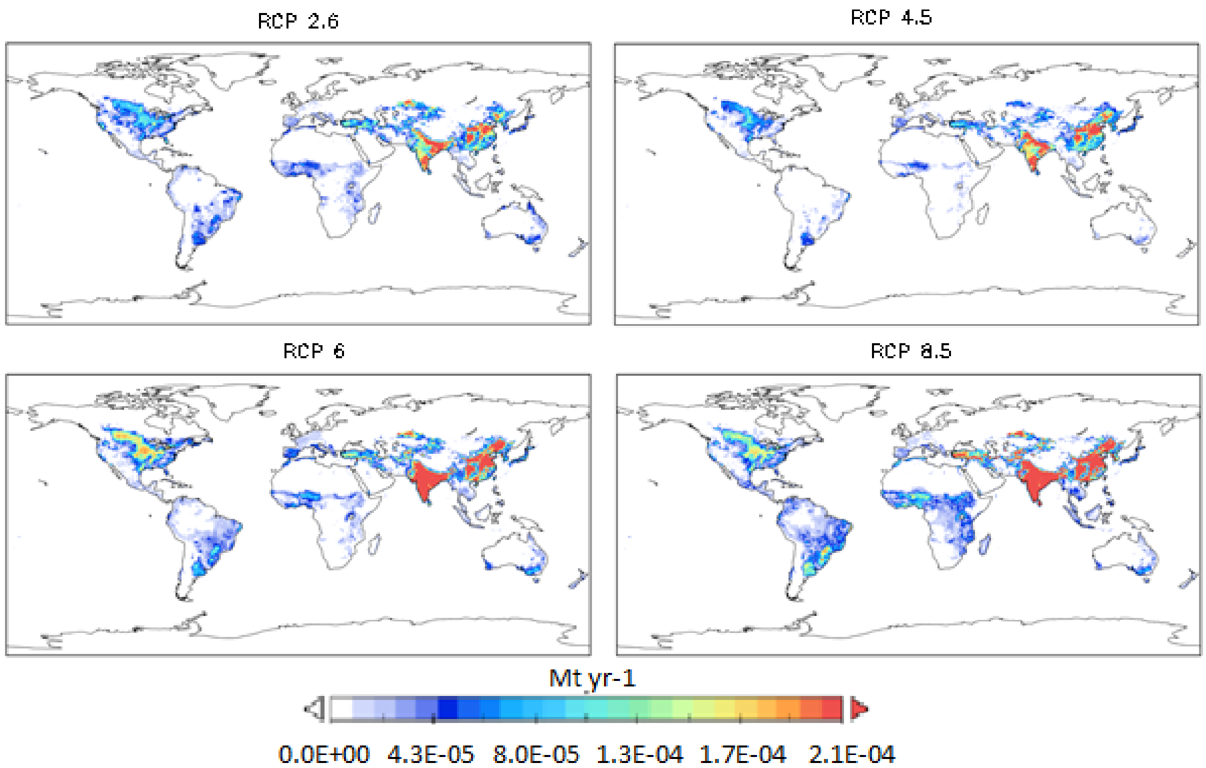

Figure 6-20: Biochar yield (Mt yr^{-1}) from fibre crop residues in 2100 for the four RCPs under the assumptions of Scenario 1. The panels show RCP 2.6 (top left), RCP 4.5 (top right), RCP 6 (bottom left) and RCP 8.5 (bottom right).

Biochar can be produced from fibre crop residues in a number of the world's agricultural regions. As detailed in Figure 6-14, the potential for biochar production from fibre crop residues is limited in comparison to that of the other crop residues, due to the smaller amount of commodity and related residue which may be produced. There are no regions of the world, within these RCP scenarios, that produce fibre crop residues alone, therefore fibre crop residues are unlikely to be the main biochar producing residue of any region. However, they may add to a biochar production system if it is technologically possible and economically practicable to collect and convert the fibre crop residues.

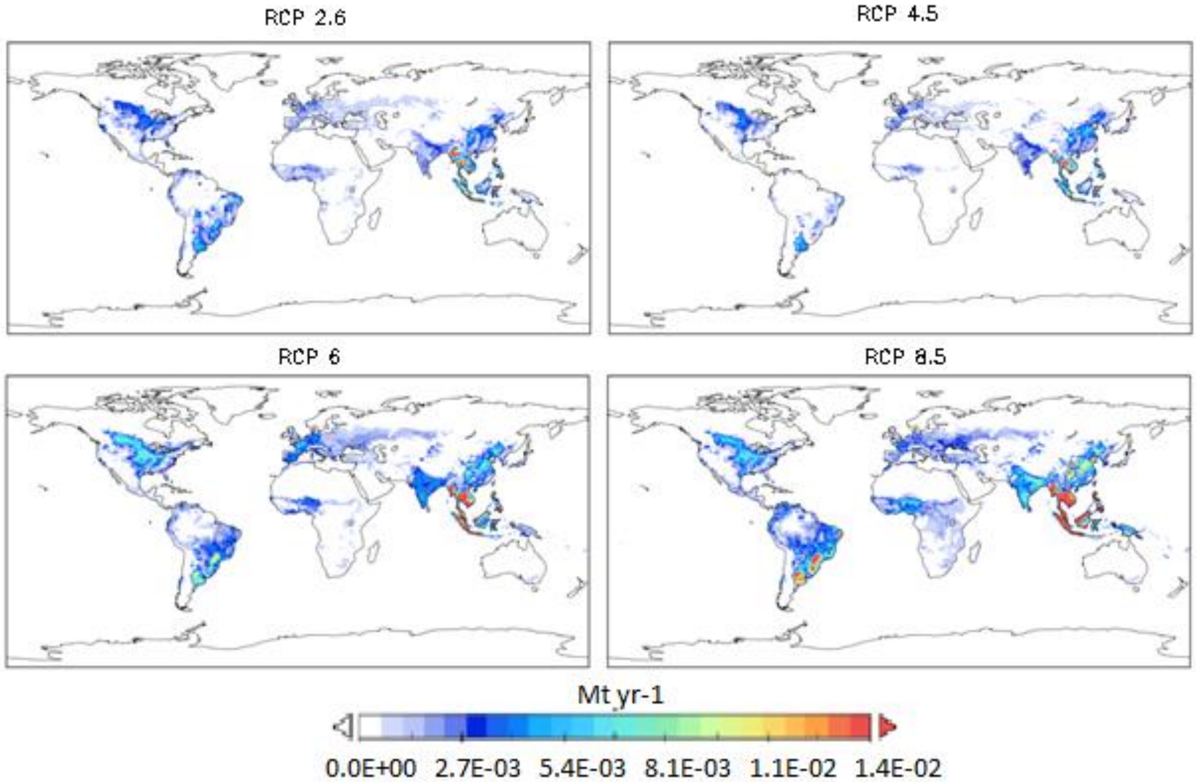

Figure 6-21: Biochar yield (Mt yr^{-1}) from oil crop residues in 2100 for the four RCPs under the assumptions of Scenario 1. The panels show RCP 2.6 (top left), RCP 4.5 (top right), RCP 6 (bottom left) and RCP 8.5 (bottom right).

Biochars from oil crop residues are also produced in many of the world's agricultural regions, with the highest intensity of production often seen in South-Eastern Asia. This intensity of production is also seen in areas of Brazil and Argentina within RCP 8.5. Geographical distribution of biochar from oil crop residues is increasingly widespread from RCP 4.5 to RCPs 2.6, 6 and 8.5 respectively.

Biochar from sugarcane residues is focussed in Asia, South America, Central America and Eastern and Southern Africa (Figure 6.22). The distribution of cropland for sugarcane production follows the same trend as discussed for oil crops, with the smallest coverage in RCP 4.5, increasing for RCP 2.6, RCP 6 and RCP 8.5 respectively. Although RCP 4.5 has the smallest geographical coverage, there are some areas of more intense production than RCP 2.6, particularly in India. South America generally is the region of highest intensity production for all of the RCPs, with India also being a region of high production in RCP 8.5.

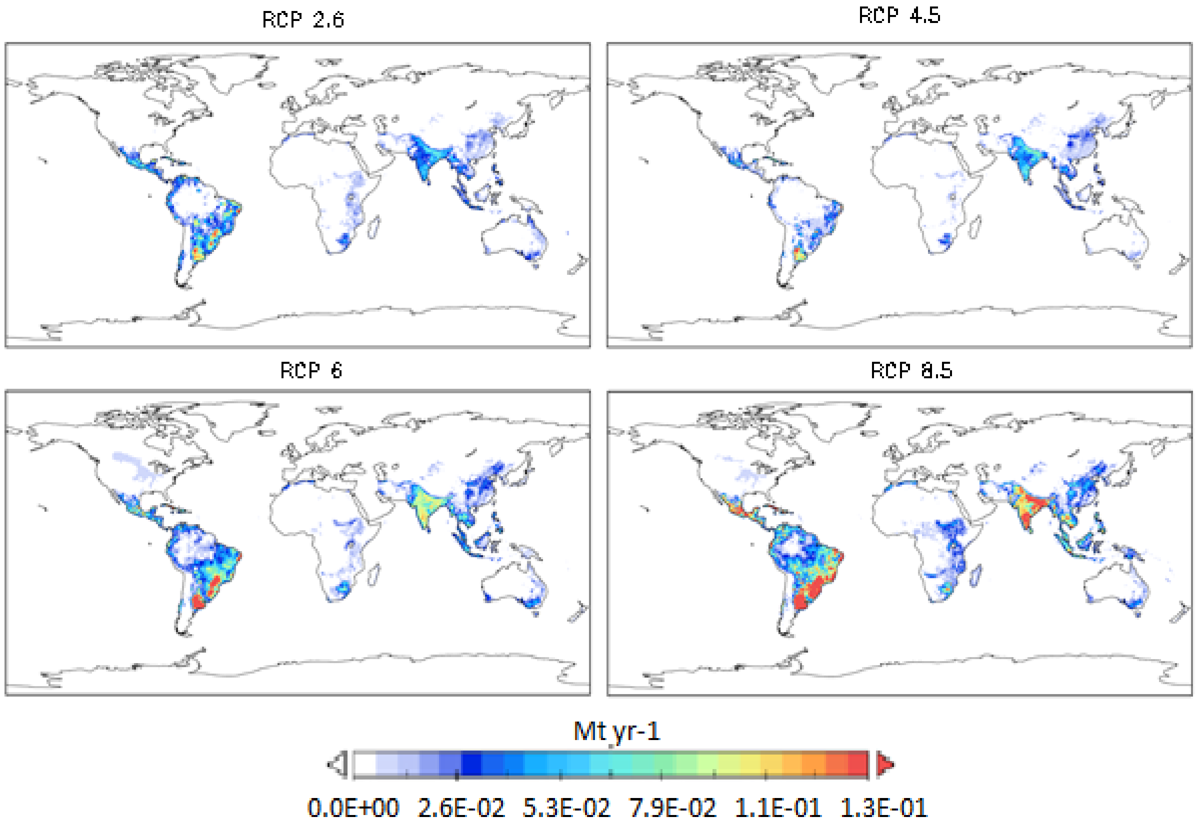

Figure 6-22: Biochar yield (Mt yr^{-1}) from sugarcane crop residues in 2100 for the four RCPs under the assumptions of Scenario 1. The panels show RCP 2.6 (top left), RCP 4.5 (top right), RCP 6 (bottom left) and RCP 8.5 (bottom right).

6.3.4 Carbon in biochar

Biochar carbon content is another necessary consideration when determining the suitability of different feedstocks for biochar production for carbon sequestration purposes. The biochar produced in 2005, under the assumptions of Scenario 1, would contain 0.49 GtC. Over time this would increase to 0.93, 0.78, 1.53 and 2.18 GtC for RCPs 2.6, 4.5, 6 and 8.5 respectively. Total carbon content of the biochar, over the 95 year period is 69.9, 65.7, 87.1 and 109.7 GtC for the four RCPs respectively. This follows the trend seen in residue production, residue availability and biochar production for the RCPs, with RCP 4.5 having the lowest potential for total biochar carbon content and RCP 8.5 having the highest potential.

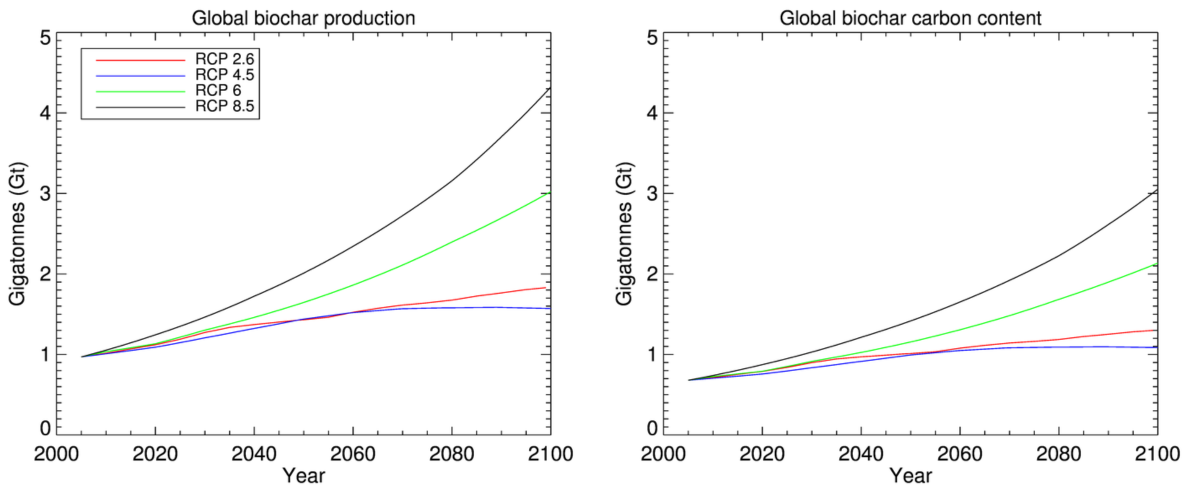

Figure 6-23: Total biochar production (Gt yr^{-1}) (left) and total carbon content (Gt yr^{-1}) (right) of the biochars produced from all residues in Scenario 1.

Total biochar carbon content, by weight, is approximately 70 % of the quantity of biochar produced. Although biochar often has high carbon content, some biochars have high ash and/or moisture content, such as the 47 % ash content of the rice husk biochar produced experimentally and detailed in Chapter 4, Section 4.3.

Figure 6-24 shows the relative contribution of each biochar type to the total biochar production (left hand plots) and also to the total carbon content of the biochars (right hand plots). This plot shows the variation which can exist in biochar carbon content, for example, in the baseline year of 2005, sugarcane biochar is 89 % carbon, whereas rice biochar is 55 % carbon. This highlights the importance of considering the carbon content and other characteristics of the biochar, rather than the yield of biochar alone. The recalcitrance of the carbon in each biochar is also of high importance, and is discussed further in Chapter 7.

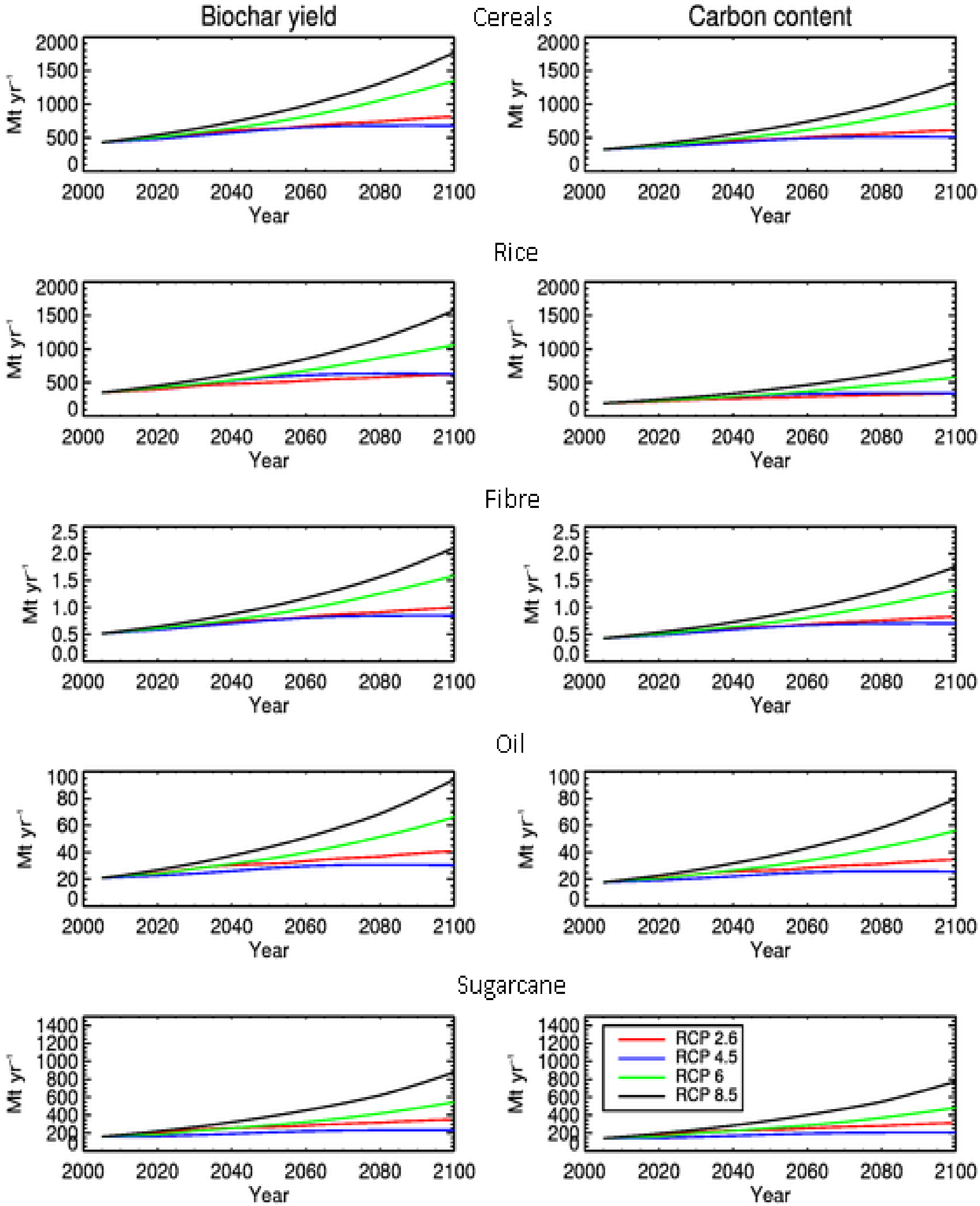

Figure 6-24: Biochar quantity (Mt yr^{-1}) (left) and carbon content (Mt yr^{-1}) (right) of the biochar produced from residues from each crop type, over time, for the four RCPs, under the assumptions of Scenario 1. N.B. Scales vary between plots.

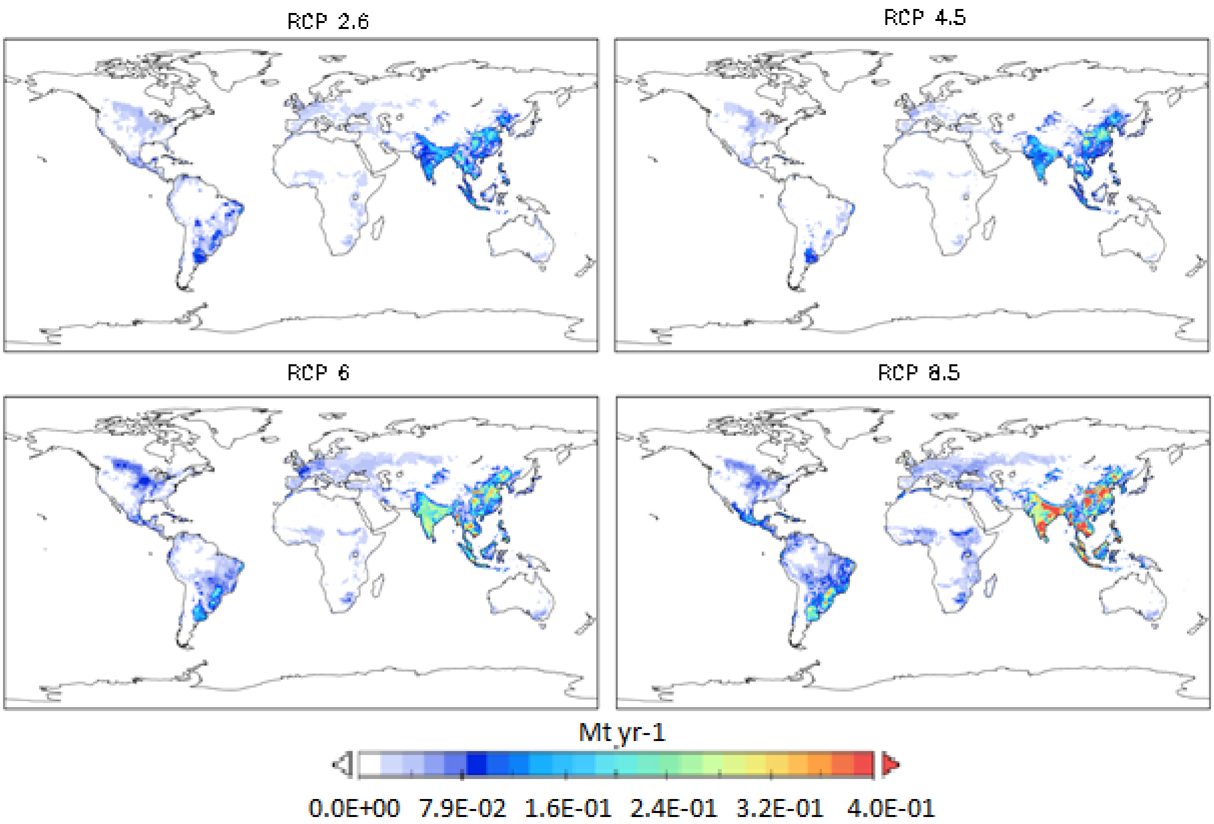

Figure 6-25: Carbon content (Mt yr^{-1}) of the total biochar produced in 2100 for the four RCPs under the assumptions of Scenario 1. Panels show RCP 2.6 (top left), RCP 4.5 (top right), RCP 6 (bottom left) and RCP 8.5 (bottom right).

Carbon content of the total biochar produced is highest in Asia for all RCPs under the assumptions of Scenario 1. South and Central America also have relatively high potential, compared to the other biochar producing regions of the world. The regions of Africa and Europe have some potential, but this is limited compared to that of Asia and South/Central America in all RCPs. The Mt C per year are equivalent to between 335.8 Pg and 563.6 Pg CO_2 over the 95 year period, these values being for RCP 4.5 and RCP 8.5 respectively. Global anthropogenic CO_2 emissions in 2005 were around 29.7 Gt CO_2 (Le Quere et al., 2009). Within Scenario 1 the carbon within the biochar in 2005 is therefore equivalent to 8.4 % of global anthropogenic CO_2 emissions, and equivalent to between 13.4 % and 37.7 % of global anthropogenic CO_2 emissions in 2100 (for RCP 4.5 and RCP 8.5 respectively and at 2005 emissions levels).

Table 6-2: The annual biochar production, biochar carbon content and CO_2 equivalent of biochar carbon content for the years 2005 and 2100. Also shown are the cumulative values for the 95 year period, for each of the four RCPs under the assumptions of Scenario 1.

Year	Units	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production					
2005	Mt yr^{-1}	969.79	969.79	969.79	969.79
2100	Mt yr^{-1}	1835.49	1570.53	3022.82	4322.58
95 year period	Gt	138.38	132.25	173.17	217.89
Total carbon in biochar					
2005	Pg C yr^{-1}	0.68	0.68	0.68	0.68
2100	Pg C yr^{-1}	1.30	1.09	2.13	3.05
95 year period	Pg C	97.87	91.48	121.69	153.56
CO_2 equivalent of carbon in biochar					
2005	Pg CO_2 yr^{-1}	2.49	2.49	2.49	2.49
2100	Pg CO_2 yr^{-1}	4.78	3.98	7.83	11.20
95 year period	Pg CO_2	359.20	335.75	446.61	563.55

Addition of the biochar to soils would see some degradation leading to the release of some of the carbon detailed in Table 6-2 back into the atmosphere as CO_2. This is discussed further in Chapter 7.

6.4 Scenario 2: Changes in crop yields

Scenario 2 examined the effect that the assumptions of crop yield increase made in Scenario 1 had on the production potential of biochar. Two alternative scenarios of crop yield assumptions, Scenario 2a and 2b, assumed no crop yield increase and optimistic yield increase respectively. Scenario 2c explored an alternative convergence year for crop yields in RCP 4.5.

6.4.1 Scenario 2a: No crop yield increase

Scenario 2a, simulating no crop yield increase over time, shows that biochar production is greatly enhanced in each RCP within Scenario 1 due to the assumptions of crop yield increase.

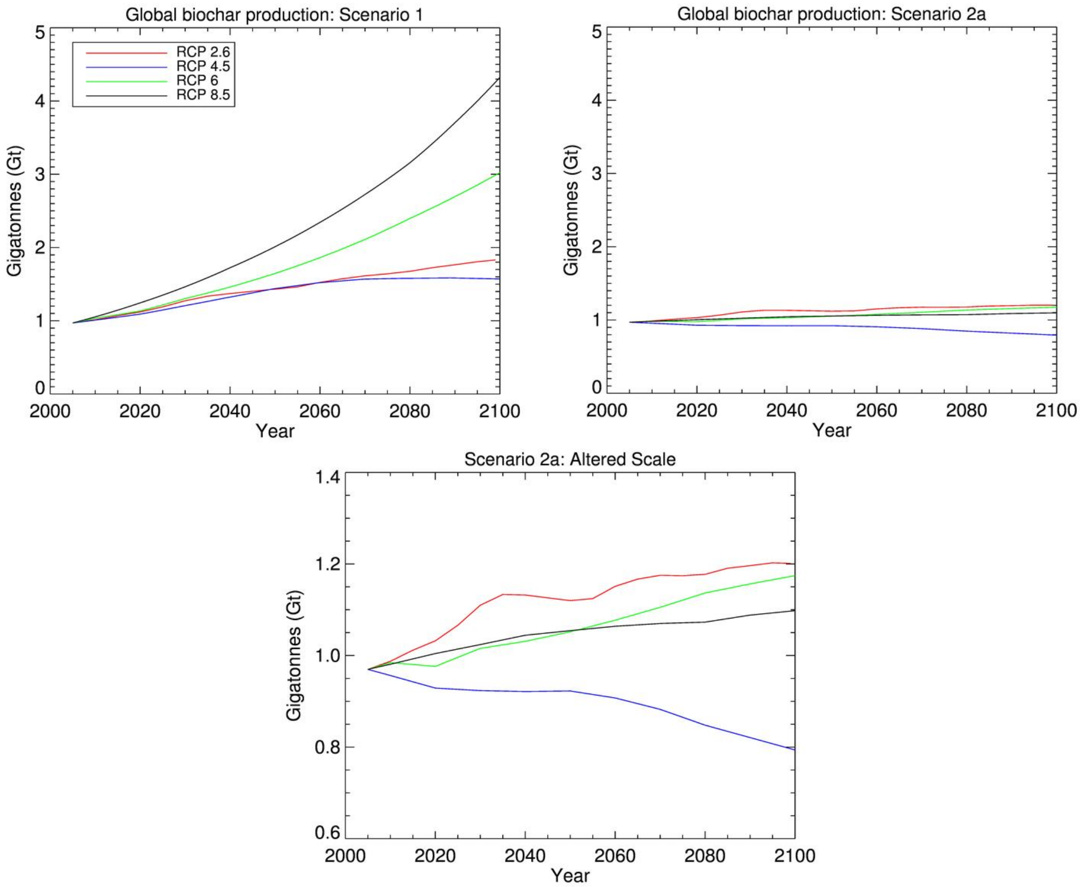

Figure 6-26: Global biochar yield (Gt yr^{-1}) for Scenario 1 (top left) and Scenario 2a (top right) and Scenario 2a with a smaller scale (bottom) for the four RCPs.

RCP 2.6 has the greatest biochar production potential when assuming no crop yield increase over time due to having the largest land area for crop production. The pathway of annual global biochar production is similar to that of total cropland area (Figure 6-3). The point at which RCP 6 overtakes RCP 8.5 occurs earlier for biochar production potential than in the total global cropland pathways. The difference between biochar production in 2100 for RCP 2.6 and RCP 6 is smaller than the difference in global cropland area. Analysis of the trends of global cropland by crop type (Figure 6-8) shows that the trend in total biochar production for Scenario 2a is influenced by the land area available for each crop type. Compared to Scenario 1, biochar production potential over the 95 year period is reduced by 30.5 Gt, 46.3 Gt, 70.9 Gt and 117.4 Gt for RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5 respectively when no yield increase occurs over the assessment period. Using the experimental values from Chapter 4 for carbon content of these biochars, this is equivalent to 15, 22.9, 35.7 and 59.0 Gt C respectively.

6.4.2 Scenario 2b: Optimistic crop yield increases

A 50 % increase in the annual crop yield increase, relative to Scenario 1 crop yield increases, results in an increase in biochar production potential of 19.1 Gt, 33.9 Gt, 57.9 Gt and 120.5 Gt for RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5 respectively over the 95 year period. This is 9.7, 16.8, 29.1 and 60.5 Gt more carbon in biochar for Scenario 2b, relative to Scenario 1. Increasing the crop yield assumptions by 50 % results in more biochar being produced both per annum and in total in RCP 4.5 than in RCP 2.6, which does not occur in Scenario 1.

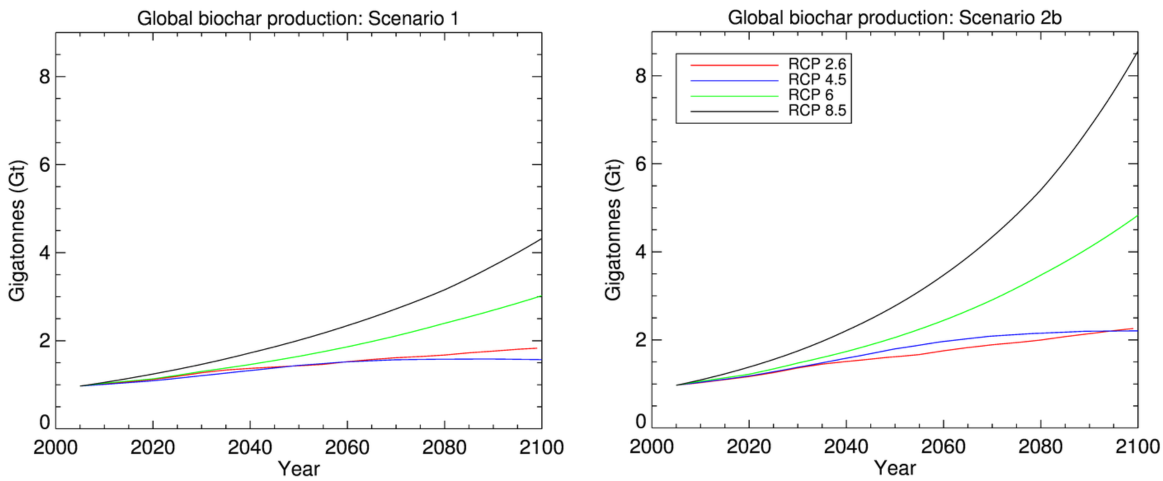

Figure 6-27: Global annual biochar yield (Gt yr^{-1}) for Scenario 1 (left) and Scenario 2b (right) for the four RCPs.

The crop yield increases examined in Scenario 2b, although possible, are more unlikely to be achieved than those of Scenario 1. Historically, the rate of crop yield increase has been declining over time, therefore large changes in areas such as crop management, technology and genetic modification would be required to see the continual large increases in crop yields seen in Scenario 2b. Crop yields in many regions are also likely to be impacted by climate change within the assessment period, with RCPs 6 and 8.5 likely to see larger impacts than RCPs 2.6 and 4.5 due to the increased likelihood and severity of climate change in the former two RCPs (Porter et al., 2014). This makes it more likely that incorporating the effects of climate change into crop yield projections will see reduced crop yields, or at least slower rates of increase, than those tested in this scenario (Porter et al., 2014). The impacts of climate change on crop yields are examined in Scenarios 8 and 9 (Section 5.4.7).

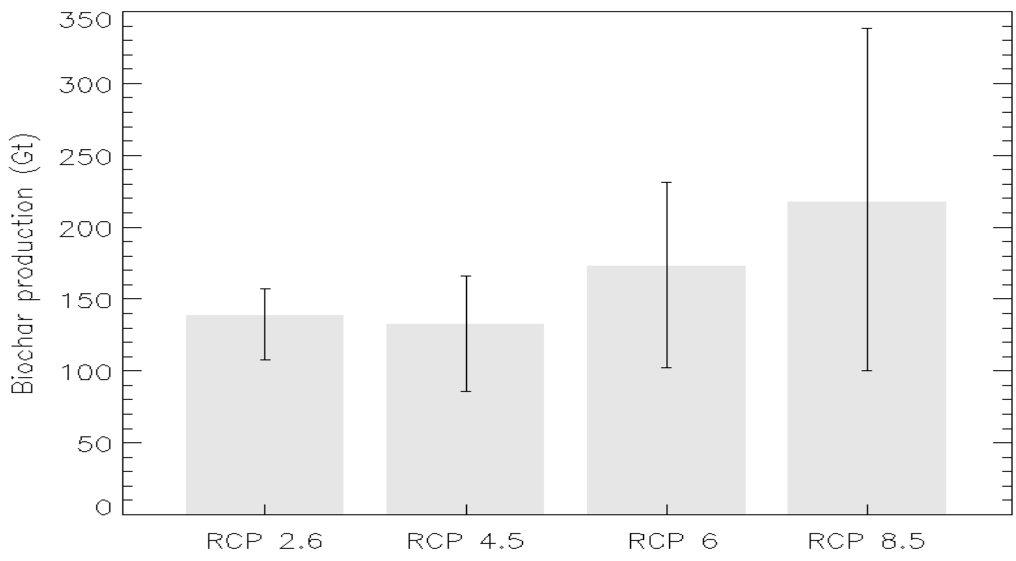

Figure 6-28: Biochar production (Gt) over the 95 year period for the range of crop yields projected. Filled bars indicate the main projections of Scenario 1 and error bars indicate the range of production values estimated using the maximum and minimum crop yield scenarios (2a and 2b).

The variation in crop yields explored in Scenario 2a and 2b creates an increasing range of potential biochar production quantities across the RCPs (from RCP 2.6 to RCP 8.5 respectively). The increased range shown in RCP 6 and RCP 8.5 illustrate the larger assumptions of crop yield increase in these RCPs for Scenario 1, which leads to larger variation in scenarios of no yield increase and large yield increase.

6.4.3 Scenario 2c: Crop yield increase convergence at 0.25 % yr^{-1} in 2050 for RCP 4.5

The rate of convergence of crop yield to 0.25 % yr^{-1} in RCP 4.5 was explored in this scenario, due to uncertainty within the RCP literature regarding the point of convergence. Scenario 1 assumed that the convergence date is 2100. Scenario 2c sees this convergence date altered to 2050, exploring the effects of the earliest potential convergence date on biochar production.

The change in convergence date decreases the cumulative yield of biochar over the 95 year period by 6.5 Gt. Total carbon in biochar is reduced by 3.2 GtC. The point of convergence is of particular importance in the continued increase of biochar production rates for RCP 4.5 due to the reduction in cropland area seen over time in the RCP. Where convergence to 0.25 % yr^{-1} is assumed in 2100, the rate of biochar production is seen to increase to around 2090. Where the point of convergence is in 2050 the production of biochar plateaus and then sees a decrease in annual biochar production to 2100.

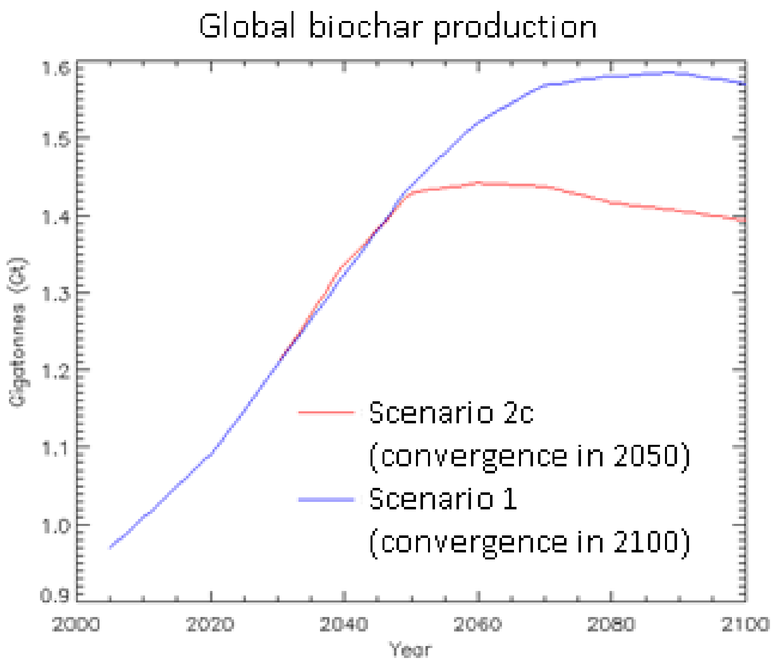

Figure 6-29: Total biochar yield (Gt yr^{-1}) for RCP 4.5 for Scenario 1 and Scenario 2c. Plot illustrates the effect of different rates of crop yield increase convergence to 0.25 % yr^{-1}. The two convergence years assessed are 2050 (red (Scenario 2c)) and 2100 (blue (Scenario 1)).

6.5 Scenario 3: Land use change

6.5.1 Scenario 3a: No land use change

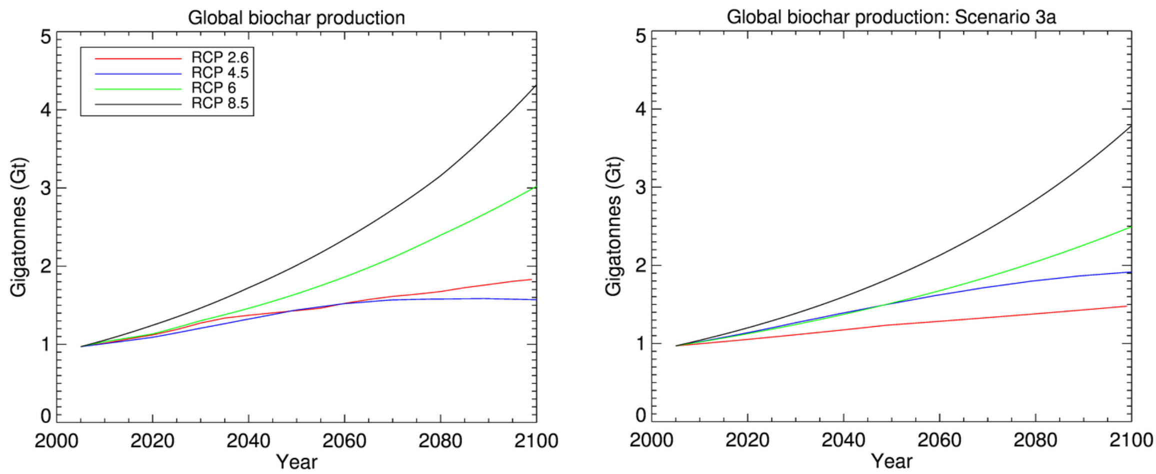

Figure 6-30: Global biochar yield (Gt yr^{-1}) for Scenario 1 (left) and Scenario 3 (right) for the four RCPs.

Scenario 3a explored the effect of land use change assumptions on biochar production potential. The area of land prescribed for agricultural production was kept constant at 2005 levels, with all other assumptions of Scenario 1 remaining the same, allowing for analysis of how the changing land use of the RCP pathways affects the total biochar potential of Scenario 1.

The Scenario 1 crop yield assumptions of RCP 6 and RCP 8.5 dominate the biochar production potential in Scenario 3. In Scenario 3a, RCP 4.5 produces similar amounts of biochar as RCP 6 up to 2055. RCP 2.6 has consistently the lowest biochar production potential. RCP 8.5 has consistently the largest production of biochar, relating to having the highest crop yield increases throughout the Scenario. Scenario 3a sees a reduction in total biochar production potential of 19.8 Gt, 18.1 Gt and 19.3 Gt over the 95 year period, relative to Scenario 1, for RCP 2.6, RCP 6 and RCP 8.5 respectively. RCP 4.5 would see an increase in biochar production potential of 12.1 Gt over the 95 year period, relative to Scenario 1, if land use remained the same throughout the RCP period.

6.5.2 Scenario 3b: Land for biofuels

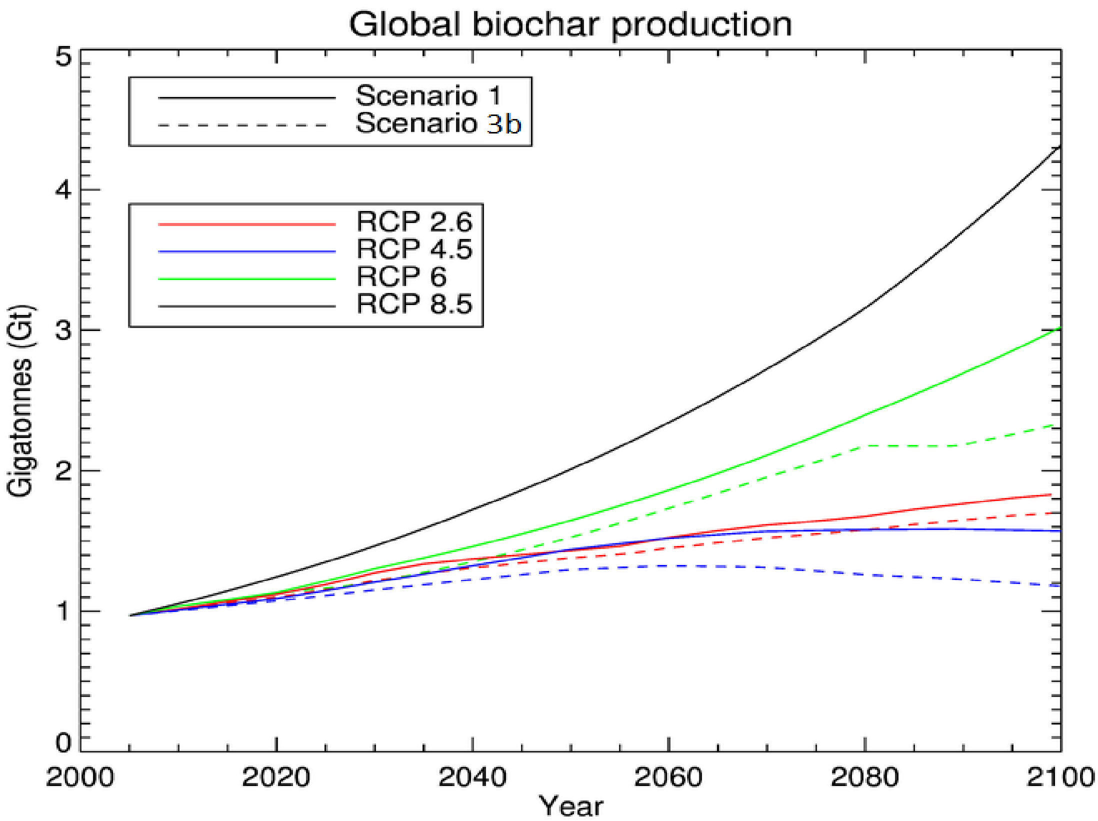

Figure 6-31: Global biochar production for Scenario 1 and Scenario 3b. Scenario 3b shows the biochar production if the land prescribed for biofuels is disregarded for RCPs 2.6, 4.5 and 6.

The land prescribed as biofuels land follows different trends for each of the three RCPs which have biofuels land area datasets. When biofuel land area is subtracted from the total cropland area for the three RCPs, excluding RCP 8.5 due to differences in accounting biofuel land, RCP 2.6 sees the smallest reduction in biochar production consistently over time. RCP 4.5 sees the largest reduction in cropland area for most of the scenario period, indicating that RCP 4.5 is a heavily biofuels reliant scenario. RCP 6 sees a steady increase in biofuels cropland across the scenario period, up to around 2080 where biofuels cropland begins to increase markedly, resulting in a reduction in cropland area of 312 Mha in 2100. This is in comparison to reductions of 195 Mha and 301 Mha for RCPs 2.6 and 4.5 respectively. Uncertainty surrounding the types of biofuel crops used within each RCP prevents further analysis of the available residues from the prescribed biofuel land. The incorporation of potential biofuel crops, including oil crops and sugarcane, into the Scenario 1 analysis is as representative of biofuels production as is possible without further detail on crop types. This would be a good area for further study in the future.

6.6 Scenario 4: Residue to product ratio (RPR)

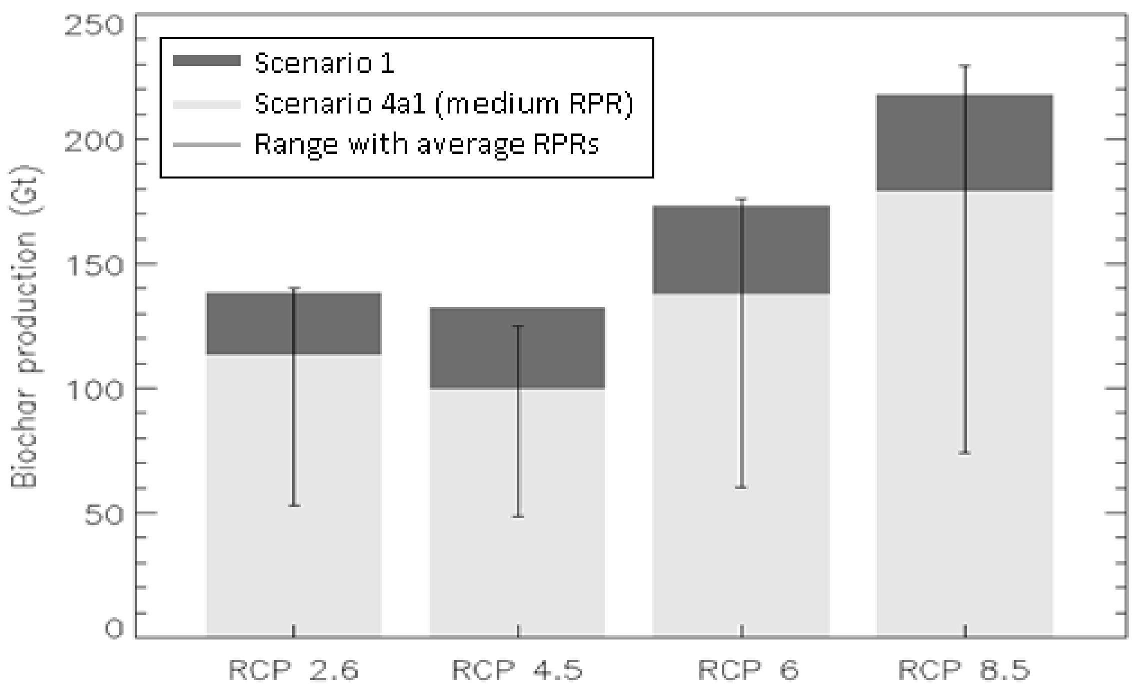

Figure 6-32: Biochar production (Gt) over the 95 year period for each RCP. Dark grey bars indicate total biochar production under the RPR assumptions of Scenario 1. Light grey bars indicate total biochar production under the RPR assumptions of Scenario 4a1. Error bars indicate the range of potential biochar production using the Scenario 4a2 and 4b as markers of low RPR and high RPR values.

A range of scenarios were explored looking at potential variation in RPR. Scenario 4a examined a future of declining RPR. Within this scenario, two scenarios (4a1 and 4a2) looked at a reduction in RPR to medium and low levels by 2100. Scenario 4b examined a future of increasing RPR.

Biochar production was reduced, from that of Scenario 1, by 25.3 Gt, 32.9 Gt, 35.7 Gt and 39.1 Gt of biochar for the RCPs under the medium RPR assumptions. The variation in biochar production, for each RCP, between the scenarios of low and high RPR is 87.2 Gt, 76.7 Gt, 115.8 Gt and 155.7 Gt respectively. When using the average values (across all crop types) for RPRs, assuming the high RPR values results in projections which are closest to the biochar production of Scenario 1. Using the medium RPR assumptions reduces the biochar production to be considerably below that of Scenario 1. The low RPR assumptions resulted in further considerable reductions in biochar production potential.

6.7 Scenario 5: Residue availability

Scenario 5 examined alternative scenarios of residue availability. Scenarios 5a, 5b and 5c examine assumptions (across all crop groups) of 25 % and 50 % and 75 % residue availability respectively. Scenarios 5d and 5e used the assumptions of Woolf et al. (2010) as alternative residue availability scenarios for comparison.

Scenario 5b, which assumes that 50 % of all residues are available, sees a reduction in biochar production of 9.9, 7.9, 11.5 and 18.1 Gt biochar relative to Scenario 1 for the four RCPs respectively. Biochar production potential varies by 80.1, 71.7, 98.9 and 120.3 Gt for the four RCPs between the assumptions of Scenarios 5a and 5c (which assume 25 % and 75 % residue availability for all crop groups respectively).

6.7.1 Scenarios 5a to 5c: 25 %, 50 % and 75 % residue available for biochar conversion

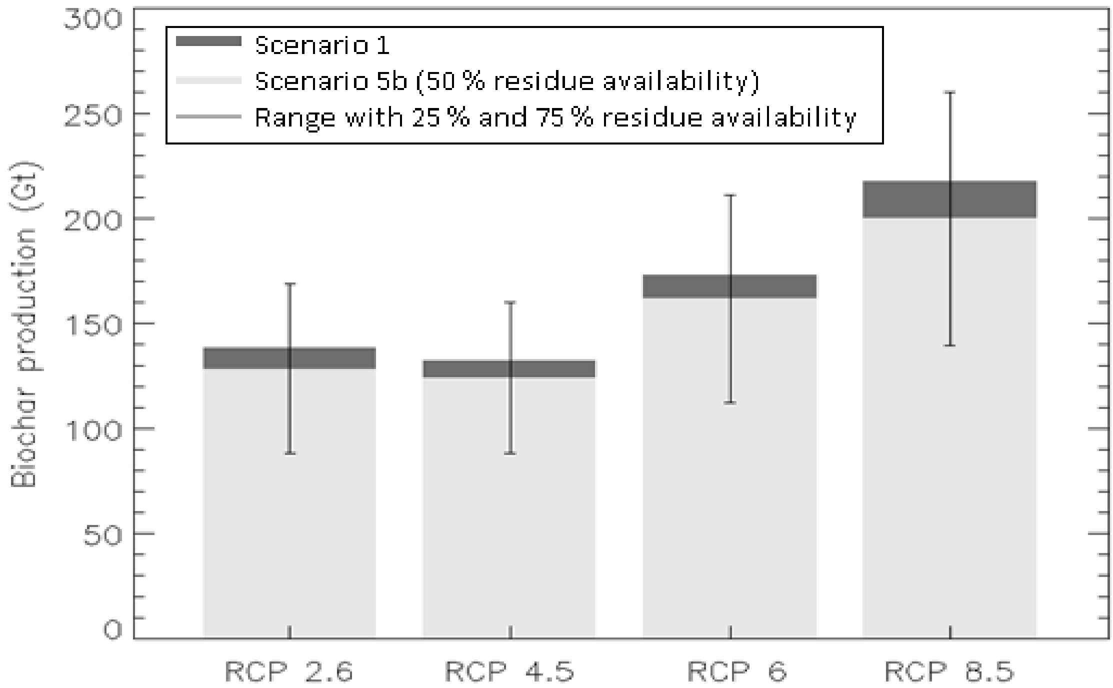

Figure 6-33: Biochar production (Gt) over the 95 year period for each RCP with altered residue availability. Dark grey bars indicate total biochar production under the residue availability assumptions of Scenario 1. Light grey bars indicate total biochar production under the residue availability assumptions of Scenario 5b (50 % availability). Error bars indicate the range of potential biochar production using the low and high residue availability assumptions of Scenario 5a and 5c (25 % and 75 % availability respectively).

6.7.2 Scenario 5d and 5e: Residue availability assumptions of Woolf et al. (2010)

Scenarios 5d and 5e assessed the conservative and maximum potential scenarios of residue availability discussed by Woolf et al. (2010) respectively (see **Table 5-7**). Both scenarios result in smaller total biochar quantities than Scenario 1. The residue availability assumptions of Scenario 1 are, overall, more optimistic than even the most optimistic assumptions made in Woolf et al. (2010). Applying the most conservative residue availability assumptions of Woolf et al. (2010) (Scenario 5d) results in a reduction in biochar production potential, from that of Scenario 1, of 52.9, 49.6, 66.1 and 79.7 Gt for the four RCPs respectively. The rationale behind the assumptions made for residue availability in Scenario 1 is discussed in Section 5.3.6 and outline a plausible future scenario for availability of residues. The assumptions detailed in Woolf et al. (2010) are also plausible, with research currently providing little probabilistic analysis of likelihood for each set of assumptions.

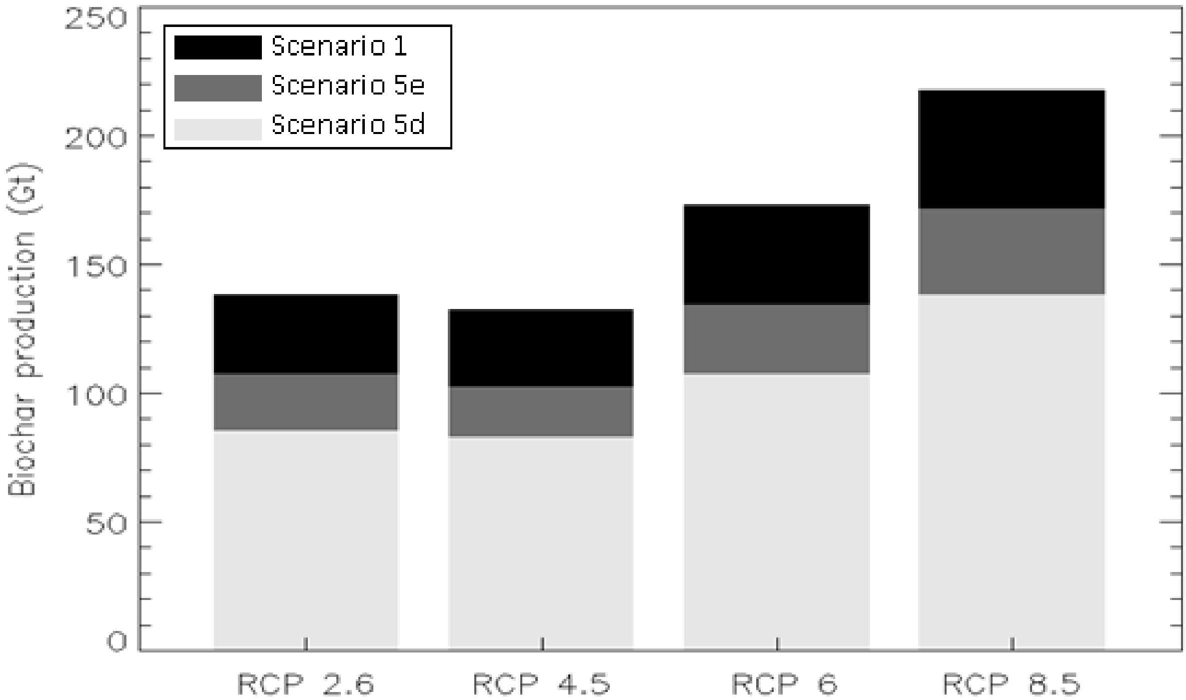

Figure 6-34: Total biochar production (Gt) for Scenario 1 (black), Scenario 5d (light grey) and Scenario 5e (dark grey).

6.8 Scenario 6: Alternative biochar yield

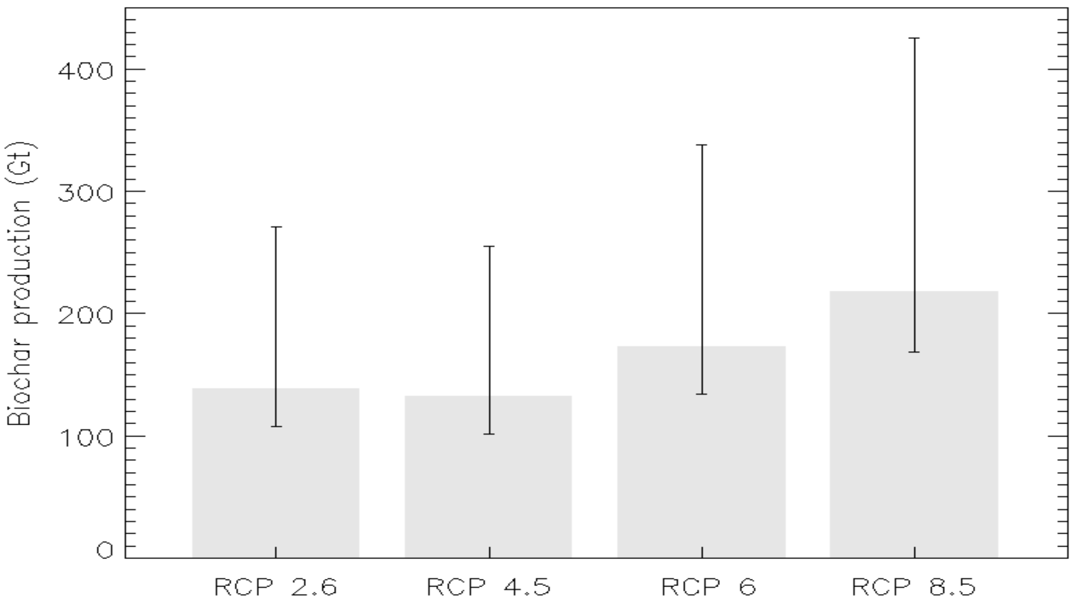

Figure 6-35: Biochar production (Gt) under the assumptions of Scenario 1 (main bars). Error bars indicate biochar production using the assumptions of minimum and maximum (Scenarios 6a and 6b respectively) typical biochar yields from literature.

The biochar yield has the potential to greatly influence the quantities of biochar produced within the scenarios. If the maximum biochar yields of 63 % from the literature (Peng et al, 2011) were achieved for all feedstocks throughout the scenarios then biochar production could be increased by 132.7, 122.9, 164.6 and 207.4 Gt relative to Scenario 1 for the four RCPs respectively. It is unlikely that these very high yields of biochar would be achievable for all feedstocks, both spatially and temporally, throughout the scenarios due to factors such as system requirements for the production of high yields and the likely use of dual energy production systems which lead to the balancing of biochar yields against yields of oil and gas from the process. Using the lower value for average biochar yield from the literature (25 %) resulted in less variation from the biochar production quantities of Scenario 1, seeing a decrease of 30.8, 31.0, 39.1 and 49.1 Gt of biochar for the four RCPs respectively. In reality biochar yields can be highly variable and are dependent on both feedstock and process. The assumptions of Scenario 1 are, therefore, probably more representative of a possible future scenario as some variation due to feedstock is applied. Scenario 1 does not include variation which may occur through altering process type or conditions, or the range which may be seen within biochar yields from one feedstock type. Scenario 6, therefore, offers an indication of best and worst case scenarios for biochar yields from crop residues, with the likely production quantity lying somewhere between the two.

6.9 Scenario 7: Alternative biochar carbon content

Using the mean or high average value for the carbon content of biochars sees an increase in the total carbon content projections relative to Scenario 1. Using the low value for average carbon content sees a decrease in the carbon content of the total biochar produced. It is probable that the use of carbon content values for each biochar type result in a more accurate representation of the total carbon in biochar due to the large variation in carbon content which can exist between biochar types, alongside the different quantities of different biochars which contribute to the total biochar production. The use of an average value for biochar carbon content increased the total biochar carbon content by 2.5, 4.4, 3.9 and 4.4 GtC over the 95 year period for the four RCPs respectively.

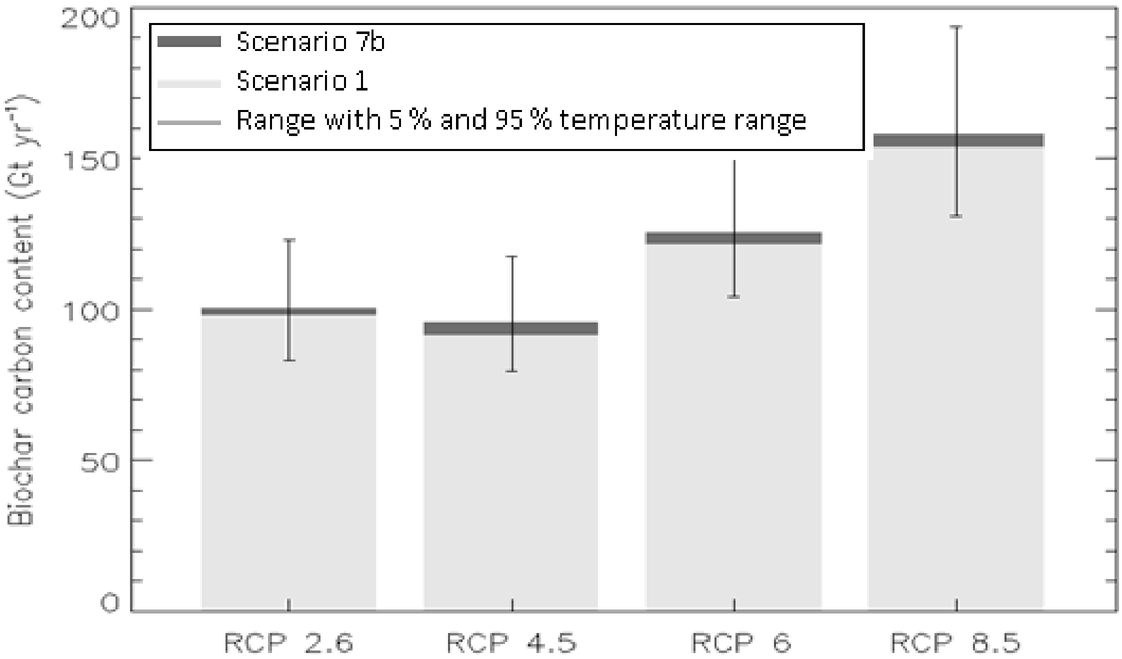

Figure 6-36: Total biochar carbon content (GtC) under the assumptions of Scenario 1 (light grey bars), and Scenario 7b (dark grey bars) which assumes the average carbon content (determined across all crop groups from experimental data and literature). Error bars indicate the range of total biochar carbon content under the assumptions of the minimum and maximum typical biochar yields from literature (Scenarios 7a and 7c respectively).

6.10 Scenario 8 and 9: Climate change effects on crop yields and the impacts of adaptation

The projected changes in temperature for the RCPs, relating to the response of the climate to the radiative forcing pathway of each RCP, are discussed in Chapter 2.4 and Section 5.4.7. These temperature changes are likely to impact crop yields, affecting the quantity of agricultural residues produced within each scenario. Scenario 8 explores the magnitude of impacts that these changes in temperature may have on biochar production potential within each RCP. Scenario 9 assessed how much impact measures of adaptation may have on the impacts of temperature change on crop yield. Those RCPs with larger emissions are projected to experience larger increases in mean global surface temperature. Resulting projections of larger related impacts on crop yields are also made for these RCPs within the literature. Section 5.4.7 details the development of temperature projections and related crop yield impacts for each biochar production scenario using the available literature.

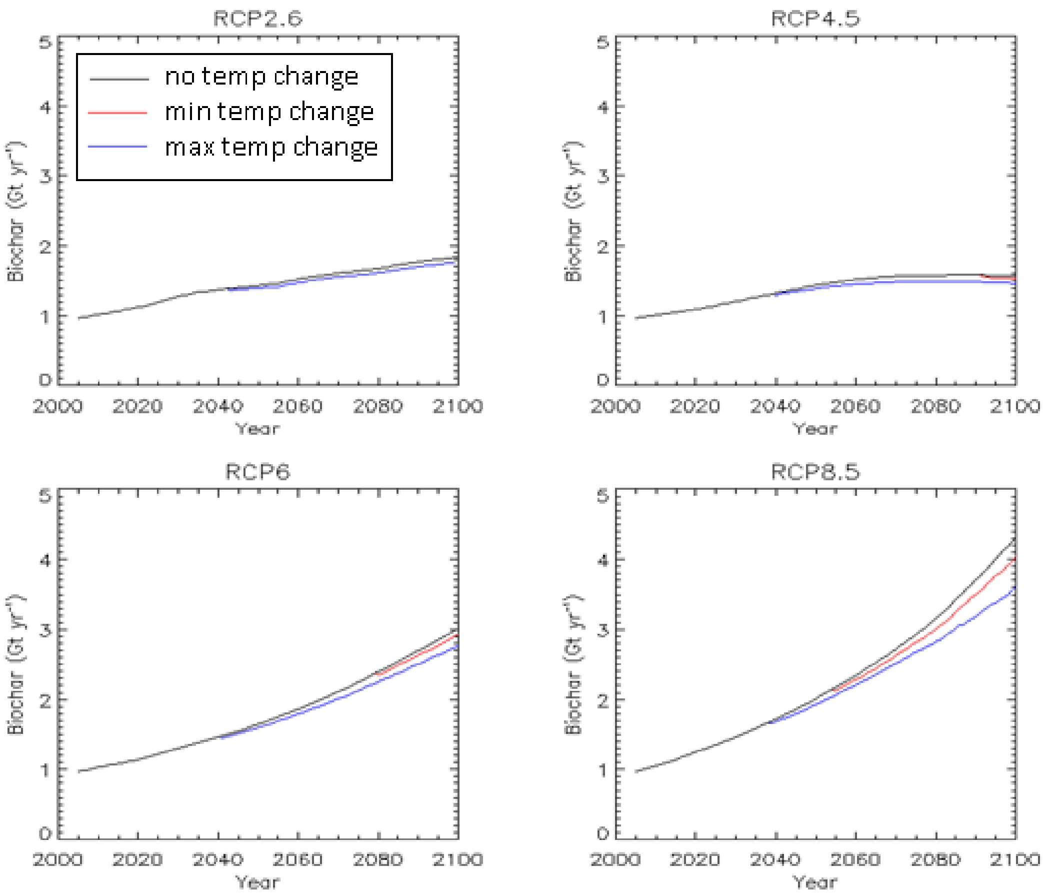

Figure 6-37: Biochar production potential (Gt yr^{-1}) for each RCP with no temperature change (black), minimum projected temperature change (red) and maximum projected temperature change (blue) for each RCP with no adaptation measures (Scenario 8).

Figure 6-37, showing the impact of the range of projected temperatures for each RCP on biochar production potential, illustrates that the projected impacts on crop yields and resulting biochar production increases in severity with increasing radiative forcing scenario. RCP 2.6 shows only minimal impact on crop yields, and this impact is only seen when applying the maximum potential temperature change to the assumptions of Scenario 1. RCP 4.5, RCP 6 and RCP 8.5 all see larger decreases in crop yield, and resulting biochar production potential, even where the minimum projected temperature change is applied to the scenario. The temporal onset of these impacts becomes more rapid from RCP 2.6, in RCP 4.5, RCP 6 and then to RCP 8.5 when the maximum temperature change projections are applied. In RCP 4.5 the impacts of temperature increase can only be seen after 2090 when the minimum temperature change is applied to the scenario. The maximum projected temperature change begins to impact residue production from 2040 onwards. In RCP 6 the impacts of the maximum temperature change projection also begins to influence the biochar production potential from 2040, with the minimum temperature change impacting production from 2080, which is around 10 years earlier than in RCP 4.5. In RCP 8.5 the minimum temperature change begins to affect the production potential around 2050, whilst the maximum temperature change production has impacts from 2040.

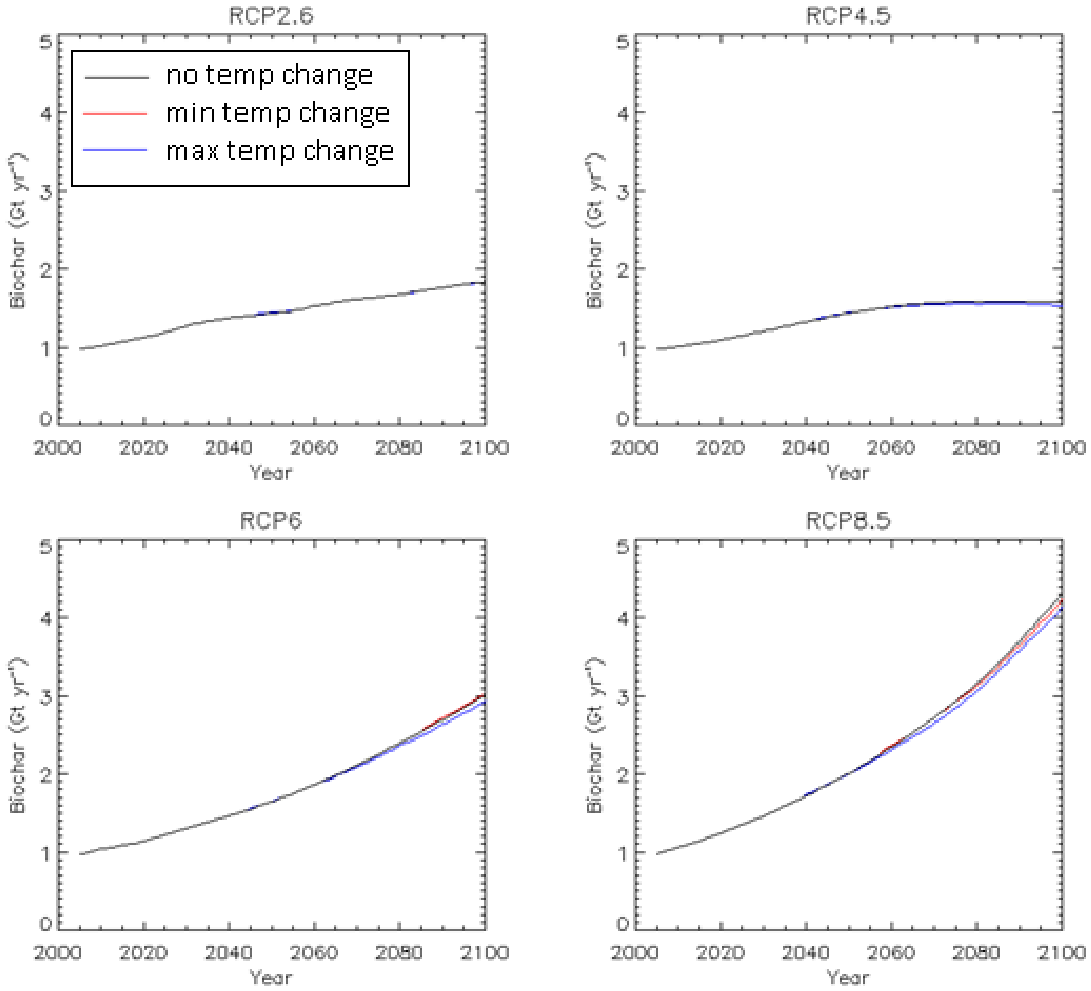

Figure 6-38: Biochar production potential (Gt yr^{-1}) for each RCP with no temperature change (black), minimum projected temperature change (red) and maximum projected temperature change (blue) with the simple crop based adaptation measures assumed in Scenario 9.

Using crop based adaptation measures has the potential to reduce the impact of temperature changes on crop yields. Figure 6-38 shows the projected impacts of temperature changes on crop yields when these adaptation measures are applied. With these adaptation measures there is no impact on crop yield production in RCP 4.5 when the minimum temperature change projection is applied. The impacts of temperature change on biochar production for RCPs 6 and 8.5 are also greatly reduced, with impacts occurring at the same time as in the scenario with no adaptation, though these impacts are reduced in magnitude.

The biochar production potential in 2100 is reviewed here as biochar potential generally increases annually therefore 2100 indicates the largest production potential within the scenario period. With regard to the climate change scenarios, Scenarios 8 and 9, 2100 is also the year with the largest manifestation of temperature change related to climate change. Analysis of 2100 results therefore demonstrates the maximum impact on biochar production that this temperature change would have within the scenario period.

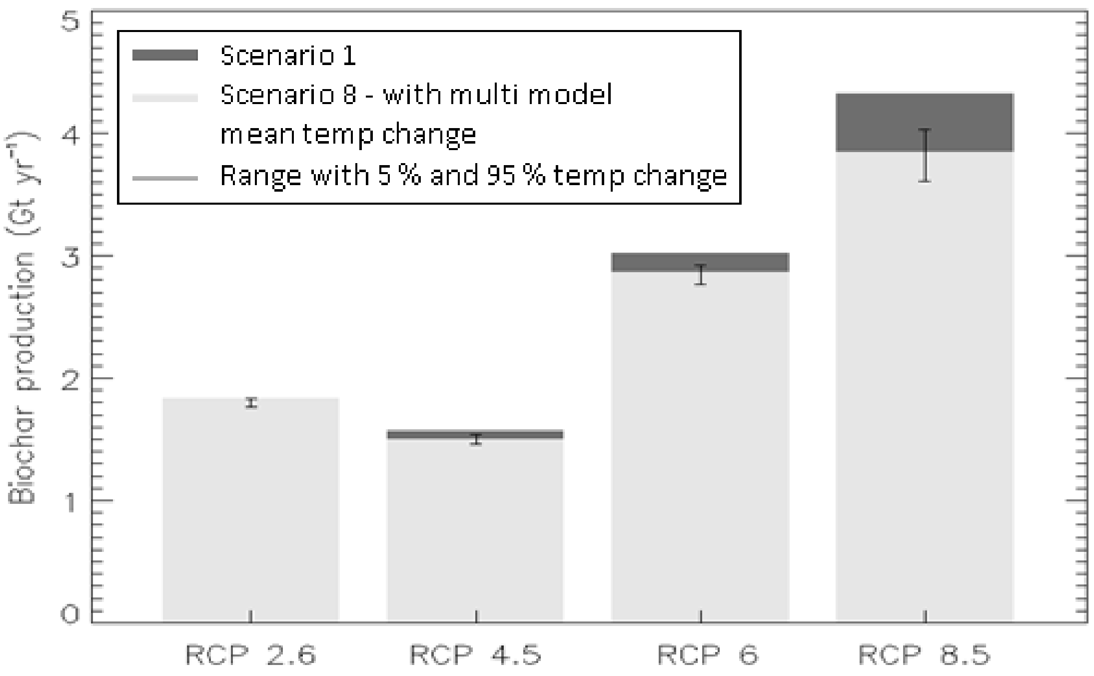

Figure 6-39: Total biochar production (Gt yr^{-1}) in 2100 for Scenario 1 (dark grey) and the mean climate change temperature projection with no adaptation (Scenario 8b) (light grey). Where no dark grey is shown (i.e. RCP 2.6) there is no reduction in biochar production projected under the mean climate change temperature scenario (relative to Scenario 1). Error bars show the range of projected biochar production related to the range in crop yield impacts relating to the minimum and maximum potential temperature change projections (Scenario 8a and 8c, 5 % and 95 % projection values respectively) related to each RCP scenario.

The mean temperature projection pathway has no impact on biochar production potential, in 2100, for RCP 2.6. A small impact is seen where the maximum projected temperature change is applied to RCP 2.6. The minimum temperature change projection for the RCP 4.5 pathway also sees relatively little reduction in biochar production potential relative to Scenario 1 production. In RCP 4.5 the maximum projected temperature change results in a reduction in biochar production potential of 106.8 Mt yr^{-1} in 2100 relative to Scenario 1. RCPs 6 and 8.5 experience a reduction in biochar production potential for all temperature projections applied. The maximum projected temperature increase for RCP 6 results in a reduction from the Scenario 1 biochar production potential of 256.9 Mt yr^{-1} by 2100. The maximum projected temperature increase for RCP 8.5 results in a reduction of 713.2 Mt yr^{-1} of biochar in 2100 relative to Scenario 1. Scenarios 9 a-c saw the impact on biochar production potential reduced, for all RCPs, with the application of simple adaptation methods (Figure 6-40).

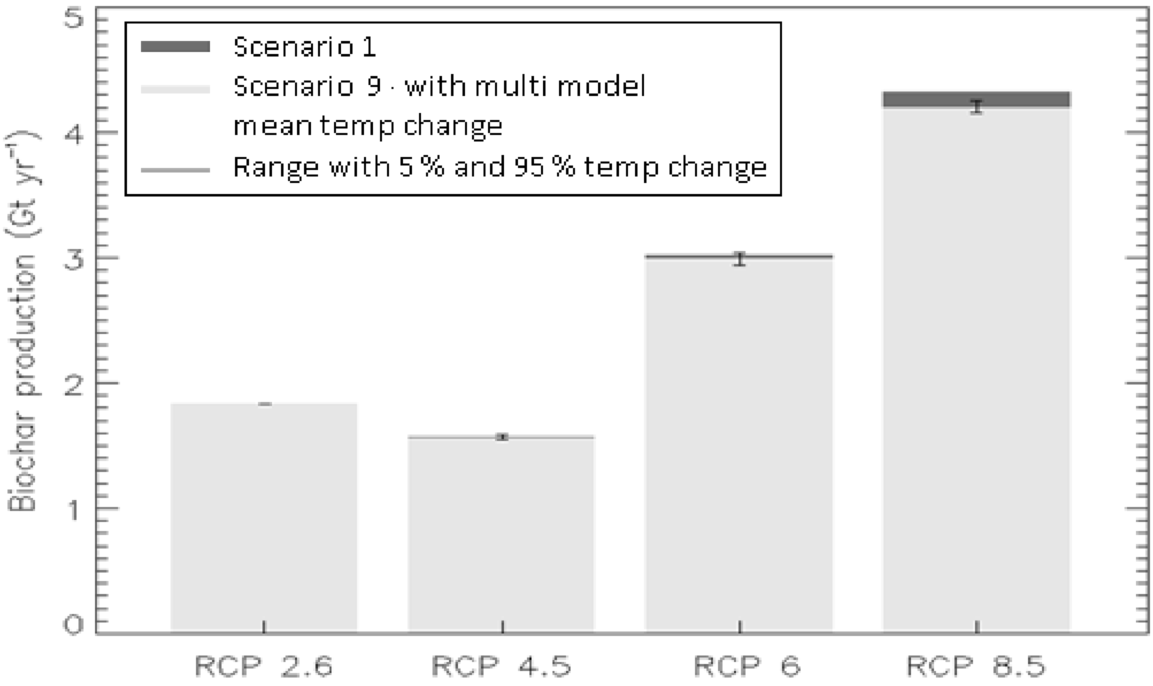

Figure 6-40: Total biochar production (Gt yr^{-1}) in 2100 for Scenario 1 (dark grey) and the median climate change projection with adaptation (light grey). Where no dark grey is shown (i.e. RCP 2.6) there is no reduction in crop yields projected under the median climate change scenario (relative to Scenario 1). Error bars show the range of projected crop yield impacts relating to the minimum and maximum potential temperature change (5 % and 95 % values) related to each RCP scenario (see Table 2-3).

Table 6-3: The mitigation potential (in 2100) of simple adaptation measures on the impacts on biochar production of climate change related temperature change. The mitigation potential is displayed in Mt yr^{-1} of biochar produced by Scenarios 9 a-c relative to the biochar production of Scenarios 8 a-c.

Temperature projection	Mitigation of impact on biochar production (Mt yr^{-1})			
	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Minimum temperature projection (9a)	0	31.4	102.8	198.8
Mean temperature projection (9b)	0	59.7	123.9	345.8
Maximum temperature projection (9c)	66.1	72.2	166.3	523.0

The effect of applying the maximum temperature change projection alongside adaptation measures, to RCP 4.5 reduces the impact of temperature change on biochar production from the no-adaptation scenario by 72.2 Mt yr^{-1} in 2100. This results in a reduction in biochar production potential relative to Scenario 1 of 34.6 Mt yr^{-1} in 2100. RCP 6 sees some impact on biochar production potential in 2100 even when the minimum projected temperature is applied. This reduces the impact, from the non-adaptation climate change scenario, by 102.8 Mt yr^{-1} biochar in 2100 resulting in a reduction in 2100 of 6.1 Mt yr^{-1} biochar relative to Scenario 1. Applying the maximum temperature change to RCP 6 in a scenario with adaptation reduces the effect of climate change on biochar production potential in 2100 by 166.3 Mt yr^{-1}, resulting in a reduction in biochar potential of 90.7 Mt yr^{-1} in 2100 relative to Scenario 1. The loss in biochar yield seen in Scenario 8 for RCP 8.5 is reduced by 198.8 Mt yr^{-1} in 2100 through the adaptation measures applied under the minimum temperature projections, resulting in a reduction of 95 Mt yr^{-1} relative to Scenario 1. The application of adaptation measures to the impacts of the maximum temperature projection of RCP 8.5 sees a reduction in crop yield impact of 523 Mt yr^{-1} in 2100, resulting in a reduction in biochar production potential of 190.2 Mt yr^{-1} in 2100.

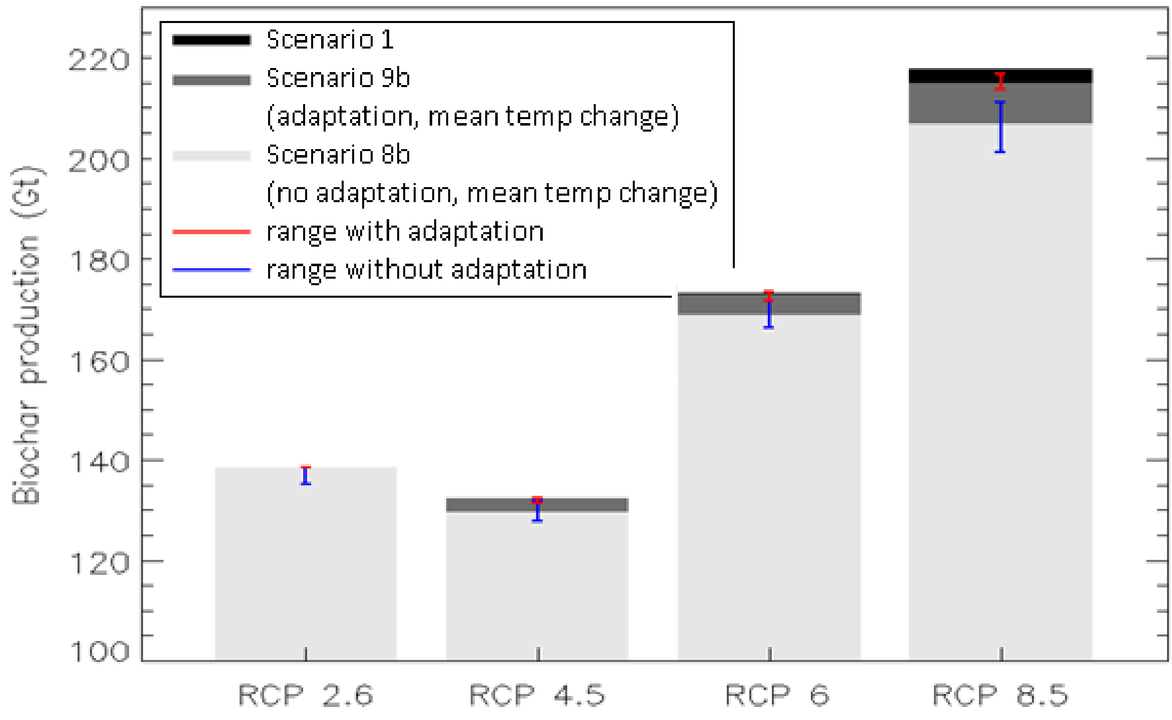

Figure 6-41: Total cumulative biochar production (Gt) for Scenario 1 (black), Scenario 9b (dark grey) and Scenario 8b (light grey) over the 95 year period. Scenarios 9b and 8b are the mean temperature change projection for each RCP with adaptation and with no adaptation respectively. Where only light grey is shown (i.e. RCP 2.6) there is no reduction in crop yields projected under the median climate change scenario (relative to Scenario 1). Red bars show the range of projected crop yield impacts relating to the minimum and maximum potential temperature change (5 % and 95 % values) related to each RCP scenario with adaptation. Blue bars show the range of projected crop yield impacts relating to the minimum and maximum potential temperature change (5 % and 95 % values) related to each RCP scenario with no adaptation.

The reduction in biochar production potential caused by climate change, relative to Scenario 1, increases across the RCPs, from RCP 2.6 to RCP 8.5, when this potential is assessed for the 95 year period. RCP 2.6 sees no reduction in biochar production potential, except where the maximum temperature change is combined with assumptions of no adaptation, resulting in a reduction of 3.2 Gt biochar over the 95 year period. Assuming the minimum temperature projection and no adaptation (scenario 8a) resulted in a reduction in biochar production potential of 0.3, 1.4 and 6.7 Gt for RCPs 4.5, 6 and 8.5 respectively. This could be mitigated by 0, 0.3, 1.7 and 5.5 Gt biochar by employing simple adaptation measures (Scenario 9a). Mean temperature change and no adaptation (Scenario 8b) cause a reduction in biochar production potential of 2.6, 4.3 and 11.2 Gt biochar over the 95 year period for RCPs 4.5, 6 and 8.5 respectively. This could be mitigated by 0, 2.6, 3.9 and 8.2 Gt biochar by employing adaptation measures (Scenario 9b). Maximum temperature projections alongside no adaptation measures (Scenario 8c) results in a reduction in biochar production potential of 3.2, 4.5, 7 and 16.7 Gt biochar respectively for the four RCPs, relative to Scenario 1, for the 95 year period. This could be mitigated by 3.2, 3.6, 5.3 and 12.4 Gt biochar by employing simple adaptation measures (Scenario 9c). The range of projections of biochar production potential, using the minimum and maximum temperature projections, is smaller where adaptation measures are applied than where no adaptation is applied. These results indicate that any efforts to reduce the temperature change seen with climate change, and any applications of crop based adaptation methods will provide increased yields of biochar over the 95 year period.

6.10.1 Effect of crop yield change uncertainty

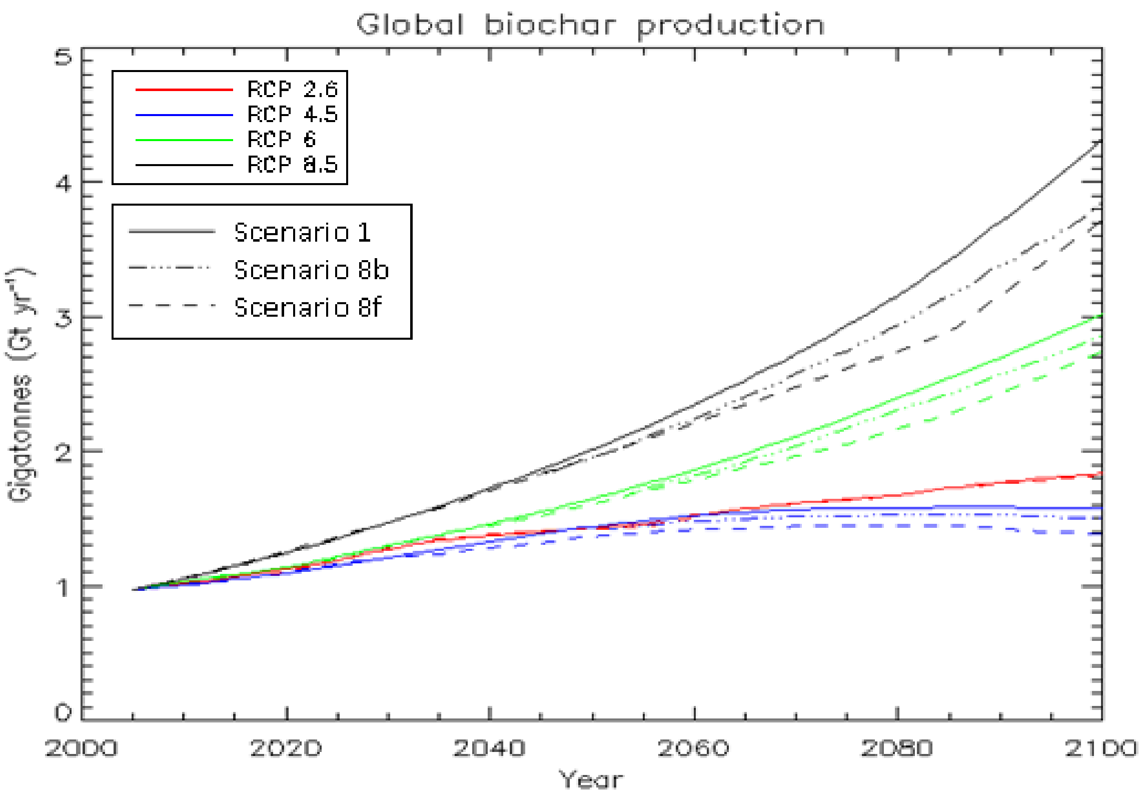

Figure 6-42: Annual biochar production (Gt yr^{-1}) for the four RCPs under the assumptions of Scenario 1, Scenario 8b (the mean yield and temperature change scenario using the IPCC projections of yield impacts) and Scenario 8f (using the crop yield impacts of climate change detailed in Kyle et al. (2014).

Using the crop yield impacts discussed by Kyle et al. (2014) illustrates again the increasing impact of the increasing temperature projections on crop yields and biochar potential, both over time and across the RCPs (from RCP 2.6 to RCP 8.5). Scenario 8f sees a marked reduction in biochar production potential from that of Scenario 8b for RCPs 4.5, 6 and 8.5. No impact is seen on RCP 2.6 due to the low levels of temperature change projected for that scenario. The use of crop yield impact projections by Kyle et al. (2014) offers an alternative pathway for biochar production which more closely resembles the pathway of biochar production projected using the maximum temperature projection from the IPCC (Scenario 8c).

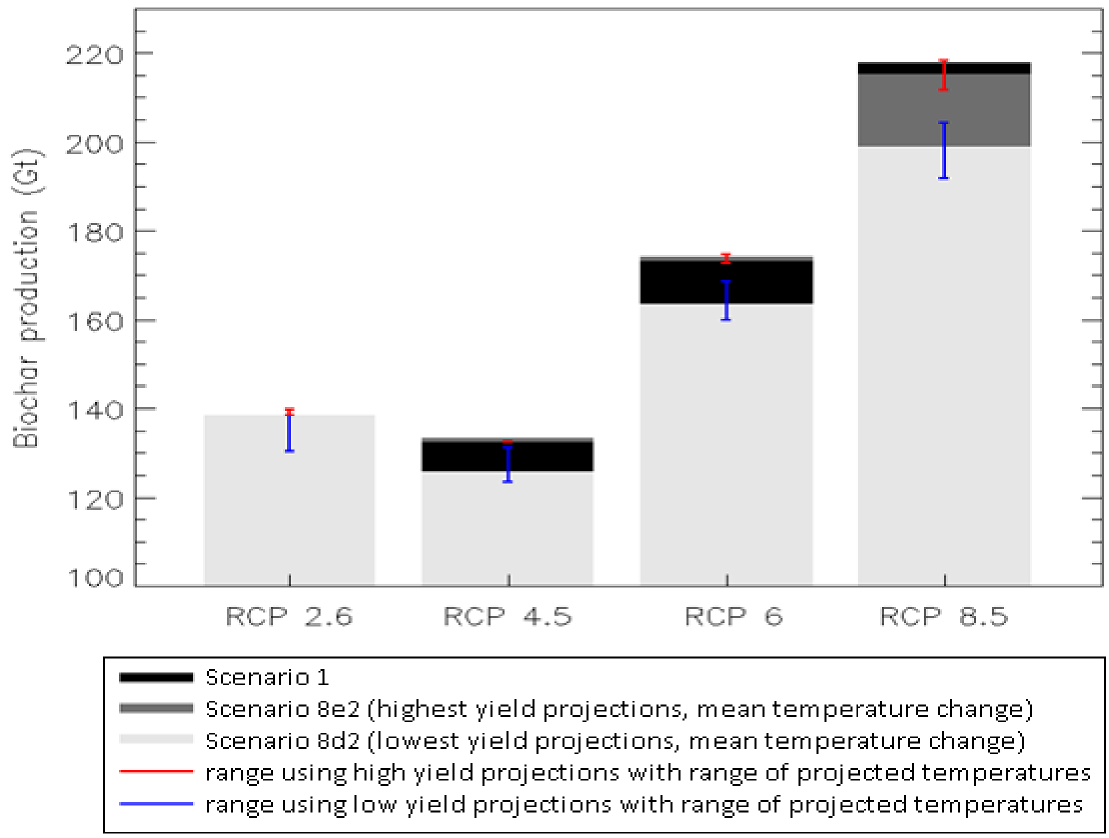

Figure 6-43: Total biochar production (Gt) for the four RCP scenarios under the assumptions of Scenario 1 (black), Scenario 8e2 (which assumes the highest yield projections discussed in Section 5.4.7.1, alongside the mean projected temperature change (dark grey)), and Scenario 8d2 (which assumes the lowest yield projections discussed in Section 5.4.7.1, alongside the mean projected temperature range (light grey)). Blue bars indicate the range where low yield projections are assumed with the low and high temperature projection assumptions. Red bars indicate the range when the high yield projections are assumed with the low and high temperature change assumptions. All of the scenarios shown in this figure assume no 'simple agricultural' adaptation measures are taken.

Biochar production in RCP 2.6 was not impacted, relative to Scenario 1, when using the mean temperature range with either the high or low yield projections. Low yield projections with the low temperature projections see a reduction in biochar production of 1.1, 4.7 and 13.6 Gt for RCPs 4.5, 6 and 8.5. Low yield projections combined with the mean temperature change makes this reduction in biochar potential greater, seeing 6.6, 9.7 and 19.0 Gt less biochar produced than in Scenario 1 for RCPs 4.5, 6 and 8.5. Low yield projections alongside the high temperature projections result in large reductions in biochar potential from those of Scenario 1, seeing 8.1, 8.9, 13.2 and 26.1 Gt less biochar for RCPs 2.6, 4.5, 6 and 8.5. Applying the high yield projections to the low temperature projections resulted in an increase in biochar production of 0.5, 1.4 and 0.3 Gt for RCPs 4.5, 6 and 8.5 respectively. High yields with mean temperature projections see an increase in biochar production of 1.2 and 1.1 Gt respectively for RCPs 4.5 and 6, and a decrease in biochar of 2.6 Gt for RCP 8.5. Applying the high yields and high temperature projection sees an increase of 1.5 Gt biochar for RCP 2.6, RCP 4.5 sees no change and RCPs 6 and 8.5 see a decrease of 0.5 and 6.3 Gt respectively.

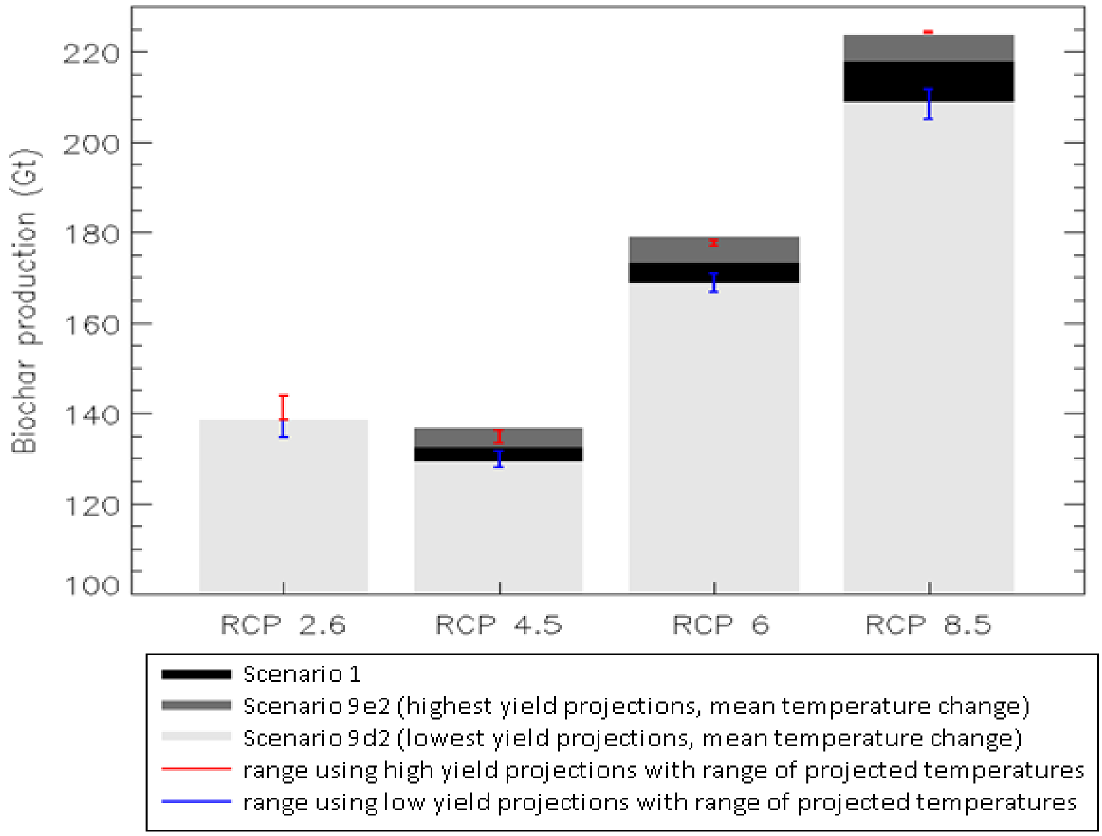

Figure 6-44: Total biochar production (Gt) for the four RCP scenarios under the assumptions of Scenario 1 (black), Scenario 9e2 (which assumes the highest yield projections discussed in Section 5.4.7.1, alongside the mean projected temperature change (dark grey)), and Scenario 9d2 (which

assumes the lowest yield projections discussed in Section 5.4.7.1, alongside the mean projected temperature range (light grey)). Blue bars indicate the range where low yield projections are assumed with the low and high temperature projection assumptions. Red bars indicate the range when the high yield projections are assumed with the low and high temperature change assumptions. All of the scenarios shown in this figure assume that 'simple agricultural' adaptation measures are taken.

Applying the alternate yield scenarios to the scenarios of adaptation with climate change again sees no change in biochar production potential for RCP 2.6 for the minimum and mean temperature change. Biochar yield is impacted in RCP 2.6 when the low yields are combined with the maximum temperature, seeing a reduction of 3.7 Gt biochar. Low yields and low temperature projections see 0.6, 2.2 and 6.3 Gt less biochar than Scenario 1 for RCPs 4.5, 6 and 8.5. Low yields and medium projections reduce biochar yields by 3.0, 4.4 and 9.1 Gt and high temperatures reduce biochar production by 4.1, 6.3 and 12.8 Gt biochar, relative to Scenario 1, for RCPs 4.5, 6 and 8.5. High biochar yields produce either no change or increased yields of biochar, irrespective of temperature projection. High yields combined with low temperature projection sees 0, 1.1, 3.9 and 6.5 Gt increase in biochar for RCPs 2.6, 4.5, 6 and 8.5 respectively. Medium temperature projections result in increases of 4.5, 5.8 and 5.6 Gt for RCPs 4.5, 6 and 8.5. High temperature projections result in increased biochar production of 5.5, 4.0, 5.1 and 6.2 Gt for RCP 2.6, 4.5, 6 and 8.5.

6.11 Summary

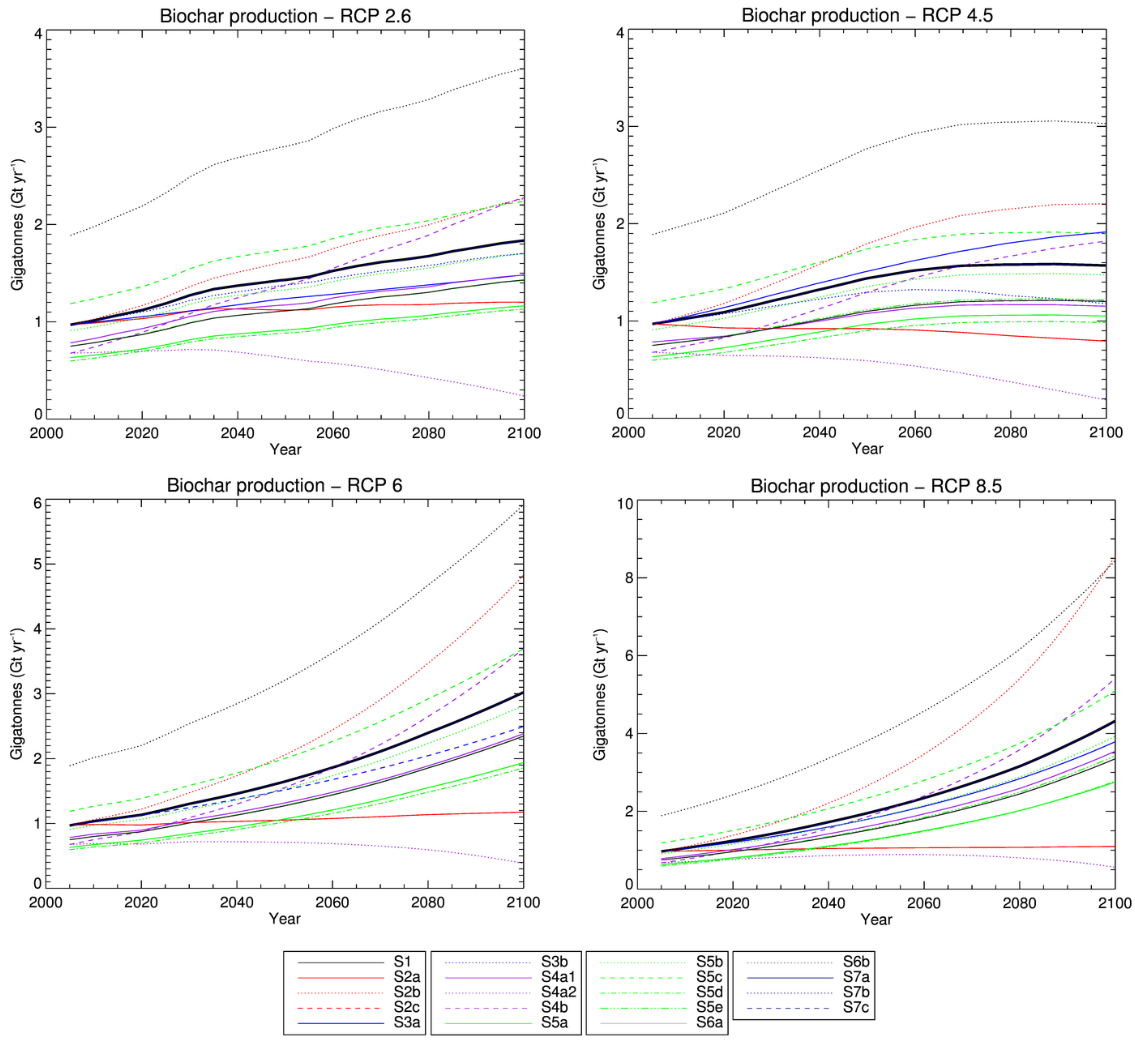

Figure 6-45: Summary of biochar produced annually for the four RCPs under the different scenario assumptions for Scenarios 1 to 7. (N.B. Scales vary between plots).

See Annexe III for tables detailing biochar production summaries for these scenarios. Figure 6-45 shows the annual global biochar production, for each RCP, for Scenarios 1 to 7. Scenario 1, which assumes the main or mean parameter values from literature and experimental data, begins with annual production of 0.97 Gt yr^{-1} for all RCPs, increasing to 1.84 Gt yr^{-1}, 1.57 Gt yr^{-1}, 3.02 Gt yr^{-1} and 4.32 Gt yr^{-1} for the four RCPs respectively in 2100. These scenarios project biochar production of 138.4 Gt, 132.3 Gt, 173.2 Gt and 217.9 Gt for RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5 respectively across the 95 year period.

Figure 6-45 highlights the variation in biochar production which is projected when exploring the various parameters of the biochar analysis, and also the variation in biochar production between the RCPs. Variation between the projections of biochar production is larger in RCP 8.5, followed by RCP 6 and this range between projections is more pronounced as the RCP timeline progresses. In 2100 the range in biochar production potential between the highest and lowest scenario projections for each RCP is 3356, 2830, 5513 and 7975 Mt yr^{-1} for RCPs 2.6, 4.5, 6 and 8.5 respectively. This larger variation in the scenario projections for RCPs 6 and 8.5 is mostly attributable to the larger rate of crop yield increase within these scenarios. This results in a wider range between scenarios using these crop yield assumptions and the scenario which assumes alternative yields. Low assumptions of residue to product ratio resulted in the lowest biochar production quantities of all of the parameters explored, indicating that factors such as the future trends in RPR could have a large impact on the biochar production potential. Scenarios exploring high crop yield and biochar yield produced the highest projections of biochar production. It is accepted here that all of the projected pathways of biochar production are possible in the future. Further research to narrow the range in projections for each RCP would benefit from better understanding of how factors such as crop yield, RPRs and available residues will change in the future.

Climate change induced changes in global mean surface temperature may have different levels of impact on biochar production, depending on the magnitude of climate change and on adaptation measures employed. The negative impacts on biochar production are seen to increase with increasing radiative forcing pathway, i.e. from lower impacts in RCP 2.6 to larger impacts in RCP 8.5. RCP 2.6 may not see an impact of biochar production, unless the changes in global mean temperatures seen are at the top end of the range of projections made within the literature. Even then the impacts on biochar production will be minimal when compared to impacts of the other RCP manifestations. All other RCPs would see impacts on the biochar production potential at some point in the scenario period, although the onset of these impacts occurs earlier with higher radiative forcing pathway. The mean climate change assumption (8b: mean crop yield impacts and mean temperature increase projection) saw a reduction in biochar production potential of 0 Gt, 2.6 Gt, 4.3 Gt and 11.2 Gt biochar over the 95 year period for RCPs 2.6, 4.5, 6 and 8.5 respectively. This could be mitigated by 0 Gt, 2.6 Gt, 3.9 Gt and 8.2 Gt of biochar by employing simple adaptation measures (Scenario 9b). This results in no reduction in biochar production potential, from that of Scenario 1, for RCP 2.6 and 4.5, and reductions of 0.4 Gt and 3 Gt over the scenario period for RCP 6 and RCP 8.5 respectively. The smallest (negative) climate impacts for the four RCPs over the 95 year period saw an increase in biochar production potential of 0 Gt, 0.5 Gt, 1.4 Gt and 0.3 Gt with assumptions of high yields and low temperature increase (Scenario 8e1), which could be increased to 0 Gt, 1.1 Gt, 3.9 Gt and 6.5 Gt of extra biochar by applying simple adaptation measures (Scenario 9e1). The largest negative impacts of climate induced increases in global mean surface temperature were a reduction of 8.1 Gt, 8.9 Gt, 13.2 Gt and 26.1 Gt of biochar across the scenario period when assuming the lowest crop yields and largest projected increase in global mean surface temperature (Scenario 8d3). This impact was mitigated to a reduction of 3.7 Gt, 4.1, 6.3 and 12.8 Gt, for the four RCPs over the scenario period, when simple adaptation measures were assumed. Simple crop based adaptation measures have the potential to mitigate much of the impacts of increased global mean surface temperature on biochar production, although these methods of adaptation are not explicitly stated by Porter et al, (2014) the may include actions such as irrigation and the planting of hardier cultivars. With these measures impacts are still seen for RCPs 6 and 8.5 under the full range of temperatures projected for these RCPs, although these impacts are greatly reduced from the non-adaptation scenarios. These results suggest that actions to mitigate changes in global mean temperature will see less impact on the production potential of biochar, though crop based adaptation measure may also have a large effect in reducing impact on biochar production even where temperature change does occur. The assessment of climate change impact here only addresses the impact of changes in global mean surface temperature on crop yields, and does not examine other potential climate change impacts such as changes in precipitation, localised surface temperature, pests and diseases or extreme weather events. See Section 5.5 for a discussion of the uncertainties and limitations associated with these results.

The projection of future scenarios will always be subject to elements of assumption and estimation as future scenarios depend on a number of as yet unknown drivers with a number of potential combinations and outcomes. As pathways become clearer, for example through long-term policy implementation, then prediction becomes easier, if still somewhat difficult. The structure of the biochar model would, in future research, allow for further alteration of parameters such as the contribution of each crop type to the total cropland utilized. Updates to the model would also be able to add further spatial and/or temporal detail to these parameters increasing the accuracy of regional projections. This would enable changes to be simulated and explored, in future research, as the uncertainty of future drivers is reduced.

7 Biochar carbon sequestration potential: Methodology

7.1 Introduction

One method of biochar utilization discussed within the literature is sequestering carbon over long time periods, mainly by means of the addition of biochars to soils. The stability of the carbon in biochar, upon this addition to soil, is still uncertain and dependent on a number of variables including the characteristics of the feedstock material, type and conditions of the biochar production process, and the environmental conditions. These environmental conditions are, for example climate and soil conditions such as moisture and microbial activity.

Chapter 4 examined the characteristics of biochars produced from different crop residue feedstocks and under different process conditions. Chapter 6 then used this experimental data in combination with the current biochar literature to develop and examine a number of scenarios which projected how much biochar could be produced from available crop residues, from the four prescribed cropland of the four RCPs, from 2005 to 2100. Following on from this work Chapter 7 details the methodology used to examine the potential recalcitrance of the biochar carbon in these biochar production scenarios, giving a potential quantity of carbon which could be stored long term within each scenario. The quantities of CO_2 which would be removed from the atmosphere and stored long-term in soils are examined. These scenarios of long-term carbon storage are compared to the carbon emission pathway of their respective RCPs, examining the mitigation potential of the biochar produced.

7.2 Methodology

7.2.1 Rates of biochar application

Within the scenarios detailed in Chapter 6 many different quantities of biochar are produced and are available, per hectare, for addition to soil. Some regions may have no localised biochar production capacity due to factors including limited agricultural production, production of low residue producing species, or high localised competition for residues. Other areas may produce more biochar than may be safely or beneficially added to soils within that locality. It was assumed here that surplus biochar produced within one region can be transported to regions with less than optimum production rates of biochar. As this assessment looks at the maximum technical potential for biochar production and soil addition, the economic or logistical issues associated with such assumptions were not addressed here but would be an insightful avenue of further research. For indicative purposes, the maximum and average quantities of biochar produced per hectare, under the assumptions of Scenario 1, were calculated to give an indication of the average and maximum rates of addition to soil if all biochar is added to soil in the same location as produced. These mean and maximum values were calculated for each of the four RCPs under the assumptions of Scenario 1 to indicate possible rates of biochar addition to soil within each RCP.

7.2.2 Carbon sequestration potential

A number of methods of assessing the recalcitrance of biochar carbon are discussed within the literature and summarised in Chapter 2, Section 2.2.5.2. These methods include using historical analogues, laboratory incubation tests, field tests and modelling techniques. There is often variation between parameters used in the different methodologies, for example some methods look at the recalcitrance of biochars in different soils, where others may look at degradation rates in other mediums or of biochar alone. This often makes direct comparison between studies difficult. A number of modelling based techniques, which draw on both the literature and primary experimental data, are used here to determine the potential carbon sequestration potential of the biochar quantities projected in the scenarios of Chapter 6. The three methods applied here are (1) the carbon sequestration potential (CS) methodology of Zhao et al. (2013), (2) an adaptation of this CS potential equation which was developed using correlations found through the experimental work of Chapter 4, and (3) the two-pool methodology of Woolf et al. (2010). The alternative CS equation, using correlation between the feedstock volatile content and the biochar R_{50} value was developed to assess its potential as an alternative method of recalcitrance estimation.

7.2.2.1 Carbon sequestration methodology of Zhao et al (2013)

The carbon sequestration potential (CS) methodology, which builds on the biochar recalcitrance work (R_{50} recalcitrance index) of Harvey et al. (2012), was proposed by Zhao et al. (2013). This R_{50} recalcitrance index methodology (See Equation 3-1) was used in Chapter 4 to calculate the relative recalcitrance of the biochars produced experimentally within this study. The biochars produced were classified as either Class B or Class C, meaning under the classification system of Harvey et al. (2012) they would undergo 'minimal degradation' and 'more severe degradation' respectively, over time when added to soils. None of the biochars produced experimentally were found to be Class A biochars which are the 'most recalcitrant', though some biochars have been characterised as Class A within other studies (Harvey et al., 2012, Zhao et al., 2013). The R_{50} indexing of biochars by Harvey et al. (2012) does not indicate a specific timescale for the degradation of the biochar, or give a range of values for the amount of degradation which would occur, only a ranking against the recalcitrance of graphite which is highly stable in soils. Zhao et al. (2013) used the R_{50} index of Harvey et al. (2012) to develop a method of determining the amount of carbon, from the original feedstock carbon content, which would be stored long term in soils upon addition of a biochar to soil. They termed this the carbon storage potential (CS) of the biochar.

$$CS\ (\%) = (M \times Ch \times C_{Ch} \times R_{50}) / M \times C_F \qquad (7\text{-}1)$$

Where: M = mass of feedstock (g), Ch = yield of biochar (%), C_{Ch} = carbon content of the biochar (%), R_{50} = recalcitrance index, C_F = carbon content of the feedstock (%).

The CS potential equation of Zhao et al. (2013), was used here to determine the carbon storage potential of the biochar quantities produced within the scenarios projected within Chapter 6. The experimental data of Chapter 4 was used where relevant, with the ultimate analysis results for elemental carbon content for both the feedstocks and biochars (detailed in Table 4.2) used for carbon contents within the equation. Biochar yield (%) from the experimental data was also used. Values for the mass of feedstock available for biochar production were taken from the relevant biochar scenario as detailed in Chapter 3. Where more than one crop residue type for a particular crop group (see Table 5-2) was tested experimentally, the average biochar yield value was taken to determine average production for that crop group. The CS potential (%) of the biochar produced in each scenario was calculated using Equation 7-1 determining how much of the original feedstock carbon, per grid cell, would be retained long term in soil upon charring and addition to soils. As with the R_{50} index of Harvey et al. (2012), no definition of the time period assumed to be 'long term' is given within the literature for the CS potential. As the Harvey et al. (2012) study, which developed the R_{50} index used by Zhao et al. (2013) to calculate CS, discussed, the lifetime of biochar in soils can range from 'under a century to several millennia'. It is therefore assumed here that the period of stability defined by Zhao et al. (2013) as 'long term' is longer than the 95 year assessment period used as the scenario period here. This was deemed to be an acceptable assumption as 95 years is at the lower end of the biochar lifetime range discussed in Harvey et al. (2012).

7.2.2.2 Recalcitrance from volatile content equation (RVC)

The discussion by Harvey et al. (2012) regarding the assessment of biochar lifetime also proposed a number of alternative methods, which use various biochar properties, to predict the lifetime of particular biochars, including using the thermal degradation and volatile content of biochars as indicators of biochar stability in soils. They proposed that these methods may provide estimated lifetimes for each biochar, and could potentially provide simplified methods of estimation where only some of the biochar characteristics are known, or if only simple analytical techniques can be applied due factors such as to cost or technical capacity. Further work is required to validate the effectiveness of these simple estimation methodologies. This discussion within literature on alternative indicators of biochar lifetime was expanded here by further development of the CS equation of Zhao et al. (2013) to use the feedstock volatile content as a predictor of biochar stability, in place of the R_{50} index. The new equation uses feedstock volatile content (see Table 4.2) due to the correlation determined between R_{50} and feedstock volatile content (r^2 = 0.67, p = 0.01) (see Figure 7-1).

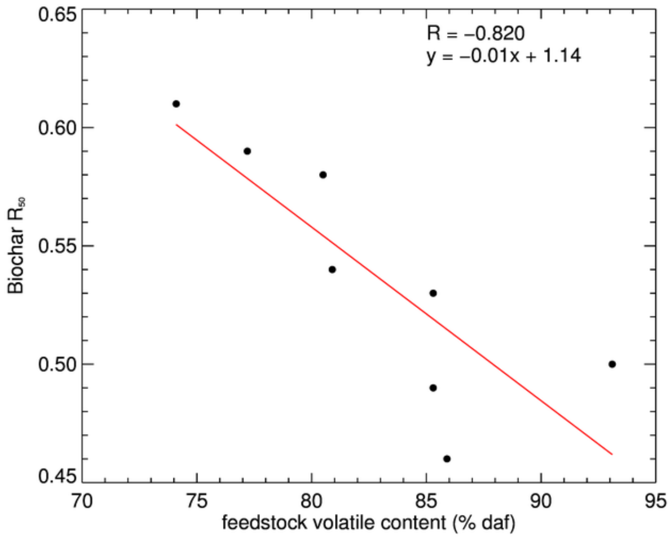

Figure 7-1: Relationship between feedstock volatile content (% daf (dry, ash free)) and biochar R_{50} index values. Equation of line (y=mx+c) is shown, where m is the line gradient and c is the y intercept.

The equation of straight line produced from the correlation analysis of the two variables is:

$$y = -0.0073x + 1.1449 \quad (7\text{-}2)$$

Equation 7-2 was used in place of the biochar R_{50} values in Equation 7-1 resulting in the equation:

$$CS\ (\%) = (M \times Ch \times C_{Ch} \times (-0.0073x + 1.1449)) / M \times C_F \quad (7\text{-}3)$$

Where: x = the feedstock volatile content on a dry, ash free (daf) basis.

This new equation for the calculation of biochar carbon sequestration potential (Equation 7-3) is, from this point, termed the recalcitrance from volatile content (RVC) equation. The uncertainty of the regression slope (from Figure 7-1) was also calculated and used to determine whether the original projections of carbon sequestration potential (using Equation 7-1) lie within the projection range of carbon sequestration potential made using Equation 7-3 when applying this uncertainty of slope.

7.2.2.3 Two-pool calculation methodology

In their study of biochar carbon sequestration potential under current land-use regimes, Woolf et al. (2010) used a two-pool method of assessing the decay kinetics of biochars in soil. The equation (Equation 7-4) assumes that biochar consists of two fractions, one labile and one recalcitrant, which are modelled as two separate pools with different decay properties.

$$M(t) = M_0 \left[L\, exp(-ln(2)/t_{1/2L}\, t) + R\, exp(-ln(2)/t_{1/2R}\, t)\right] \quad (7\text{-}4)$$

Where:

M(t) = mass of carbon at time t, M_0 = initial mass of biochar carbon, L = labile fraction of biochar, R = recalcitrant fraction of biochar, $t_{1/2t}$ = labile half-life, $t_{1/2R}$ = recalcitrant half-life.

The method assumes that each pool follows an exponential decay curve, with the assumptions of the main scenario in Woolf et al. (2010) being that the labile fraction, constituting 15 % of the biochar carbon, has a half-life of 20 years, and the recalcitrant fraction (the remaining 85 % of the biochar carbon), has a half-life of 300 years. Variance in $t_{1/2L}$ of 1 to 25 years, and $t_{1/2R}$ of 50 – 1000 years is used by Woolf et al. (2010) to assess the effects of the range of degradation timescales reported within the literature. They discuss that using an upper limit of 1000 years for $t_{1/2R}$ may be a conservative upper estimate as some reporting in the literature would extend $t_{1/2R}$ beyond this value. They also explore uncertainty in the assumptions of the size of the labile and recalcitrant fractions of biochar carbon by applying values of L = 5 – 30 % (thus R = 95 – 70 % respectively).

The two-pool lifetime method was applied here to the biochar scenarios of Chapter 6 to assess whether the use of this alternative method for calculating biochar stability over time resulted in different projections from the carbon storage potential projections determined using the CS equation of Zhao et al. (2013) and the RVC equation. The main assumptions of L = 15 %, $t_{1/2L}$ = 20 and $t_{1/2R}$ = 300 from Woolf et al. (2010) were used, and the upper and lower uncertainty estimates for L, $t_{1/2L}$ and $t_{1/2R}$ were also explored to see how variance in the assumptions of the size of the labile and recalcitrant fractions, and the half-lives of these fractions, affected the lifetime projections. The timeframe of assessment of the stored carbon was also altered, examining the quantity of biochar carbon remaining stable after, for example, 500 and 1000 years under different assumptions of recalcitrance. This gave an indication of the overall longevity of the biochars, not just the carbon stored over the 95 year period.

7.3 Summary

The methodologies for determining the efficacy of each biochar scenario at long-term carbon sequestration are detailed. The mean and maximum rates of biochar production per hectare of cropland were determined for each RCP under the assumptions of Scenario 1. This gives an indication of the amount of biochar which would be added to soils, per hectare. This is an indication of the addition to soil rates as the crop residues are likely to be collected to a more central point and then re-distributed, potentially to other regions, after biochar production. The three methods used to assess the carbon sequestration of the biochars in each scenario are the CS potential (Equation 7-1), the recalcitrance from volatile content (RVC) equation (Equation 7-3) and the two-pool method (Equation 7-4). The RVC equation, developed from the correlation between feedstock volatile content and the R_{50} index value of the biochar, was examined for effectiveness as an alternative biochar lifetime estimation tool. The CS and RVC equations were used to estimate the long-term carbon storage potential of the biochars in each scenario from Chapter 6. The two-pool method was used to assess the remaining carbon after the 95 year scenario period, and also to examine the long-term sequestration potential of biochars with different assumptions of labile and recalcitrant fraction size and decay rates. The CS equation (Equation 7-1) was then used to assess the long-term carbon storage of the biochars produced in all scenarios, for all RCPs. These values were used to determine the potential of each scenario for the mitigation of carbon emissions for each RCP. The results of these analyses are detailed and discussed in Chapter 8.

8 Biochar carbon sequestration potential: Results and discussion

8.1 Introduction

The maximum and mean rates of biochar production, per hectare, were determined to give an indication of the rates of biochar addition to soil which may occur within the scenarios discussed in Chapter 6. Three modelling methods were used to estimate the potential for long-term carbon storage of the scenarios of biochar production. These methods are the carbon sequestration (CS) equation of Zhao et al. (2013), the Recalcitrance from Volatile Content (RVC) equation developed in Section 7.2.2.2, and the two-pool equation methodology from Woolf et al. (2010). The projections of the CS and RVC equations were compared, assessing whether the uncertainty range of the projections made using the RVC equation encompassed the projections made using the CS equation. This comparison was used to determine the effectiveness of the RVC as an alternative recalcitrance estimation tool. The two-pool methodology was used to offer another comparison tool, and also to provide estimates of the overall recalcitrance timeframes of the biochars.

8.2 Rates of biochar addition to soil

The mean and maximum rates of biochar production were calculated for each RCP under the assumptions of Scenario 1 to give an indication of the mean and maximum rates of biochar application to soil which may occur within each RCP.

Table 8-1: Mean and maximum annual biochar per hectare for the four RCPs in 2005, 2100 and across the whole scenario period for Scenario 1.

	Rates of biochar production (tonnes per hectare (t ha yr^{-1})					
	2005		2100		Whole scenario	
RCP	Mean	Max	Mean	Max	Mean	Max
2.6	0.10	1.51	0.17	2.20	0.14	2.20
4.5	0.10	1.51	0.19	2.93	0.16	2.93
6	0.10	1.51	0.27	3.81	0.16	3.81
8.5	0.10	1.51	0.37	5.96	0.20	5.96

The British Biochar Foundation (2014) recommend that biochar addition to soil is kept to a minimum of 3 kg m^2 until further research is conducted to investigate the safety of larger additions. The maximum rate of biochar production for any of the RCPs during the scenario period is almost 6 t ha yr^{-1} which is equivalent to 0.6 kg m^2 yr^{-1}. This is, therefore, well within the recommended addition rates. This 0.6 kg m^2 yr^{-1} rate is assuming that biochar addition is made at the point of residue collection and redistribution is even. This is, of course, a simplification of any potential distribution scenario but as the 0.6 kg m^2 yr^{-1} is well below the recommended upper limit of 3 kg m^2 there is capacity for much of the biochar to be added where it is deemed most useful and economical, rather than by the even redistribution scenario detailed here. As this biochar accumulates, over time, to closer to the 3 kg m^2 threshold then alternative distribution sites could be used as required. As discussed previously, in reality all biochar is unlikely to be added to soil where the crop residues are produced. Depending on the scale of the biochar production system residues may be collected and transported to biochar production plants. Biochar may then be distributed to different locations from these plants, as required. This transport and distribution may add an emissions penalty to the biochar system which would be a useful focus for further research.

8.3 Carbon sequestration potential (CS) equation

8.3.1 Total carbon storage

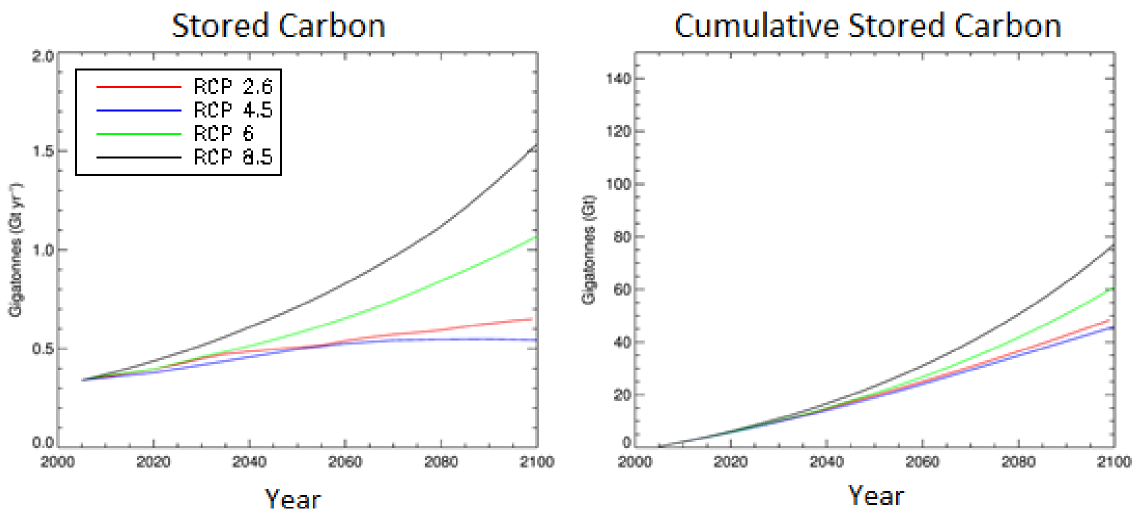

Figure 8-1: Annual carbon storage potential (GtC yr^{-1}) of the biochar produced within the RCPs under the assumptions of Scenario 1 (left) and the cumulative carbon storage potential (GtC) of this biochar over the scenario period (right). 'Stored carbon' refers to the biochar carbon which would remain in stable form in soils from the point of addition to the scenario end point of 2100.

Under the assumptions of Scenario 1, 0.34 Gt yr^{-1} of the biochar carbon added in 2005 would remain stable in soils for long time periods. For all RCPs the annual amount of carbon stored long term generally increases over time, resulting in 0.65, 0.54, 1.07 and 1.54 GtC yr^{-1} in 2100 for RCPs 2.6, 4.5, 6 and 8.5 respectively. Cumulatively the addition of the biochar produced in each scenario to soils throughout the scenario time-period results in the long-term storage of 49 GtC, 46 GtC, 61 GtC and 77 GtC respectively for RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5. The contribution of each biochar type is discussed in Section 8.4.2. The impact that this storage of carbon may have on the emission pathways of CO_2 for each RCP is discussed in Section 8.7.

Figure 8-2 shows the cumulative carbon storage potential of Scenarios 1 to 7 using the CS potential equation. The effects on carbon sequestration potential of uncertainty in crop yields, land-use change, crop RPRs, residue availability, biochar yields, and biochar carbon content are shown in the different panels. The effects of scenario uncertainty often led to larger ranges in the potential carbon storage projections as the RCPs increase from RCP 2.6 to RCP 8.5. This often means that the carbon storage potential of scenarios projected under the RCP2 pathway have smaller uncertainty ranges, with uncertainty increasing with increasing RCP up to RCP 8.5 where the largest uncertainty range is often seen.

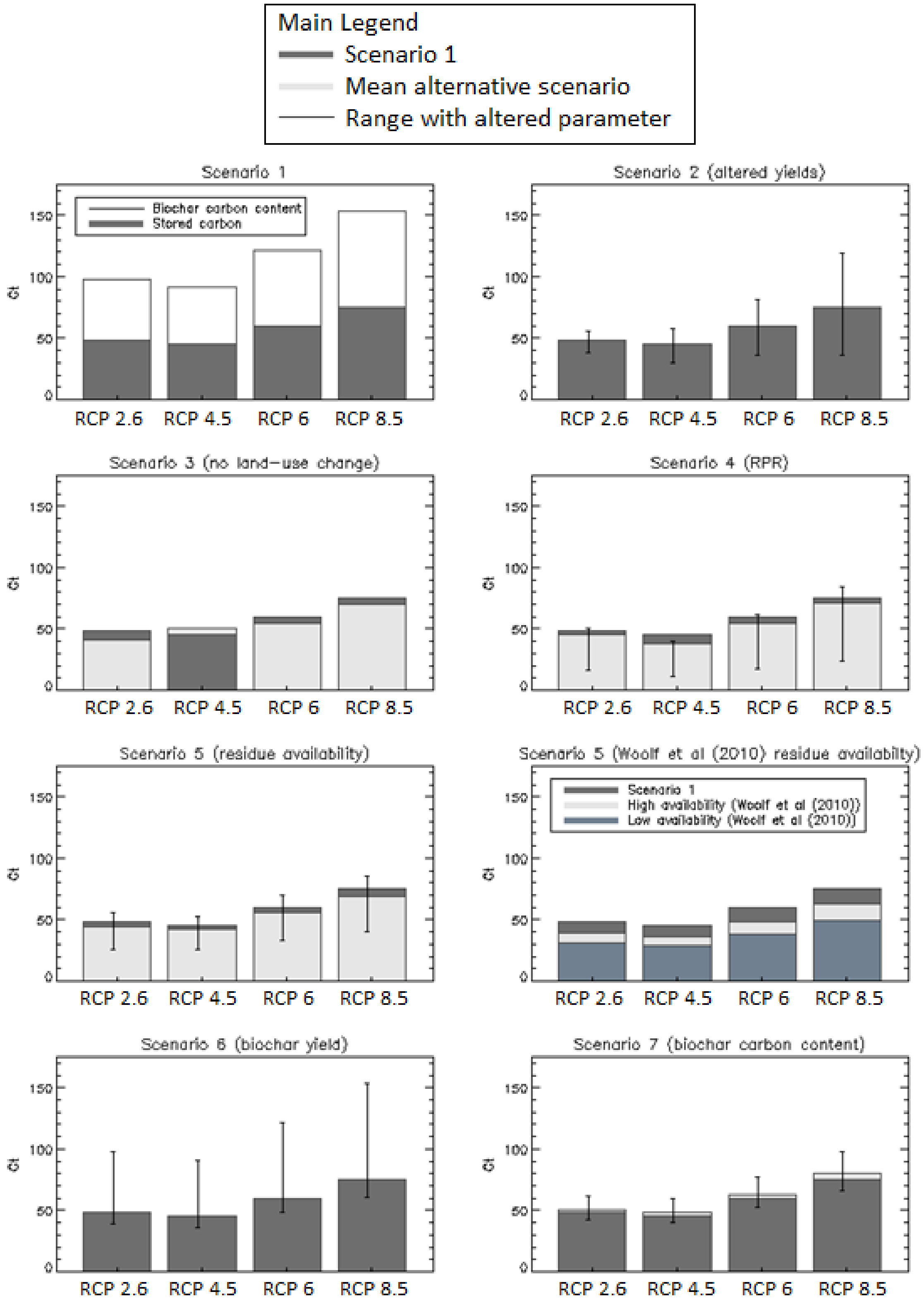

Figure 8-2: Total carbon storage potential (GtC) of Scenarios 1 to 7 using the CS equation of Zhao et al. (2013). Plots show the cumulative carbon storage potential for the 95 year scenario period. The main legend is shown at the top of the figure. Individual legends shown inside a plot corresponds to that plot only.

If no crop yield increases are applied throughout the scenarios then total carbon storage potential of the RCPs are reduced to similar amounts for all RCPs, ranging from 36 GtC to 38 GtC. Keeping land use static at 2005 levels reduces the total carbon sequestration potential of each RCP, from that of Scenario 1, except for that of RCP 4.5 which is slightly increased by almost 5 GtC over the scenario period. The occurrence of very low RPR factors (Scenario 4a2) would greatly reduce the carbon sequestration potential of the RCPs, resulting in 20.3 GtC, 18.2 GtC, 23 GtC and 28.5 GtC stored long-term for the four RCPs respectively. These values are increased to nearer Scenario 1 levels with the application of medium RPR values (Scenario 4a1). The application of high average RPR values results in carbon storage similar to Scenario 1 for RCP 2.6 and RCP 6, slightly lower than Scenario 1 sequestration for RCP 4 and slightly above Scenario 1 sequestration for RCP 8.5. This variation in the effects of RPR may be due to the effect altering the RPRs of different crop types, which may have different weightings in the different RCPs due to the regional distribution of land over time in each RCP. When examining scenarios of residue availability both the minimum and medium availability scenario (5a and 5b) reduce the carbon sequestration potential of the RCPs relative to Scenario 1. The minimum carbon sequestration potential of the residue availability scenarios would see 29.3 GtC, 28.9 GtC, 37.1 GtC and 46.2 GtC stored long term for RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5 respectively. Using both the high and low residue availability scenarios of Woolf et al. (2010) reduces the carbon sequestration potential relative to Scenario 1. The minimum carbon storage under these alternative residue availability scenarios is projected to be 30.5 GtC, 28.5 GtC, 37.8 GtC and 49.3 GtC for the four RCPs respectively. This is increased to 39.2 GtC, 36.2 GtC, 48.5 GtC and 62.3 GtC respectively when the high residue availability scenario of Woolf et al. (2010) is applied. Applying the low biochar yield assumptions reduces the carbon sequestration potential of Scenario 1 by between 10 GtC and 20 GtC for the four RCPs over the whole scenario period. Applying the highest biochar yield assumptions increases the potential of carbon sequestration greatly for all RCPs, resulting in between 90.1 GtC and 153.6 GtC stored (RCP 4.5 and RCP 8.5 respectively). The achievement of these high biochar yields from all crop residues for the full scenario period is unlikely compared to the other biochar yield scenarios. This is due to a number of factors, including the technological requirements necessary to achieve such yields, the variation in yields achievable from different feedstocks and the likely economic requirement to optimise the biochar producing process to also produce oil and/or gas as a fuel product. Altering the assumed biochar carbon content had little effect on the carbon sequestration of the RCPs in comparison to some of the other parameters. Scenarios 7b and 7c (medium and high average biochar carbon content values respectively) both have the potential to sequester more carbon than Scenario 1. Using the low biochar carbon content assumptions (Scenario 7a) reduces the total carbon storage potential of the scenario to 41.9 GtC, 48.5 GtC, 63.2 GtC and 79.8 GtC for the four RCPs respectively.

8.3.2 The Impacts of climate change on carbon sequestration potential

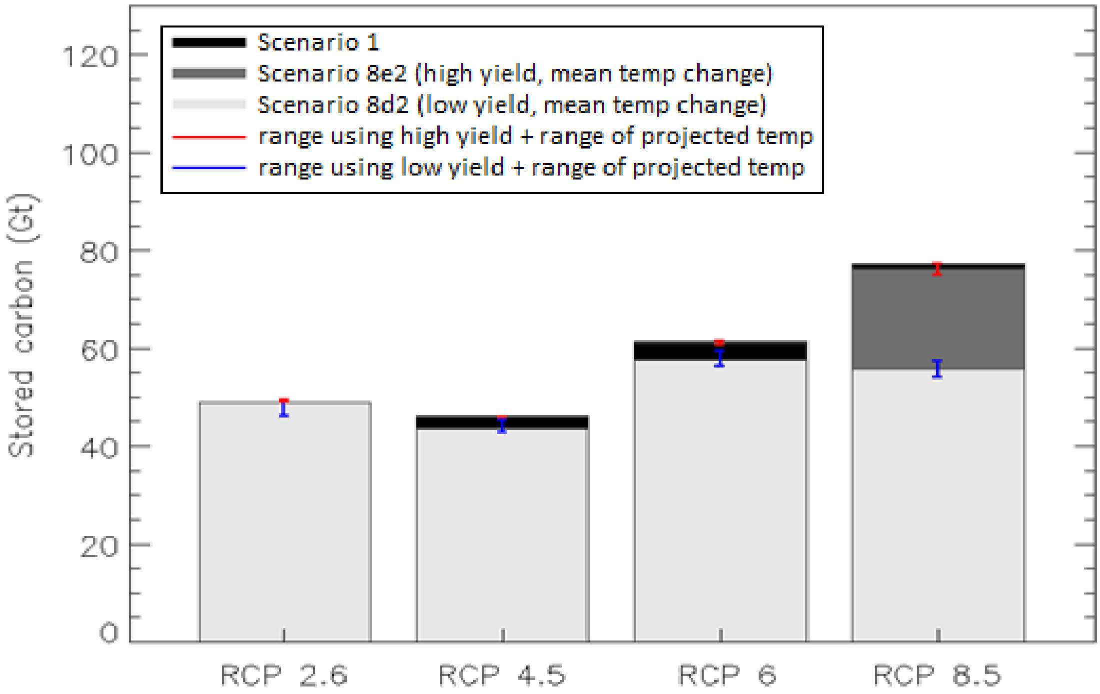

Figure 8-3: Total carbon storage potential of the RCPs under the climate change impact assumptions of Scenario 8d and 8e. Scenarios 8d2 and 8e2 (light grey and dark grey respectively) are shown in comparison to the carbon storage potential of Scenario 1 (black). Scenario sub-set 8 details the projections for biochar potential under climate change where no adaptation measures are applied.

As discussed previously the impact on climate change is likely to reduce the potential of the biochar scenarios to sequester carbon, with increasing impact on the CS potential likely with increasing changes in climate. The climate impacts examined within these scenarios are changes in global mean surface temperature caused by the projected change in radiative forcing which would be expected from the emissions pathway of each RCP. The effects of these projected changes in global mean surface temperature were applied to the residue production potential of each scenario (in Chapter 6). The effect on carbon sequestration potential was then determined using the CS equation of Zhao et al. (2013) (Equation 7-1). Figure 8-3 and Figure 8-4 show the impacts of the range of crop yield impacts projected by Porter et al. (2014) on the CS potential of Scenario 1. The figures show only the projections of Scenarios 8 and 9 e and d as these scenarios assess the maximum and minimum yield impacts, alongside the range of temperature projections. The projections of scenarios 8 and 9 a – c, which assess the mean yield projections alongside the range of temperatures, are encompassed within the range explored in Figure 8-3 and Figure 8-4.

The CS potential of RCP 2.6 was the same when the range of potential yield impacts under the mean temperature change scenario were applied (Figure 8-3). A reduction in the CS potential of RCP 2.6, when compared to that of Scenario 1, was seen under the scenario of low yield and high temperature assumptions (Scenario 8d3). The low yield projections combined with the mean projected temperature change resulted in a reduction in carbon sequestration, relative to that of Scenario 1, of 2.27 GtC, 3.45 GtC and 21.25 GtC respectively for RCP 4.5, RCP 6 and RCP 8.5. This highlights the increasing impact of global mean temperature change as the radiative forcing of the pathway increases (i.e. with increasing RCP). Applying high yield and mean temperature change assumptions resulted in small increases in total CS potential of 0.42 GtC and 0.38 GtC respectively for RCP 4.5 and RCP 6 relative to Scenario 1. The application of these assumptions to RCP 8.5 resulted in a reduction of 0.92 GtC for the total CS potential relative to Scenario 1. The impact of the range of temperature projections on CS potential for each RCP widens in range with increasing RCP (from RCP 2.6 up to RCP 8.5) when applied with assumptions of either low or high yield. Figure 8-4 shows the impact of simple adaptation measures to the CS potential of the climate change scenarios.

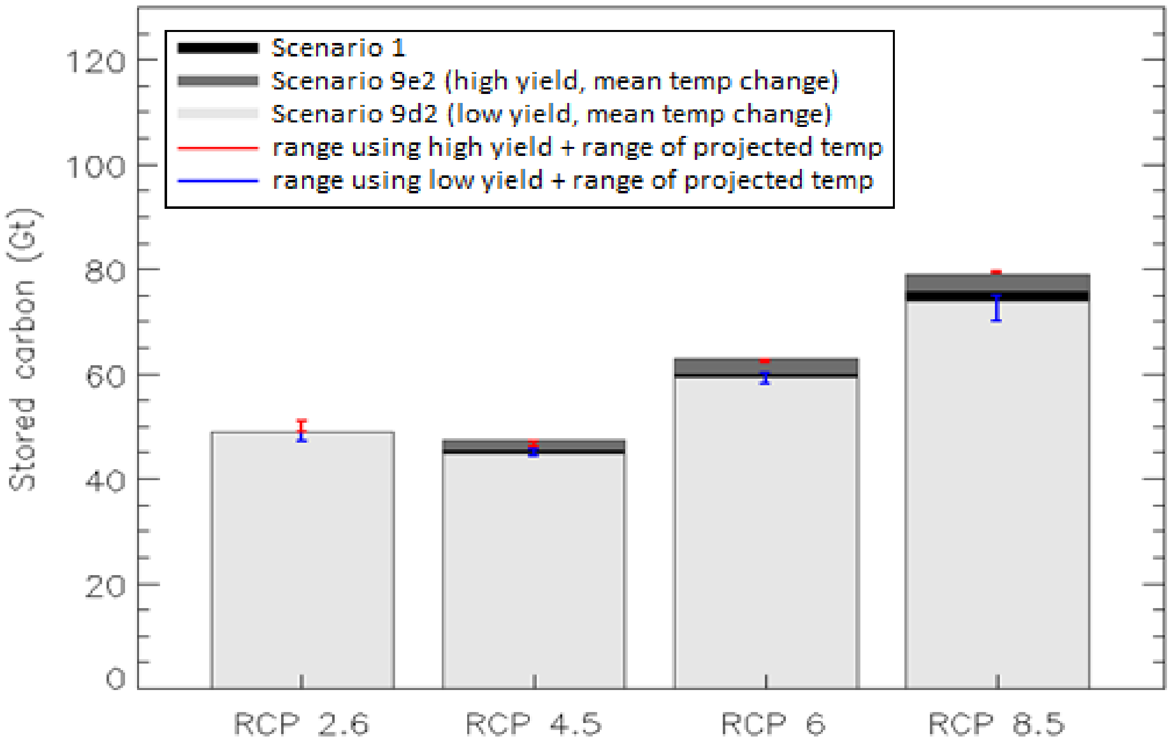

Figure 8-4: Total carbon storage potential of the RCPs under the climate change impact assumptions of Scenario 9d and 9e. Scenarios 9d2 and 9e2 (light grey and dark grey respectively) are shown in comparison to the carbon storage potential of Scenario 1 (black). Scenario sub-set 9 details the projections for biochar potential under climate change but where some simple adaptation measures are applied.

The application of simple crop based adaptation methods improved the carbon sequestration potential of biochar in all of the RCPs (Figure 8-4). No impact was seen in carbon sequestration potential where high or low yield projections were applied to the mean temperature projections for RCP 2.6. The high yield projection, alongside the high temperature projection, may provide some benefit in increased carbon sequestration due to the potential increase of crop yields with small increases in global mean temperature coupled with adaptation measures for RCP 2.6. The reduction in total carbon storage potential seen in RCP 4.5, RCP 6 and RCP 8.5 in the scenarios of low yield projections with no adaptation (Scenario 8d) was lessened when adaptation measures were employed (Scenario 9d). This brought the CS potentials much more in line with those of Scenario 1, seeing a reduction of only 1.55 GtC, 2.03 GtC and 1.99 GtC for the highest three RCPs respectively. This is a marked improvement on the reduction in CS potential seen in Scenario 8d2. The increases in CS potential which were seen with the high yield projections of Scenario 8e were further increased where adaptation measures are applied. These increases, relative to

Scenario 1, were: 1.03 GtC, 1.54 GtC and 3.23 GtC for the total scenario period for RCP 4.5, RCP 6 and RCP 8.5 respectively.

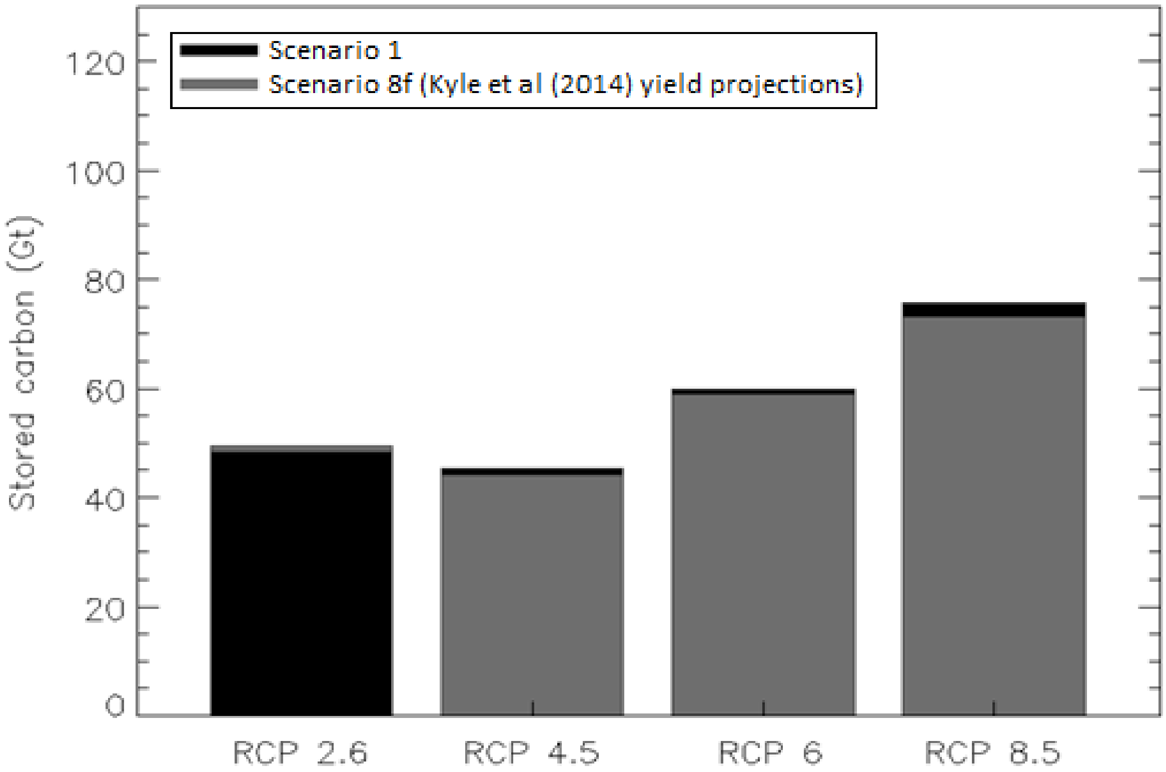

Figure 8-5: Total carbon storage potential of the RCPs under the climate change impact assumptions of Scenario 8f. Scenario 8f (dark grey) is shown in comparison to the carbon storage potential of Scenario 1 (black).

Using the climate change yield impact projections of Kyle et al (2014) as an alternative to the projections used in Scenarios 8 a to e and 9 a to e sees total CS potentials similar to those of Scenario 1. A small increase in CS potential of 0.43 GtC was seen in RCP 2.6, which can perhaps be attributed to increases in crop yields related to a small increase in global mean temperature. Reductions in CS potential are seen for the other three RCPs, with a reduction of 1.78 GtC, 2.08 GtC and 4.02 GtC for RCP 4.5, RCP 6 and RCP 8.5 respectively. This demonstrates an increasing negative impact on carbon sequestration potential as radiative forcing increases.

8.4 Recalcitrance from volatile content (RVC) equation

8.4.1 Projection of total carbon storage potential

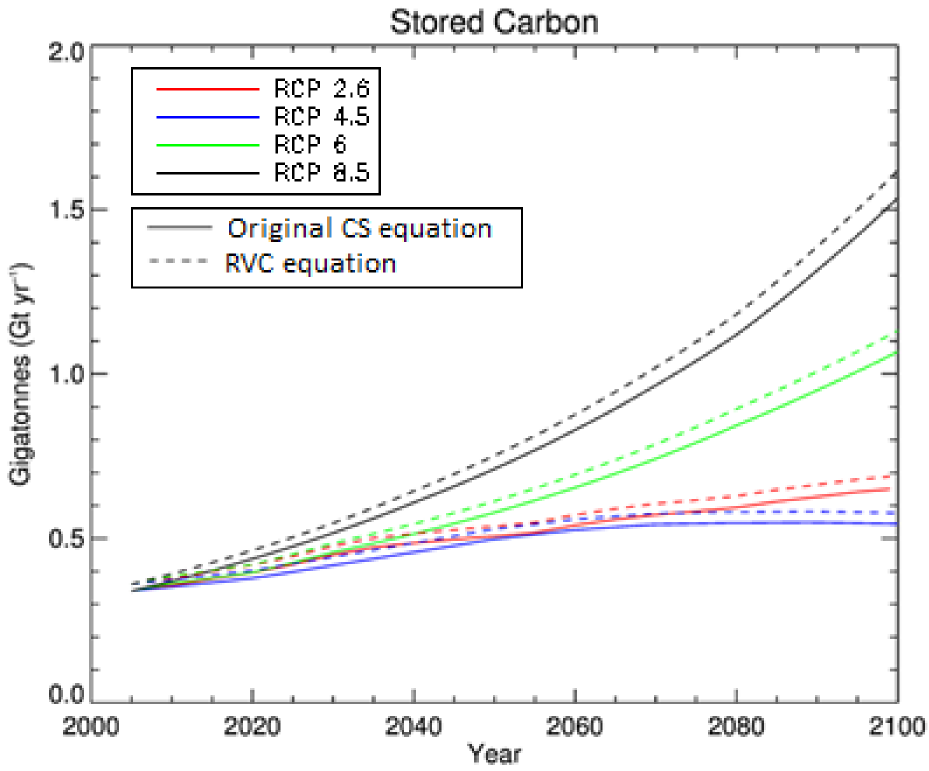

Figure 8-6: Carbon storage potential of the four RCPs under the assumptions of biochar scenario 1 using the two variations of CS equation. The solid line denotes the carbon storage potential of Scenario 1 using the CS equation of Zhao et al. (2013) (Equation 7-1). The dashed line denotes the carbon storage potential of Scenario 1 using the RVC equation (7-3).

Using the RVC equation in place of the CS equation led to increases in the projected total carbon sequestration potential of the biochar produced within each RCP, under the assumptions of Scenario 1, of 2.85, 2.80, 3.65 and 4.36 GtC in for RCPs 2.6, 4.5, 6 and 8.5 respectively. The original projection of carbon storage potential (using Equation 7-1) was found to lie within the uncertainty range of the adapted equation (Equation 7-3). This indicates that Equation 7-3 can be used as an alternative equation to Equation 7-1 for the estimation of the long term carbon storage potential of biochars, as defined by Zhao et al. (2013). This may be of benefit where only limited data regarding the feedstock and biochar characteristics is available, with proximate analysis of the feedstock giving the feedstock volatile content, rather than requiring thermogravimetric analysis of the biochar to provide the R_{50} index value. This may also be of benefit if a number of feedstocks are available, and feedstock analysis can help to inform the choice of feedstock made.

8.4.2 Projection of carbon storage potential of different biochars

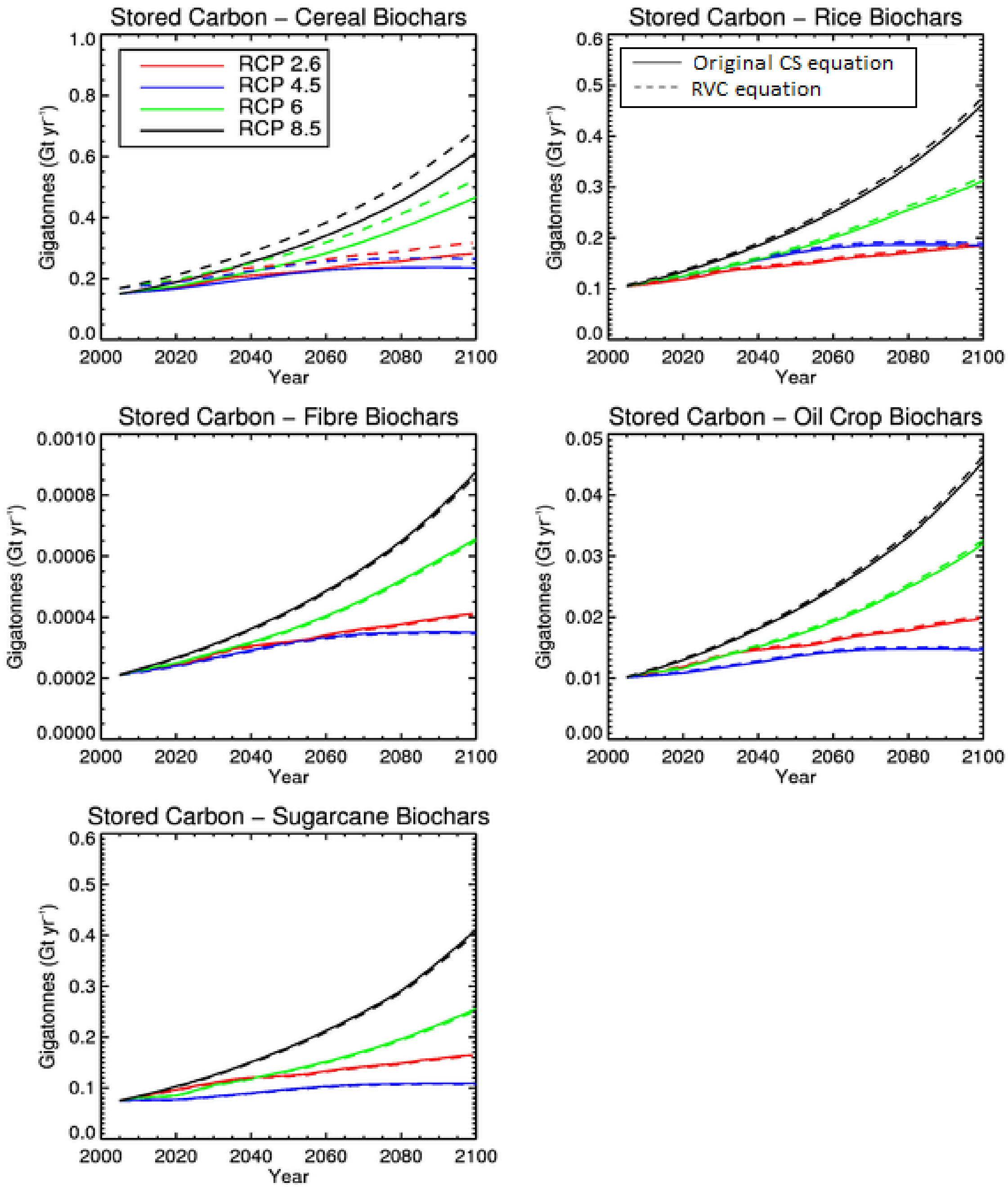

Figure 8-7: Carbon storage potential of the different biochar types under the assumptions of biochar scenario 1 using the two variations of CS equation. The solid line denotes the carbon storage potential of Scenario 1 using the CS equation of Zhao et al. (2013) (Equation 7-1). The dashed line denotes the carbon storage potential of Scenario 1 using the RVC equation (7-3). N.B. Scales vary between plots.

The carbon sequestration potential of the biochars produced from different crop groups varies greatly, as detailed in Figure 8-7. Cereal biochars have, throughout the scenario period, the greatest potential for long term carbon storage. This is followed by sugarcane bagasse. Cereal residues have high CS potential mainly due to the large residue quantities produced and available for biochar production, relative to the other residue types. Rice biochars are projected to have just over half of the potential of cereal biochars to sequester carbon long-term. The CS potential of oil biochars is around 10^{-2} smaller than that of cereal biochars. Fibre biochars have a relatively small CS potential, being of the order of 10^{-4} smaller than that of cereal biochars. Both oil and fibre crops have lower residue production and availability factors. Compared to the other crop groups, sugarcane bagasse has a relatively low R_{50} index, and olive pomace has a relatively low C content, which contribute to the lower CS potentials of these groups.

Figure 8-7 shows the difference in projections of CS potential between the CS equation (Equation 7-1) and the RVC equation (Equation 7-3). The projections of CS potential made for the different biochar types using the RVC equation are well fitting with the projections made using the CS equation, except perhaps for that of cereal residues, where the difference in 2005 in CS potential is 0.02 GtC yr^{-1}, or 12.6 %. The difference projected in the sequestration potential of cereal biochars lies within the bounds of uncertainty determined for Equation 7-2, making it a suitable projection for use here. All other projections were an excellent fit between the two datasets. The differences between projections of total carbon stored over the full scenario period made using the RVC equation and CS equations, for the different biochar types, are detailed in Table 8-2.

Table 8-2: Difference in total CS projection (GtC) resulting from the use of the RVC equation (Equation 7-3) in place of R50 index in the CS equation of Zhao et al. (2013) (Equation 7-1).

Feedstock	Change in CS projection (GtC)			
	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Cereals	2.63	2.50	3.33	3.99
Rice	0.37	0.41	0.49	0.62
Oil	0.03	0.02	0.03	0.04
Fibre	-0.0004	-0.00037	-0.00047	-0.00057
Sugarcane	-0.18	-0.13	-0.21	-0.29

8.5 Carbon sequestration potential – 2 pool method

8.5.1 95 Year sequestration potential

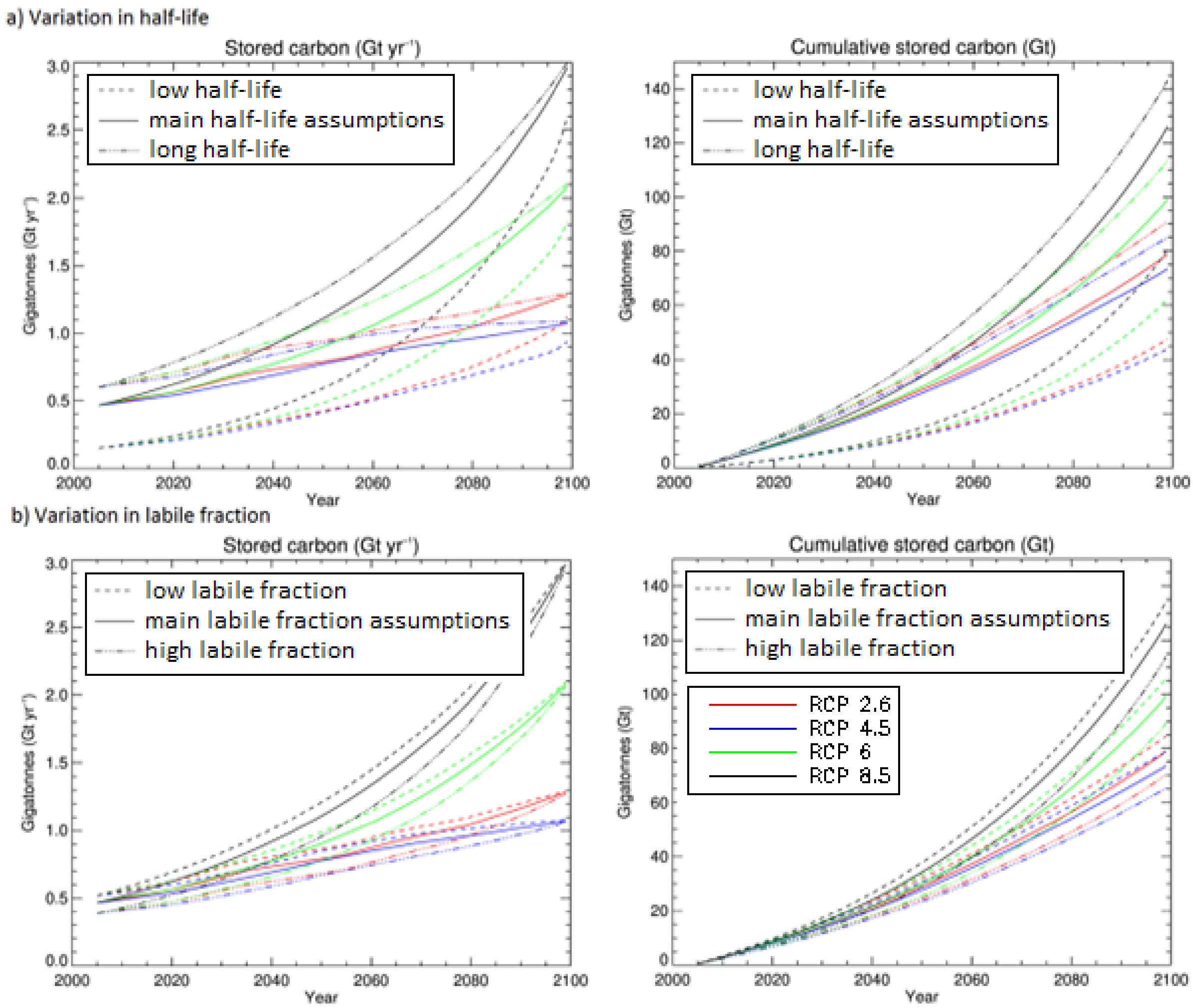

Figure 8-8: Annual carbon storage potential (GtC yr-1) (left) and the cumulative carbon storage potential (GtC) (right) of this biochar over the scenario period. Values were calculated, using the two pool method (Equation 7-4), for the biochar production projected under the assumptions of Scenario 1 (see Section 5.3). The carbon sequestration potential is shown using a) the range of biochar half-lives (recalcitrant fraction: 50 – 1000 years and labile fraction 1 – 25 years) and b) the range of labile fraction size (5 to 30 %) used by Woolf et al. (2010)). 'Stored carbon' refers to the biochar carbon which would remain in stable form in soils from the point of addition to the scenario end point of 2100.

The alternative two-pool calculation method resulted in different projections of the carbon storage potential of the scenarios, generally giving higher carbon storage potential values than where Equations 7-1 and 7-3 were used. These differences may be due, in large part, to the specification of carbon storage timeframe (i.e. to 2100) using the two-pool method. In comparison, the CS equation only specifies that the carbon stored will be stable 'long-term'. As this 'long-term' carbon storage projection is likely to extend beyond this 2100 assessment point this makes direct comparison between the two assessments difficult. To examine the longer term carbon storage potential longer time periods were also assessed using the two-pool method (see Section 8.5.2).

More impact was seen on the biochar scenarios where the variation in half-life was explored than where labile fraction was varied (see Figure 8-8). Applying low half-life assumptions meant that much of the biochars applied to soils in the would quickly degrade, meaning that biochars added to soils towards the end of the scenario period would have much greater potential of storing carbon to the end of the scenario period (2100), but would quickly degrade past the end of the 95 year scenario period. Applying longer half-life values increased the carbon storage potential, at the end of the scenario period, of the biochars produced in the early part of the scenarios. This led to an increase in the cumulative stored carbon potential of the scenario when compared to the main half-life assumptions and the low half-life assumptions. Cumulative carbon sequestration potential across the 95 year period was increased by between 6.3 % and 7.2 % (across the four RCPs) when a low labile fraction was assumed, and decreased by 10.5 % and 12.2 % where a high labile fraction was assumed.

8.5.2 Longer-term carbon storage potential

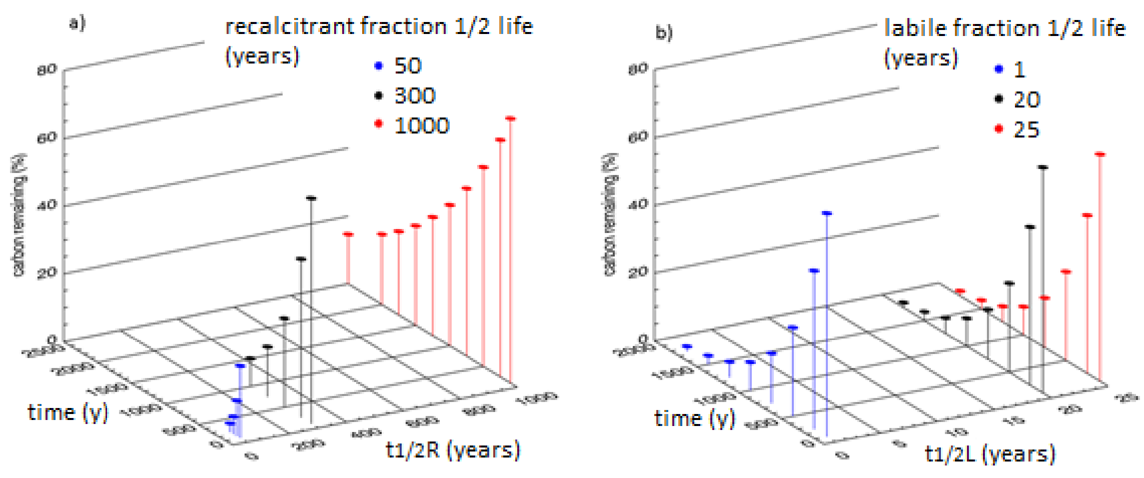

Figure 8-9: The effect of variance in the assumed half-life of a) the recalcitrant fraction and b) the labile fraction of biochar on the long term carbon sequestration potential of the biochars produced in RCP 2.6 under the assumptions of Scenario 1.

The variance explored in the half-life of the recalcitrant fraction of biochar was 50 to 1000 years, with the main assumption being 300 years. Half-life assumptions for the labile fraction of biochar were 1 to 25 years, with the main assumption being 20 years. Where a half-life of 50 years was assumed for the recalcitrant fraction the biochar carbon was degraded within 100 years after addition. Where 1000 year recalcitrant fraction half-life was assumed the biochar maintained some stability past 2500 years from addition. The lifetime of the recalcitrant fraction had the largest effect on the overall stability of the biochar carbon under the main assumptions of fraction size. Where the shorter lifetime assumptions of the labile fraction were applied, an initial small reduction in the long term stability of the biochar carbon was seen.

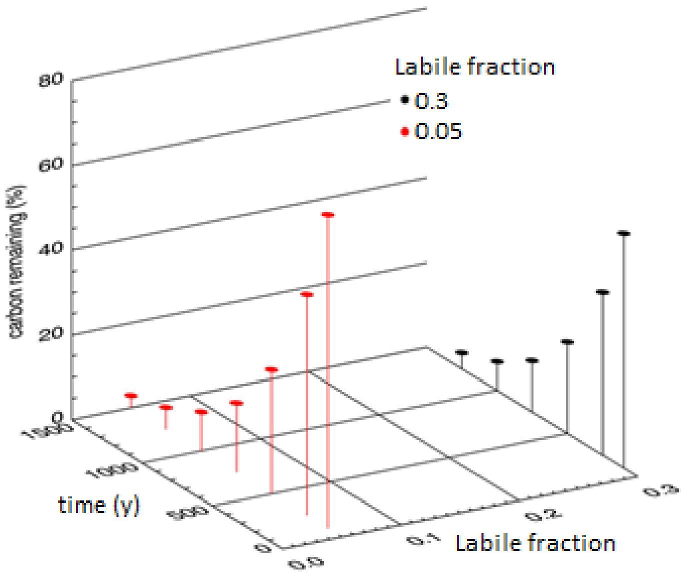

Figure 8-10: The effect of variance in the size of the labile fraction of biochar on the long term carbon sequestration potential of the biochars produced in RCP 2.6 under the assumptions of Scenario 1.

The range in labile fraction size discussed by Woolf et al. (2010) was also tested, with the effects summarised in Figure 8-10. A larger labile fraction resulted in a faster degradation of biochar which then became more stable as the labile fraction was exhausted and the recalcitrant fraction remained.

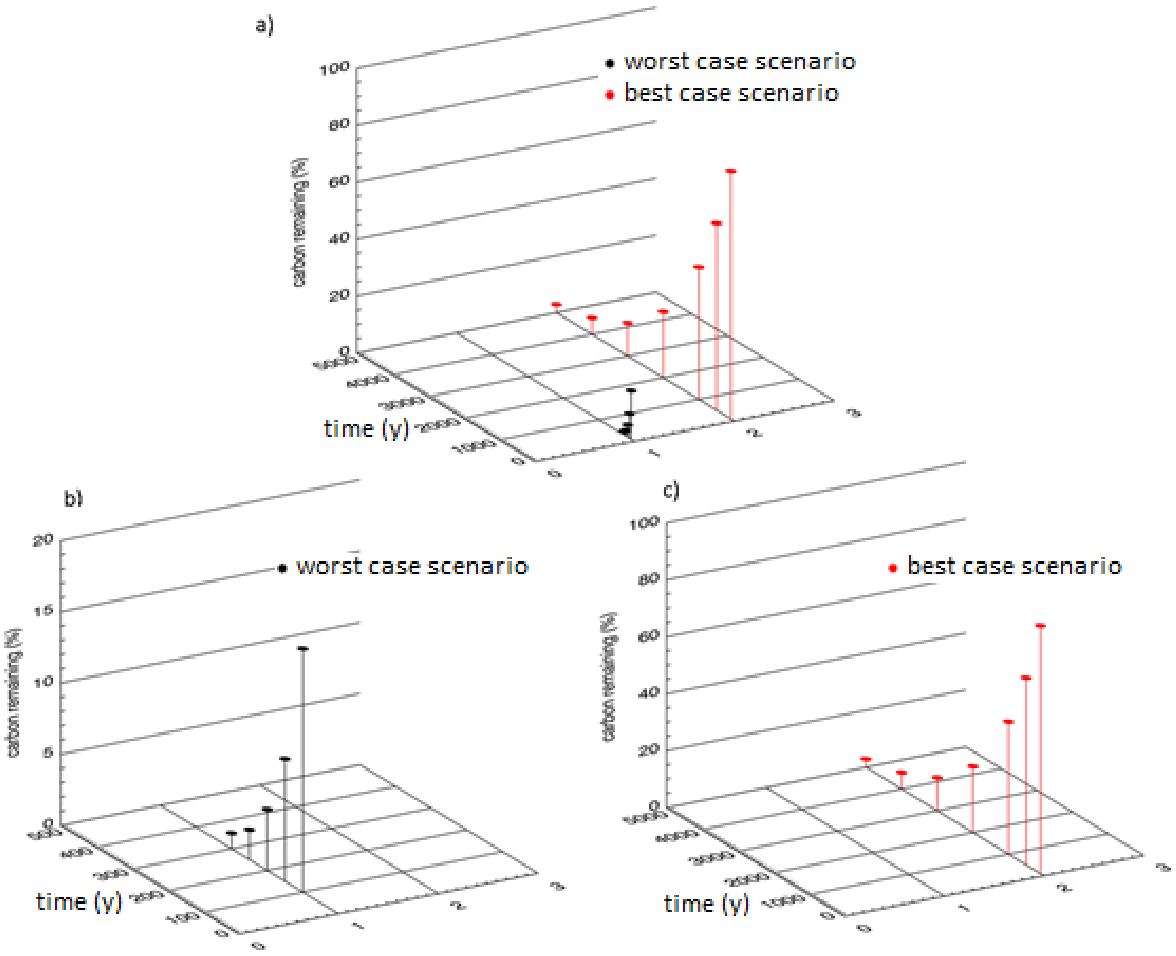

Figure 8-11: The effect, on the long term carbon sequestration potential, of the minimum and maximum assumptions (labile and recalcitrant fraction half-life and fraction size) of biochar recalcitrance for biochars produced in RCP 2.6 under the assumptions of Scenario 1. The minimum assumptions (large labile fraction and short half-lives) are shown in black in plots A and B. The maximum assumptions (large recalcitrant fraction and long half-lives) are shown in plots A and C. N.B. Scales vary between plots.

Figure 8-11 shows the stability of the biochar produced in RCP 2.6, under the assumptions of Scenario 1, under the worst case and best case recalcitrance assumptions examined here. The difference between the two projections is large, and is in the most part influenced by the half-life of the recalcitrant fraction of biochar, where the recalcitrant fraction is large enough to have a real long-term influence. As discussed in Section 7.2.2.1, the CS equation (Equation 7-1) has no specific time frame for the lifetime of the stable carbon, only specifying the calculation of 'long-term carbon storage'. Comparison of the quantity of carbon remaining at the end of the scenario period, as projected using Equation 7-1, with the rates of decay projected using the worst case assumptions with the two-pool method (Equation 7-4) shows large differences in the projections of remaining carbon. This indicates that the length of time projected for carbon sequestration using the CS equation is likely to be longer than the 95 year assessment period. There are a number of combinations of labile vs. recalcitrant fraction sizes and half-life assumptions which may result in the same quantity of carbon remaining in 2100 as projected using Equation 7-1, although these assumptions are not within the range assumed here or in Woolf et al. (2010). Using the assumptions, in Equation 7-4, of a labile fraction size of 5 %, alongside half-lives of 25 years and 1000 years for the labile and recalcitrant fraction respectively projects similar carbon storage quantities after 1000 years as the 'long-term' storage projections of Equation 7-1. This is also true after 750 years where a labile fraction of 15 % is assumed alongside labile and recalcitrant fraction half-lives of 20 and 1000 years and after 250 years where a labile fraction of 15 % is assumed alongside labile and recalcitrant half-lives of 1 and 300 years respectively. This highlights that uncertainty may arise when making very long term projections of biochar carbon storage potential using Equation 7-1 or 7-3, making a definite lifetime prediction difficult. If a detailed estimate of sequestration timeframe is required then the use of equation 7-4 may be more suitable.

8.5.3 Comparison of the three methodologies

Using the RVC equation (7-3) increased projections of carbon storage in 2100 by around 5 % relative to the projections made using the CS equation (7-1). The two-pool method (Equation 7-4) increased projections of stored carbon potential by between 38 % and 40 % for the different RCPs, relative to the CS equation (7-1). As discussed previously this large difference in the projections of stored carbon made between using either Equation 7-1 or 7-3 and Equation 7-4 is in large part due to the specification of decay period for Equation 7-4, where the other equations do not specify a decay period. They determine a 'long-term' carbon sequestration potential which may be far longer than the 95 year stability period specified for the main analysis using Equation 7-4. The assumption of longer assessment period in Equation 7-4 may better align the assessment periods of the two equations, reducing the variance seen in the projections of CS potential.

8.6 CO_2 Reduction Potential

Table 8-3, shows the stored carbon and CO_2 removal potential of the first and last years of the scenario period, highlighting change over time, and the total scenario period projected using the three methods of calculation.

Table 8-3: Carbon remaining at the end of the scenario period (in 2100 and for Scenario 1 assumptions) which was added to soil in 2005, 2100 and the across the total scenario period for the three methods of calculation (CS equation (Equation 7-1), RVC equation (Equation 7-3), and two-pool method (Equation 7-4)) and the related carbon in units of CO_2.

Stored carbon									
	$GtC\ yr^{-1}$						GtC		
RCP	2005			2100			Total		
	CS	**RVC**	**2 Pool**	**CS**	**RVC**	**2 Pool**	**CS**	**RVC**	**2 Pool**
RCP 2.6	0.34	0.36	0.46	0.65	0.69	1.29	49.01	51.90	80.13
RCP 4.5	0.34	0.36	0.46	0.54	0.58	1.08	45.83	48.63	74.60
RCP 6	0.34	0.36	0.46	1.07	1.13	2.12	60.93	64.58	101.34
RCP 8.5	0.34	0.36	0.46	1.54	1.62	3.03	77.15	81.51	129.02
Carbon stored in unit of CO_2									
	$Gt\ CO_2\ yr^{-1}$						$Gt\ CO_2$		
RCP 2.6	1.25	1.32	1.69	2.39	2.53	4.73	179.9	190.5	294.1
RCP 4.5	1.25	1.32	1.69	1.98	2.13	3.96	168.2	178.5	273.8
RCP 6	1.25	1.32	1.69	3.93	4.15	7.78	223.6	237.0	371.9
RCP 8.5	1.25	1.32	1.69	5.65	5.95	11.12	283.1	299.1	473.5

Using the two-pool methodology to determine the C storage potential indicates that between 274 Gt CO_2 and 474 Gt CO_2 could be removed from the atmosphere and stored for the 95 year scenario period. Depending on the size and decay periods of the labile and recalcitrant fractions of the biochars much of this CO_2 could be sequestered for long time scales. The reaction of the other carbon sinks to this removal may be to release some CO_2 back into the atmosphere (Lenton and Vaughan, 2009). The long term CO_2 sequestration potential of the four RCPs, calculated using the CS equation, is 180 Gt CO_2, 168 Gt CO_2, 224 Gt CO_2 and 283 Gt CO_2 for RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5 respectively.

8.7 Impact of Biochar on RCP CO_2 Emissions Pathways

8.7.1 Scenario 1

Under the assumptions of Scenario 1, the mitigation impact of biochar production on the CO_2 emissions pathway of each RCP, throughout the 95 year period, shows a generally increasing impact from RCP 4.5 to RCP 8.5. As detailed in Table 8-3, projections for RCP 2.6 show more potential for biochar to reduce the RCP carbon emissions than RCP 4.5, which can be seen in

Figure 8-12. Figure 8-12 also illustrates the increasing potential of biochar to mitigate carbon emissions across the scenario period, with every RCP seeing greater potential in 2100 than 2005.

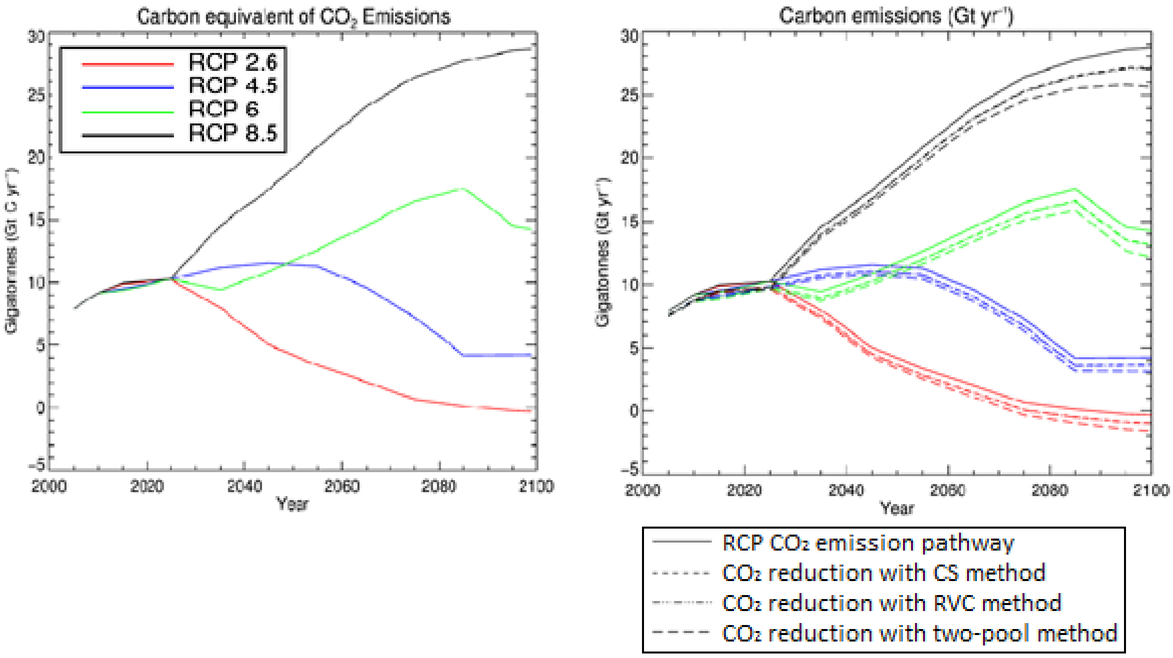

Figure 8-12: Carbon equivalent of the CO_2 emissions projections of the RCPs under the assumptions of Scenario 1 (left), and the potential reduction in emissions which can be achieved for each RCP using the three different equations for calculating long term carbon storage (right).

This increasing potential for carbon sequestration using biochar, across the scenario period, is due to assumptions in Scenario 1 such as increasing crop yields.

The total projected carbon emissions without any biochar systems in place, across the 95 year period, are 434.7 GtC, 837.7 GtC, 1208.7 GtC and 1856.4 GtC for RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5 respectively. Under the assumptions of scenario 1, using the CS equation, these values may be reduced by 49.0 GtC, 45.8 GtC, 60.9 GtC and 77.2 GtC for the four RCPs respectively with the application of biochar carbon sequestration. These are reductions of 11 %, 5 %, 5 % and 4 % on the carbon emissions pathway of the four RCPs respectively. The CO_2 reduction seen where the CS and RVC equations are used are extremely similar projections, highlighting again that the use of Equation 7-3 is acceptable in the place of Equation 7-1. Where the carbon sequestration potential over a specific time period is required, the two-pool equation (Equation 7-4) can offer a more detailed projection. The use of Equations 7-1 and 7-3 is a more accurate indicator of the longer term CO_2 reduction potential of the RCP emission pathways than the use of Equation 7-4 with a 95 year time-sequestration frame. The greater mitigation potential seen from using Equation 7-4 would, in the longer term be reduced as more of the biochar degraded.

8.7.2 Mitigation potential of the alternative biochar scenarios

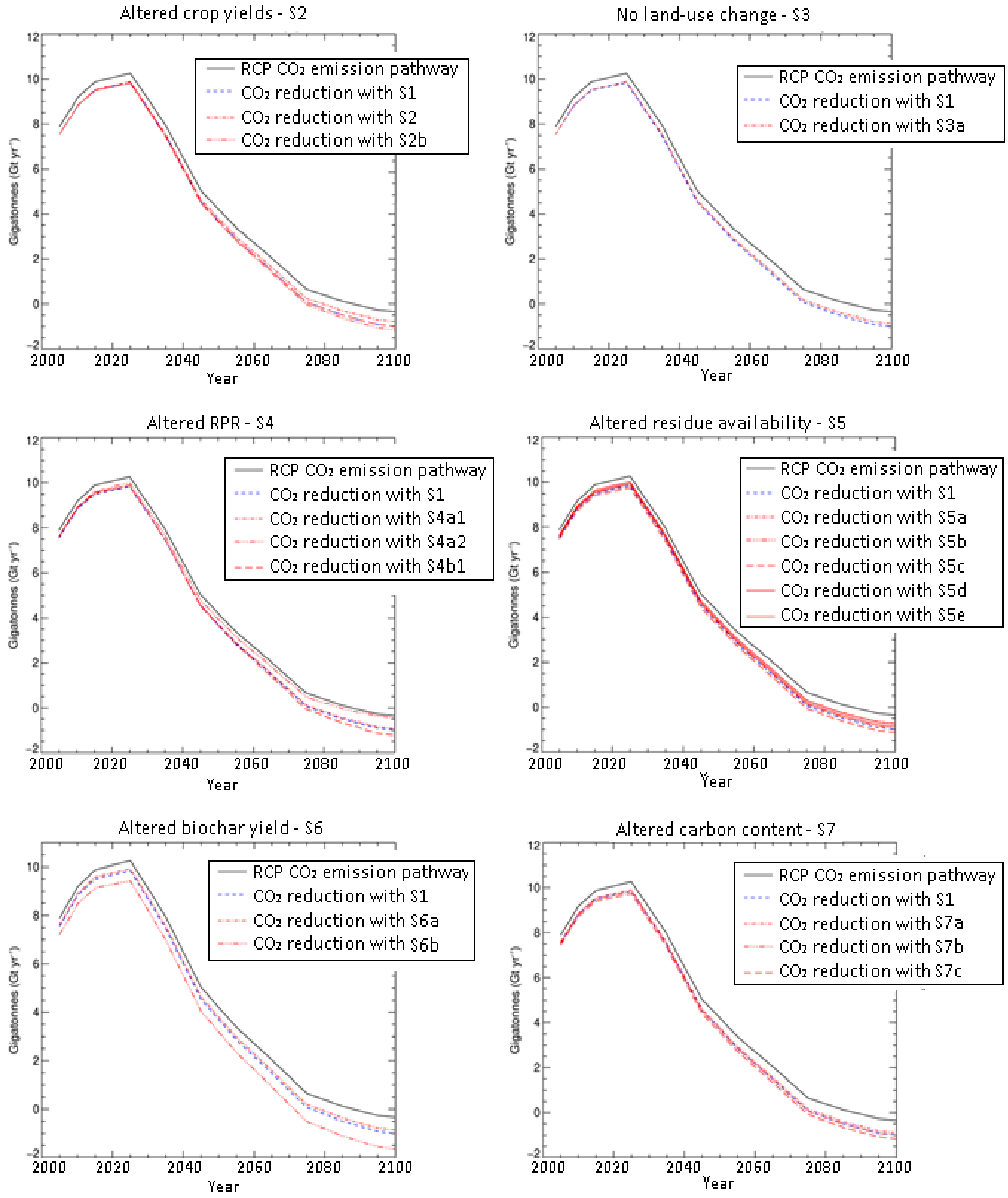

Figure 8-13: Potential emission reductions for RCP2.6, relative to the carbon emission pathway of projection RCP2.6 (black line). Blue line shows emissions reduction potential of Scenario 1 biochar assumptions. Other scenario assumptions shown are: top left, Scenario 2; top right, Scenario 3; mid-left, Scenario 4; mid-right, Scenario 5; bottom left, Scenario 6; bottom right, Scenario 7.

The mitigation potential of the alternative biochar scenarios was examined, looking at the potential reduction in emissions possible for each RCP. Figure 8-13 shows the potential emissions reduction, from the RCP 2.6 carbon emissions pathway, which is projected for the biochar scenarios 1 to 7. Figure IV-1 to Figure IV-3 in Annexe IV show the mitigation potentials of Scenarios 1 to 7 for RCPs 4.5, 6 and 8.5.

The different assumptions of biochar scenarios 1 to 7 have varied level of impact on the carbon emissions pathway of RCP 2.6. Where different potential crop yield changes are applied (Scenario 2), divergence between the impacts of different sub-scenarios becomes more evident from around 2045. This divergence then continues up to 2100. The application of a scenario of no land-use change (Scenario 3a) resulted in comparatively little change in CO_2 reduction potential, relative to Scenario 1, for RCP 2.6, indicating that land-use change in RCP 2.6 has little effect on the projections made using Scenario 1 assumptions. Exploring potential uncertainty in the RPR values of crops shows that variability in this parameter may have a large impact in the potential for carbon sequestration using biochar. The assumption of low RPR values throughout the scenario period in Scenario 4a2 had a large impact, reducing the carbon mitigation potential, relative to Scenario 1, for RCP 2.6. The assumption of high RPR values increased the mitigation potential, relative to Scenario 1, but not to the same magnitude as with the assumption of low RPR values. Variation in residue availability (Scenario 5) produced a smaller range of projections than the variation seen with Scenario 4 assumptions. Scenarios 5a to 5c produced relatively little variation around the projection of Scenario 1 for RCP 2.6. The application of both conservative and optimistic residue availability assumptions of Woolf et al. (2010) (Scenarios 5d and 5e respectively) both reduced the mitigation potential of biochar production within RCP 2.6 relative to both Scenario 1 and Scenarios 5a-c. Biochar yield may also have a large impact on the mitigation potential of the scenario. Where the high biochar yield was assumed (Scenario 6b) the mitigation potential of the scenario was approximately doubled relative to the potential of Scenario 1. Using the low yield assumptions (Scenario 6a) reduced the mitigation potential of Scenario 1 but with a much smaller impact than the high biochar yield assumptions. This highlights the benefit which could be derived from achieving the highest biochar yields possible, but it should also be noted that the high biochar yield values assumed in Scenario 6b are difficult to achieve and would only be achievable at the expense of oil and gas production from the process. It is highly unlikely that these high biochar yields would be achievable for all feedstocks in all regions throughout the full 95 year scenario period. The variation seen in biochar carbon content (Scenario 7) made relatively little difference to the carbon mitigation potential of Scenario 1 for RCP 2.6.

The same patterns of effect seen in RCP 2.6, from the assumptions of the different scenarios, are seen in RCPs 4.5, 6 and 8.5 (see Annexe IV for summary plots of the mitigation potential of Scenarios 1 to 7 in these RCPs). The maximum mitigation potential achievable under the assumptions of Scenarios 1 to 7, for each RCP, is a reduction of 97.9 GtC, 90.1 GtC, 121.1 GtC and 153.6 GtC for the four RCPs respectively. This is a reduction of 22.5 %, 10.8 %, 10.0 % and 8.3 % from the original carbon emissions pathways of the RCPs. These maximum potentials all result from the assumptions of Scenario 6b which sees maximum biochar yields of 63 % for all crop residues. The minimum mitigation potential of the biochar Scenarios 1 to 7 is a reduction of 20.3 GtC, 18.2 GtC, 23.0 GtC and 28.5 GtC respectively for the four RCPs. These are reductions of 4.7 %, 2.2 %, 1.9 % and 1.5 % from the original carbon emissions pathways of the RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5 respectively. The minimum mitigation potential is a result of the assumptions of Scenario 4a2 which assumes a very large decrease in the residue to product factor (RPR) of crops over time, reaching 0.14 in 2100. In reality, neither a uniform biochar yield of 63 % nor a uniform RPR of 0.14 is likely to manifest both spatially and temporally to 2100. These scenarios should, therefore be used as indicators of best and worst case scenarios, with a range of potential outcomes in between.

The potential variation of each parameter was applied to all of the RCPs, with no probability of actual manifestation applied to values within the range. In reality, each an assumed parameter value may be more likely to manifest in one RCP than another. For example crop residue availability in a world following the RCP 2.6 pathway may be low, whereas it may be high in an RCP 8.5 world due to the different underlying drivers within the scenarios. The detail of all of these drivers, such as diet, biofuel crop types, industrial processes and economic development was not sufficiently available within the background literature used in this study therefore all potential variance in parameters has been applied to all RCPs. This enables the effect of these uncertainties on all scenarios to be seen, showing the range of potential outcomes. A particular manifestation of each RCP may also be pulled out from the data, for example from using Figure 8-13 and its counterparts in Annexe IV, and assessed as required.

8.7.3 Climate change impacts on emissions reductions

The CS equation (Equation 7-1) was used to project the impact of climate change on the biochar mitigation potential of the scenarios. The CS equation was used as it could be employed using the experimental data of Chapter 4 which was produced using reliable, tested methodologies and was validated against data from the wider literature.

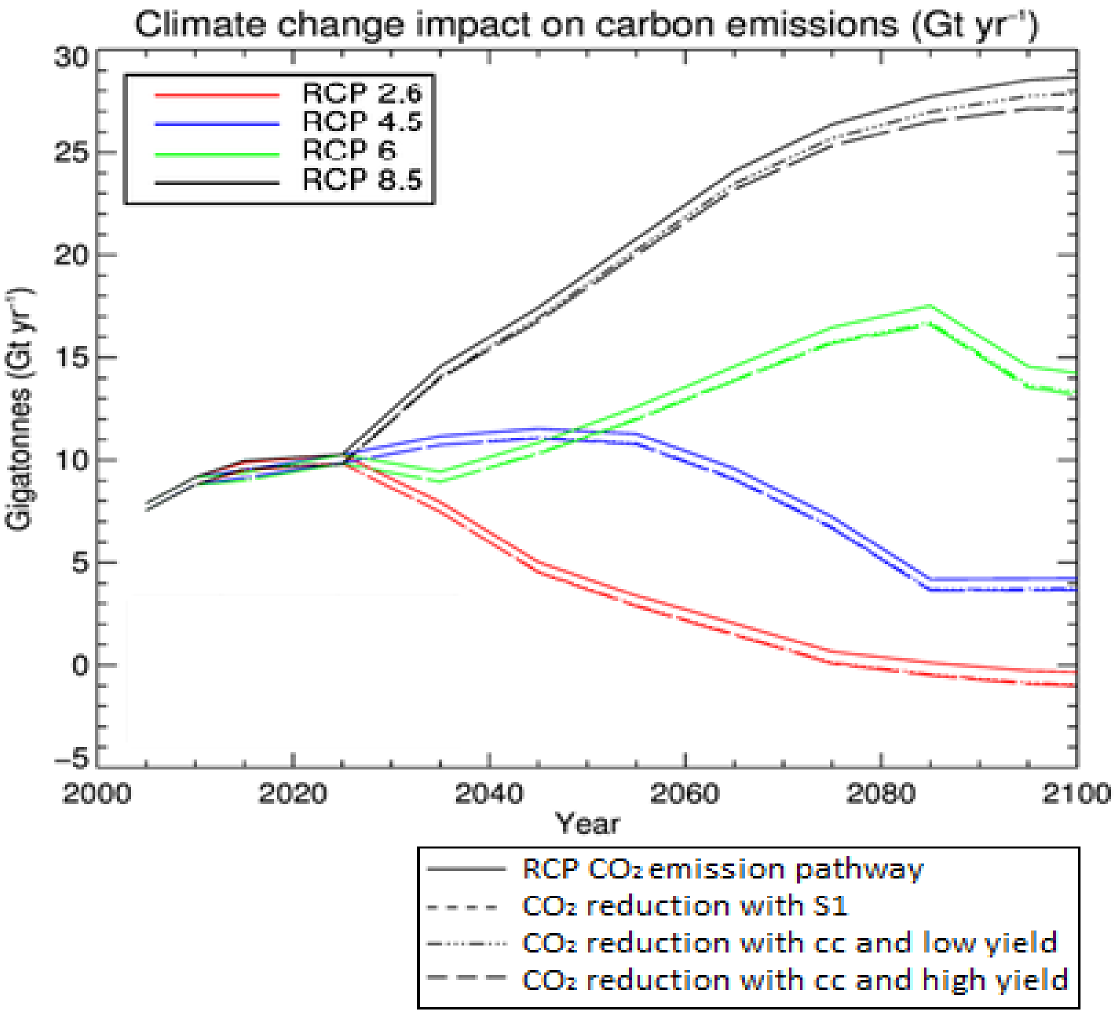

Figure 8-14: The impact of climate change on the carbon emissions reduction potential of the biochar sequestered in the four RCPs using the assumptions of Scenario 1 and Equation 7-1 for CS potential. The figure indicates the impacts on projected emissions mitigation potential for the scenarios of highest yield with lowest temperature change (8e1) and lowest yield with highest temperature change (8d3), which are deemed to be the minimum and maximum climate impact scenarios respectively.

The potential of biochar to mitigate the RCPs carbon emissions pathways is diminished when the impacts of climate change on crop yield are applied. Mitigation potential is decreased with increasing RCP. The impacts due to climate change also increase in severity over the scenario period, with a larger impact in 2100 as climate change induced temperature change becomes increasingly prominent across the scenario period. The largest impact of climate change, in 2100, is in RCP 8.5 where the mitigation potential may be reduced by 0.72 GtC yr^{-1} by the assumptions of Scenario 8d3. The mitigation potential of RCP 6, RCP 4.5 and RCP 2.6

respectively may be reduced by 0.14, 0.061 and 0.059 GtC yr^{-1} in 2100 under the same scenario assumptions.

Across the 95 year scenario period, the maximum impacts of climate change (Scenario 8d3) sees the mitigation potential of biochar, under the assumptions of Scenario 1, reduced from 49.0 GtC, 45.8 GtC, 60.9 GtC and 77.2 GtC respectively, to 46.2 GtC, 42.7 GtC, 56.3 GtC and 54.0 GtC respectively for the four RCPs. This is where the largest impacts on crop yields are combined with the highest temperature change projections for each RCP. Assuming the mean projections of temperature change impact on crop yields (Scenario 8b), sees the mitigation potential of the RCPs reduced to 49.0 GtC, 44.9 GtC, 59.4 GtC and 73.2 GtC respectively. Applying simple adaptation measures (Scenario 9b) sees these projections of mitigation potential increased to 49.0 GtC, 45.8 GtC, 60.8 GtC and 76.1 GtC for the four RCPs respectively over the scenario period.

The 95 year scenario timeframe here may be relatively short compared to timeframes of biochar degradation, and to the timeframes potentially needed for biochar production and addition to soil in order to continually provide some mitigation of carbon emissions. The trends seen in the impacts of climate change on biochar mitigation potential would be expected to continue after 2100 if the pathways remain on much the same course as pre-2100. This means that where increasing climate change reduces crop yields, the potential for biochar production from crop residues will also continue to decrease. These effects will potentially be heightened by other increasing impacts of climate change such as water scarcity, changes in crop pest/disease vectors and increased frequency and/or intensity of extreme weather events (IPCC, 2014c), none of which are currently incorporated into this assessment of biochar CO_2 mitigation potential.

8.8 Uncertainties and limitations

There are a number of areas of uncertainty within the scenarios of carbon sequestration here. Some of this uncertainty arises from the development of the biochar production scenarios, which is detailed in Chapter 5.

A number of generalisations must be made to project global scenarios across a 95 year timescale. The CS and RVC equations make generalised assumptions across each crop type group, where in reality more variation will exist in the carbon sequestration potential of these biochars. The range of values used for analysis using the two pool method are those detailed in Woolf et al. (2010) and are assumed to be uniform across all of the biochars assessed. There are, in reality, many possible combinations of the assumptions of size and half-life of the labile and recalcitrant fractions. As uncertainty in the size and stability of the labile and recalcitrant fractions of biochars decreases with further research, the application of these values to Equation 7-4 will allow for the assessment of carbon sequestration to incorporate values for individual or groups of biochars. Further development of the knowledge of labile and recalcitrant fractions will also allow the time frame of the 'long-term' carbon storage potential of Equations 7-1 and 7-3 to be estimated by comparing results with the projections for carbon storage over time made using Equation 7-4.

There are a number of other mechanisms relating to a biochar system, which are not considered here, which may see increased or decreased emissions. These include the potential for increased net primary productivity through increased crop yields, reductions in emissions from fertilizer production due to increased fertilizer efficiency use, and the emissions related to the transportation of feedstocks and biochars within the biochar system. Research estimating these effects on the overall emissions balance would be useful further research which could not be undertaken here due to limitations including limited understanding within the wider literature and time constraints. Another consideration when assessing the removal of carbon from the atmosphere and long-term sequestration is the adjustment of the other land and ocean sinks in the carbon cycle, upon this removal, as these sinks reach new equilibria. The carbon cycle consists of a number of complex, inter-related mechanisms. An example of this is the exchange of CO_2 between the atmosphere and ocean which takes place through gas exchange and through respiration and photosynthesis of biota (Siegenthaler and Sarmiento, 1993). Lenton and Vaughan (2009) discussed that the effect of a removal of carbon from the atmosphere would degrade over time due to the reactions of other these other sinks. They used the Bern carbon cycle model to estimate that, for relatively small reductions in carbon, 92 % would still be removed after 1 year, 64 % after 10 years, 34 % after 100 years and 19 % after 1000 years. This indicates that the effect of carbon sequestration through the biochar scenarios detailed here will diminish over time as the other carbon sinks adjust to the atmospheric removal. The values detailed in Chapter 8 do not account for this reaction, but it should be assumed that the effect of atmospheric removal will be diminished over time. This effect could have co-benefits such as decreased ocean acidification as CO_2 is released from the oceans into the atmosphere as a new equilibrium is reached. The assessment of biochar production and carbon sequestration potential detailed here is, also, an assessment of the technical potential of biochars, with no consideration given to the economic, regulatory or social barriers which may prevent these maximum technical potential scenarios from being implemented. They should, therefore, be seen as maximum potential scenarios which may be impacted by these other considerations.

The scenario timeframe begins in 2005, which is now a historical date. This beginning point was used as each RCP begins from this point and so a uniform starting point could be implemented, with diversion from this point observed. This means that the maximum technical potential of each scenario could not, now in reality be achieved. This does not have a major impact on the scenarios over time, as divergence between the RCPs does not begin in earnest until around 2025 (see Figure 8-14).

8.9 Summary

The mean biochar production rates for the four RCPs, over the 95 year period, are 0.01, 0.02, 0.02 and 0.02 kg m^2 yr^{-1}. The maximum rate of biochar production is 0.6 kg m^2 yr^{-1}. These values indicate potential rates of biochar addition to soils if all biochar was added to soils at the point of the production. In reality, this is unlikely to happen due to the scale of biochar production technology, where feedstock is likely to be collected and converted in larger batches, then distributed to the point of addition. The mean and maximum values are, therefore, meant to be indicators and not actual distribution values. The maximum rate of 0.6 kg m^2 yr^{-1} is also well below the advised upper limit for biochar addition to soils, allowing for addition over time. Once this upper limit for biochar addition is reached in an area the excess biochar can be used in other locations or stored until degradation allows for further addition.

The RVC equation, which was developed here using correlation found between feedstock volatile content and biochar R_{50} index, is a useful addition to the currently available tools for biochar stability estimation as it may offer a simple method of estimation which can be applied where only a small number of characteristic details are available for the biochar feedstocks. It could also offer a simple analysis method to help determine which feedstocks may be the most suitable for the long-term storage of carbon. Comparison of the RVC equation with the CS equation of Zhao et al. (2013) showed that projections made using the RVC equation are very similar to projections using the CS equation. When assessing the projections of long-term biochar carbon storage potential for the different crop groups assessed, the RVC equation made excellent projections for all crop groups except the cereals group, which was still seen to a good projection. Analysis using the uncertainty in slope from the correlation between volatiles and R_{50} showed that the CS projections lie within the uncertainty range of RVC projections.

Biochar has the potential to sequester carbon in all RCPs, and can reduce the carbon emissions of each RCP under all of the scenarios examined. The range of carbon mitigation projections made using Scenarios 1 to 7 is smallest for RCP 2.6 and increases across RCP 4.5 and RCP 6, up to the widest range for RCP 8.5 (See Figure 8-15).

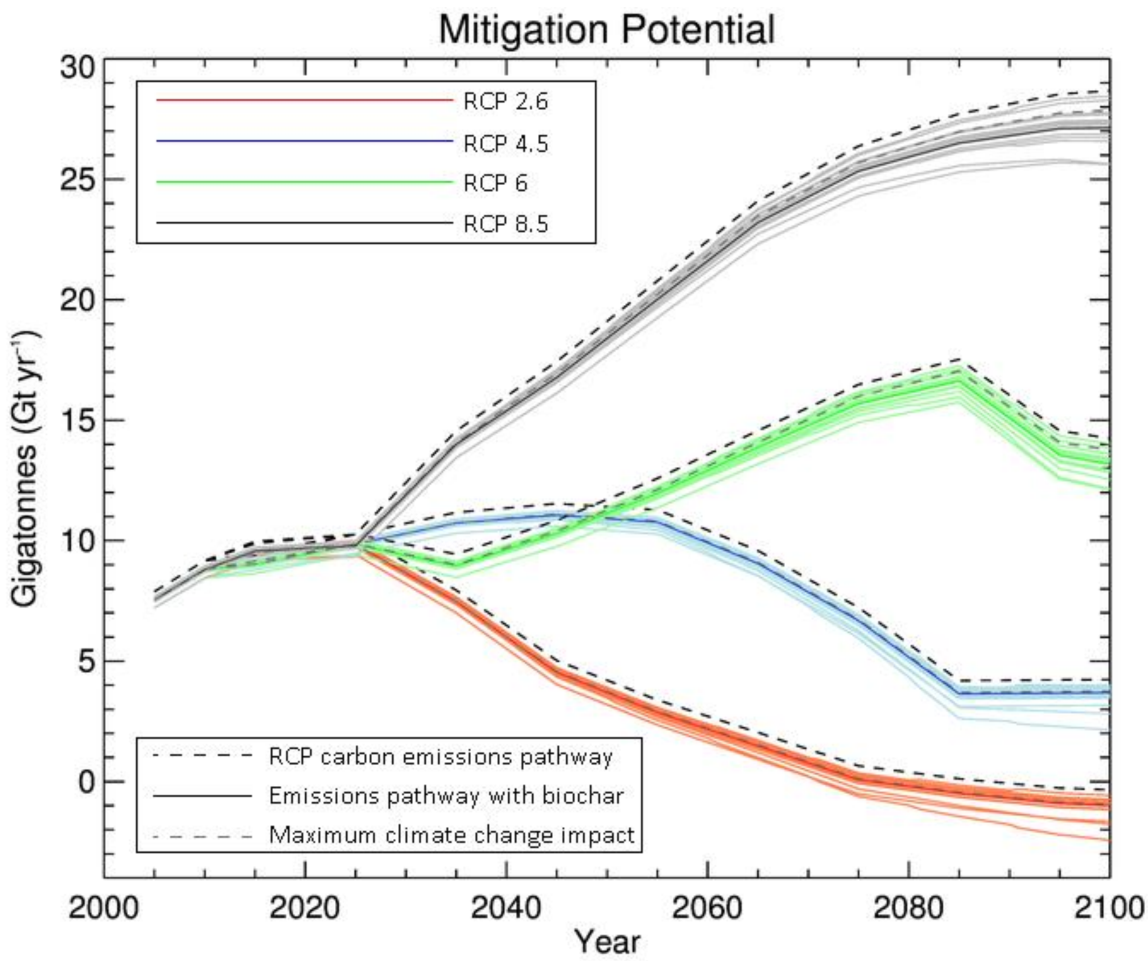

Figure 8-15: Summary of the mitigation potential of the biochar scenarios, in relation to the carbon emission pathways of the RCPs as calculated using the CS equation. The Scenario 1 is shown in bold for each RCP. Scenarios 2 to 7 are shown in lighter tones to highlight the range of impacts projected for each RCP. The maximum impact of climate change on the carbon mitigation potential of Scenario 1 is also shown for each RCP.

Under the assumptions of Scenario 1, and as assessed using the CS equation, biochar systems have the potential to mitigate 49.0 GtC, 45.8 GtC, 60.9 GtC and 77.2 GtC across the 95 year scenario period, for RCP 2.6, RCP 4.5, RCP and RCP 8.5 respectively, and store this carbon for long time periods. The maximum reductions in carbon emissions, from the initial RCP emissions pathway, under biochar Scenarios 1 to 7 are: 97.9 GtC, 90.1 GtC, 121.1 GtC and 153.6 GtC carbon respectively for RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5 and result from the high biochar yield scenario (Scenario 6b: biochar yields of 63 %). The minimum mitigation potential of scenarios 1 to 7 seen in Scenario 4a2, the scenario of lowest RPR in 2100, was a reduction of 20.3 GtC, 18.2 GtC, 23.0 GtC and 28.5 GtC relative to the original RCP carbon emissions pathway for the four RCPs respectively. Projected impacts of climate change induced changes in global mean temperature on crop yields has been seen to impact the mitigation potential of biochar scenarios. These impacts increase as the projected change in global mean temperature increases, seeing increasing impact, therefore, as radiative forcing scenario increases and also as time passes within each scenario. In 2100 the impacts of climate change (using the maximum impact climate change scenario of 8d3) may reduce the mitigation potential of biochar, under the assumptions of Scenario 1, by 0.059 GtC yr^{-1}, 0.061 GtC yr^{-1}, 0.14 GtC yr^{-1} and 0.72 GtC yr^{-1} for RCPs 2.6, 4.5, 6 and 8.5 respectively. This highlights the increasing impact of temperature change across the RCPs. Across the 95 year period the mitigation potential of Scenario 1 was reduced by the maximum climate change impact projections to 46.2 GtC, 42.7 GtC, 56.3 GtC and 54.0 GtC. Simple adaptation methods were found to reduce the impact of increases in global mean temperature on the mitigation of carbon emissions, resulting in a carbon mitigation potential for Scenario 1 of 49.0 GtC, 45.8 GtC, 60.8 GtC and 76.1 GtC for the four RCPs.

The RVC equation projected the maximum and minimum lifetimes of biochars as being from < 400 years to > 5000 years, highlighting the current uncertainty of biochar lifetime. This uncertainty could be reduced through further research into the size of labile and recalcitrant fraction size and decay rates.

9 Conclusions and recommendations for further work

Seven research objectives were outlined in the introduction to this work which aimed to address the overarching research question of quantifying the CS potential of biochars from crop residues using the land-use scenarios of the four RCPs. Below, each sub-objective is numbered and followed by discussion of how this study has addressed the research question. The discussion also highlights where further research beyond this study would add important detail and reduce uncertainty in areas that were either beyond the scope of this study, or where current uncertainty did not allow a more accurate analysis.

1. To produce and characterise biochars from eight crop residues under uniform pyrolysis conditions, examining the effect of feedstock characteristics on subsequent biochar characteristics.

Biochars, bio-oils and syngas from the slow pyrolysis of the eight crop residues were characterised under uniform pyrolysis conditions, enabling analysis of the variance in the yields and the characteristics of these products attributable to the feedstock characteristics. Relationships were determined between feedstock and biochar nutrient content and ash content, with high feedstock quantities tending to remain in the biochars. The majority of biochars were slightly alkaline (pH 6.1 to pH 11.6), with relationships seen between K content and pH. Chan and Xu (2009) reported a pH range of 6.2 to 9.6 from a review of biochar nutrient content literature. Feedstocks with high lignin content produced biochars with high carbon content and with a relatively high recalcitrance. Increasing aromaticity of the biochar structure upon pyrolysis was identified through the decreasing H/C and O/C ratios. This decrease in ratios was also detailed in a review of the literature by Krull et al. (2009), who discuss that although decreasing ratios are seen upon pyrolysis the resulting ratios in biochars vary. CS potential of the biochars, between 21.3 % and 32.5 %, was influenced by the yields of biochar and carbon content, as well as the stability of this carbon content. This is within the range of 21.1 % to 47.1 % found by Zhao et al. (2013). Our results were at the lower end of the Zhao et al. (2013) range due to the higher biochar yields and higher recalcitrance of some of the biochars examined by Zhao et al. (2013). A number of the biochars produced by Zhao et al. (2013) were produced at different temperatures and from a variety of feedstock types, including manures and water weeds, making direct comparison with many of their biochars difficult. The CS potentials determined here add to the documentation of various biochars begun by Zhao et al. (2013). The biochar characterisation has added to the current biochar documenting literature, furthering knowledge of the variation and similarities which may be seen in biochars. Studies such as

Verheijen et al. (2010) and Lehmann and Joseph (2009) conducted literature reviews on various aspects of biochar properties, including characteristics and subsequent effects on crop yields. Both studies concluded that the variation seen in biochars requires the study and documentation of many more biochars, from various feedstocks and production regimes, is necessary to gain a rounded understanding of biochars and their effects in soils. The results presented here aid further understanding of biochars, including how feedstocks and production quantities affect biochar properties, and particularly understanding of the recalcitrance and CS potential of different crop residue biochars. Characterisation including both feedstock and biochar is limited within the current literature (Downie et al., 2009). The detailed characterisation of other feedstock types, for example animal wastes and municipal wastes, and their resulting biochars under a uniform pyrolysis regime would add further insight of feedstock effects on biochar properties. A small number of other characterisations, such as the cation exchange capacity, were beyond the scope of this study due to time constraints and irrelevance to CS potential. Characterisation of these biochar properties would further understanding of properties such as the nutrient properties of biochars in soils.

2. To produce and characterise biochars from one crop residue, sugarcane bagasse, under varied pyrolysis conditions (peak temperature and heating rate), examining the effects of process conditions on subsequent biochar characteristics.

The effects of process conditions on biochar characteristics have been further documented by this study, using sugarcane bagasse to examine the effects of different peak temperatures and heating rates on biochar characteristics, building on the current literature (Amonette and Joseph, 2009, Bruun et al., 2011, Chan and Xu, 2009, Demirbas, 2004b, Demirbas, 2006, Downie et al., 2009, Hossain et al., 2011, Kim et al., 2012, Peng et al., 2011, Williams and Besler, 1996, Zhao et al., 2013). A strong correlation indicated a relationship between increased peak pyrolysis temperature and increased biochar pH. Feedstock carbon stored in biochar decreased with increasing peak pyrolysis temperature, and to a lesser extent with increased heating rate, although carbon recalcitrance increased with increasing peak temperature. Biochar CS potential decreased with increasing peak pyrolysis temperature and heating rate, likely caused by the decreasing yields seen. The current literature on biochar characteristics can be difficult to compare, study by study, due to the different process types, conditions and feedstocks used. This study aids this comparison by documenting the use of one process type for biochar production from a number of feedstocks and also for one feedstock under a range of conditions. This will enable biochars to be produced from the most suitable material and process conditions to produce the characteristics which make it most suitable for its purpose. For example, pyrolysing the feedstock at high peak temperature will increase carbon stability thus making a biochar suitable for long term CS, whereas a low peak temperature biochar may have more suitable characteristics for other uses such as agronomy. Although the work presented here offers insight into how the pyrolysis process can be tailored to produce biochars with specific characteristics, the sample size of the analysis was small. Further benefit would be gained from determining whether the same effects are seen for different feedstocks. As detailed in Section 2.2.2 processing conditions may vary beyond those tested here, for example low temperature pyrolysis/torrefaction and high temperature gasification conditions often lie beyond the conditions tested here. These conditions may produce different biochar yields and characteristics to those observed here. Assessing the effects of a wider range of process conditions would be a beneficial next step.

3. To assess the recalcitrance of the biochars produced using the R_{50} Index described by Harvey et al. (2012).

The eight biochars produced under standard conditions were found to be either moderately or more highly degradable, with palm shell and wheat straw biochars having the highest and lowest recalcitrance values respectively. These trends are similar to those in Harvey et al (2012, although different feedstocks were assessed here, with woody and physically harder feedstocks having higher recalcitrance index values than grasses and straws. None of the biochars here were of the most recalcitrant classification. Supporting the results of Harvey et al (2012) biochar recalcitrance was found to increase with increasing pyrolysis temperature, with the R_{50} of sugarcane bagasse increasing from 0.47 to 0.56 for biochars produced at 400 ^{o}C and 800 ^{o}C respectively. This reclassified the biochar from Class C, defined by Harvey et al (2012) as 'most susceptible to degradation', to Class B, 'some susceptibility to degradation', and indicates that higher pyrolysis temperature may be optimum for very long-term carbon storage. Similar to the findings of Harvey et al (2012) and Zhao et al (2013) the R_{50} index was found to be a useful tool for comparing the stability of biochars against other biochars, being a good tool for estimating which biochars may exhibit long-term stability. The CS equation of Zhao et al. (2013) projects carbon storage using the R_{50} index, but the timeframe of this storage is not defined further than 'long-term'. Further investigation into the timeframe of CS and its relation to the R_{50} index, for example through enhanced degradation experiments, would enable accurate projections of CS lifetime using these two factors.

4. To examine the potential influence of alkali metal content on biochar degradation, assessing possible conservative R_{50} estimates in high alkali biochars.

The work on biochar characterisation has further developed the work on biochar recalcitrance by (Harvey et al., 2012). Thermogravimetric analysis of washed and unwashed wheat straw biochars demonstrated a catalytic effect of alkali metals such as potassium on the thermal degradation of biochars. These alkali metals have been seen to undergo rapid leaching in soils (Major et al., 2009). The recalcitrance of wheat straw biochar was increased after the washing out of alkali metals indicating that the R_{50} index of Harvey et al. (2012) may underestimate the recalcitrance of biochars high in alkali metals. Further research examining this effect in biochars from different feedstocks would add further support to these conclusions.

5. The development of scenarios of biochar production using the land-use projections of the RCPs, examining the effects of various uncertainties and variation within the biochar literature and experimental work on these production potentials.

Following the biochar characterisation documentation, this study made an original assessment of the potential for biochar production and carbon sequestration in the four Representative Concentration Pathways (RCPs). A number of parameters which would influence the biochar production and carbon sequestration potential of the biochar system were tested, including land-use change, crop yields, residue factors, residue availability, biochar yield, carbon content and recalcitrance, and the impacts of climate change.

Biochar production varied over time in each RCP, with the greatest temporal variation seen in the biochar scenarios of RCP 6 and RCP 8.5, mainly due to the assumptions of rates of crop yield increase. Variation was also seen in each RCP across the seven scenario groups developed to explore uncertainty in model parameter inputs. Scenario 1, the scenario with main assumptions taken from experimental and literature assessment, projected biochar production of 138.4 Gt, 132.3 Gt, 173.2 Gt and 217.9 Gt biochar for RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5 respectively across the 95 year period. Exploring the potential range in parameter values through Scenarios 1 to 7 resulted in a range of 218 Gt, 207 Gt, 277 Gt and 251 Gt biochar between the highest and lowest scenarios of biochar production, for RCPs 2.6, 4.5, 6 and 8.5 respectively across the 95 year period. In 2100 the range in annual biochar production projections, for the four RCPs respectively, varied by 0.34, 0.28, 0.55 and 0.80 Mt yr^{-1} between the highest and lowest biochar production scenarios. Climate change was also projected to impact production of biochar, with the mean climate change scenario (Scenario 8b) seeing a reduction in biochar production potential of 0 Gt, 2.6 Gt, 4.3 Gt and 11.2 Gt biochar over the 95 year period for RCPs 2.6, 4.5, 6 and 8.5 respectively. This could be mitigated by over 70% by employing simple adaptation measures (Scenario 9b), resulting in no reduction in biochar production potential for RCP 2.6 and 4.5, and reductions of 0.4 Gt and 3 Gt over the 95 year period for RCP 6 and RCP 8.5 respectively. These simple adaptation measures are not defined by Porter et al (2014), although they are likely to include measures such as planting hardier cultivars and irrigation systems. A range of impacts were explored around these mean impact projections, exploring the potential minimum and maximum impacts of climate change induced increases in global mean surface temperature and the mitigation potential of simple adaptation measures. Although a number of parameters were explored within the scenarios developed here, the work is a preliminary investigation which aims to draw together a number of facets of biochar and climate change mitigation research. A number of areas of further research have been highlighted throughout the study. The biochar scenarios could be further developed in a number of ways, using future developments in biochar literature to reduce uncertainty and to expand parameter exploration both spatially and temporally. The use of spatially specific temperature change projections would give an increased understanding of how crop yields may be impacted spatially throughout the scenarios. Incorporation of other climate change impacts, such as changes in the occurrence of extreme events or precipitation patterns, would also offer valuable insight as these impacts are all potential manifestations of climate change and may reduce the CS projections made here (IPCC, 2013).

6. Development and evaluation of a new equation for estimating long-term carbon storage, based on the CS equation of Zhao et al. (2013) and incorporating the experimental data from the biochar characterisation.

Biochar characterisation has also added to the work on long-term carbon sequestration by Zhao et al (2013) whose CS equation used the recalcitrance index of Harvey et al. (2012) and other biochar characteristics. The assessment of relationships between feedstock and biochar characteristics in this thesis detailed a relationship between feedstock volatile content and the R_{50} recalcitrance of biochars. From this the recalcitrance from volatile content (RVC) equation was developed and tested against the CS equation of Zhao et al. (2013). Projection of the CS potential of cereal crops using the RVC equation had the largest variation from the projections made using the CS equation. All projections of sequestration potential for the other crop types were extremely close fitting with the CS projections. The CS projections were found to be always within the uncertainty range of the RVC projections. The accuracy of long-term CS projections, in relation to the projections made using the CS equation, were good, making the RVC equation a useful alternative methodology if the R_{50} value of the biochar is not determined. The RVC equation enables the CS potential to be estimated through characterisation of the feedstock, and knowledge of biochar yield and carbon content. This gives an alternative method of analysis which adds flexibility to the testing requirements of determining biochar CS. The use of a muffle furnace to determine the feedstock volatile content, rather than using TGA to calculate R_{50} values gives an assessment method which may be more accessible to many stakeholders. This would greatly improve the potential for assessing the recalcitrance of a biochar in many regions.

7. Assessment of the long-term carbon storage potential of the biochars produced within these scenarios, using the CS methodology of Zhao et al. (2013) and the two-pool methodology of Woolf et al. (2010).

Biochar has the potential to sequester carbon for long time periods in all of the RCPs, and across all of the biochar production scenarios to different extents. Three methodologies, the CS method of Zhao et al. (2013), the two-pool method of Woolf et al. (2010), and the RVC method developed in this thesis were used to calculate the long-term CS potential of the biochars produced for each RCP under the assumptions of Scenario 1. Projections from the three methods were compared, concluding, as discussed previously, that the RVC equation can be used in place of the CS equation of Zhao et al. (2013) to estimate the amount of feedstock carbon stored in soils long-term. The two-pool method of Woolf et al. (2010) is a useful tool for estimating carbon storage after a particular time period. The method, as used by (Woolf et al., 2010), currently uses one average value across all biochar types. Further research into the size and decay rates of the labile and recalcitrant fractions of different biochars would increase the accuracy of this methodology. Using Zhao et al. (2013)'s CS equation, due to its incorporation of individual biochar stabilities, compatibility with our experimental data, long-term projections, and validation within the literature, the main scenario assumptions (Scenario 1) projected that 49.0 GtC, 45.8 GtC, 60.9 GtC and 77.2 GtC of carbon would be sequestered over the 95 year scenario period in RCPs 2.6, 4.5, 6 and 8.5 respectively. The range of CS potential across all of the alternative parameter scenarios explored was 77.6 GtC, 71.9 GtC, 98.1 GtC and 125.1 GtC for the four RCPs respectively. The lowest projections were from the scenario of decreasing residue to product factor (Scenario 4a2) at 20.3 GtC, 18.2 GtC, 23.0 GtC and 28.5 GtC for the 95 year period. The maximum CS projections were from the scenario of high biochar yield assumptions, at 97.9 GtC, 90.1 GtC, 121.1 GtC and 153.6 GtC over 95 years for the four RCPs. In reality, neither a uniform biochar yield of 63 % nor a uniform RPR of 0.14 is likely to manifest both spatially and temporally. These scenarios should, therefore be used as indicators of best and worst case scenarios, encompassing a range of potential outcomes.

Reductions in biochar production caused by increasing global mean temperature will potentially be heightened by other climate change impacts such as water scarcity, changes in crop pest/disease vectors and the increased frequency and intensity of extreme weather events (IPCC, 2013, IPCC, 2014c). The impacts of these other manifestations on the mitigation potential of the biochar scenarios are an important focus for further work. The values for the CS potential of the different scenarios detailed in Chapter 8 also do not account for the reactions of other carbon sinks to the removal of atmospheric CO_2, but it should be assumed that the effect of atmospheric removal will be diminished over time. Lenton and Vaughan (2009) discuss that the response of other carbon sinks could reduce the impact of CO_2 removal by 66 % after 100 years and by 89 % after 1000 years. The projections made here would benefit from consideration of the reactions of other carbon sinks. The consideration of parameters such as potential effects of biochar addition to soil on crop yields (Verheijen et al., 2010) and any associated feedbacks from this increased net primary production would add to the study, as would the incorporation of wider emissions analysis such as other emissions from soil and potential emissions reductions due to increased efficiency of fertilizers from biochar addition (Woolf et al., 2010). The incorporation of transport infrastructure emissions analysis into the assessment would also be a useful future development as most biochar systems will require transport for the feedstock and/or biochars. The biochar systems assessed here have considered the maximum biochar production and CS potential for each scenario, we have not considered any potential economic, logistical, social or regulatory barriers to implementation of the biochar systems.

This thesis aimed to assess the global potential for carbon sequestration using biochar from crop residues, under four land-use scenarios, to 2100. Useful insights have been determined for a number of areas within the biochar research field including biochar characterisation, assessing biochar production potential and long-term carbon storage, and the development of a new method of carbon storage. The research is also a useful tool to direct further research as, due to its broad nature, it has identified a number areas which would benefit from further investigation.

I. Annexe 1

Table I-1: Macronutrient concentrations of the feedstocks and biochars (mg kg^{-1})

Macro-nutrient species (mg kg^{-1})							
Feedstocks							
	Sugarcane bagasse	Rice husk	Coconut shell	Wheat straw	Cotton stalk	Olive pomace	Coconut fibre
P	447.1	835.1	0.0	165.5	1248.0	1287.6	530.0
K	4289.1	10140.0	415.0	17446.4	10900.8	20868.2	4110.2
Ca	390.2	1995.1	370.9	1035.7	6694.6	8069.7	7852.8
Mg	258.2	879.9	133.4	438.0	3037.4	1860.8	621.9
Biochars							
P	1728.4	263.8	0.0	957.4	4775.7	4155.7	2961.3
K	16055.9	4173.3	2223.9	60372.3	27570.9	51678.2	18210.1
Ca	1730.6	751.0	779.3	5189.5	9546.8	26998.3	8368.8
Mg	1248.5	302.3	156.1	2514.9	4728.9	5333.1	4288.5

Table I-2: Gas composition and calorific value (HHV) of syngas produced from the pyrolysis of the eight agricultural residue feedstocks under standard conditions. Species determined are: carbon dioxide (CO_2); permanent gases: hydrogen (H_2) and carbon monoxide (CO); and hydrocarbon gases: methane (CH_4), ethene (C_2H_4), ethane (C_2H_6), propene (C_3H_6),propane (C_3H_8), butene (C_4H_8), butane (C_4H_{10})).

		Gas Characteristics									
	CV	**Gas Composition** (%)									
Feedstock	MJm^{-3}	CO	H_2	CO_2	CH_4	C_2H_4	C_2H_6	C_3H_6	C_3H_8	C_4H_8	C_4H_{10}
coconut shell	10.2	29.1	16.1	43.3	10.3	0.2	0.7	0.1	0.2	0.1	0.1
cotton stalk	11.6	27.2	6.6	54.8	8.0	0.7	1.4	0.5	0.5	0.2	0.1
palm shell	12.7	22.8	16.2	42.4	16.1	0.3	1.4	0.2	0.3	0.1	0.1
coconut husk	12.3	18.1	11.3	51.5	15.5	0.5	1.8	0.4	0.4	0.3	0.3
olive waste	14.2	13.4	15.0	50.9	13.8	0.7	3.4	0.6	1.1	0.6	0.5
rice husk	15.0	23.8	8.6	48.7	14.2	0.6	1.5	0.5	0.3	1.5	0.3
wheat straw	10.5	30.8	13.1	45.0	8.4	0.5	1.4	0.3	0.3	0.3	0.0
s bagasse	12.3	22.4	11.0	48.4	14.9	0.5	1.6	0.4	0.3	0.2	0.3

Table I-3: Gas composition and calorific value of syngas produced from the pyrolysis of sugarcane bagasse at different pyrolysis temperatures (top) and heating rates (bottom). Species determined are: carbon dioxide (CO_2); permanent gases: hydrogen (H_2) and carbon monoxide

(CO); and hydrocarbon gases: methane (CH_4), ethene (C_2H_4), ethane (C_2H_6), propene (C_3H_6),propane (C_3H_8), butene (C_4H_8), butane (C_4H_{10})).

	Gas Characteristics										
	CV	Gas Composition (%)									
	MJm^{-3}	CO	H_2	CO_2	CH_4	C_2H_4	C_2H_6	C_3H_6	C_3H_8	C_4H_8	C_4H_{10}
Altered Final Temperature											
400 ^oC	6.6	18.0	1.2	73.5	4.4	0.5	0.9	0.3	0.2	0.3	0.7
600 ^oC	12.3	22.4	11.0	48.4	14.9	0.5	1.6	0.4	0.3	0.2	0.3
800 ^oC	14.5	6.9	24.5	44.6	20.1	0.5	1.7	0.4	0.4	0.5	0.4
Altered Heating Rate											
5 $^oC\ min^{-1}$	12.3	22.4	11.0	48.4	14.9	0.5	1.6	0.4	0.3	0.2	0.3
20 $^oC\ min^{-1}$	11.2	17.7	8.0	56.6	14.3	0.6	1.6	0.4	0.3	0.3	0.1
50 $^oC\ min^{-1}$	11.5	14.7	7.2	58.0	16.8	0.7	1.6	0.4	0.3	0.1	0.2

II. Annexe 2

a. Regional classifications

Table II-1: The 5 regional and 22 sub-regional groups used for the analysis, and the constituent countries of each group.

Region	Sub-Region	Country
Africa	Eastern Africa	Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Ethiopia PDR, Kenya, Madagascar, Malawi, Mauritius, Mayotte, Mozambique, Reunion, Rwanda, Seychelles, Somalia, South Sudan, Uganda, United Republic of Tanzania, Zambia, Zimbabwe
	Middle Africa	Angola, Cameroon, Central African Republic, Chad, Congo, Democratic Republic of the Congo, Equatorial Guinea, Gabon, Sao Tome and Principe
	Northern Africa	Algeria, Egypt, Libya, Morocco, Sudan, Sudan (former), Tunisia, Western Sahara
	Southern Africa	Botswana, Lesotho, Namibia, South Africa, Swaziland
	Western Africa	Benin, Burkina Faso, Cabo Verde, Cote d' Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Saint Helena, Ascension and Tristan da Cunha, Senegal, Sierra Leone, Togo
Americas	Northern America	Bermuda, Canada, Greenland, Saint Pierre and Miquelon, United States of America
	Central America	Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama
	Caribbean	Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Bonaire, Sint Eustatius and Saba, British Virgin Islands, Cayman Islands, Cuba, Curacao, Dominica, Dominican Republic, Grenada, Guadeloupe, Haiti, Jamaica, Martinique, Montserrat, Netherlands Antilles, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Sint Maarten (Dutch Part), Trinidad and Tobago, Turks and Caicos Islands, United States Virgin Islands
	South America	Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Falkland Islands, French Guiana, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela
Asia	Central Asia	Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan
	Eastern Asia	China, Democratic People's Republic of Korea, Japan, Mongolia, Republic of Korea
	Southern Asia	Afghanistan, Bangladesh, Bhutan, India, Iran (Islamic Republic of), Maldives, Nepal, Pakistan, Sri Lanka
	South-Eastern Asia	Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste, Viet Nam
	Western Asia	Armenia, Azerbaijan, Bahrain, Cyprus, Gaza Strip (Palestine), Georgia, Iraq, Israel, Jordan, Kuwait, Lebanon, Occupied Palestinian Territory, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Turkey, United Arab Emirates, West Bank, Yemen
Europe	Eastern Europe	Belarus, Bulgaria, Czech Republic, Czechoslovakia, Hungary,

		Poland, Republic of Moldova, Romania, Russian Federation, Slovakia, Ukraine, USSR
	Northern Europe	Channel Islands, Denmark, Estonia, Faroe Islands, Finland, Guernsey, Iceland, Ireland, Isle of Man, Latvia, Lithuania, Norway, Sweden, United Kingdom
	Southern Europe	Albania, Andorra, Bosnia and Herzegovina, Croatia, Gibraltar, Greece, Holy See, Italy, Malta, Montenegro, Portugal, San Marino, Slovenia, Spain, The former Yugoslav Republic of Macedonia, Yugoslav SFR
	Western Europe	Austria, Belguim, Belgium-Luxembourg, France, Germany, Liechtenstein, Luxembourg, Monaco, Netherlands, Switzerland
Oceania	Australia & N Zld	Australia, New Zealand, Norfolk Island
	Melanesia	Fiji, New Caledonia, Papua New Guinea, Solomon Islands, Vanuatu
	Micronesia	Guam, Kiribati, Marshall Islands, Micronesia (Federated States of), Nauru, Northern Mariana Islands, Pacific Islands Trust Territory, Palau
	Polynesia	American Samoa, Cook Islands, French Polynesia, Niue, Pitcain Islands, Samoa, Tokelau, Tonga, Tuvalu, Wallis and Futuna Islands

Table II-2: Fraction of total cropland which is cultivated by each of the five crop types for each of the 22 sub-regions (where total cropland = 1).

		Fraction of total cropland				
Region	Sub-region	Cereal crops	Fibre crops	Oil crops	Sugarcane	Total
Africa	Eastern Africa	0.441	0.030	0.108	0.007	0.586
	Middle Africa	0.277	0.021	0.116	0.009	0.423
	Northern Africa	0.471	0.010	0.138	0.005	0.624
	Southern Africa	0.301	0.002	0.055	0.025	0.383
	Western Africa	0.450	0.028	0.154	0.001	0.633
Americas	Northern America	0.327	0.025	0.203	0.002	0.557
	Central America	0.342	0.005	0.026	0.034	0.407
	Caribbean	0.126	0.004	0.032	0.097	0.258
	South America	0.270	0.017	0.344	0.053	0.684
Asia	Central Asia	0.555	0.081	0.107	0.000	0.744
	Eastern Asia	0.608	0.041	0.211	0.010	0.871
	Southern Asia	0.602	0.059	0.188	0.021	0.869
	South-Eastern Asia	0.533	0.007	0.197	0.022	0.758
	Western Asia	0.488	0.021	0.070	0.000	0.579
Europe	Eastern Europe	0.396	0.001	0.077	0.000	0.473
	Northern Europe	0.474	0.001	0.062	0.000	0.537
	Southern Europe	0.377	0.011	0.164	0.000	0.553
	Western Europe	0.492	0.003	0.102	0.000	0.597
Oceania	Australia & New Zealand	0.394	0.006	0.032	0.009	0.441

Melanesia	0.010	0.000	0.370	0.049	0.429
Micronesia	0.002	0.000	0.764	0.000	0.766
Polynesia	0.000	0.000	0.605	0.001	0.606

Table II-3: Developing countries and their regions, as classified by the World Bank (2013).

Region	Country
East Asia and Pacific	American Samoa, Cambodia, China, Fiji, Indonesia, Kiribati, Korea, Dem. Rep., LAO (People's Democratic Republic), Malaysia, Marshall Islands, Micronesia, Fed. Sts., Mongolia Myanmar, Palau, Papua New Guinea, Philippines Samoa, Solomon Islands, Thailand, Timor-Leste, Tuvalu, Tonga, Vanuatu, Vietnam
Europe and Central Asia	Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Georgia, Kazakhstan, Kosovo, Kyrgyz Republic, Latvia, Lithuania, Macedonia, FYR, Moldova, Montenegro, Romania, Russian Federation, Serbia, Tajikistan, Turkey, Turkmenistan, Ukraine, Uzbekistan
Latin America and the Caribbean	Antigua and Barbuda, Argentina, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, St. Lucia, St. Vincent and the Grenadines, Suriname, Uruguay, Venezuela, RB
Middle East and North Africa	Algeria, Djibouti, Egypt, Arab Rep., Iran, Islamic Rep., Iraq, Jordan, Lebanon, Libya, Morocco, Syrian Arab Republic, Tunisia, West Bank and Gaza, Yemen, Rep.
South Asia	Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka
Sub-Saharan Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Dem. Rep., Congo, Rep., Cote d'Ivoire, Eritrea, Ethiopia, Gabon, Gambit, The, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, South Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe

b. Crop yields within the RCPs

RCP 2.6

RCP 2.6 represents the lowest radiative forcing target of the RCPs, peaking at 3 W m^2 mid-century and then declining to 2.6 W/m^2 in 2100 (van Vuuren et al., 2011b). The aim of the scenario is to model a plausible pathway of a future which limits global average climate change to below 2 ^oC. The main assumptions and scenario drivers are detailed in van Vuuren et al. (2010) and van Vuuren et al. (2011b). Further discussion of the RCP scenario can be found in Section 2.4.1.1.

The baseline scenario used by the IMAGE modelling team to develop the RCP assumes an average rate of yield improvement for cereals of + 0.75 % yr^{-1} over the period to 2100. Van Vuuren et al. (2011b) discuss that agricultural land area in RCP 2.6 is increased in relation to the baseline scenario due to drivers such as an increased use of bioenergy and the reduction seen in the CO_2 fertilization effect. This reduction in CO_2 fertilization will potentially reduce crop yields within the RCP scenario. New values for the rates of crop yield change, relative to those in the baseline scenario, are not discussed in the RCP literature therefore estimations for the CO_2 fertilization effect from the literature have been used here to estimate the reduction in yields which may be seen in the RCP 2.6 pathway. Lobell and Field (2008) discuss that the average effect of CO_2 fertilization used regularly in crop models, for C_3 crops, is 0.1% yield increase for each 1 ppm CO_2 increase. They discuss that with the historical rate of CO_2 increase seen since 1960 (1.35 ppm yr^{-1}) a yield increase of 0.14 % yr^{-1} would be expected. Analysis of the CO_2 fertilization effect on rice, wheat and maize crops by (Lobell and Field, 2008) was consistent with the current value of 0.1 % yield increase per 1 ppm CO_2. The average value of 0.1 % yield was also determined by Kimball (1983), in a meta-analysis of 430 observations, who discussed that an average yield increase of 33% could be expected with a 330 ppm increase in CO_2 concentration. This equates to 0.1 % increase per 1 ppm CO_2. This value of 0.1 % yield increase per 1 ppm CO_2 increase has therefore been assumed here as the CO_2 fertilization effect. To calculate the projected effect of this reduction in CO_2 fertilization effect in RCP 2.6, from the 0.75 % yr^{-1} yield increase of the baseline scenario, CO_2 concentrations from the baseline scenario were used. Van Vuuren et al. (2007) projected atmospheric CO_2 concentrations of 708 ppm, in 2100, for the baseline scenario. Data for RCP 2.6 from the RCP database showed the CO_2 concentration for 2005 to be 378.81 ppm (IIASA, 2009). This value was used as the 2005 concentration for both the baseline and RCP 2.6 scenario. The average increase in CO_2 concentration for the baseline scenario was determined as 3.47 ppm yr^{-1} using the 2005 and 2100 values. Using the 0.1 % plant yield increase discussed above, this equates to 0.35 % of the yield increase seen every year being attributable to the CO_2 fertilization effect. Subtracting this from the 0.75 % yr^{-1} yield increase used in the baseline scenario, 0.40 % yr^{-1} yield increase would have been expected without any CO_2 fertilization effect. Following this, the change in CO_2 concentration in RCP 2.6 was calculated for each year relative to the previous year, giving a change in atmospheric CO_2 concentration. This was multiplied by the 0.1 % yield increase factor per ppm CO_2 increase, resulting in a CO_2 fertilization factor for each year of the RCP. Added to the 0.4 % yield increase that would be expected in RCP 2.6 without CO_2 fertilization an average value of 0.45 % yr^{-1} increase in crop yields was determined for RCP 2.6. The average crop yield increase for the period 2005-2050 was 0.55 % yr^{-1} and the period 2051-2100 was 0.36 % yr^{-1}. These two periods were differentiated due to the peak in CO_2 concentration mid-century and then subsequent decline. It would be expected from this that there would be more of an enhanced CO_2 fertilization effect in the first half of the century, which would be reduced as atmospheric CO_2 declines. The two rates of crop yield increase (2005-2050 and 2051-2100) were used for the main RCP 2.6 biochar scenario.

RCP 4.5

RCP 4.5 uses global carbon emissions pricing to achieve a radiative forcing stabilization target of 4.5 W/m^2 in 2100. More discussion about the development of the scenario and its underlying assumptions can be found in Section 2.4.1.2. The supplementary literature around RCP 4.5 details the assumptions made by the modelling team about crop yields (Thomson et al., 2010). They discuss that for RCP 4.5, literature from the FAO, 'World Agriculture Towards 2015/2030: An FAO Perspective', was used by the RCP modelling team to determine crop yields to 2030 (FAO, 2003). This FAO report discusses an expected 67 % of the growth in annual crop production (1.6 % yr^{-1}) to come from increases in crop yields for developing countries to 2030. This results in ~ 1.1 % yr^{-1} crop yield increase for the period. For the developed countries, a projected increase in crop production of 0.9 % yr^{-1} to 2030 is determined, with the discussion that all of this increase will be achieved through increased yield and more intensive land use, rather than increased agricultural land area. These yield increases of 1.1 % yr^{-1} and 0.9 % yr^{-1}, for developing and developed countries respectively, were used for the period 2005 to 2030 in the biochar scenarios. Developed and developing nation status is detailed in Annexe II a. The RCP 4.5 modelling team assumed, following 2030, a convergence to 0.25% yr^{-1} within the second half of the century, which has also been assumed within the biochar scenario (Wise et al., 2009). The date of this convergence was not detailed within the literature. Convergence to 0.25 % yr^{-1} yield increase in 2100 was implemented by an incremental change in the rate of yield change every 10 years, resulting in a yield increase of 0.25 % yr^{-1} in 2100 for the main model scenarios. Assuming this 10 year incremental change in rate of crop yield change enabled the complexity of yield assumptions to remain at similar levels to the other biochar scenarios, and remain within the bounds and time constraints of the study. These yield projections have been used to determine overall productivity data for RCP 4.5. Analysis of a scenario where the rate of crop yield increase converges to 0.25 % yr^{-1} in 2050 was also conducted to determine the effects of applying the earliest and latest convergence dates (see section 5.4.1.3). Thomson et al., (2010) also examine scenarios of productivity extremes, applying yield changes of 0 % (from baseline yields) and 50 % greater increase than the standard scenario assumptions detailed above. These scenarios of no yield increase and 50 % extra yield increase were investigated for the RCP scenarios (see Section 5.4.1).

RCP 6

RCP 6 uses climate policy to reduce emissions, limiting radiative forcing to 6 W/m^2 in 2100. The crop yield assumptions of RCP 6 are not directly indicated within the literature, and therefore have been derived here from the background scenario literature. RCP 6 was developed from the IPCC's Special Report on Emission Scenarios (SRES) B2 scenario. Arnell et al. (2004) discuss that to develop crop yields for the SRES B2 scenario, baseline rates of yield increase of 1 % yr^{-1} for developed nations and 1.7 % yr^{-1} for developing nations (global average of 1.2 % yr^{-1}) were taken from Parry et al. (1999) and then adapted to the assumptions of the B2 scenario. They determined a figure of 1 % yr^{-1} yield increase for both developed and developing nations. This reduction in the projected rate of yield increase for developing nations is largely due to the assumption that much of the achievable yield increase through intensification and mechanisation has already been achieved and that diminishing rates of return are likely to be seen for further increases in input. They assume that increase in input is likely in some developing nations, but an eventual levelling off is highly likely. The assumptions made about yield increases within the previously detailed literature regarding RCP 6 are projected to 2080. Due to a lack of literature detailing other assumptions, these crop yield increases are assumed to remain constant for the period 2080 to 2100 for the RCP 6 biochar in Scenario 1.

RCP 8.5

RCP8.5 represents a scenario of radiative forcing based on the upper end of the range of radiative forcing pathways within the literature, reaching a radiative forcing of 8.5 W/m^2 in 2100. This RCP is also often used by the modelling communities as a baseline climate scenario as it does not include any specific climate mitigation actions (Riahi et al., 2011).

There is no direct discussion of crop yield projections within the RCP 8.5 literature therefore it was necessary to use the background literature to derive crop yields. RCP 8.5 was developed from a revised version of the IPCC's SRES A2 scenario, named the A2r scenario (Nakicenovic et al., 2000, Riahi et al., 2007). Further details of the underlying assumptions of RCP 8.5 can be found in Chapter 2.4.1, Section 2.4.1.4. Arnell et al. (2004), who discussed crop yield changes for the SRES B2 scenario used for the development of crop yields for RCP 6 also discussed crop yield projections for the SRES A2 scenario. They detailed that increases of 1.0 % yr^{-1} and 1.5 % yr^{-1} for developed and developing countries respectively are projected within the A2 scenario. These values have therefore been assumed as annual crop yield changes for the main RCP 8.5 biochar scenario to 2100.

c. Residue availability

Cereal residues

Li et al. (1999) discuss that, in 1995, 2.3 % of residues in China were used for industrial processes, 24 % of this used as forage and between 29 % and 59 % used as fuel. Liu et al. (2008) states similar values, with 4 % of residues used within industrial processes, 23 % as forage and 0.5 % for biogas production. They also discuss that of the remaining residues, 37 % were burnt for fuel by farmers, 15 % were lost during the collection process and returned to the field, and 20.5 % were burnt in the field. This would give 20.5 % residue availability for biochar production if those cereal residues burnt in the field were utilized. A further 37 % could be potentially included (totalling 57.5 % of cereal residues) if farmers used pyrolysis systems, or other dual biochar-fuel producing systems, for energy production. For the main biochar scenarios developed here an assumption of 30 % cereal residue removal (from the field) rate has been made, in accordance with the work of Lal (2005) and Lindstrom (1986) (see Section 5.3.6.1). The 25 % and 10 % of crop residues currently burnt in the field, in developing and developed nations respectively, are also assumed to be available and collected here for biochar production. This makes the amount of cereal residues collected in the field 55 % and 40 % of total produced residues for developing and developed nations respectively. The values used here for developing nations (55 % removal rate) correspond well with the work of Liu et al. (2008) where 57.5 % of residues would be available using those residues currently burnt in the field and currently used for localised energy purposes. The values used here for cereal residue removal rates are optimistic compared to those used by Woolf et al. (2010), who use 25 %, 35 % and 45 % removal respectively in their scenarios, though the Woolf et al. (2010) values do not consider the use of those residues currently burnt in the field, or those currently used for localised energy purposes which could be converted to duel biochar-energy systems. The impacts on Scenario 1 of the residue availability assumptions of Woolf et al. (2010) are investigated in Scenario 5 (see Section 5.4.4).

Sugarcane residues

Smil (1999) discusses that sugarcane bagasse is often used as animal feed or industrial fuel sources within their processing streams. Woolf et al. (2010) assumed that all bagasse residues can be utilised for biochar production, as those currently used for power generation in the sugar production industry could be utilised in a dual energy-biochar production system. This would require conversion of energy systems, which would add further economic cost to a biochar system. They also discuss that sugarcane leaves are currently often left in the field rather than burnt, with the assumption that 50 % of this trash is currently recoverable, projected to rise to 75 % recoverability with improved technology and conservation practices. In the main biochar scenarios here (Scenario 1) 100 % bagasse utilization and 50 % field trash utilization are assumed.

Rice straw

100 % residue removal from the field is safely achievable for rice residues (Kim and Dale, 2004). Devendra (1997) discusses the utilization of rice straw in Asia, with an average value of 30 % determined for 9 Southeast Asian countries inclusive of China and the Philippines. Woolf et al., (2010b) determined that 26 % of rice straw produced is used for animal fodder. The average value of 30 % for Southeast Asia has been adopted here for the main scenarios due to the large share of total global rice production which is achieved by these nine Asian nations (FAO, 1998)). Following the work of Devendra (1997) an average value for the utilization of rice straw for animal feed of 30 % was assumed here for developing nations. This was applied to rice straw only, and as the majority of rice production occurs in Asia (over 90 % of the world's rice cultivation (FAO, 2000)) this was deemed to be globally representative. Assuming that all rice straw currently used for energy production could be utilised in dual biochar-energy producing pyrolysis systems, this leaves 70 % of rice straw residues available for biochar production.

Oil crop residues

The oil crop category includes crops such as cottonseed and rape, and also crops such as groundnuts, coconuts and olives. The diversity of the oil crop category makes applying an availability factor to the whole group difficult. As with cereal crops, a 30 % residue removal rate from fields is assumed here for Scenario 1, leaving 70 % of oil crop residues in-situ for soil quality purposes. Many of the residues considered here would become available after processing of the commodity, such as coconut shells and groundnut shells. Such residues may often be burnt for energy within the processing system. Residues from oil crops can be used for biofuel production (European Biofuels Technology Platform, 2014), though it is assumed within Scenario 1 that all residues available, which would normally be used for energy production, are utilized in pyrolysis systems for dual biochar-energy production.

Fibre crop residues

The main fibre crops assessed here are cotton and jute. Cotton residues are mostly cotton stalk, of which on average 40 % are available as surplus. A conservative estimate of 30 % is assumed here for collection for pyrolysis leaving 10 % of the surplus for other uses or losses during collection. Saha and Sagorika (2013) detail that alongside jute production 5.43 Mt of dry leaf matter is produced each year. The only current use for this leaf matter is to leave it in-situ for soil conditioning purposes. It was assumed here for Scenario 1, as with cereals residues, that 30 % of the leaf litter could be collected for pyrolysis without detrimental effects on soil quality.

d. Crop yields

Table II-4: Summary of the annual crop yield change (% yr^{-1}) for the four RCPs under the crop yield changes of Scenario 2b. Developed and developing refer to the developed and developing nations respectively.

		Annual crop yield change (% yr^{-1})									
RCP		2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
2.6	developed	0.825	0.825	0.825	0.825	0.825	0.54	0.54	0.54	0.54	0.54
2.6	developing	0.825	0.825	0.825	0.825	0.825	0.54	0.54	0.54	0.54	0.54
4.5	developed	1.35	1.35	1.35	1.215	1.065	0.93	0.795	0.66	0.51	0.375
4.5	developing	1.65	1.65	1.65	1.47	1.29	1.11	0.915	0.735	0.55	0.375
6	developed	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
6	developing	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
8.5	developed	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
8.5	developing	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25

e. Biochar carbon content

Table II-5: Elemental carbon content, from the literature, for biochars produced from various biomass materials. Process type and temperature for each biochar are shown, alongside the reporting basis of the values and reference.

Process Temp (°C)	Feedstock	Carbon Content (%)	Reference
550	sugarcane bagasse	63.3[a c]	(Cross and Sohi, 2011)
550	sugarcane bagasse	62.43[a c]	
550	sugarcane bagasse	58.31[a c]	
550	sugarcane bagasse	59.34[a c]	
550	sugarcane bagasse	63.37[a c]	

550	sugarcane bagasse	45.31 [a c]	
550	papermill wastes	50 [a c]	(Van Zweiten et al., 2010)
550	papermill wastes	52 [a c]	
500	switchgrass	39.4 [a c]	(Brewer et al., 2009)
500	corn stover	62.8 [a c]	
500	hardwood	65.3 [a c]	
500	switchgrass	38.7 [a d]	
500	corn stover	37.8 [a d]	
500	hardwood	63 [a d]	
760	switchgrass	42.8 [a e]	
550	tea waste	63 [b c]	(Demirbas, 2004b)
550	corncob	64 [b c]	
550	olive husk	65 [b c]	
500	Wood (pinus ponderosa)	81.9 [b c]	(Keiluweit et al., 2010)
600	wood (pinus ponderosa)	89 [b c]	
500	grass (festuca arundinacea)	82.2 [b c]	
600	grass (festuca arundinacea)	89 [b c]	
550	wood (pinus ponderosa)	79.2 [b c]	(Singh et al., 2012)
550	papermill sludge	83.6 [b c]	
550	leaf	71.9 [b c]	
500	wood	84 [b c]	(Vaccari et al., 2011)
500	wheat straw	60.2 [b d]	(Bruun et al., 2011)
525	wheat straw	64.3 [b d]	
550	wheat straw	67 [b d]	
575	wheat straw	69.2 [b]	
500	hazelnut	62 [b c]	(Enders et al., 2012)
500	pine	62 [b c]	
500	oak	68 [b c]	

[a] = dry basis, [b] = dry, ash free basis, [c] = slow pyrolysis, [d] = fast pyrolysis, [e] = gasification

f. Climate change impacts

Table II-6: Projected changes in crop yield (%) from the baseline crop yields of Scenario 1, with temperature increase (^oC). Values shown are the mean, lowest and highest projected changes (%) in crop yield, both with and without adaptation, for each temperature increase (low and high values determined using the 95 % confidence interval data from Porter et al. (2014)).

Temp increase	Change in crop yield from baseline (%)					
	Mean		Low yield projection		High yield projection	
(^oC)	No Adapt	Adapt	No Adapt	Adapt	No Adapt	Adapt
1	-2	1	-8	-4	3.2	7.6
1.1	-2.3	0.8	-8.1	-4	2.8	7.2
1.2	-2.6	0.6	-8.3	-4	2.5	6.8
1.3	-2.9	0.4	-8.4	-3.9	2.1	6.5
1.4	-3.2	0.2	-8.5	-3.9	1.8	6.1
1.5	-3.5	0	-8.7	-3.9	1.4	5.7
1.6	-3.8	-0.2	-8.8	-3.9	1.1	5.3
1.7	-4.1	-0.4	-8.9	-3.9	0.7	4.9
1.8	-4.4	-0.6	-9.1	-3.8	0.4	4.6
1.9	-4.7	-0.8	-9.2	-3.8	0	4.2

2	-5	-1	-9.3	-4.1	-0.3	3.9
2.1	-5.3	-1.2	-9.7	-4.3	-0.6	3.7
2.2	-5.6	-1.4	-10	-4.6	-0.8	3.5
2.3	-5.9	-1.6	-10.3	-4.9	-1	3.2
2.4	-6.2	-1.8	-10.6	-5.1	-1.3	3
2.5	-6.5	-2	-10.9	-5.4	-1.5	2.7
2.6	-6.8	-2.2	-11.2	-5.6	-1.7	2.5
2.7	-7.1	-2.4	-11.6	-5.9	-2	2.3
2.8	-7.4	-2.6	-11.9	-6.2	-2.2	2
2.9	-7.7	-2.8	-12.2	-6.4	-2.4	1.8
3	-8	-3	-12.5	-6.6	-2.7	1.9
3.1	-8.5	-3	-13.1	-6.7	-3	2.1
,3.2	-9	-3	-13.8	-6.9	-3.4	2.2
3.3	-9.5	-3	-14.4	-7	-3.8	2.4
3.4	-10	-3	-15.0	-7.2	-4.1	2.5
3.5	-10.5	-3	-15.7	-7.3	-4.5	2.6
3.6	-11	-3	-16.3	-7.5	-4.9	2.8
3.7	-11.5	-3	-16.9	-7.6	-5.2	2.9
3.8	-12	-3	-17.6	-7.8	-5.6	3.1
3.9	-12.5	-3	-18.2	-8	-6	3.2
4	-13	-3	-18.8	-8.6	-6.3	3.3
4.1	-13.5	-3.2	-19.5	-9.2	-6.6	3.4
4.2	-14	-3.4	-20.2	-9.8	-6.9	3.6
4.3	-14.5	-3.6	-20.9	-10.4	-7.2	3.7
4.4	-15	-3.8	-21.6	-11	-7.5	3.8
4.5	-15.5	-4	-22.3	-11.7	-7.8	3.9
4.6	-16	-4.2	-23	-12.3	-8.1	4
4.7	-16.5	-4.4	-23.7	-12.9	-8.4	4.1
4.8	-17	-4.6	-24.4	-13.5	-8.7	4.3
4.9	-17.5	-4.8	-25.1	-14.1	-9	4.4
5	-18	-5	-25.8	-14.7	-9.3	4.5

III. Annexe 3: Biochar production: Results tables

Table III-1: Total cropland (in million hectares (Mha)) for the years 2005, 2025, 2050, 2075 and 2100 for the four RCPs.

	Total cropland (Mha yr^{-1})			
Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
2005	1554.98	1554.98	1554.98	1554.98
2025	1765.54	1362.93	1580.05	1634.52
2050	1909.01	1284.09	1651.59	1718.95
2075	2036.09	1208.75	1776.50	1773.16
2100	2097.55	1122.99	1930.81	1839.43

Table III-2: Total commodity production (in gigatonnes (Gt)) for the years 2005, 2025, 2050, 2075 and 2100 for the four RCPs.

	Total commodity production (Gt yr^{-1})			
Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
2005	3.06	3.06	3.06	3.06
2025	3.66	3.60	3.81	4.14
2050	4.45	4.46	5.11	6.00
2075	5.10	4.86	7.01	8.61
2100	5.66	4.85	9.49	12.46

Table III-3: Annual biochar production (Mt yr^{-1}), total carbon content of biochar (Pg yr^{-1}), and CO_2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 1.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1430.82	1439.53	1645.92	2010.89
2075	1641.29	1575.01	2249.55	2932.67
2100	1835.49	1570.53	3022.82	4322.58
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.84	0.80	0.85	0.95
2050	1.01	0.99	1.16	1.42
2075	1.16	1.09	1.58	2.07
2100	1.30	1.09	2.13	3.05
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.08	2.92	3.12	3.48
2050	3.71	3.65	4.24	5.20
2075	4.27	3.99	5.80	7.59
2100	4.78	3.98	7.83	11.20

Table III-4: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 2a.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1066.18	926.17	995.98	1014.17
2050	1119.98	922.57	1051.83	1054.38
2075	1174.35	865.17	1120.98	1071.51
2100	1201.11	793.75	1174.58	1098.01
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.75	0.64	0.70	0.71
2050	0.79	0.64	0.74	0.74
2075	0.83	0.60	0.79	0.76
2100	0.85	0.55	0.83	0.78
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	2.76	2.36	2.56	2.62
2050	2.91	2.34	2.71	2.73
2075	3.05	2.19	2.89	2.78
2100	3.13	2.02	3.04	2.85

Table III-5: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 2b.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1256.60	1275.48	1341.44	1555.15
2050	1616.42	1795.63	2055.50	2772.01
2075	1939.14	2121.58	3178.50	4843.12
2100	2267.94	2205.38	4832.33	8564.66
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.89	0.88	0.94	1.09
2050	1.14	1.24	1.44	1.95

2075	1.37	1.46	2.23	3.41
2100	1.61	1.52	3.41	6.04
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.25	3.24	3.45	4.01
2050	4.19	4.55	5.30	7.16
2075	5.04	5.37	8.20	12.52
2100	5.91	5.59	12.52	22.17

Table III-6: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 2c.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1430.82	1429.78	1645.92	2010.89
2075	1641.29	1427.28	2249.55	2932.67
2100	1835.49	1393.71	3022.82	4322.58
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.84	0.80	0.85	0.95
2050	1.01	0.99	1.16	1.42
2075	1.16	0.99	1.58	2.07
2100	1.30	0.96	2.13	3.05
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.08	2.92	3.12	3.48
2050	3.71	3.62	4.24	5.20
2075	4.27	3.62	5.80	7.59
2100	4.78	3.54	7.83	11.20

Table III-7: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 3a.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				

2005	969.79	969.79	969.79	969.79
2025	1082.23	1200.68	1183.33	1289.64
2050	1238.94	1511.47	1517.54	1844.38
2075	1355.39	1762.78	1946.14	2641.70
2100	1482.01	1915.98	2495.79	3788.86
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.76	0.84	0.83	0.90
2050	0.87	1.06	1.06	1.29
2075	0.95	1.23	1.36	1.85
2100	1.04	1.34	1.75	2.65
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	2.78	3.09	3.04	3.31
2050	3.19	3.89	3.90	4.74
2075	3.49	4.53	5.01	6.78
2100	3.81	4.92	6.42	9.71

Table III-8: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 3b. Values shown for each RCP use the land-use and highest temperature projections for that particular RCP.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	968.71	969.79	969.79	969.79
2025	1156.77	1111.83	1164.37	1349.65
2050	1379.21	1295.85	1526.03	2010.89
2075	1550.33	1286.54	2062.50	2932.67
2100	1704.09	1178.22	2338.71	4322.58
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.82	0.77	0.81	0.95
2050	0.97	0.89	1.06	1.42
2075	1.10	0.89	1.43	2.07
2100	1.21	0.81	1.65	3.05
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	2.99	2.82	2.97	3.48
2050	3.58	3.27	3.89	5.20

2075	4.03	3.25	5.25	7.59
2100	4.43	2.98	6.08	11.20

Table III-9: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 4a1.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	784.20	784.20	784.20	784.20
2025	988.96	881.59	971.56	1106.35
2050	1174.80	1080.66	1318.86	1663.34
2075	1333.88	1164.38	1772.53	2404.46
2100	1479.28	1152.39	2386.55	3546.26
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.60	0.60	0.60	0.60
2025	0.77	0.67	0.75	0.86
2050	0.92	0.82	1.02	1.30
2075	1.04	0.89	1.37	1.88
2100	1.16	0.88	1.86	2.78
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.22	2.22	2.22	2.22
2025	2.83	2.47	2.75	3.15
2050	3.36	3.01	3.75	4.76
2075	3.82	3.25	5.04	6.89
2100	4.24	3.22	6.81	10.19

Table III-10: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 4a2.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	677.04	677.04	677.04	677.04
2025	699.25	637.89	695.09	785.19
2050	655.70	618.55	740.98	924.74
2075	435.38	390.21	583.49	780.95
2100	247.89	198.39	402.69	590.00
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				

2005	0.51	0.51	0.51	0.51
2025	0.53	0.48	0.52	0.59
2050	0.50	0.46	0.56	0.70
2075	0.33	0.29	0.44	0.59
2100	0.19	0.15	0.31	0.45
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	1.87	1.87	1.87	1.87
2025	1.95	1.74	1.92	2.18
2050	1.83	1.68	2.05	2.58
2075	1.22	1.06	1.62	2.18
2100	0.69	0.54	1.12	1.65

Table III-11: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 4b.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	677.04	677.04	677.04	677.04
2025	987.55	900.90	981.67	1108.92
2050	1349.43	1272.98	1524.93	1903.12
2075	1836.30	1645.79	2461.02	3293.84
2100	2266.44	1813.88	3681.74	5394.32
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.51	0.51	0.51	0.51
2025	0.75	0.67	0.74	0.84
2050	1.03	0.94	1.15	1.45
2075	1.40	1.22	1.86	2.51
2100	1.73	1.35	2.80	4.12
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	1.87	1.87	1.87	1.87
2025	2.75	2.46	2.71	3.08
2050	3.77	3.46	4.23	5.31
2075	5.14	4.48	6.83	9.21
2100	6.35	4.95	10.26	15.12

Table III-12: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 5a.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	632.26	632.26	632.26	632.26
2025	763.76	764.65	793.45	872.66
2050	915.05	967.36	1068.73	1290.96
2075	1044.41	1056.94	1457.91	1876.00
2100	1163.58	1050.76	1939.51	2751.70
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.41	0.41	0.41	0.41
2025	0.50	0.49	0.51	0.57
2050	0.60	0.62	0.69	0.84
2075	0.68	0.67	0.95	1.22
2100	0.76	0.67	1.27	1.78
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	1.50	1.50	1.50	1.50
2025	1.82	1.80	1.88	2.08
2050	2.19	2.27	2.54	3.07
2075	2.51	2.48	3.47	4.46
2100	2.80	2.46	4.64	6.55

Table III-13: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 5b.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	909.53	909.53	909.53	909.53
2025	1103.72	1080.67	1137.94	1252.59
2050	1328.51	1354.53	1535.10	1848.56
2075	1521.83	1479.43	2098.45	2680.63
2100	1700.39	1473.57	2818.35	3925.59
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.63	0.63	0.63	0.63
2025	0.76	0.74	0.78	0.86
2050	0.92	0.92	1.06	1.27
2075	1.06	1.00	1.45	1.85

2100	1.18	1.00	1.95	2.71
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.30	2.30	2.30	2.30
2025	2.80	2.70	2.87	3.17
2050	3.38	3.37	3.88	4.68
2075	3.88	3.68	5.31	6.78
2100	4.34	3.67	7.17	9.94

Table III-14: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 5c.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	1186.80	1186.80	1186.80	1186.80
2025	1443.68	1396.68	1482.43	1632.52
2050	1741.96	1741.70	2001.48	2406.16
2075	1999.25	1901.92	2739.00	3485.25
2100	2237.19	1896.38	3697.18	5099.49
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.84	0.84	0.84	0.84
2025	1.03	0.98	1.05	1.16
2050	1.24	1.22	1.42	1.71
2075	1.43	1.33	1.95	2.48
2100	1.60	1.33	2.64	3.63
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	3.09	3.09	3.09	3.09
2025	3.78	3.61	3.86	4.26
2050	4.57	4.48	5.22	6.28
2075	5.25	4.89	7.15	9.10
2100	5.88	4.88	9.69	13.33

Table III-15: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 5d.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	596.91	596.91	596.91	596.91

2025	741.24	713.06	751.63	843.11
2050	883.87	902.62	1022.43	1272.46
2075	1012.13	988.69	1393.74	1868.18
2100	1129.62	984.36	1858.53	2775.34
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.40	0.40	0.40	0.40
2025	0.50	0.47	0.50	0.57
2050	0.60	0.59	0.68	0.86
2075	0.69	0.64	0.93	1.26
2100	0.77	0.64	1.25	1.88
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	1.46	1.46	1.46	1.46
2025	1.84	1.71	1.84	2.08
2050	2.19	2.16	2.51	3.15
2075	2.52	2.36	3.43	4.63
2100	2.82	2.36	4.60	6.90

Table III-16: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 5e.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	749.92	749.92	749.92	749.92
2025	928.95	887.35	941.68	1053.01
2050	1111.79	1115.69	1279.63	1580.83
2075	1275.23	1220.98	1746.97	2313.44
2100	1424.40	1216.43	2343.00	3425.39
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.52	0.52	0.52	0.52
2025	0.65	0.60	0.65	0.73
2050	0.78	0.76	0.89	1.10
2075	0.89	0.83	1.21	1.62
2100	1.00	0.83	1.64	2.40
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	1.90	1.90	1.90	1.90
2025	2.38	2.22	2.39	2.68
2050	2.85	2.77	3.25	4.04
2075	3.28	3.03	4.45	5.93
2100	3.67	3.03	6.00	8.80

Table III-17: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO_2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 6a.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	749.49	749.49	749.49	749.49
2025	923.19	879.76	938.47	1044.39
2050	1111.68	1100.42	1272.81	1557.58
2075	1277.20	1204.18	1740.82	2272.13
2100	1429.99	1201.86	2347.61	3351.11
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.54	0.54	0.54	0.54
2025	0.67	0.62	0.67	0.75
2050	0.80	0.78	0.91	1.12
2075	0.93	0.85	1.25	1.64
2100	1.04	0.85	1.70	2.42
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	1.97	1.97	1.97	1.97
2025	2.45	2.29	2.47	2.76
2050	2.95	2.86	3.36	4.13
2075	3.40	3.13	4.60	6.02
2100	3.81	3.12	6.23	8.90

Table III-18: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO_2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 6b.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	1888.71	1888.71	1888.71	1888.71
2025	2326.44	2216.99	2364.94	2631.86
2050	2801.44	2773.06	3207.49	3925.10
2075	3218.56	3034.54	4386.88	5725.78
2100	3603.56	3028.69	5915.99	8444.80
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	1.36	1.36	1.36	1.36
2025	1.68	1.57	1.70	1.89

2050	2.03	1.96	2.31	2.83
2075	2.33	2.15	3.16	4.14
2100	2.62	2.15	4.28	6.11
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	4.97	4.97	4.97	4.97
2025	6.17	5.78	6.22	6.95
2050	7.44	7.20	8.46	10.40
2075	8.56	7.88	11.58	15.18
2100	9.60	7.87	15.69	22.43

Table III-19: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 7a.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1430.82	1439.53	1645.92	2010.89
2075	1641.29	1575.01	2249.55	2932.67
2100	1835.49	1570.53	3022.82	4322.58
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.58	0.58	0.58	0.58
2025	0.72	0.69	0.73	0.81
2050	0.86	0.87	0.99	1.21
2075	0.99	0.95	1.35	1.77
2100	1.10	0.95	1.82	2.60
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.14	2.14	2.14	2.14
2025	2.63	2.53	2.68	2.98
2050	3.16	3.18	3.64	4.44
2075	3.63	3.48	4.97	6.48
2100	4.06	3.47	6.68	9.55

Table III-20: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 7b.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5

Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1430.82	1439.53	1645.92	2010.89
2075	1641.29	1575.01	2249.55	2932.67
2100	1835.49	1570.53	3022.82	4322.58
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.70	0.70	0.70	0.70
2025	0.86	0.83	0.88	0.98
2050	1.04	1.04	1.19	1.46
2075	1.19	1.14	1.63	2.13
2100	1.33	1.14	2.19	3.13
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.58	2.58	2.58	2.58
2025	3.17	3.05	3.23	3.59
2050	3.81	3.83	4.38	5.35
2075	4.37	4.19	5.99	7.80
2100	4.88	4.18	8.04	11.50

Table III-21: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 7c.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1430.82	1439.53	1645.92	2010.89
2075	1641.29	1575.01	2249.55	2932.67
2100	1835.49	1570.53	3022.82	4322.58
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.86	0.86	0.86	0.86
2025	1.06	1.02	1.08	1.20
2050	1.27	1.28	1.46	1.79
2075	1.46	1.40	2.00	2.61
2100	1.63	1.40	2.69	3.85
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	3.17	3.17	3.17	3.17
2025	3.89	3.75	3.97	4.41
2050	4.67	4.70	5.38	6.57

2075	5.36	5.14	7.35	9.58
2100	6.00	5.13	9.87	14.12

Table III-22: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO_2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 8a. Values shown for each RCP use the land-use and lowest temperature projections for that particular RCP.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1430.81	1439.53	1645.91	2010.89
2075	1641.29	1575.01	2249.55	2821.23
2100	1835.48	1539.12	2926.09	4028.64
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.84	0.80	0.85	0.95
2050	1.01	0.99	1.16	1.42
2075	1.16	1.09	1.58	1.99
2100	1.30	1.06	2.07	2.84
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.08	2.92	3.12	3.48
2050	3.71	3.65	4.24	5.20
2075	4.27	3.99	5.80	7.30
2100	4.78	3.90	7.58	10.44

Table III-23: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 8b. Values shown for each RCP use the land-use and average temperature projections for that particular RCP.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1430.81	1439.53	1645.92	1952.58
2075	1641.29	1519.88	2170.82	2742.04

2100	1835.48	1501.43	2862.61	3847.10
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.84	0.80	0.85	0.95
2050	1.01	0.99	1.16	1.38
2075	1.16	1.05	1.53	1.93
2100	1.30	1.04	2.02	2.72
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.08	2.92	3.12	3.48
2050	3.71	3.65	4.24	5.05
2075	4.27	3.85	5.60	7.10
2100	4.78	3.81	7.42	9.97

Table III-24: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 8c. Values shown for each RCP use the land-use and highest temperature projections for that particular RCP.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1397.91	1393.47	1598.18	1934.48
2075	1583.84	1491.53	2130.32	2683.39
2100	1765.74	1463.74	2765.88	3609.35
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.84	0.80	0.85	0.95
2050	0.99	0.96	1.12	1.36
2075	1.12	1.03	1.50	1.89
2100	1.25	1.01	1.95	2.55
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.08	2.92	3.12	3.48
2050	3.63	3.53	4.12	5.00
2075	4.12	3.78	5.49	6.94
2100	4.60	3.71	7.17	9.35

Table III-25: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 8d1. Values shown for each RCP use the land-use and highest temperature projections for that particular RCP.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1430.81	1439.53	1645.91	2010.89
2075	1641.29	1575.01	2249.55	2674.59
2100	1835.48	1444.89	2765.88	3838.45
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.84	0.80	0.85	0.95
2050	1.01	0.99	1.16	1.42
2075	1.16	1.09	1.58	1.89
2100	1.30	1.00	1.95	2.71
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.08	2.92	3.12	3.48
2050	3.71	3.65	4.24	5.20
2075	4.27	3.99	5.80	6.92
2100	4.78	3.67	7.17	9.95

Table III-26: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 8d2. Values shown for each RCP use the land-use and highest temperature projections for that particular RCP.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1430.81	1439.53	1645.92	1841.98
2075	1641.29	1437.98	2053.84	2613.01
2100	1835.49	1427.61	2729.61	3618.00
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68

2025	0.84	0.80	0.85	0.95
2050	1.01	0.99	1.16	1.30
2075	1.16	0.99	1.44	1.84
2100	1.30	0.99	1.93	2.55
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.08	2.92	3.12	3.48
2050	3.71	3.65	4.24	4.76
2075	4.27	3.64	5.30	6.76
2100	4.78	3.62	7.07	9.38

Table III-27: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 8d3. Values shown for each RCP use the land-use and highest temperature projections for that particular RCP.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1314.92	1317.17	1507.66	1833.93
2075	1498.50	1422.23	2031.34	2548.49
2100	1673.96	1394.63	2626.83	3298.13
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.84	0.80	0.85	0.95
2050	0.93	0.91	1.06	1.29
2075	1.06	0.98	1.43	1.80
2100	1.19	0.96	1.85	2.33
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.08	2.92	3.12	3.48
2050	3.41	3.34	3.88	4.74
2075	3.90	3.60	5.24	6.60
2100	4.36	3.54	6.81	8.55

Table III-28: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, *for each of the RCPs assessed under biochar Scenario 8e1. Values shown for each RCP use the land-use and highest temperature projections for that particular RCP.*

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1430.81	1439.53	1645.91	2010.89
2075	1641.29	1575.01	2249.55	2964.93
2100	1835.48	1620.79	3077.23	4249.10
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.84	0.80	0.85	0.95
2050	1.01	0.99	1.16	1.42
2075	1.16	1.09	1.58	2.09
2100	1.30	1.12	2.17	3.00
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.08	2.92	3.12	3.48
2050	3.71	3.65	4.24	5.20
2075	4.27	3.99	5.80	7.67
2100	4.78	4.11	7.97	11.01

Table III-29: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 8e2. Values shown for each RCP use the land-use and highest temperature projections for that particular RCP.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1430.81	1439.53	1645.92	2053.12
2075	1641.29	1597.06	2281.05	2888.68
2100	1835.49	1576.81	3004.69	4110.77
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.84	0.80	0.85	0.95
2050	1.01	0.99	1.16	1.45
2075	1.16	1.10	1.60	2.04

2100	1.30	1.09	2.12	2.90
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.08	2.92	3.12	3.48
2050	3.71	3.65	4.24	5.31
2075	4.27	4.05	5.88	7.48
2100	4.78	4.00	7.79	10.65

Table III-30: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 8e3. Values shown for each RCP use the land-use and highest temperature projections for that particular RCP.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1470.88	1465.45	1680.48	2033.01
2075	1664.27	1565.56	2236.05	2844.69
2100	1855.68	1543.83	2932.14	3959.48
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.84	0.80	0.85	0.95
2050	1.04	1.01	1.18	1.43
2075	1.18	1.08	1.57	2.01
2100	1.32	1.07	2.07	2.80
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.08	2.92	3.12	3.48
2050	3.82	3.71	4.33	5.26
2075	4.33	3.97	5.77	7.36
2100	4.83	3.92	7.60	10.26

Table III-31: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 8f. Values shown for each RCP use the land-use and highest temperature projections for that particular RCP.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5

Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1183.99	1166.09	1202.72	1366.37
2050	1421.01	1367.01	1607.21	1952.76
2075	1638.16	1443.11	2050.68	2612.74
2100	1818.54	1389.20	2740.77	3722.19
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.84	0.82	0.85	0.97
2050	1.02	0.96	1.15	1.41
2075	1.18	1.02	1.47	1.91
2100	1.30	0.98	2.00	2.75
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.09	3.00	3.11	3.56
2050	3.73	3.52	4.22	5.17
2075	4.31	3.74	5.41	7.00
2100	4.79	3.61	7.33	10.08

Table III-32: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO_2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 9a. Values shown for each RCP use the land-use and lowest temperature projections for that particular RCP.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1430.81	1439.53	1645.91	2010.89
2075	1641.29	1575.01	2249.55	2926.80
2100	1835.48	1570.53	3028.87	4227.48
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.84	0.80	0.85	0.95
2050	1.01	0.99	1.16	1.42
2075	1.16	1.09	1.58	2.06
2100	1.30	1.09	2.14	2.99
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49

2025	3.08	2.92	3.12	3.48
2050	3.71	3.65	4.24	5.20
2075	4.27	3.99	5.80	7.57
2100	4.78	3.98	7.85	10.96

Table III-33: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO_2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 9b. Values shown for each RCP use the land-use and average temperature projections for that particular RCP.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1430.81	1439.53	1645.92	2018.94
2075	1641.29	1575.01	2249.55	2874.01
2100	1835.49	1561.11	2986.55	4192.90
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.84	0.80	0.85	0.95
2050	1.01	0.99	1.16	1.42
2075	1.16	1.09	1.58	2.03
2100	1.30	1.08	2.11	2.96
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.08	2.92	3.12	3.48
2050	3.71	3.65	4.24	5.22
2075	4.27	3.99	5.80	7.44
2100	4.78	3.96	7.74	10.87

Table III-34: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 9c. Values shown for each RCP use the land-use and highest temperature projections for that particular RCP.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65

2050	1442.26	1442.41	1652.50	2006.87
2075	1641.29	1556.11	2222.56	2844.69
2100	1831.82	1535.98	2932.14	4132.39
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.84	0.80	0.85	0.95
2050	1.02	1.00	1.16	1.41
2075	1.16	1.07	1.56	2.01
2100	1.30	1.06	2.07	2.92
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.08	2.92	3.12	3.48
2050	3.74	3.65	4.26	5.19
2075	4.27	3.94	5.73	7.36
2100	4.77	3.90	7.60	10.71

Table III-35: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 9d1. Values shown for each RCP use the land-use and highest temperature projections for that particular RCP.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1430.81	1439.53	1645.91	2010.89
2075	1641.29	1575.01	2249.55	2818.29
2100	1835.48	1507.71	2904.93	4080.52
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.84	0.80	0.85	0.95
2050	1.01	0.99	1.16	1.42
2075	1.16	1.09	1.58	1.99
2100	1.30	1.04	2.05	2.88
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.08	2.92	3.12	3.48
2050	3.71	3.65	4.24	5.20
2075	4.27	3.99	5.80	7.29
2100	4.78	3.83	7.53	10.58

Table III-36: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 9d2. Values shown for each RCP use the land-use and highest temperature projections for that particular RCP.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1430.81	1439.53	1645.92	1932.47
2075	1641.29	1513.58	2161.82	2774.30
2100	1835.49	1510.85	2892.84	3998.39
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.84	0.80	0.85	0.95
2050	1.01	0.99	1.16	1.36
2075	1.16	1.05	1.52	1.96
2100	1.30	1.04	2.04	2.82
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.08	2.92	3.12	3.48
2050	3.71	3.65	4.24	5.00
2075	4.27	3.84	5.57	7.18
2100	4.78	3.83	7.50	10.36

Table III-37: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 9d3. Values shown for each RCP use the land-use and highest temperature projections for that particular RCP.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1373.58	1383.39	1581.73	1932.47
2075	1577.28	1507.28	2152.82	2736.18
2100	1763.90	1482.58	2820.29	3764.97
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				

2005	0.68	0.68	0.68	0.68
2025	0.84	0.80	0.85	0.95
2050	0.97	0.95	1.11	1.36
2075	1.12	1.04	1.51	1.93
2100	1.25	1.02	1.99	2.66
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.08	2.92	3.12	3.48
2050	3.56	3.50	4.08	5.00
2075	4.10	3.82	5.55	7.08
2100	4.59	3.76	7.31	9.76

Table III-38: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 9e1. Values shown for each RCP use the land-use and highest temperature projections for that particular RCP.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1430.81	1439.53	1645.91	2010.89
2075	1641.29	1575.01	2249.55	3088.10
2100	1835.48	1689.89	3207.22	4430.64
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.84	0.80	0.85	0.95
2050	1.01	0.99	1.16	1.42
2075	1.16	1.09	1.58	2.18
2100	1.30	1.17	2.26	3.13
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.08	2.92	3.12	3.48
2050	3.71	3.65	4.24	5.20
2075	4.27	3.99	5.80	7.99
2100	4.78	4.29	8.31	11.48

Table III-39: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, *for each of the RCPs assessed under biochar Scenario 9e2. Values shown for each RCP use the land-use and highest temperature projections for that particular RCP.*

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1430.81	1439.53	1645.92	2141.60
2075	1641.29	1664.78	2377.78	3011.85
2100	1835.49	1642.78	3134.67	4443.61
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.84	0.80	0.85	0.95
2050	1.01	0.99	1.16	1.51
2075	1.16	1.15	1.67	2.12
2100	1.30	1.14	2.21	3.14
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.08	2.92	3.12	3.48
2050	3.71	3.65	4.24	5.54
2075	4.27	4.22	6.13	7.79
2100	4.78	4.17	8.12	11.52

Table III-40: Annual biochar production (Mt yr-1), Total carbon content of biochar (Pg yr-1), and CO2 equivalent of the carbon stored in biochar for the years 2005, 2025, 2050, 2075 and 2100, for each of the RCPs assessed under biochar Scenario 9e3. Values shown for each RCP use the land-use and highest temperature projections for that particular RCP.

Year	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar production (Million tonnes (Mt yr^{-1}))				
2005	969.79	969.79	969.79	969.79
2025	1189.80	1147.03	1215.28	1349.65
2050	1533.84	1527.35	1752.90	2117.47
2075	1734.84	1633.28	2332.78	2994.25
2100	1932.77	1609.80	3086.30	4499.81
Total carbon in biochar (Petagrams (Pg C yr^{-1})) (1Pg = 1Gt)				
2005	0.68	0.68	0.68	0.68
2025	0.84	0.80	0.85	0.95
2050	1.08	1.05	1.23	1.49
2075	1.23	1.13	1.64	2.11

2100	1.37	1.11	2.18	3.18
CO_2 equivalent of carbon in biochar (Petagrams (Pg CO_2 yr^{-1}))				
2005	2.49	2.49	2.49	2.49
2025	3.08	2.92	3.12	3.48
2050	3.98	3.87	4.52	5.48
2075	4.51	4.14	6.02	7.75
2100	5.03	4.08	8.00	11.66

Table III-41: Total biochar production (Gt), biochar carbon content (GtC) and CO_2 equivalent of carbon content (Gt CO_2) for each scenario, over the 95 year period.

	Units	95 year total values			
Scenario 1		RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Total biochar	Gt	138.38	132.25	173.17	217.89
Total carbon	PgC	97.87	91.48	121.69	153.56
Total CO_2 equivalent of carbon in	$PgCO_2$	359.20	335.75	446.61	563.55
Scenario 2					
2a					
Total biochar	Gt	107.90	86.00	102.26	100.53
Total carbon	PgC	76.29	59.57	71.82	70.91
Total CO_2 equivalent of carbon in	$PgCO_2$	280.00	218.61	263.58	260.25
2b					
Total biochar	Gt	157.48	166.19	231.02	338.34
Total carbon	PgC	111.39	114.89	162.39	238.32
Total CO_2 equivalent of carbon in	$PgCO_2$	408.82	421.66	595.97	874.65
2c					
Total biochar	Gt	As S1	125.78	As S1	As S1
Total carbon	PgC	As S1	87.04	As S1	As S1
Total CO_2 equivalent of carbon in	$PgCO_2$	As S1	319.42	As S1	As S1
Scenario 3					
3a					
Total biochar	Gt	118.58	144.35	155.10	198.57
Total carbon	PgC	83.12	101.11	108.72	138.86
Total CO_2 equivalent of carbon in	$PgCO_2$	305.06	371.08	398.99	509.62
3b					
Total biochar	Gt	131.91	115.61	155.94	217.89
Total carbon	PgC	93.20	79.78	108.79	153.56
Total CO_2 equivalent of carbon in	$PgCO_2$	342.04	292.81	399.25	563.55
Scenario 4					
4a1					
Total biochar	Gt	113.11	99.39	137.50	178.80
Total carbon	PgC	40.20	36.04	45.47	56.20
Total CO_2 equivalent of carbon in	$PgCO_2$	147.54	132.27	166.88	206.27
4a2					
Total biochar	Gt	52.88	48.43	60.22	73.99
Total carbon	PgC	28.03	25.29	31.77	39.16
Total CO_2 equivalent of carbon in	$PgCO_2$	102.86	92.80	116.59	143.72
4b					

Total biochar	Gt	140.03	125.17	176.04	229.65
Total carbon	GtC	106.62	93.01	133.11	174.78
Total CO_2 equivalent of carbon in	$GtCO_2$	391.30	341.33	488.52	641.43
Scenario 5					
5a					
Total biochar	Gt	88.39	88.46	112.22	139.68
Total carbon	GtC	57.70	56.60	72.85	90.56
Total CO_2 equivalent of carbon in	$GtCO_2$	211.76	207.72	267.36	332.37
5b					
Total biochar	Gt	128.46	124.33	161.65	199.82
Total carbon	GtC	89.07	84.54	111.48	137.78
Total CO_2 equivalent of carbon in	$GtCO_2$	326.89	310.25	409.13	505.64
5c					
Total biochar	Gt	168.53	160.19	211.08	259.96
Total carbon	GtC	120.44	112.47	150.11	184.99
Total CO_2 equivalent of carbon in	$GtCO_2$	442.01	412.78	550.90	678.91
5d					
Total biochar	Gt	85.48	82.70	107.12	138.23
Total carbon	GtC	57.85	54.03	71.74	93.26
Total CO_2 equivalent of carbon in	$GtCO_2$	212.31	198.29	263.27	342.27
5e					
Total biochar	Gt	107.58	102.44	134.38	171.49
Total carbon	GtC	75.31	69.56	93.24	119.61
Total CO_2 equivalent of carbon in	$GtCO_2$	276.37	255.28	342.19	438.98
Scenario 6					
6a					
Total biochar	Gt	107.57	101.26	134.03	168.78
Total carbon	GtC	77.86	71.75	96.42	121.84
Total CO_2 equivalent of carbon in	$GtCO_2$	285.75	263.34	353.86	447.17
6b					
Total biochar	Gt	271.07	255.16	337.75	425.32
Total carbon	GtC	196.21	180.82	242.98	307.05
Total CO_2 equivalent of carbon in	$GtCO_2$	720.09	663.62	891.73	1126.86
Scenario 7					
7a					
Total biochar	Gt	138.38	132.25	173.17	217.89
Total carbon	GtC	83.31	79.61	104.25	131.17
Total CO_2 equivalent of carbon in	$GtCO_2$	305.74	292.18	382.59	481.39
7b					
Total biochar	Gt	138.38	132.25	173.17	217.89

Total carbon	GtC	100.33	95.88	125.55	157.97
Total CO_2 equivalent of carbon in	$GtCO_2$	368.21	351.88	460.76	579.74
7c					
Total biochar	Gt	138.38	132.25	173.17	217.89
Total carbon	GtC	123.16	117.70	154.12	193.92
Total CO_2 equivalent of carbon in	$GtCO_2$	452.00	431.96	565.62	711.68

Table III-42: Total biochar production (Gt), biochar carbon content (Gt) and CO_2 equivalent of carbon content (Gt) for each climate change with no adaptation scenario (Scenario 8), over the 95 year period.

	Units	**95 year total values**			
Scenario 8		RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
8a (minimum temp)					
Total biochar	Pg	138.38	131.96	171.73	211.21
Total carbon	PgC	97.87	91.29	120.68	148.84
Total CO_2 equivalent of carbon in	$PgCO_2$	359.20	335.03	442.88	546.25
8b (median temperature)					
Total biochar	Pg	138.38	129.69	168.90	206.73
Total carbon	PgC	97.87	89.72	118.69	145.68
Total CO_2 equivalent of carbon in	$PgCO_2$	359.20	329.27	435.59	534.65
8c (maximum temperature)					
Total biochar	Pg	135.22	127.72	166.17	201.18
Total carbon	PgC	95.63	88.36	116.77	141.77
Total CO_2 equivalent of carbon in	$PgCO_2$	350.97	324.26	428.53	520.30
8d1 (Lowest yield projections, minimum temperature)					
Total biochar	Pg	138.38	131.11	168.50	204.33
Total carbon	PgC	97.87	90.70	118.41	143.99
Total CO_2 equivalent of carbon in	$PgCO_2$	359.20	332.87	434.55	528.45
8d2 (lowest yield projections, mean temperature)					
Total biochar	Pg	138.38	125.69	163.45	198.87
Total carbon	PgC	97.87	86.95	114.85	140.14
Total CO_2 equivalent of carbon in	$PgCO_2$	359.20	319.11	421.50	514.32
8d3 (lowest yield projections, maximum temperature)					
Total biochar	Pg	130.31	123.34	159.99	191.79
Total carbon	PgC	92.16	85.34	112.42	135.15
Total CO_2 equivalent of carbon in	$PgCO_2$	338.22	313.18	412.59	495.99
8e1 (highest yield projections, minimum temperature)					
Total biochar	Pg	138.38	132.70	174.61	218.23
Total carbon	PgC	97.87	91.80	122.71	153.80

Total CO_2 equivalent of carbon in	$PgCO_2$	359.20	336.90	450.33	564.44
8e2 (highest yield projections, mean temperature)					
Total biochar	Pg	138.38	133.46	174.24	215.31
Total carbon	PgC	97.87	92.32	122.44	151.74
Total CO_2 equivalent of carbon in	$PgCO_2$	359.20	338.83	449.36	556.87
8e3 (highest yield projections, maximum temperature)					
Total biochar	Pg	139.84	132.25	172.68	211.63
Total carbon	PgC	98.91	91.49	121.34	149.14
Total CO_2 equivalent of carbon in	$PgCO_2$	362.99	335.76	445.33	547.33
8f					
Total biochar	Pg	137.83	124.79	163.74	200.61
Total carbon	PgC	98.45	87.80	117.33	145.53
Total CO_2 equivalent of carbon in	$PgCO_2$	361.31	322.23	430.60	534.09

Table III-43: Total biochar production (Gt), biochar carbon content (Gt) and CO_2 equivalent of carbon content (Gt) for each climate change with adaptation scenario (Scenario 9), over the 95 year period.

	Units	**95 year total values**			
Scenario 9		RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
9a (minimum temp)					
Total biochar	Pg	138.38	132.25	173.38	216.71
Total carbon	Pg	97.87	91.48	121.84	152.73
Total CO_2 equivalent of carbon in	Pg	359.20	335.75	447.16	560.51
9b (median temperature)					
Total biochar	Pg	138.38	132.26	172.79	214.90
Total carbon	Pg	97.87	91.49	121.42	151.45
Total CO_2 equivalent of carbon in	Pg	359.20	335.79	445.63	555.81
9c (maximum temperature)					
Total biochar	Pg	138.40	131.35	171.50	213.59
Total carbon	PgC	97.89	90.87	120.52	150.52
Total CO_2 equivalent of carbon in	$PgCO_2$	359.24	333.48	442.29	552.42
9d1 (Lowest yield projections, minimum temperature)					
Total biochar	Pg	138.38	131.68	170.93	211.64
Total carbon	PgC	97.87	91.09	120.11	149.15
Total CO_2 equivalent of carbon in	$PgCO_2$	359.20	334.31	440.81	547.37
9d2 (lowest yield projections, mean temperature)					
Total biochar	Pg	138.38	129.27	168.81	208.79
Total carbon	PgC	97.87	89.43	118.63	147.14
Total CO_2 equivalent of carbon in	$PgCO_2$	359.20	328.20	435.36	540.00

9d3 (lowest yield projections, maximum temperature)					
Total biochar	Pg	134.72	128.13	166.85	205.11
Total carbon	PgC	95.28	88.64	117.25	144.55
Total CO_2 equivalent of carbon in	$PgCO_2$	349.68	325.30	430.29	530.48
9e1 (highest yield projections, minimum temperature)					
Total biochar	Pg	138.38	133.33	177.09	224.34
Total carbon	PgC	97.87	92.23	124.46	158.11
Total CO_2 equivalent of carbon in	$PgCO_2$	359.20	338.48	456.76	580.26
9e2 (highest yield projections, mean temperature)					
Total biochar	Pg	138.38	136.74	178.93	223.51
Total carbon	PgC	97.87	94.58	125.74	157.52
Total CO_2 equivalent of carbon in	$PgCO_2$	359.20	347.12	461.47	578.12
9e3 (highest yield projections, maximum temperature)					
Total biochar	Pg	143.85	136.21	178.29	224.06
Total carbon	PgC	101.75	94.22	125.29	157.91
Total CO_2 equivalent of carbon in	$PgCO_2$	373.41	345.78	459.83	579.52

IV. Annexe 4: Carbon storage: Results tables

Table IV-1: Total carbon stored long-term after the addition of biochar to soils for the different scenarios developed in Chapter 3. The stored carbon values were calculated from the biochar production scenarios using the CS equation of Zhao et al. (2013).

	Total carbon stored long-term (GtC)			
Scenario	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
1	49.0	45.8	60.9	77.2
2a	38.2	29.8	36.0	35.6
2b	55.8	57.6	81.3	119.9
2c	49.0	43.6	60.9	77.2
3a	41.6	50.6	54.4	69.6
3b	46.7	40.0	54.4	77.2
4a1	45.0	38.5	54.2	71.3
4a2	20.3	18.2	23.0	28.5
4b	53.9	46.9	67.3	88.7
5a	29.3	28.9	37.1	46.2
5b	44.4	42.3	55.6	69.0
5c	59.6	55.7	74.2	91.8
5d	30.5	28.5	37.8	49.3
5e	39.2	36.2	48.5	62.3
6a	38.8	35.8	48.1	61.0
6b	97.9	90.1	121.1	153.6
7a	41.9	40.2	52.5	66.3
7b	50.5	48.4	63.2	79.8
7c	62.0	59.4	77.6	97.9

Table IV-2: Long term carbon storage potential of biochars using the two pool assessment methodology of Woolf et al. (2010) under different assumptions. The assumptions made are variances in the size of the labile and recalcitrant fractions, and in the half-lives of these pools.

RCP	L	R	$T_{1/2L}$	$T_{1/2R}$	T	CS
2.6			(years)	(years)	(years)	(GtC)
Variation in labile half-life						
Low labile half-life						
	0.15	0.85	1	300	100	66.0
	0.15	0.85	1	300	250	46.7
	0.15	0.85	1	300	500	26.2
	0.15	0.85	1	300	750	14.7
	0.15	0.85	1	300	1000	8.3
	0.15	0.85	1	300	1250	4.6
	0.15	0.85	1	300	1500	2.6
	0.15	0.85	1	300	1750	1.5
Main labile half-life assumption						

	0.15	0.85	20	300	100	66.5
	0.15	0.85	20	300	250	46.7
	0.15	0.85	20	300	500	26.2
	0.15	0.85	20	300	750	14.7
	0.15	0.85	20	300	1000	8.3
	0.15	0.85	20	300	1250	4.6
	0.15	0.85	20	300	1500	2.6
	0.15	0.85	20	300	1750	1.5
Long labile half-life						
	0.15	0.85	25	300	100	66.9
	0.15	0.85	25	300	250	46.7
	0.15	0.85	25	300	500	26.2
	0.15	0.85	25	300	750	14.7
	0.15	0.85	25	300	1000	8.3
	0.15	0.85	25	300	1250	4.6
	0.15	0.85	25	300	1500	2.6
	0.15	0.85	25	300	1750	1.5
Variation in recalcitrant half-life						
Low recalcitrant fraction half-life						
	0.15	0.85	20	50	100	21.3
	0.15	0.85	20	50	150	10.5
	0.15	0.85	20	50	200	5.2
	0.15	0.85	20	50	250	2.6
Main recalcitrant fraction half-life assumptions						
	0.15	0.85	20	300	100	66.5
	0.15	0.85	20	300	250	46.7
	0.15	0.85	20	300	500	26.2
	0.15	0.85	20	300	750	14.7
	0.15	0.85	20	300	1000	8.25
High recalcitrant fraction half-life						
	0.15	0.85	20	1000	100	78.1
	0.15	0.85	20	1000	250	70.0
	0.15	0.85	20	1000	500	58.8
	0.15	0.85	20	1000	750	49.5
	0.15	0.85	20	1000	1000	41.6
	0.15	0.85	20	1000	1250	35.0
	0.15	0.85	20	1000	1500	29.4
	0.15	0.85	20	1000	1750	24.7
	0.15	0.85	20	1000	2000	20.8
	0.15	0.85	20	1000	2500	14.7
	0.15	0.85	20	1000	3000	10.4
	0.15	0.85	20	1000	4000	5.2
Variation in labile fraction						
High labile fraction						
	0.3	0.7	20	300	100	55.3
	0.3	0.7	20	300	250	38.5

	0.3	0.7	20	300	500	21.6
	0.3	0.7	20	300	750	12.1
	0.3	0.7	20	300	1000	6.8
	0.3	0.7	20	300	1250	3.8
Low labile fraction						
	0.05	0.95	20	300	100	74.0
	0.05	0.95	20	300	250	52.2
	0.05	0.95	20	300	500	29.3
	0.05	0.95	20	300	750	16.4
	0.05	0.95	20	300	1000	9.2
	0.05	0.95	20	300	1250	5.2
	0.05	0.95	20	300	1500	2.9
Best and Worst Case Assumptions						
'Worst case' assumptions						
	0.3	0.7	1	50	100	17.1
	0.3	0.7	1	50	150	8.6
	0.3	0.7	1	50	200	4.3
	0.3	0.7	1	50	250	2.1
	0.3	0.7	1	50	300	1.1
'Best case' assumptions						
	0.05	0.95	25	1000	100	87.1
	0.05	0.95	25	1000	500	65.7
	0.05	0.95	25	1000	1000	46.5
	0.05	0.95	25	1000	2000	23.2
	0.05	0.95	25	1000	3000	11.6
	0.05	0.95	25	1000	4000	5.8
	0.05	0.95	25	1000	5000	2.9

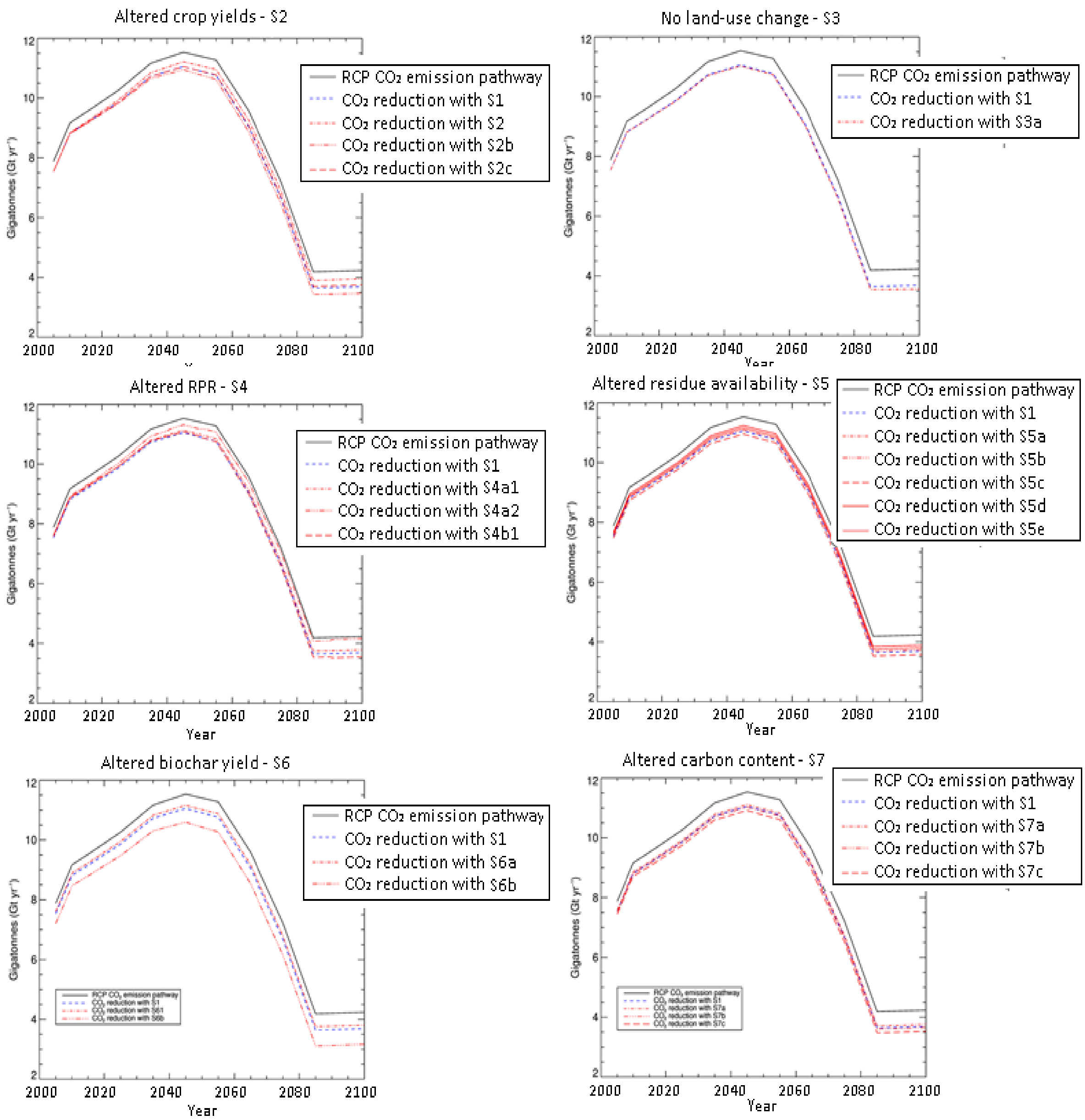

Figure IV-1: Potential emission reductions for RCP4.5, relative to the carbon emission pathway of projection RCP4 (black line). Blue line shows emissions reduction potential of Scenario 1 biochar assumptions. Other scenario assumptions shown are: top left, Scenario 2; top right, Scenario 3; mid-left, Scenario 4; mid-right, Scenario 5; bottom left, Scenario 6; bottom right, Scenario 7.

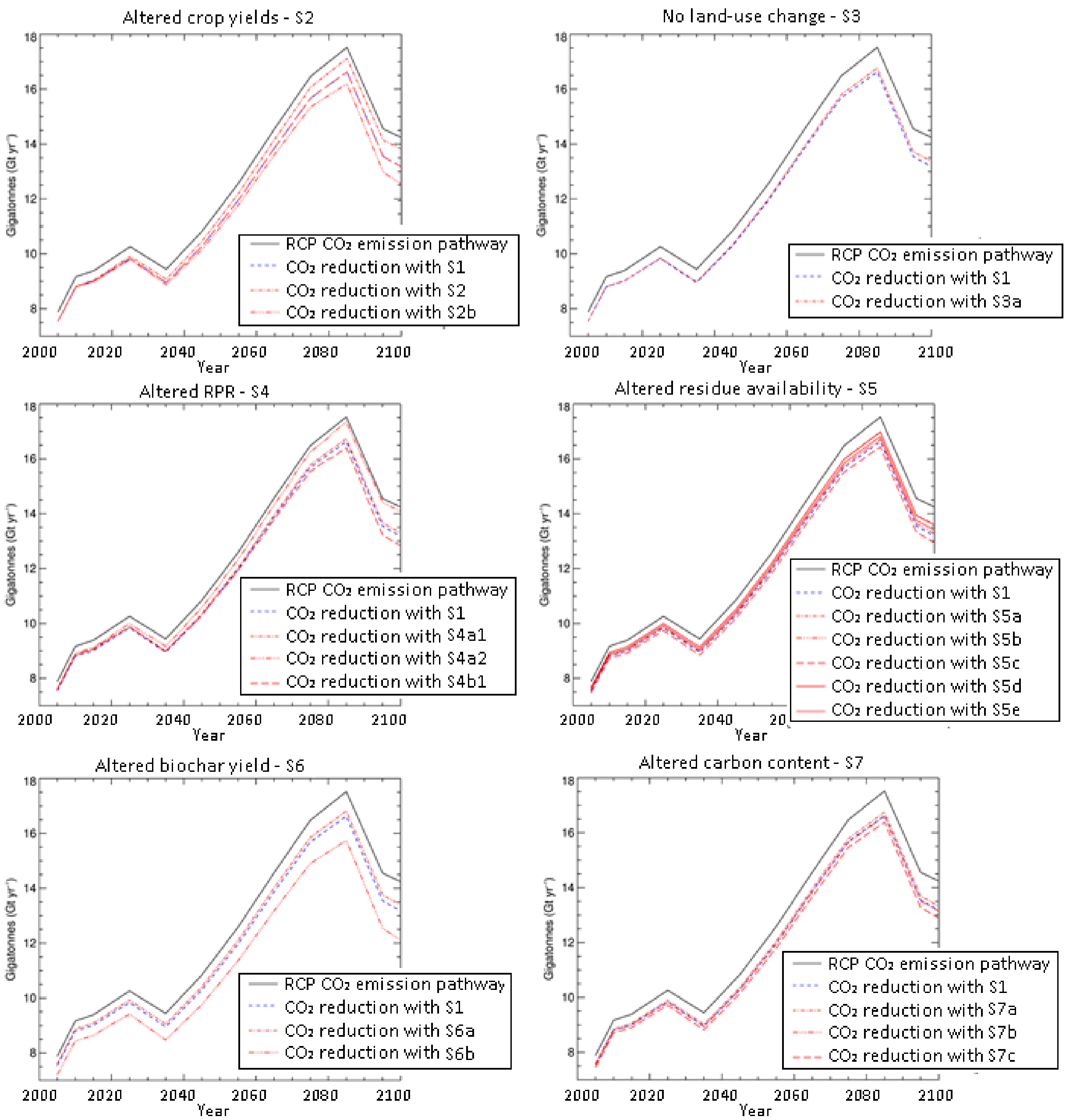

Figure IV-2: Potential emission reductions for RCP6, relative to the carbon emission pathway of projection RCP6 (black line). Blue line shows emissions reduction potential of Scenario 1 biochar assumptions. Other scenario assumptions shown are: top left, Scenario 2; top right, Scenario 3; mid-left, Scenario 4; mid-right, Scenario 5; bottom left, Scenario 6; bottom right, Scenario 7.

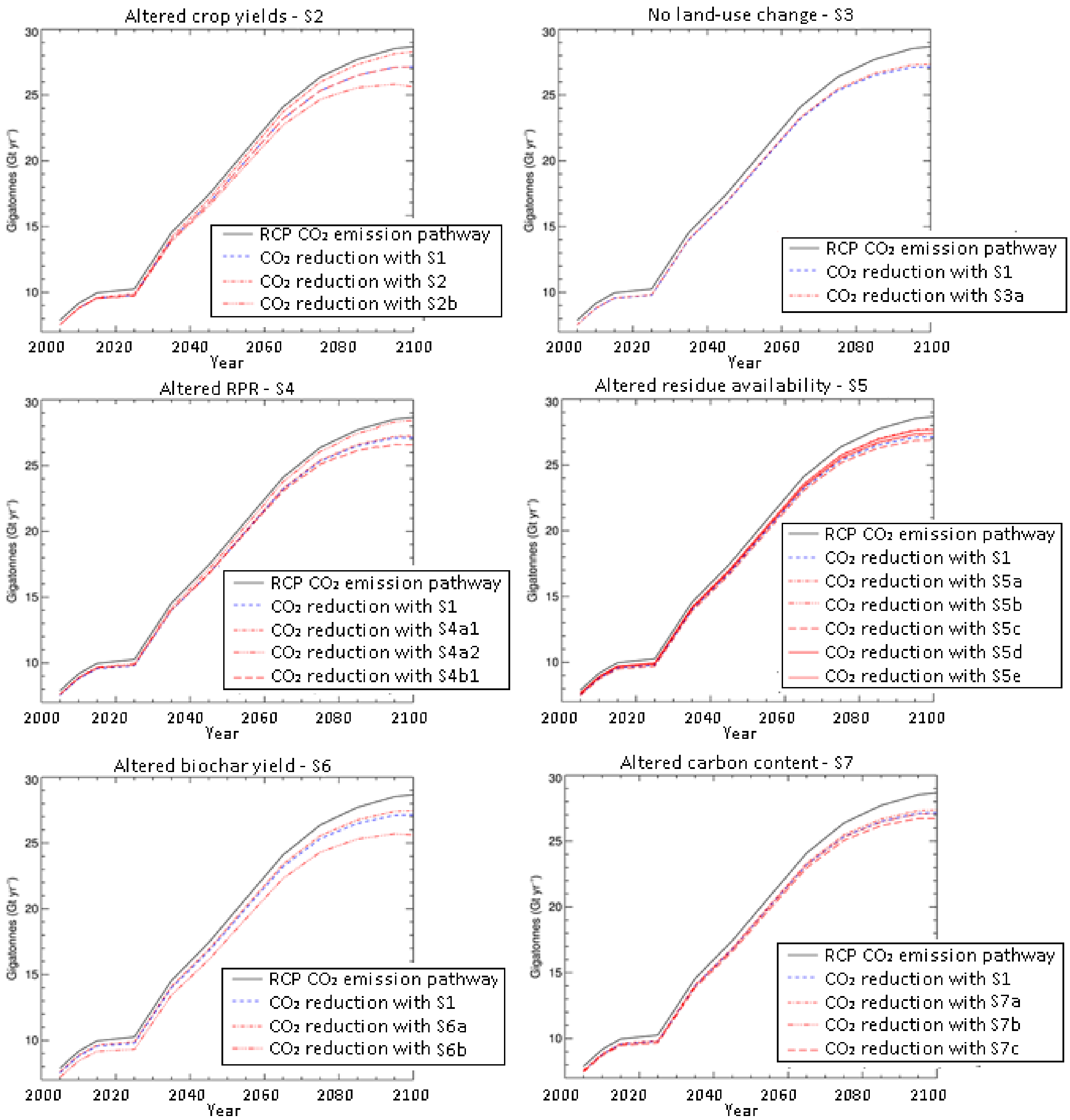

Figure IV-3: Potential emission reductions for RCP8.5, relative to the carbon emission pathway of projection RCP8 (black line). Blue line shows emissions reduction potential of Scenario 1 biochar assumptions. Other scenario assumptions shown are: top left, Scenario 2; top right, Scenario 3; mid-left, Scenario 4; mid-right, Scenario 5; bottom left, Scenario 6; bottom right, Scenario 7.

V. Annexe 5: Figure licences

Figure 6-2: Percentage grid cell area under cropland in 2000. Adapted from SEDAC (2014) was licenced for use here under the Creative Commons 3.0 Attribution Licence: http://creativecommons.org/licenses/by/3.0/legalcode

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Figures	Figure 1 | Average yield gaps for maize, wheat and rice. These were measured as a percentage of the attainable yield achieved circa the year 2000. Yield gap in each grid cell is calculated as an area-weighted average across the crops and is displayed on the top 98% of growing area.
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License Number	3443050549334
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Number of figures/tables/illustrations	1
High-res required	no
Figures	Figure 2 | Global maps of current crop yield trends. At each political unit where (a) maize, (b) rice, (c) wheat and (d) soybean crop yields were tracked globally, we determined the status of their current yield trend. The trends were divided into the six categories and colour coded.We show in the maps only those areas in the political unit where the crop was harvested.
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