

**ENVIRONMENTAL AND ECONOMIC IMPACT ASSESSMENT OF BIOCHAR-BASED
BIOENERGY PRODUCTION IN NORTHWESTERN ONTARIO, CANADA**

By

Krishnahari Homagain

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ABSTRACT

Homagain, K. 2016. Environmental and Economic Impact Assessment of Biochar-Based Bioenergy Production (BBBP) in Northwestern Ontario, Canada

Bioenergy is becoming very popular in Ontario with the 2014 ban on the use of coal in power generation. Biochar is produced as a by-product or a co-product of bioenergy. Past literature shows that if biochar is produced as a co-product with bioenergy from sustainably managed forests and used for soil amendment, it could provide a carbon neutral or even carbon negative solution for current environmental problems. It also shows that detailed life cycle assessment (LCA) and life cycle cost assessment (LCCA) that compares the potential environmental and economic impacts of BBBP system with those of conventional coal-based system is missing. This study fills that gap by assessing environmental and economic implications of a BBBP system in northwestern Ontario throughout its lifecycle using SimaPro® Ver. 8.1, EIOLCA® software and spreadsheet modeling. Under the assumption that only forest residues and/or under-utilized species are used, results show that although a system including biochar based land application consumes 4,847 MJ t⁻¹ dry feedstock more energy than the conventional coal-based system, it reduces the GHG emissions by 68 kgCO_{2e} t⁻¹ dry feedstock during its life cycle. It also improves the ecosystem quality by 18%, reduces global warming potential by 15%, and resource use by 13% but may impact human health by increasing disability adjusted life years (DALY) by 1.7% if biomass availability is low to medium. The economic viability of this BBBP system, within the LCA system boundary, is directly dependent on the costs of pyrolysis, feedstock processing (drying, grinding and pelletization), feedstock collection and the value of total carbon offset provided by the system. The BBBP system is economically viable only in case of high biomass availability within 200km and when the cost of carbon sequestration exceeds C\$60 t⁻¹ of CO_{2e}. The environmental and economic impact assessment results developed through this study, can be scaled up to a larger regional scale which is expected to help in reinforcing the confidence of industries and its partners in promoting BBBP systems and the use of biochar as a soil amendment in the region.

KEYWORDS

Biochar, Bioenergy, Biochar-based Bioenergy, Biomass feedstock, CO_{2e}, Economic analysis, EIOLCA®, Forest biomass, Lifecycle Assessment (LCA), Lifecycle Cost Assessment (LCCA), Northwestern Ontario, SimaPro®, Soil amendment

LIST OF PAPERS

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CONTENTS

ABSTRACT	II
KEYWORDS	II
LIST OF PAPERS	III
TABLES	VI
FIGURES.....	VII
FOREWORD AND ACKNOWLEDGEMENT	VIII
CHAPTER 1 INTRODUCTION	1
THESIS RATIONALE AND OVERVIEW	1
THEORETICAL FRAMEWORK	7
<i>Biochar-Based Bioenergy and carbon negativity</i>	7
<i>Life Cycle Assessment</i>	8
<i>Benefits of conducting LCA</i>	12
<i>Life Cycle Environmental Impact Assessment</i>	9
<i>Limitations of conducting LCA</i>	13
<i>Life Cycle Cost and Economic Assessment</i>	14
RESEARCH OBJECTIVES.....	15
CHAPTER 2.....	16
PAPER 1: BIOCHAR-BASED BIOENERGY AND ITS ENVIRONMENTAL IMPACT IN NORTHWESTERN ONTARIO CANADA: A REVIEW.....	16
ABSTRACT	16
INTRODUCTION.....	17
METHODS	22
REVIEW RESULTS	23
<i>Biochar production potential in Northwestern Ontario</i>	23
<i>Biochar effects on soil properties and productivity</i>	28
<i>Environmental impacts and life cycle assessment of Biochar</i>	34
<i>Economics of biochar based bioenergy production</i>	39
RESEARCH NEEDS AND POTENTIAL ENVIRONMENTAL IMPACT ASSESSMENT METHODS....	41
CONCLUSIONS	43
REFERENCES	44
CHAPTER 3.....	45
PAPER 2: LIFE CYCLE ENVIRONMENTAL IMPACT ASSESSMENT OF BIOCHAR-BASED BIOENERGY PRODUCTION AND UTILIZATION IN NORTHWESTERN ONTARIO, CANADA.....	45
ABSTRACT	45
INTRODUCTION.....	46
MATERIALS AND METHODS.....	51
<i>Goal and Scope definition</i>	51
LCA System Boundary and Functional Unit.....	51
Study location and case assumptions	52
<i>Inventory analysis</i>	53
Raw material collection.....	53
Transportation at different stages	53
Biochar production	54
Storage	54

Land application	54
<i>Impact assessment</i>	54
<i>Interpretation</i>	56
<i>Life cycle net energy analysis</i>	56
RESULTS	59
<i>Life-cycle inventory</i>	59
<i>Net energy and GHG emissions</i>	61
<i>Environmental impacts</i>	62
<i>Sensitivity analysis</i>	64
DISCUSSION	65
CONCLUSIONS	67
REFERENCES	68
CHAPTER 4.....	69
PAPER 3: LIFE CYCLE COST AND ECONOMIC ASSESSMENT OF BIOCHAR-BASED BIOENERGY PRODUCTION AND BIOCHAR LAND APPLICATION IN NORTHWESTERN ONTARIO, CANADA.....	69
ABSTRACT	69
INTRODUCTION.....	71
METHODS	74
<i>LCCA System Boundary, Study area and Analysis Scenarios</i>	75
<i>Life Cycle Costing and Net Present Value</i>	77
RESULTS.....	81
DISCUSSION	85
CONCLUSION.....	88
<i>Acknowledgments</i>	89
<i>Authors' contributions</i>	89
<i>Authors' information</i>	90
<i>Competing interests</i>	90
<i>List of abbreviations and definitions</i>	90
REFERENCES	92
CHAPTER 5 BIOENERGY, BIOCHAR AND SUSTAINABILITY: A SYNTHESIS.....	93
THESIS SUMMARY.....	93
SPECIFIC CONCLUSIONS	96
GENERAL CONCLUSIONS	99
SIGNIFICANCE OF THE STUDY	102
REFERENCES.....	103

TABLES

Table 2. 1 Woody biomass availability (million t yr ⁻¹) in Northwestern Ontario	24
Table 2. 2 Properties of biochar produced from fast and slow pyrolysis techniques ...	25
Table 2. 3 Variability of different biomass feedstock composition	27
Table 2. 4 Nutrient content of selected biochars	29
Table 2. 5 Impact of biochar application on crop yield	31
Table 2. 6 Summary of ecosystem benefits of biochar application	33
Table 2. 7 Environmental impacts of biochar application	35
Table 2. 8 Life cycle analysis studies covered in this review	37
Table 3. 1 Inventory data and general assumptions of study	57
Table 3. 2 Life-cycle inventory for biochar production from forest biomass feedstock	60
Table 3. 3 Net energy and GHG emissions per tonne dry feedstock comparison	61
Table 3. 4 Comparative environmental impact potential per t of biochar produced	63
Table 3. 5 Life cycle impacts of biochar-based bioenergy per t of biochar produced ..	64
Table 4. 1 Life Cycle Cost Assessment Scenarios	77
Table 4. 2 Description of specific cost information	80

FIGURES

Figure 1. 1 Carbon negativity of biochar-based bioenergy	7
Figure 1. 2 Life cycle stages.....	10
Figure 1. 3 The life cycle analysis model.....	11
Figure 1. 4 Conceptual framework of environmental LCC.....	14
Figure 2. 1 Study spectrum and number of studies covered in this paper.....	22
Figure 2. 2 Number of studies reviewed in different regions	23
Figure 3. 1 System boundary for LCA of biochar-based bioenergy production	52
Figure 3. 2 Sensitivity analysis of biomass feedstock availability	65
Figure 4.1 System boundary for LCCA of biochar-based bioenergy production.....	75
Figure 4. 2 Average annual life cycle cost inventory (undiscounted).....	81
Figure 4. 3 Annual (undiscounted) and present value (discounted) of biochar-based bioenergy	82
Figure 4. 4 Cumulative life cycle cost (undiscounted) for 25-yr project period	83
Figure 4. 5 Sensitivity of rate of return for biochar based bioenergy system	84
Figure 4. 6 Life cycle break-even analysis of 1-mwh biochar-based bioenergy system	85

FOREWORD AND ACKNOWLEDGEMENT

This dissertation is formatted as a series of journal articles as per direction from my committee. While each individual chapter in this thesis is self-contained, the dissertation as a whole is an integrated piece of work, with linkages throughout.

Although I am the author for chapters 1 and 5 (Introduction and Conclusions, respectively), Chapters 2, 3 and 4 were scripted for peer-review journal submission, and co-authored with my graduate committee members - Drs. Chander Shahi, Nancy Luckai, and Mahadev Sharma. Each of these scholars brought a unique aptitude to the table as they mentored me and helped me to navigate the PhD discourse.

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Krish Homagain,
Timmins, Ontario

CHAPTER 1 INTRODUCTION

Krishnahari Homagain*

* Lakehead University, Faculty of Natural Resources Management, 955 Oliver Road, Thunder Bay, Ontario, Canada P7B 5E1

THESIS RATIONALE AND OVERVIEW

Ever increasing global demands for energy and concerns for the sustainability of planet earth and its natural resources have dictated the use of bioenergy¹ in various forms. Bioenergy is one of the largest renewable energy sources, which provides about 10% of world primary energy supply (IEA 2015). Most bioenergy is consumed in developing countries for cooking and heating, using mostly inefficient open fires or simple cookstoves, with considerable impact on health (smoke pollution) and the environment (deforestation). Although modern bioenergy supply is comparably small, it has been growing steadily at the rate of about 3% per year in the last decade. One of the most significant areas of modern bioenergy is bioelectricity², which accounts for about 2% of world's electricity production as of 2014 (IEA 2015). Bioelectricity is considered to be more carbon friendly than conventional coal based electricity as it replaces the use of fossil fuel (mainly coal) based energies from the energy production

¹ Bioenergy is the energy derived from the conversion of biomass where biomass may be used directly as fuel, or processed into liquids and gases.

² Electricity generated from bioenergy

system. Several technologies for generating bioenergy heat and power already exist; these range from solid wood heating systems for buildings to biogas digesters for power generation and large-scale biomass gasification plants for heat and power. Co-firing biomass with coal in existing coal-fired power plants is also becoming an important option to achieve short-term emission reductions and make more sustainable use of existing assets. In addition, new improved bioenergy plants with pyrolysis³ systems are becoming increasingly common in meeting growing demand for bioelectricity and biochar⁴. In woody biomass⁵ rich regions, like Ontario and Canada, there have been several bioenergy initiatives to comply with Canada's commitment to reducing climate change and in line with Ontario's Green Energy Act. This trend will increase in coming years as the province of Ontario formally banned the use of coal for power generation effective 2014 Dec 31. Use of biomass-based feedstocks especially from agriculture and forestry has been popular in recent years. Northwestern Ontario (NWO), in particular, has a rich and sustainable source of woody biomass supply through the sustainable management of about 12 million ha of productive forest through 18 Forest Management Plans (MNR 2015). Several previous studies (Alam et al. 2012;

³ Pyrolysis is a thermal degradation process producing heat, bio-oil, syngas and biochar in the absence of oxygen (Spokas et al. 2012)

⁴ Biochar is a porous and stable carbon-rich co-product of the pyrolysis process that has diverse uses including soil amendments and long term carbon sequestration (Lehmann et al. 2006). Biochar differs from charcoal in the sense that it is not used as fuel. Although biochar can be produced from a variety of biomaterials in a variety of ways, in this paper we refer only to biochar produced from woody biomass in a bioenergy plant.

⁵ Biomass is any organic, i.e. decomposable, matter derived from plants or animals available on a renewable basis. Biomass includes wood and agricultural crops, herbaceous and woody energy crops, municipal organic wastes as well as manure. Within the scope of this thesis, biomass refers to the woody materials derived from sustainably managed forests of northwestern Ontario, Canada in the form of harvest residue, sawmill residue and underutilized trees.

Hacatoglu et al. 2011; Kennedy et al 2011; Wood and Layzell 2003) have also indicated that the NWO forests are capable of sustainably supplying enough biomass feedstock to generate electricity from power-generating stations, which used coal as feedstock until 2014. Therefore the study area for this dissertation is chosen to be within Northwestern Ontario, Canada.

Use of woody biomass in producing bioenergy is becoming a common practice elsewhere in the world as agriculture grain based biofuel is facing criticism from food security experts (Elbehri et al. 2013). Production of bioenergy as a stand-alone product (e.g. heat, biofuel etc.) from woody biomass is technically viable but may not be financially sustainable (Stephen 2013). A trade-off between different co-products of bioenergy and biochar is widely considered as one of the GHG emission reduction strategies given that land application of biochar sequesters the carbon for a relatively very long time. An effective implementation of biochar as a climate-change mitigation tool would however require an application of massive quantities of biochar into the environment (Biederman and Harpole 2013), which may result in its exposure to non-target terrestrial and aquatic systems as wind and water can erode up to 50% of applied biochar material during application (Major et al. 2010). Therefore, a comprehensive study of biochar-based bioenergy production (BBBP) and its subsequent application to land is required to assess its potential environmental and economic impacts. Ideally, such a study would include every stage of production and utilization of the product in its life cycle. Woody biomass can be converted into bioenergy (heat or electricity) or energy carriers (char, oil or gas) by different thermochemical and biochemical conversion technologies (Van-Loo and Koppejan 2008).

Life cycle assessment (LCA, also known as life-cycle analysis or ecobalance) is a standard technique (ISO 14040: 2006 series) to assess environmental impacts associated with all stages of a product's life from cradle-to-grave (i.e. from raw material extraction through materials processing, manufacturing, distribution, use, repair and maintenance, and disposal or recycling) (Afrane and Ntiamoah 2011). A few studies have also used LCA to compare GHG mitigation and direct carbon sequestration potential of biochar produced from different feedstocks (Hammond et al. 2011; Roberts et al. 2010; Gaunt and Lehmann 2008; Woolf et al. 2010).

Although these studies conclude that all biochar systems have GHG mitigation and direct carbon sequestration potential, there exists an inherent trade-off between bioenergy and biochar production (Fowles 2007). The typical tradeoff is less biochar yield if bio-oil and syngas is preferred and vice versa. Cost of bioenergy production is being high when compared to coal-based electricity production as these new systems are expensive to install and run. In many cases, economic incentives are currently needed to off-set cost differences between bioenergy and fossil fuel-generated electricity. Such support is justified by the environmental, energy security and socio-economic advantages associated with sustainable bioenergy, but should be introduced as a transitional measure leading to cost competitiveness in the medium term. Support measures should be backed by a strong policy framework which balances the need for energy with other important objectives such as greenhouse-gas reduction, food security, biodiversity, and socio-economic development.

Therefore, this thesis, with a detailed life cycle assessment, life cycle cost assessment and economic analysis of proposed biochar-based bioenergy intervention, provides a comprehensive environmental impact of utilizing biochar based bioenergy system in Northwestern Ontario. This chapter includes a general rationale of the study, provides a theoretical basis for biochar-based bioenergy systems and environmental impacts in terms of life cycle assessment, life cycle cost assessment and economic analysis along with thesis objectives.

Chapter 2, 3 and 4 have been prepared as separate independent peer-reviewed journal papers. Two of these have already been published in the Springer Journal of Forestry Research and the third one is accepted with minor revision in the Journal of Forest Ecosystems. Because of the independent nature of the peer-review article, some of the background information, study rationale and research analysis information are interlinked and repeated in multiple places. In individual papers, some research context and processes are overly summarized and some are a little bit elaborated during the peer review process.

Chapter 2 deals with a comprehensive review of biochar production as a co-product of bioenergy and its implications. The review focused on biochar production with reference to biomass availability and sustainability, and on biochar utilization for its soil amendment and greenhouse gas emissions reduction properties. It further explored Northwestern Ontario's supply of biomass feedstock that can be used to produce biochar-based bioenergy and its possible land application with the purpose of replacing fossil fuel consumption, increase soil productivity and sequester carbon in the long run.

Chapter 3 provides a thorough life cycle assessment of biochar-based bioenergy production and biochar's land application in Northwestern Ontario by using ISO standard SimaPro® Ver. 8.1 software. The energy consumption and potential environmental impact of biochar-based bioenergy production system are assessed and compared with those of conventional coal-based system.

Similarly, Chapter 4 contains a comprehensive life cycle cost and economic assessment of biochar-based bioenergy production for Northwestern Ontario, Canada. By using SimaPro®, EIO LCA® software and spreadsheet modeling, this assessment compared biochar-based bioenergy production and its land application under four different scenarios: i) biochar production with low feedstock availability; ii) biochar production with high feedstock availability; iii) biochar production with low feedstock availability and its land application; and iv) biochar production with high feedstock availability and its land application. It also includes an economic assessment for the break-even and viability of a medium scale slow-pyrolysis biochar-based bioenergy technology over 25 year project period.

Finally, Chapter 5 synthesizes the findings of the three papers and presents conclusions, critiques and implications of this study based on life cycle assessment of biochar-based bioenergy production and biochar's land application in Northwestern Ontario.

THEORETICAL FRAMEWORK

Biochar-Based Bioenergy and carbon negativity

Bioenergy production is based on the principle of carbon neutrality as it releases the same amount of carbon that the plant absorbed during the process of photosynthesis. Biochar-based bioenergy converts carbon into a more stable form. Biochar is highly resistant to decay thus storing the remaining carbon and preventing re-release to the atmosphere (Lehman 2007). Because biochar is thought to remain stable for up to several hundred years, the input cycle (i.e. the growth and harvest of biomass) can occur many times with the outcome that the whole system becomes a carbon-negative process (Figure 1.1).

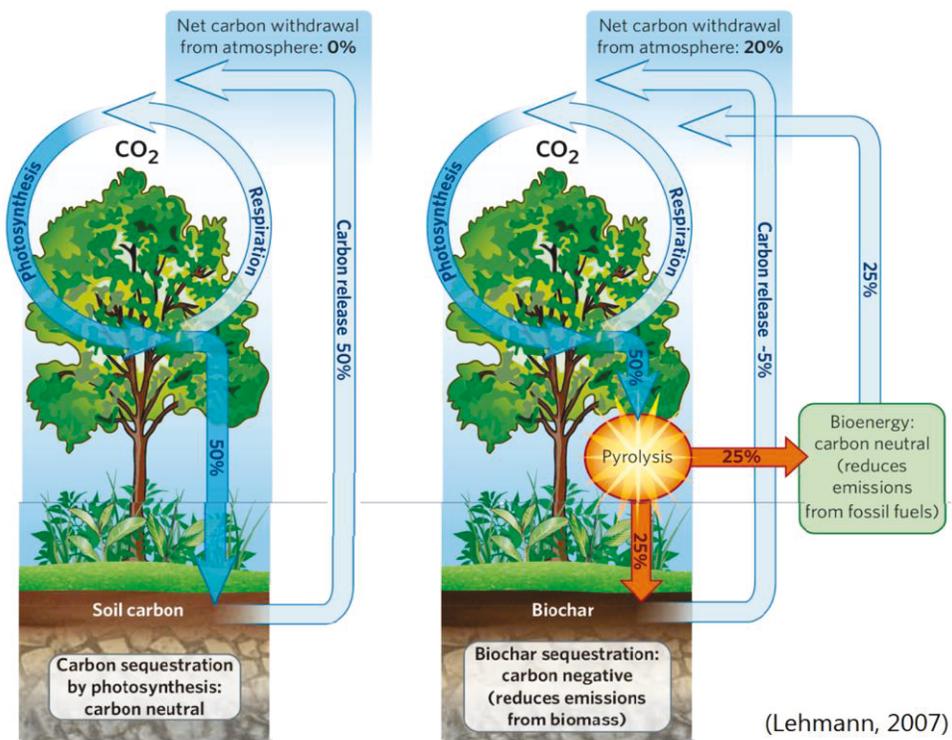


Figure 1. 1 Carbon negativity of biochar-based bioenergy

Life Cycle Assessment

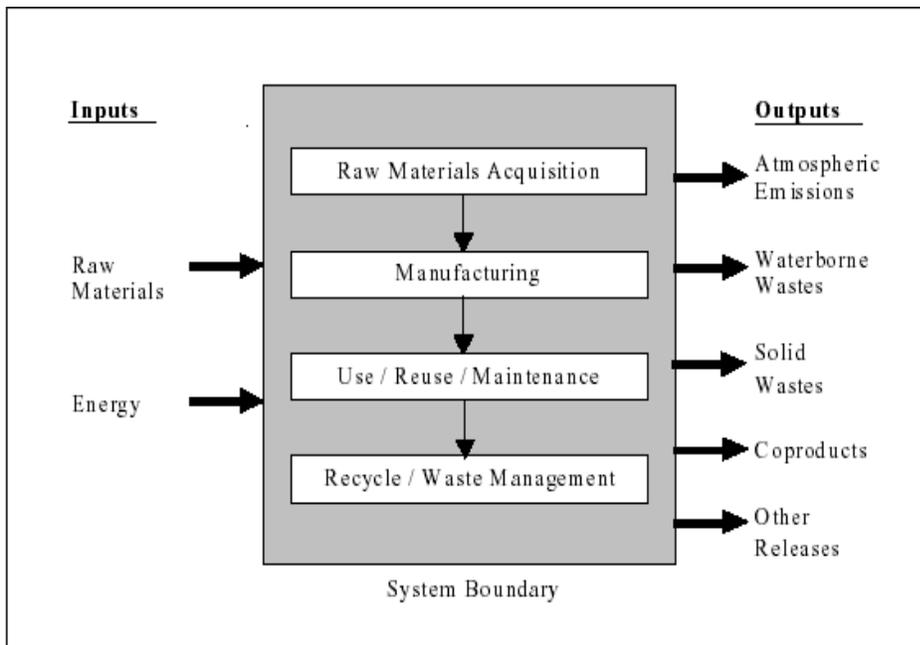
LCA is an environmental assessment tool used to quantify potential environmental burdens throughout the life cycle of a product or service. The life cycle stages of a product include extraction and processing of raw materials, manufacture, transportation, distribution, use/re-use/maintenance, recycling, final disposal, and transport at all stages. Assessment is done by compiling relevant inputs and outputs of the product system and calculating the possible associated impacts. The environmental impacts are calculated based on a functional unit which provides a reference for both the inputs and outputs. The magnitude of overall environmental impacts can be used to evaluate environmental performance of the product.

The environmental impact categories assessed in LCA can be divided into three main groups: resource depletion, human health impacts and ecosystem consequences. The LCA methodology, as described in ISO 14040 series, comprises four phases: Goal and scope definition, Inventory analysis, Impact assessment, and Interpretation (Figure 1.3). While conducting LCA, the objectives and intended application of the LCA study, the system boundary and the methodological choices are identified in the Goal and scope definition phase. The environmental inputs and outputs associated with the product system are quantified in the Inventory analysis phase, and the results are used to calculate the potential environmental impacts in the Impact assessment phase. The results of the Inventory and Impact assessment phases are analyzed in the Interpretation phase and recommendations for environmental improvement suggested.

Life Cycle Environmental Impact Assessment

An environmental impact is a change to the environment that is caused either partly or entirely by one or more environmental aspects such as water pollution, air quality deterioration etc. An environmental aspect can have either a direct and decisive impact on the environment or contribute only partially or indirectly to a larger environmental change. In addition, it can have either a beneficial or an adverse environmental impact. The term “life cycle” refers to the major activities in the course of the product’s life-span from its manufacture from raw materials, use, and maintenance, to its final disposal. Figure 1.2 illustrates the possible life cycle stages that can be considered in an LCA and its typical inputs/ outputs measurements (SAIC, 2006). It is a “Cradle-to-Grave” approach for assessing any industrial system’s environmental performance which begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. A life cycle assessment is also defined as a comprehensive analysis of the environmental burdens and impacts incurred when a specific goal or project is realized (BASF 2000).

LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service, by: i) Compiling an inventory of relevant energy and material inputs and environmental releases; ii) Evaluating the potential environmental impacts associated with identified inputs and releases; and iii) Interpreting the results to help decision-makers make a more informed decision.



Source: (EPA 1997)

Figure 1. 2 Life cycle stages

Life cycle assessment is a systematic and phased approach and consists of four components: goal definition and scoping, inventory analysis, impact assessment, and interpretation as illustrated in Figure 1.3.

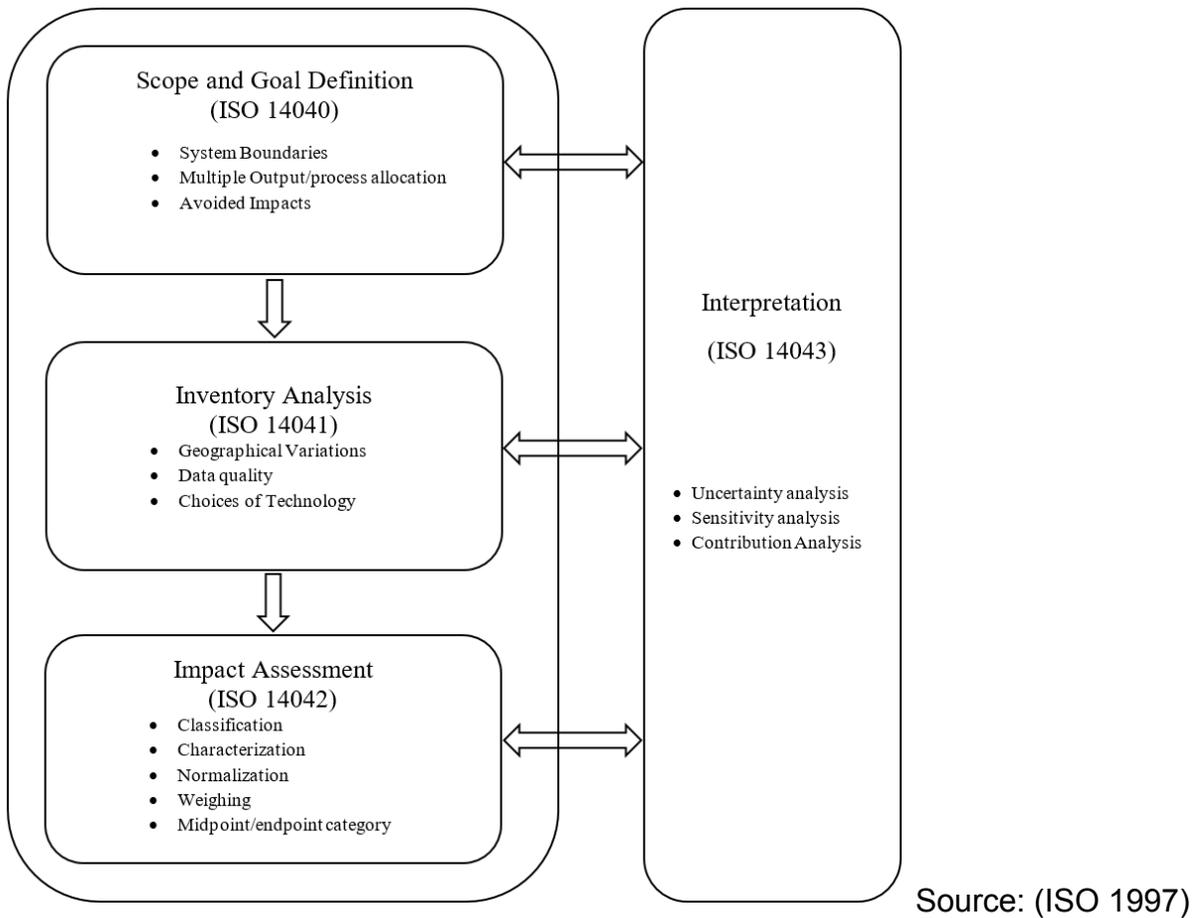


Figure 1. 3 The life cycle analysis model

Stage 1 Goal Definition and Scoping: Define and describe the product, process or activity. Establish the context in which the assessment is to be made and identify the boundaries and environmental effects to be reviewed for the assessment.

Stage 2 Inventory Analysis: Identify and quantify energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges).

Stage 3 Impact Assessment: Assess the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.

Stage 4 Interpretation: Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and assumptions used to generate the results.

Benefits of conducting LCA

Life cycle assessment, along with cost and performance data, can support management in the selection of a product or process that results in the least impact to the environment. LCA data identifies the transfer of environmental impacts from one medium to another (e.g. eliminating air emissions by creating a wastewater effluent instead) and/or from one life cycle stage to another (e.g. from end use of a sawmill residue to the wood pellet raw material collection phase). If a detailed LCA is not performed, the transfer impacts might not be recognized and properly included in the analysis because it is outside of the typical scope or focus of product selection processes.

Life cycle analysis gives a more complete picture of the waste and energy associated with a product. Rather than just looking at the amount of waste that ends up in a landfill or an incinerator, life cycle analysis is a cradle-to-grave approach which measures energy use, material inputs and waste generated (in terms of carbon and other emissions) from the raw materials collection to the final disposal of the product

into the environment after the end use. Adding life cycle assessment to the decision-making process offers an understanding of the human health and environmental impacts that is not considered conventionally when selecting a product or process. This valuable information offers a way to account for the full impacts of decisions, especially those that arise outside of the particular stage that are directly influenced by the selection of a product or process. It should be mentioned here that LCA is only a tool to better inform decision-makers and should always be included with other decision criteria such as cost and economic assessment, to make a well-balanced and widely informed decision.

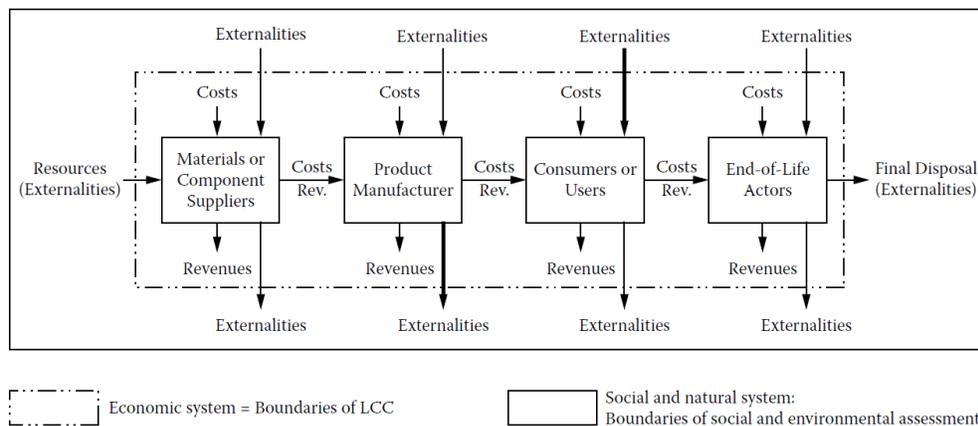
Limitations of conducting LCA

Performing an LCA can be resource and time intensive. Depending upon how exhaustive an LCA we wish to conduct, gathering the data can be challenging as life cycle inventories (LCI) are not developed for each region/ country and the availability of data can greatly impact the accuracy of the final results. Therefore, it is important to balance the availability of data, the time necessary to conduct the study, and the financial resources required against the projected benefits. LCA will not govern which product or process is the most cost effective or works the best. Therefore, the information developed in an LCA study should be used as a component of a more comprehensive decision process that assesses the trade-offs between cost and performance (e.g., Life Cycle Management). A life cycle assessment is a snapshot of the conditions prevailing at a particular time and place at which the data were collected.

Any future improvements that may be introduced after the life cycle inventory cannot be taken into consideration.

Life Cycle Cost and Economic Assessment

Environmental life cycle costing (LCC) is a process to summarize and appraise all costs associated with the life cycle of a product that are directly covered by one or more of the stages in that life cycle (e.g. production, transportation or consumption) and those involved at the end of a product or service's life. LCC should include externalities that are expected to be adopted in the decision-relevant future interventions. A complementary life cycle assessment (LCA), with the same or comparable system boundaries and functional units, is a pre-requisite for LCC. It is performed on a basis analogous to that of LCA, with both being steady-state in nature. Figure 1.4 shows a conceptual framework of environmental LCC model for the life cycle cost analysis (LCCA).



Source: (Rebitzer and Hunkeler 2003)

Figure 1. 4 Conceptual framework of environmental LCC

In many cases LCC is further supplemented by a comparative economic assessment which in turn helps analyze the return on investment of a particular intervention.

RESEARCH OBJECTIVES

With the use of life cycle assessment, life cycle cost assessment and economic analysis this dissertation assesses the environmental and economic impacts of biochar production from woody biomass and its application as a soil amendment in Northwestern Ontario, Canada. The first objective is to identify the knowledge gaps in the published literature by documenting the current state of knowledge relating to the potential for biochar production as a co-product of bioenergy using woody biomass in Northwestern Ontario and to relate this knowledge nationally and globally looking outside of Ontario when necessary for insights into the Ontario context. The second objective is to conduct a comprehensive life cycle assessment (LCA) of a Biochar-Based Bioenergy Production system with biochar land application as a soil amendment in Northwestern Ontario by comparing greenhouse gas emission, net energy and global warming potential. This life cycle assessment will be further analyzed in the third objective by conducting a life cycle costing (LCCA) based economic analysis of a BBBP system in Northwestern Ontario.

Finally the LCA and LCCA results will be synthesized as the fourth objective to generate a comprehensive environmental and economic impact assessment tool for biochar-based bioenergy production in Northwestern Ontario.

CHAPTER 2

PAPER 1: BIOCHAR-BASED BIOENERGY AND ITS ENVIRONMENTAL IMPACT IN NORTHWESTERN ONTARIO CANADA: A REVIEW

Krish Homagain*¹ • Chander Shahi • Nancy Luckai • Mahadev Sharma

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ABSTRACT

Biochar is normally produced as a by-product of bioenergy. However, if biochar is produced as a co-product with bioenergy from sustainably managed forests and used for soil amendment, it could provide a carbon neutral or even carbon negative solution for current environmental degradation problems. In this paper, we present a comprehensive review of biochar production as a co-product of bioenergy and its implications. We focus on biochar production with reference to biomass availability and sustainability and on biochar utilization for its soil amendment and greenhouse gas emissions reduction properties. Past studies confirm that Northwestern Ontario has a sustainable and sufficient supply of biomass feedstock that can be used to produce

The online version is available at <http://www.link.springer.com>

*¹ Krish Homagain

Faculty of Natural Resources Management, Lakehead University, 955 Oliver Road, Thunder Bay, ON, Canada P7B 5E1.
E-mail: khomagai@lakeheadu.ca; (807) 343 8665

Chander Shahi, Nancy Luckai

Faculty of Natural Resources Management, Lakehead University, 955 Oliver Road, Thunder Bay, ON, Canada P7B 5E1.

Mahadev Sharma

Ministry of Natural Resources, Ontario Forest Research Institute (OFRI), 1235 Queen St E, Sault Ste. Marie, ON, Canada P6A 2E5.

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bioenergy, with biochar as a co-product that can replace fossil fuel consumption, increase soil productivity and sequester carbon in the long run. For the next step, we recommend that comprehensive life cycle assessment of biochar-based bioenergy production, from raw material collection to biochar application, with an extensive economic assessment is necessary for making this technology commercially viable in Northwestern Ontario.

Keywords: biomass, life cycle assessment, LCA, CO₂, carbon sequestration, greenhouse gas emissions, soil amendment.

INTRODUCTION

The earth has sustained hazardous and rapid climate change patterns due to anthropogenic carbon dioxide (CO₂) emissions that have been rising by more than 3% annually since 2000 (Solomon et al. 2009; Raupach et al. 2007). Climate change and global warming have been among the most important and widely debated issues for the last decade and will continue to be so for many years to come. Anthropogenic CO₂ is responsible for about 25% of the total greenhouse gas (GHG) emissions in the atmosphere (Cherubini and Stromman 2011), and its current global level (385ppm of CO₂) has already exceeded the safe limit (350ppm of CO₂) for human beings (Rockstrom et al. 2009). As a result, global environmental changes including severe weather events (like flood and drought) and land degradation have posed immediate threats to biodiversity and productivity at the same time that demands for food and energy are increasing worldwide (Eriksen et al. 2009). The International Energy Agency

predicts that world demand for energy will double by 2035 (IEA 2012). At present, most of the energy demand is being met through the use of non-renewable energy sources (e.g. fossil fuels), which are in fact the most significant contributors of GHG emissions.

Canada is one of the highest energy using countries per capita (16,800 kWh household⁻¹ year⁻¹), next only to Iceland and Norway (Nepal et al. 2012). About 15% of this energy is being generated by coal-fired generating stations, which are responsible for 11% of Canada's total GHG emissions and 77% of GHG emissions from the heat and electricity sector alone (EC 2011). In the province of Ontario, coal fired power generating stations working at 10% of the installed capacity meet 2.7% of the total energy demand (IESO 2013), but produce more than 50% of GHG emissions from the electricity sector (EC 2012). In order to reduce the GHG emissions from coal-fired power generating stations, the Ontario Government decided to replace coal with biomass as a feedstock by the end of 2014 (MOE 2010, MOE 2010a). Ontario Power Generation's (OPG) Atikokan Generating Station (AGS) in Northwestern Ontario is being converted to use 100% wood pellet feedstock using forest biomass. The converted AGS with an installed capacity of 230 megawatts will be the largest (Basso et al. 2013) 100% biomass fueled power plant in North America (OPG 2012) requiring about 90,000 tonnes of wood pellets annually. The converted AGS plant will supply renewable energy, on demand peak capacity power, and create about 200 jobs. Therefore, the use of woody biomass feedstock for power generation not only has the potential to address the environmental problems related to air pollution and climate change but also ensures energy security for local communities (BioCAP 2008). However, concerns have been raised about the sustainability of the supply of woody

biomass to AGS and other power generating stations, without causing any negative environmental impacts.

Productive forest on Ontario Crown land in the managed forest area (Area of Undertaking or AOU) covers about 26.2 million hectares with a significant portion located within the boreal. About 18.8 million hectares of this area are eligible for forest management activities. Studies on forest based fibre availability suggest that Ontario has enough surplus biomass available (Wood and Layzell 2003; OPG 2011) to meet the AGS's requirements. There are 18 actively operating forest management units in Northwestern Ontario, capable of supplying about 2.1 million green tonnes (gt) of forest harvest residues and 7.6 million gt of underutilized woody biomass for bioenergy production; these numbers are based on an average annual forest depletion rate of 0.6% of the total productive forest area (Alam et al. 2012). This amount is more than enough to produce the 90,000 tonnes of wood pellets annually required for AGS.

Biomass can be converted into energy (heat or electricity) or energy carriers (char, oil or gas) by different thermochemical and biochemical conversion technologies (Van-Loo and Koppejan 2008). The common thermal conversion technologies in bioenergy systems include: direct combustion, liquefaction, gasification and pyrolysis. Direct combustion, where the biomass is burnt to produce heat with wood ash as a waste product, is the most commonly used complete oxidation process (Obernberger and Thek 2010). Liquefaction, or the conversion of biomass to the liquid phase (biofuel) at low temperature and high pressure (Van-Loo and Koppejan 2008), also produces a significant portion of wood ash as waste. Biomass gasification produces combustible gases including carbon monoxide, hydrogen and traces of other gasses in controlled

partial combustion of biomass under high heat and pressure. Pyrolysis is a thermal degradation process producing heat, bio-oil, syngas and biochar in the absence of oxygen (Spokas et al. 2012). Biochar is a porous and stable carbon-rich co-product of the pyrolysis process that has diverse uses including soil amendments and long term carbon sequestration (Lehmann et al. 2006). Biochar differs from charcoal in the sense that it is not used as fuel. Although biochar can be produced from a variety of biomaterials in a variety of ways, in this paper we refer only to biochar produced from woody biomass in a bioenergy plant. Biochar is commonly produced using slow pyrolysis techniques based on heating rate and duration. Slow pyrolysis at 300-500°C with a vapor residence time of 5–30 min is preferred as it maximizes the biochar production (Bruun et al. 2012; Boateng et al. 2010; Sohi et al. 2010).

Co-production of biochar with bioenergy, with its subsequent application to the soil, has been suggested as one possible method to reduce atmospheric CO₂ concentration (Laird 2008; Fowles 2007; Lehmann 2007; Lehmann et al. 2006). At present, there is no bioenergy production plant that uses the slow pyrolysis process for producing biochar as a co-product in Northwestern Ontario. Resolute Forest Products (Thunder Bay) burns biomass in its boiler and produces a significant amount of bottom ash, which contains varying amounts of biochar (RFP 2012).

Therefore, conversion from traditional power generation using fossil fuel to bioenergy production with biochar as a co-product can have both short and long term positive environmental impacts. Biochar-based bioenergy can reduce the rate of current GHG emissions by fixing atmospheric carbon into the soil, thereby mitigating the problem of global warming in the long term (Campbell et al. 2008). However, a

comprehensive study of the potential environmental and economic impacts of bioenergy and biochar co-production in the region that includes each stage of production and utilization of the product in its life cycle needs to be conducted. Life cycle assessment (LCA, also known as life-cycle analysis or ecobalance) is a standard technique (ISO 14040: 2006 series) to assess environmental impacts associated with all stages of a product's life from cradle-to-grave (i.e., from raw material extraction through materials processing, manufacturing, distribution, use, repair and maintenance and disposal or recycling) (Afrane and Ntiamoah 2011). We could find no study documenting the LCA of biochar and bioenergy co-production in Northwestern Ontario and we suggest that this is because the necessary background information has yet to be collected. Therefore, the general purpose of this review paper is to establish the context within which such an analysis could occur. The specific objectives are to review the literature that: (1) explores biochar production potential based on biomass availability and feasibility of sustainable bioenergy production in Northwestern Ontario; (2) documents the effects of biochar on soil property and productivity; (3) examines the life cycle environmental impacts of biochar production and application in terms of GHG emissions and climate change mitigation; and (4) identifies research needs and potential environmental impact assessment methods for woody biomass utilization for biochar-based bioenergy production in Northwestern Ontario in a sustainable manner.

METHODS

We conducted a thorough literature search on biochar-based bioenergy production and its environmental impacts in Northwestern Ontario through ISI Web of Science and Google Scholar. Based on the search keywords (biomass, bioenergy, biochar, life cycle assessment, biochar soil amendment, Canada, Ontario and Northwestern Ontario and combinations) we selected 91 peer reviewed publications (Figure 2.1).

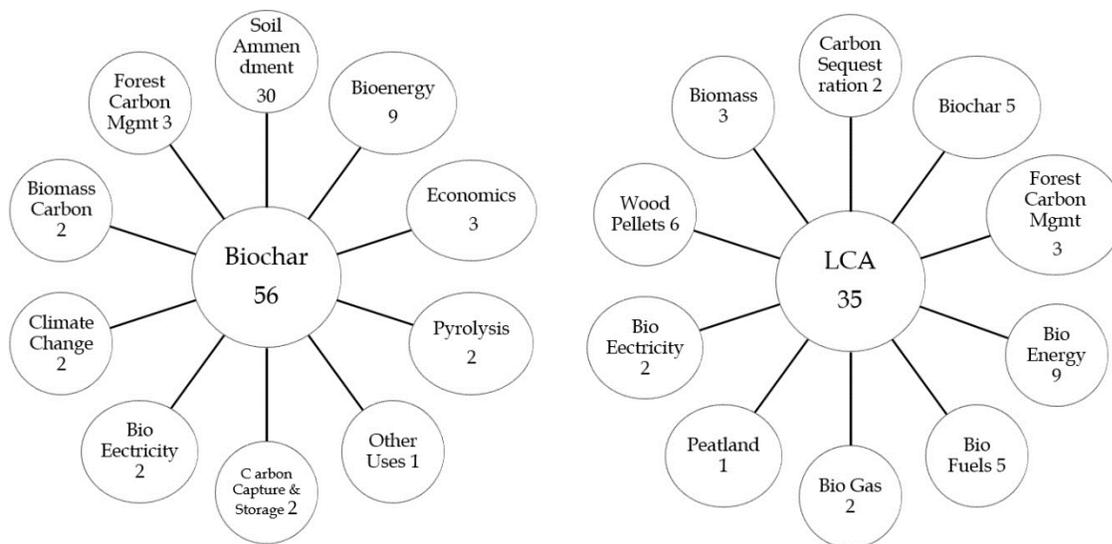


Figure 2. 1 Study spectrum and number of studies covered in this paper

The extent of papers reviewed is more or less global, with one third focusing on studies related to the USA (Figure 2.2). Only 13 papers focused on Canada and only 6 of those were directly related to Northwestern Ontario. This shows the lack of attention biochar and its environmental impact assessment has received in Canada in general and in Northwestern Ontario in particular.

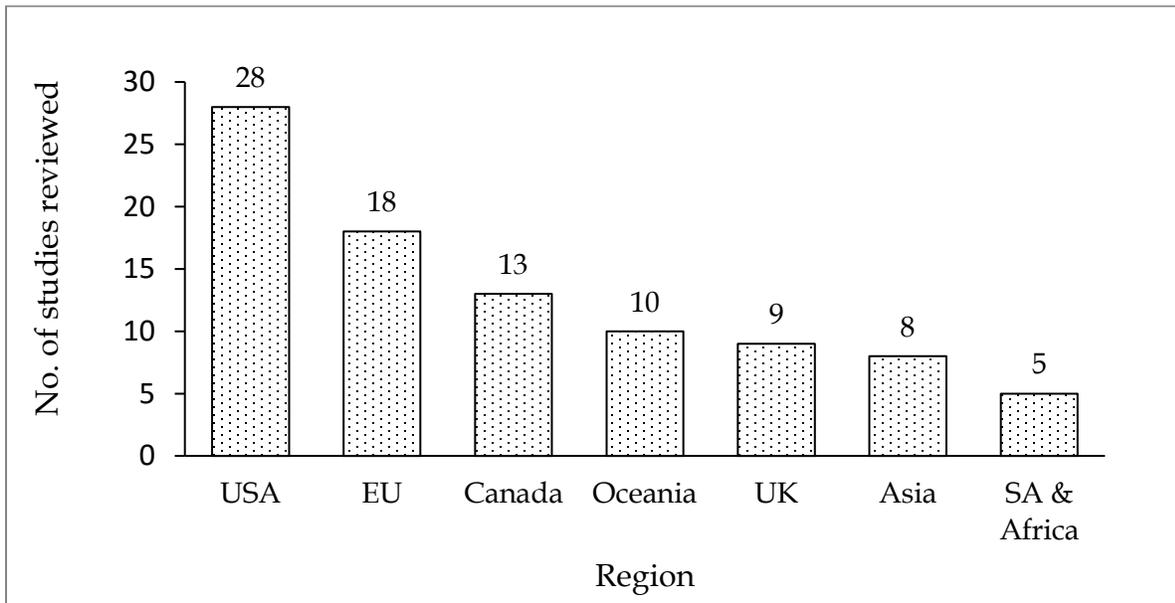


Figure 2. 2 Number of studies reviewed in different regions

REVIEW RESULTS

Biochar production potential in Northwestern Ontario

Biochar is emerging as an important co-product of bioenergy production in Canada (Thomas 2013). Over the last decade, there has been a constant increase in the use of sawmill and harvesting residue to produce bioenergy that meets the industrial energy demand (NRCan 2010). Northwestern Ontario has a forest area of about 48 million ha of which 67% is covered by productive forests (MNR 2011). There are 18 active forest management units (FMU) in Northwestern Ontario (MNR 2012). Harvesting residue and underutilized tree species in the FMUs and sawmill waste are already being used as feedstocks in Northwestern Ontario for energy generation. Studies reviewed in this paper vigorously agree that there is an abundant supply of woody biomass for sustainable bioenergy production in Northwestern Ontario (Table 2.1). Depending upon

the pyrolysis technique used, there is a possibility of producing up to 35% biochar from available woody biomass (Brick and Wisconsin 2010).

Table 2. 1 Woody biomass availability (million tonnes year⁻¹) in Northwestern Ontario

Source	Quantity available year ⁻¹	Region covered	Reference
Forest harvest residue and underutilized tree species	7.9 million green tonnes	Northwestern Ontario	Alam et al. 2012
Woody and agri-based biomass	34 million dry tonnes	Canadian side of Great Lakes region	Hacatoglu et al. 2011
Harvest residue, sawmill residue and underutilized hardwoods	2.3 million dry tonnes	Parts of Northeastern Ontario	Kennedy et al. 2011
Traditionally unmerchantable, unused and available trees	7.6 to 7.9 million green tonnes	All over Ontario but harvest and saw mill residue not included	MNR 2011
Harvest residue and sawmill residue and residual trees	3.8 million dry tonnes	Northwestern Ontario	Wood and Layzell 2003

Biomass is widely accepted as the oldest source of energy in the world (Van-Loo and Koppejan 2008). Woody biomass, used as a primary source of energy for cooking and heating in many parts of the world, made up approximately 10% of the world's energy use as of 2009 (Van-Loo and Koppejan 2008). Biomass combustion, responsible for over 90% of the global contribution to bioenergy, is the main technology used for bioenergy production. However, ash formation is one of the major challenges associated with biomass combustion and directly impacts the hearth, boiler or stove

depending upon the feedstock (Obernberger and Thek 2010). In recent years, many technological developments, such as fast and slow pyrolysis, in the field of biochar based bioenergy production have taken place. The properties of biochar from these techniques vary with the production technique used (Table 2.2).

Table 2. 2 Properties of biochar produced from fast and slow pyrolysis techniques

Properties	Fast Pyrolysis	Slow Pyrolysis	Reference
Biochar yield (% by Volume)	12	35	Sohi et al. 2010
Carbon (C) Content (% by Volume)	69.6	49.3	Bruun et al. 2012
Hydrogen (H) Content (% by Volume)	2.1	3.7	ibid
Oxygen (O) Content (% by Volume)	7.1	24.1	ibid
Nitrogen (N) Content (% by Volume)	1.5	1.2	ibid
H/C Ratio	0.02	0.06	ibid
O/C Ratio	0.08	0.38	ibid
C/N Ratio	47	40	ibid
Ash Content	19.8	21.6	ibid
pH Value	10.1	6.8	ibid
Biochar surface area (cm ² g ⁻¹)	220	10	Brown et al. 2006

Fast - Moderate temperature (~600⁰C), short vapor residence time (<2 sec); Slow - Low temperature (~400⁰C), long vapor residence time (>30 min)

Biochar produced at high temperatures from fast pyrolysis results in lower biochar mass recovery, greater surface area, elevated pH, higher ash content, and

minimal total surface charge (Novak et al. 2009). Removal of volatile compounds at high pyrolysis temperatures also results in higher percentages of carbon, and much lower hydrogen and oxygen contents (Novak et al. 2009). The properties of biochar also vary with the type of biomass used (Mohan et al. 2006). A typical analysis of average dried woody biomass yields about 52% C, 6.3% H, 40.5% O and less than 1% N. A comparison of the proximate, ultimate and elemental analysis of typical woody biomass with herbaceous plants and agricultural waste is presented in Table 2.3 (Tillman et al. 2009).

Table 2. 3 Variability of different biomass feedstock composition (Tillman et al. 2009)

Parameter	Woody biomass	Herbaceous plants	Agricultural waste
Proximate analysis (wt. %)			
Moisture	42.0	9.84	8.00
Ash	2.31	8.09	6.90
Volatile matter	47.79	69.14	69.74
Fixed Carbon	7.90	12.93	15.36
Ultimate analysis (wt. %)			
Carbon	29.16	42.00	42.60
Hydrogen	2.67	5.24	5.06
Oxygen	23.19	33.97	36.52
Nitrogen	0.60	0.69	0.83
Sulfur	0.07	0.17	0.09
Ash	2.31	8.09	6.90
Chlorine	0.01	0.18	0.24
Calorific Value (kcal kg ⁻¹)	2790	3890	3900
Elemental analysis (% Dry)			
Al ₂ O ₃	3.55	4.51	3.80
CaO	45.46	5.60	8.80
Fe ₂ O ₃	1.58	2.03	1.80
P ₂ O ₅	7.40	4.50	2.70
SiO ₂	17.78	65.18	52.10

Biochar effects on soil properties and productivity

Biochar possesses varying amounts of nutrients including essential elements such as nitrogen, phosphorous and potassium that contribute positively to soil fertility and productivity (Table 2.4). Properties such as large surface area, micro porosity, high mechanical strength and stability contribute positively to soil texture and fertility of the land (Waters et al. 2011).

Table 2. 4 Nutrient content of selected biochars [Modified from (Waters et al. 2011)]

Biochar source	N	P	K	Ca	CEC (cmol kg ⁻¹)	C	pH	C:N	Tem p °C	References
Green wastes	0.18	0.07	0.82	<0.01	24	36	9.4	200	450	Chan et al. 2007
Hardwood bark	1.04				37	40	7.4	38	300	Yamato et al. 2006
Paper mill sludge and wood (1:1)	0.48		0.22	6.20	9	50	9.4	104	550	Van Zwieten et al. 2010
Paper mill sludge and wood (1:2)	0.31		1.00	11.00	18	52	8.2	168	550	Van Zwieten et al. 2010
Pine bark	<0.01	<0.01	-	-	34	72	4.8	-	350	Gundale and DeLuca 2007
Pine wood chips	0.25	0.01	0.15	0.17	7	74	7.6	290	400	Gaskin et al. 2008
Hardwood chips	0.30		3.10	4.40	10	87	7.5	290	-	Asai et al. 2009

Biochar application, as a soil enhancer, increases initial growth and crop productivity in tropical soils (Sohi et al. 2010). The growth of organisms involved in N cycling in the soil, specifically those that decrease the flux of N_2O , improves with biochar application, thereby resulting in decreased plant pathogens (Anderson et al. 2011). Biochar also influences mycorrhizal abundance by altering soil physico-chemical properties (Smith et al. 2010; Zimmerman 2010), and detoxifying allelochemicals, which provide refuge from fungal grazers (Warnock et al. 2007).

Reports of the effects of biochar application on soil quality and crop productivity are highly variable in the literature. High yield improvements (up to 300%) were noticed in some studies when biochar was applied to soils of low fertility (Koide et al. 2011; Kookana et al. 2011; Mankasingh et al. 2011; Sparkes and Stoutjesdijk 2011; Sohi et al. 2010; Van Zwieten et al. 2010; Laird et al. 2010; Sohi et al. 2009; Chan et al. 2007; Lehmann and Rondon 2006), whereas soils of temperate climates and of generally higher fertility showed modest biomass production improvements in the range of 4–20% (Laird et al. 2010; Husk and Major 2010). The forage value of mixed species grown on soil with biochar application ($3.9 \text{ t}\cdot\text{ha}^{-1}$ for 3 years) was also found to be greater than in un-amended soil (Husk and Major 2010). The increase in forage quality was followed by an increase in cow milk production (44% increase) and animal biomass production (Major et al. 2010a). Sohi et al. (2009) provide a comprehensive review of the impact of biochar application on crop yield (Table 2.5).

Table 2. 5 Impact of biochar application on crop yield [Modified from Sohi et al. (2009)]

Application amount	Results summary	Reference
0.5 Mg·ha ⁻¹ wood-char	Increased biomass 160% (pea) and 122% (Soybean)	Iswaran et al. 1980
0.5 Mg·ha ⁻¹ wood-char	Increased yield 151%	Kishimoto and Sugiura 1985
5 Mg·ha ⁻¹ wood-char	Decreased yield to 63%	Kishimoto and Sugiura 1985
15 Mg·ha ⁻¹ wood-char	Decreased yield to 29%	Kishimoto and Sugiura 1985
NA	Increased biomass by 13% and height by 24%	Chidumayo 1994*
67 Mg·ha ⁻¹ char	Increased biomass 150%	Glaser et al. 2002
135 Mg·ha ⁻¹ char	Increased biomass 200%	Glaser et al. 2002
NA	Increased biomass production by 38 to 45%	Lehmann et al. 2003
NA	Increased grain yield 91% and biomass yield 44%	Oguntunde 2004
Acacia bark charcoal plus fertilizer	Increased maize and peanut yields	Yamato 2006
100 t·ha ⁻¹	Increased yield by three times	Chan et al. 2007
10 to 50 t·ha ⁻¹	Increased yield	Chan et al. 2007
Without added N	No effect	Chan et al. 2007
90 g·kg ⁻¹ biochar	Increased biomass production by 46%	Rondon 2007
60 g·kg ⁻¹ biochar	Increased biomass production by 39%	Rondon 2007
Charcoal amended with chicken manure (12.4 Mg·ha ⁻¹)	Highest cumulative crop yield	Steiner 2007
NA	Crop yield doubled in maize yield	Kimetu et al. 2008*

(The term 'Biochar' was coined in 2005, terms like char, and charcoal were used in previous research)

* As cited in Sohi et al. 2009 (Original record not retrieved)

Some studies also attribute changes in N immobilization to biochar application (Kookana et al. 2011; Blackwell et al. 2010; Asai et al. 2009) but this phenomenon is of relatively short duration while the unstable fraction of biochar is decomposed. Kishimoto and Sugiura (1985) found 37% and 71% lower soybean yields with biochar application of 5 and 15 tonne per hectare ($t\cdot ha^{-1}$) respectively, and attributed this reduction to the rise in pH, which led to micronutrient deficiencies induced by the biochar application. In a 2-year trial, Gaskin et al. (2008) observed lower corn yields with peanut hull biochar applied at $22 t\cdot ha^{-1}$ compared to the control under fertilized conditions. With pine chip biochar application, yield reductions occurred at both 11 and $22 t\cdot ha^{-1}$ of biochar application in the first but not the second year of the trial. However, trials in both years were affected by drought. The interaction of biochar application with fertilizer rate and type as well as inoculation with mycorrhizae is also complex and not yet well understood (Blackwell et al. 2010).

Biochar application benefits are not only limited to increased production of biomass and crop yield in the short term. Its long term impacts on plant soil systems, nutrient cycling, climate change and mitigation have also been documented (Waters et al. 2011). A summary of significant impacts on ecosystem function is presented in Table 2.6.

Table 2. 6 Summary of ecosystem benefits of biochar application (Waters et al. 2011)

Plant-Soil System	Climate Change adaptation	Climate Change Mitigation
<ul style="list-style-type: none"> • Improve soil air and water storage • Improve soil structure • Increase soil CEC, pH, C and nutrients • Increase soil microbial activity and diversity • Enhance plant growth conditions 	<ul style="list-style-type: none"> • Enhance agriculture input efficiencies • Enhance soil water use • Improve water quality • Reduce nutrient leaching and runoff • Enhance global food security • Increase ecosystem resilience 	<ul style="list-style-type: none"> • Increase stable soil C pool • Reduce soil greenhouse gas emissions • Reduce soil degradation • Reduce N fertilizer use • Reduce CH₄ emissions from biomass decay

Biochar applications monitored over several years in agricultural lands have shown many short and long term positive effects, such as a liming effect and improved water holding capacity of the soil along with improved crop nutrient availability (Jeffery et al. 2011; Kookana et al. 2011; Scheer 2011; Sohi et al. 2010; Van Zwieten et al. 2010; Major et al. 2010b; Sohi et al. 2009). Because of the variability of biochar applied and the soil types used in these studies, it is difficult to recommend biochar application as a soil amendment for all soil types and cropping systems. More field trials are required on several sites assessing the effect of biochar application in combination with other production factors.

Environmental impacts and life cycle assessment of Biochar

Soil carbon is one of the major sources of GHG emissions (Lal 2007). Carbon Dioxide (CO₂), Methane (CH₄) and Nitrous Oxide (N₂O) are the most prevalent GHGs in the atmosphere and these three gases together make up about 99% of GHGs (EC 2011). In addition to the potential long term soil carbon sequestration value, biochar application also provides considerable greenhouse gas mitigation benefit by reducing N₂O emissions over time (Table 2.7). The extent of this reduction, however, depends on soil type, application rate, soil moisture content, and biochar type (Taghizadeh-Toosi et al. 2012; Park et al. 2011; Sparkes and Stoutjesdijk 2011; Waters et al. 2011; Sohi et al. 2009). However, in some studies, neutral to slight increases of emissions of N₂O from soil were observed in the short term (Clough and Condron 2010). N₂O, produced as a result of microbial processes of nitrification and denitrification, has high global warming potential and contributes more than 8% to global GHGs (Harter et al. 2014). The exact mechanisms for observed effects of biochar application on N₂O emissions remain unknown (Van Zwieten et al. 2010). The effectiveness of biochar application in reducing soil N₂O emissions can increase over time because of the increased sorption capacity of biochar through oxidative reactions on large surface area (Singh et al. 2010). In a recent laboratory study of boreal charcoal (biochar) study Hart (2013) reported that increased mineralization due to the addition of biochar is short lived and likely related to the least stable component of biochar. A brief summary of the reviewed studies on environmental impacts of biochar are outlined in Table 2.7.

Table 2. 7 Environmental impacts of biochar application

Beneficial Environmental impacts		Reference
Reduced	Improved	
Bacterial Plant Pathogens; N ₂ O emission	Phosphate solubilizing bacteria	Anderson et al. 2011
Ammonium leaching; N ₂ O emission	Availability of macro-nutrients (N and P); Electrical conductivity (EC), cation exchange capacity (CEC)	Atkinson et al. 2010
Pollutant mobility from contaminated soils	Sorption of both organic and inorganic contaminants	Beesley et al. 2011
GHG emissions	Long-term carbon sequestration	Bruun et al. 2011, Gaunt and Lehmann 2008
Microbial degradation of organic compounds	Bioavailability and efficacy of pesticides	Kookana 2010
Anthropogenic C emissions	Biological decomposition, microbial activities	Lehmann and Rondon 2006
Contaminants accumulating in soil	Physical and chemical properties of soil	Sohi et al. 2010
N ₂ O production and ambient CH ₄ ; leaching and runoff losses; fertilizer requirement	Sorption; Physical properties	Spokas et al. 2009
GHG emissions	Climate-change mitigation potential	Woolf et al. 2010

Another notable benefit of biochar application to soil is its ability to reduce nitrogen fertilizer requirements in agricultural systems (Waters et al. 2011). Production of one tonne of nitrogen fertilizer releases more than 3 tonnes of CO₂ into the atmosphere (West and Marland 2002). Biochar application can reduce the frequency and quantity of N application and subsequently lower emissions from the production of

nitrogen fertilizer. In order to have a complete picture of the contribution of biochar production and utilization to GHG emissions, environmental quality, and human health, life cycle assessment (LCA) studies have been done.

LCA considers the flows of raw materials and energy across a system boundary to determine the process' or product's full cradle-to-grave impact (Steele et al. 2012; Roberts et al. 2010). LCA techniques have quantified all stages of bioenergy production and utilization systems to assess the environmental impact (Steele et al. 2012; Roberts et al. 2010; Fantozzi and Buratti 2010). Several recent LCA studies considering GHG emissions and carbon sequestration effects have focused on the co-production of biochar and bioenergy from slow pyrolysis of various biomass feedstocks (Hammond et al. 2011; Woolf et al. 2010; Roberts et al. 2010). These studies conclude that biochar systems could mitigate 0.7–1.4 tonnes of CO₂ t⁻¹ of feedstock consumed. A review of life cycle studies with a brief finding from each study is presented in Table 2.8.

Table 2. 8 Life cycle analysis studies covered in this review

Life Cycle Study with brief finding	References
Compared slow pyrolysis biochar systems (PBS) with gasification for electricity generation and carbon abatement (CA). Gasification showed better electricity generation outputs, however, PBS offered more CA.	Ibarrola et al. 2012
295 kg CO ₂ e GHG is released for every tonne-1 pellets exported from British Columbia to Netherlands. If locally used it can reduce impacts on human health, ecosystem quality, and climate change by 61%, 66%, and 53%, respectively. Transportation consumes 35% total energy followed by harvesting.	Pa et al. 2012
There is a significant net reduction in GHG emissions when bioenergy replaces fossil energy.	Cherubini and Stromman 2011
Global warming impacts of imported pellets are greater than in-situ utilization. Imported pellets emit significantly less GHGs than fossil fuel if used to produce electricity.	Dwivedi et al. 2011
Compared PBS with other bioenergy systems for carbon abatement. PBS is 33% more efficient than direct combustion, even if soil amendment benefits of biochar are ignored.	Hammond et al. 2011
Electricity from wood pellets reduces emissions in the long run but net mitigation may be delayed by 16-38 years.	Mckechnie et al. 2011
Emissions from controlled gasification systems for wood pellets are lower as compared to wood waste. Costs and GHG emission can be reduced by 35% and 82%, respectively by wood pellets gasification.	Pa et al. 2011
GHG emission is reduced in the life cycle if coal is replaced by biomass.	Sebastian et al. 2011
Forest residue has less environmental impact in the long run than agri-residue when used for electricity production.	Butnar et al. 2010
Wood pellets from short rotation coppice crop provide long term solution for sustainable supply of feedstock. Farm operations account for most of the environmental impacts in initial years.	Fantozzi and Buratti 2010
Biomass has lower GHG emissions than conventional gasoline in the life cycle. Differences in NEV are caused by conversion technology rather than by feedstock.	Hsu et al. 2010
Initial moisture content of the feedstock and fuel consumption during the carbonization process was the greatest contributors to CO ₂ emissions within the life cycle. Farmland application of bagasse charcoal can sequester 60-90 t CO ₂ ha ⁻¹ year ⁻¹ .	Kameyama et al. 2010

Life Cycle Study with brief finding	References
Biofuels provide greater GHG mitigation benefits in the life cycle as compared to conventional fossil fuels.	Larson 2006
Biomass reduces GHG emissions by displacing fossil fuel in transportation and electricity sector and by sequestering atmospheric carbon. GHG emissions increase if bioelectricity displaces wind electricity.	Lemoine et al. 2010
The net energy produced from the slow PBS is highest but it can be a net GHG emitter. About two-thirds of emission reductions can be realized from C sequestration in the biochar.	Roberts et al. 2010
Wood pellets provided significant reductions of GHG (91%), NO ₂ (47%) and SO ₂ (81%) in the life cycle as compared to coal and natural gas. The most cost effective GHG reduction was found at \$160 tonne ⁻¹ of pellets and \$7GJ ⁻¹ natural gas.	Zhang et al. 2010
Bioenergy production, in short run, may cause higher environmental impacts (e.g. air pollution, eutrophication etc.) than fossil fuels because of site-specific issues and too many uncertainties in the LCA process. These issues should be evaluated by weighting GHG emissions trade-off in the long run.	Cherubini et al. 2009
Electric train transportation and local wood had lowest environmental impacts in the life cycle as compared to conventional diesel train and imported woods.	Gonzalez-Garcia et al. 2009
Bioenergy emits less than 25% GHGs than conventional or liquefied natural gas but may cost double than current coal based systems. Bioelectricity produced through this technology will emit only 10% carbon (in full life cycle) as compared to coal based power.	Hacatoglu 2009
Wood pellets production and shipping consumes about 39% of the total energy content of the wood pellets with one-third contribution of transportation in the life cycle.	Magelli et al. 2009
Carbon savings from biofuel depend on their feedstock. Perennial woody biomass in abandoned agri-land produce very little or no carbon debt and can offer immediate and sustained GHG advantage than biomass produced by converting rainforests, peatlands, or grasslands to agri-land.	Fargione et al. 2008
Emissions reductions from slow PBS are between 2 and 5 times greater when biochar is applied to agricultural land than used only for fossil fuel offsets.	Gaunt and Lehmann 2008
Biofuels provide greater GHG mitigation benefits in the life cycle as compared to conventional fossil fuels.	Larson 2006

Economics of biochar based bioenergy production

The economic feasibility of biochar based bioenergy production includes the comparison of cost of collection, transportation, processing of feedstock and energy generated during the pyrolysis process; and benefits obtained from the production of bioenergy and biochar as co-products (McCarl et al. 2009). The cost-benefit analysis also includes the trade-offs between economic gains and environmental and ecosystem function losses. The economics of the biochar based bioenergy system depends on the availability of advanced technology to produce and optimize the co-products based on management objectives. If long term carbon sequestration is valued above renewable energy, then more biochar should be produced in comparison to bio-oil (Palma et al. 2011). However, in order to maximize the economic outputs and beneficial outcomes, the supply chain including feedstock collection, transportation, pyrolysis plant design and operation, and product recovery need to be optimized (Moon et al. 2011; McCarl et al. 2009).

Onsite portable pyrolysis bioenergy production plants are used to reduce the transportation costs of forest biomass (McElligott et al. 2011). Portable units are economically feasible if located at stock piled sources of feedstock (McCarl et al. 2009). However, there is a low probability of a positive net present value (NPV) with portable systems as compared to stationary scenarios (Palma et al. 2011). Stationary fast pyrolysis facilities, using woody biomass feedstock, show the highest potential for profitability with a price of \$87 tonne⁻¹ of biochar (Granatstein et al. 2009). The maximum revenue using woody biomass feedstock for energy production using slow pyrolysis is

\$0.09 kg⁻¹ and using fast pyrolysis is \$0.11·kg⁻¹ (Granatstein et al. 2009). Furthermore, slow pyrolysis units will deliver net-negative emissions of greenhouse gases and revenue from C trading could make biochar production for soil application a worthy venture (Gaunt and Lehmann 2008).

The cost-effectiveness of global biochar mitigation potential using marginal abatement cost curves has been evaluated (Pratt and Moran 2010). Biochar stove and kiln projects in developing nations are more cost-effective than pyrolysis plants in developed countries, and thus could abate more fossil fuel carbon emissions (up to 1.03Gt by 2030 in Asia). Biochar based bioenergy projects are expensive, but can compete with other carbon negative technologies, depending on a range of factors including the price of carbon and significant ancillary benefits in terms of biomass productivity (Pratt and Moran 2010). One of the future economic consequences of biochar-based bioenergy may appear when there is a regulatory carbon trading mechanism such as the Carbon Trade Exchange (CTX). Assuming the existence of a carbon trading mechanism for biochar soil application, Galinato et al. (2011) estimated the economic value of biochar application on agricultural cropland for carbon sequestration and its soil amendment properties, and found that it may be profitable to apply biochar as a soil amendment if the biochar market price is low enough and/or a carbon offset market exists. These economic impact assessment studies emphasize the need for a local level accounting of all the stages of production to end use.

RESEARCH NEEDS AND POTENTIAL ENVIRONMENTAL IMPACT ASSESSMENT METHODS

Bioenergy is being widely accepted as a green alternative to fossil fuel based energy in many parts of the world. Bioenergy with biochar as a co-product is even more promising in terms of soil amendment and emission reductions benefits. A number of bioenergy production technologies have been developed that produce biochar as a co-product. Biochar application as a soil amendment not only increases crop and biomass production, but also helps in managing waste from bioenergy generation plants that would otherwise end up in landfills. In order to make biochar-based bioenergy production more efficient, past research has identified the use of wood pellets instead of direct biomass as feedstock. Wood pellets help to reduce GHG emissions and the cost of electricity production (Fantozzi and Buratti 2010). The life cycle GHG emission reduction potential and cost efficiency of electricity production from wood pellets can reduce GHG emissions by 90%, NO_x by 45–47%, and SO_x by 76–81% as compared to coal and natural gas (Zhang et al. 2010). Wood pellets produced in North America and used in European countries to replace fossil fuels in electricity generation, have considerably reduced GHG emissions (Dwivedi et al. 2011). However, it is better to use wood pellets locally than to transport them over long distances, as transportation of wood pellets consumes one third of their energy content (Pa et al. 2012; Magelli et al. 2009). In addition, if wood pellets are used to replace natural gas in district heating systems, it may reduce GHG emissions by 82% and cost by 35% (Pa et al. 2011).

Notwithstanding the beneficial uses of biomass utilization for energy production, some non-governmental organizations (Schlamadinger et al. 1997) have been raising

concerns about the sustainability of the system in the long run (Huang et al. 2013). In a recent report, which focuses on Ontario's biomass utilization policy, Green Peace (An international NGO on environmental advocacy) has strongly opposed the province's claim about carbon neutrality of biomass fuel and recommended that full and independent life cycle analyses of forest bioenergy projects be performed to track carbon emissions every year and take into account the "carbon payback time" of each bioenergy project (Mainville 2011). However, Ter-Mikaelian et al. (2008) state that the total forest carbon stock has increased under the current forest management in Ontario. They calculated that, if forests in Ontario are managed for energy production using wood pellets, it would take at least 28 years to theoretically achieve minimum break-even and carbon-neutral periods resulting from displacing coal with biomass feedstock, whereas the current forest age structure in Ontario has a minimum break-even period of 32 years after harvest for carbon balance (Ter-Mikaelian et al. 2011).

There are also differences of opinion in the net benefit of bioenergy production when considering competing interests in the energy sector. Most studies focus on maximization of energy production from biomass using combustion, which may compromise soil amendment and carbon sequestration benefits (Tilman et al. 2009; Lal and Pimentel 2007). Similarly, bioenergy produced from agriculture based feedstock may compete with food production (Pimentel et al. 2009; Searchinger et al. 2008), even though grain- and seed-based biofuels provide significant GHG mitigation benefits (Cherubini et al. 2009). Those competitions, in some extents, are being addressed by using transgenic woody plants especially in the production of biofuels (Tang and Tang 2014). There is an opportunity cost associated with biochar that is used for soil

amendment as there is some energy lost in the carbonized biomass. For example, approximately 50% of feedstock energy is lost in the form of carbon in biochar when pyrolysis technology is used for maximizing biochar production (Roberts et al. 2010). Therefore, not all biomass can either be converted to bioenergy or to biochar.

Most studies reviewed in this paper present the potential benefits of bioenergy or biochar in terms of GHG emissions reduction in the life cycle, but none of the studies conducted the carbon-balance and economic analysis of the whole biochar production and utilization within the system boundary. Therefore, a long term life cycle assessment is needed for the specific region of interest (e.g. Northwestern Ontario) to make better decisions about the viability of any biochar production and utilization system (Hammond et al. 2011; Mckechnie et al. 2011).

CONCLUSIONS

Northwestern Ontario (Canada) has a sustainable and sufficient supply of woody biomass that can be used to produce biochar based bioenergy for household and industrial purposes. While several biochar based bioenergy plants are operating around the world, the switch to biomass based energy is relatively recent in Northwestern Ontario with the AGS conversion representing a new era in large scale fuel requirements. If biochar and bioenergy are produced, they will serve two immediate functions: a) to provide fossil fuel free energy and b) to sequester stable carbon for a longer period. Biomass may be sourced from either harvesting waste or underutilized species. The former is usually piled at roadside and, if not burned *in situ*, returned to the site or used for fuel, its presence can inhibit regeneration for long periods of time. So

called “slash piles” can also pose a fire hazard (McElligott et al. 2011). Harvesting of underutilized species or extension of harvesting to include coarse woody debris (CWD) has raised concerns about reduced soil nutrient inputs thereby altering forest site productivity (Hazlet et al. 2007, Wiebe et al. 2013). CWD also contributes to the structure, microhabitat diversity, and nutrient cycling of forests (Pedlar et al. 2002). Therefore, utilization of forest biomass may warrant a regional harvesting policy. Replacing fossil fuels with biomass for power generation would certainly change the carbon budget of the regional ecosystem, through transportation, collection, processing, and pyrolysis of biomass, and possibly, land application of biochar. However, a comprehensive life cycle analysis of the biochar-based bioenergy production, from raw material collection to biochar application, with an extensive economic assessment is necessary for future development and commercial viability of this technology. Such a study would help decision makers as they create effective bioenergy policies for the region and boost confidence of potential investors to start up new businesses in the area. Future research work in the area of bioenergy production should focus on transportation, storage and processing of biomass, which could further improve the knowledge base in this area.

REFERENCES

(All references are arranged at the end of Chapter 5)

CHAPTER 3

PAPER 2: LIFE CYCLE ENVIRONMENTAL IMPACT ASSESSMENT OF BIOCHAR-BASED BIOENERGY PRODUCTION AND UTILIZATION IN NORTHWESTERN ONTARIO, CANADA

Krish Homagain*¹, Chander Shahi¹, Nancy Luckai¹ and Mahadev Sharma²

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ABSTRACT

Biochar-based bioenergy production and subsequent land application of biochar can reduce greenhouse gas emissions by fixing atmospheric carbon into the soil for a long period of time. A thorough life cycle assessment (LCA) of biochar-based bioenergy production and biochar land application in Northwestern Ontario is conducted using SimaPro® Ver. 8.1. The results of energy consumption and potential environmental impact of biochar-based bioenergy production system are compared with those of conventional coal-based system. Results show that biochar land application consumes 4,847.61 MJ per tonne dry feedstock more energy than conventional system, but

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Corresponding editor: Chai Ruihai

* Corresponding author: Krish Homagain, khomagai@lakeheadu.ca

¹ Faculty of Natural Resources Management, Lakehead University, 955 Oliver Rd. Thunder Bay, ON P7B 5E1 Canada

² Ontario Forest Research Institute, 1235 Queen Street E, Sault Ste. Marie, ON P6A 2E5 Canada

reduces the GHG emissions by 68.19 kgCO₂e per tonne of dry feedstock in its life cycle. Biochar land application improves ecosystem quality by 18%, reduces climate change by 15%, and resource use by 13% but may adversely impact on human health by increasing disability adjusted life years (DALY) by 1.7% if biomass availability is low to medium. Replacing fossil fuel with woody biomass has a positive impact on the environment, as one tonne of dry biomass feedstock when converted to biochar reduces up to 38 kg CO₂e with biochar land application despite using more energy. These results will help understand a comprehensive picture of the new interventions in forestry businesses, which are promoting biochar-based bioenergy production.

Keywords: woody biomass, carbon sequestration, environmental impact assessment, greenhouse gas emissions, life cycle analysis, soil amendment.

INTRODUCTION

Biochar is a highly porous and stable carbon-rich co-product of pyrolysis that has many uses including soil amendments and long term carbon sequestration (Lehmann et al 2006). Pyrolysis is defined as a thermochemical decomposition process occurring in the absence of oxygen (Spokas et al. 2012). Although chemically similar, Biochar differs from charcoal in the sense that it is not used as fuel (Lehmann et al. 2009). In this paper we deal with biochar produced from woody biomass in a bioenergy plant using the slow pyrolysis technique, a process that maximizes production, at 300–500°C with a vapor residence time of 5–30 min (Boateng et al. 2010; Bruun et al. 2012; Sohi et al. 2012).

Co-production of bioenergy with biochar, with the latter's subsequent application to the soil, has been suggested as one possible method to reduce atmospheric carbon-dioxide (CO₂) concentration [Lehmann et al 2006; Fowles 2007; Laird 2008; Lehmann 2007], thereby mitigating the problem of global warming in the long term (Campbell et al. 2008). However, very few studies have been conducted to assess the comprehensive environmental impacts of biochar-based bioenergy production (IBI 2013). A comparison of a pyrolysis biochar system (PBS) with other bioenergy production systems for carbon abatement found that PBS is 33% more efficient than direct combustion, even if the soil amendment benefits of biochar are ignored (Hammond et al. 2011). There are also many environmental, economic and legal concerns about the production of biochar and the incorporation of this manufactured material into soils on farms, in forests and elsewhere in the environment (Kookana et al. 2011). Although PBS can be a net GHG emitter (Roberts et al. 2010), biochar produced from forest residue can significantly reduce GHG emissions if biochar is used in land application (Dutta and Raghavan 2014).

Power generation is one of the significant contributors to current GHG emissions (IEA 2013). As of 2009, the electricity and heat generation sectors alone contributed about 9% of total GHG emissions in the province of Ontario (OPG 2012). Ontario enacted its green energy act (MOE 2010) in 2009 with a major milestone of achieving significant reduction of GHG emissions related to power production. The province has banned the use of coal in electricity production by replacing its coal-generating plants with biomass as feedstock by the end of 2014 (MOE 2010). Accordingly, Ontario Power Generation's (OPG) two coal-fired generating stations (Thunder Bay and Atikokan) are

being converted to use wood pellets, from Ontario-sourced forest biomass, as feedstock. The Atikokan station (AGS), with an installed capacity of 230 megawatts (OPG 2012), is now one of the largest 100% biomass fuelled power plant in North America (Basso et al. 2013). If wood pellets used for power production are locally produced, these will have much less impact on ecosystem quality, climate change, and human health as compared to fossil fuels, whereas transporting wood pellets over long distances adds to the GHG emissions, as transportation is estimated to consume about 35% of total energy (Dwivedi et al. 2011; Pa et al. 2012). However, conversion from traditional power generation using fossil fuel to wood pellets may have both short and long term unknown (positive or negative) environmental impacts.

Ontario has a large forestland base including 26.2 million hectares of boreal forest. A significant proportion of this (about 18.8 million hectares) is available for intensive forest management activities (MNR 2014). However, concerns have been raised about sustainable supply of woody biomass to produce wood pellets for power generating stations. As the new operations will require more than a million metric tonnes of wood pellets annually, the harvesting of biomass for wood pellets production could possibly have negative environmental impacts. Studies on forest based fibre availability suggest that Ontario has enough surplus biomass available (Wood and Layzell 2003) to meet the demand. There are 18 actively operating forest management units in Northwestern Ontario, which can supply about 2.1 million green tonnes (Finnveden et al. 2009) of forest harvest residue and 7.6 million green tonnes of underutilized woody biomass for bio-energy production, assuming an average annual forest depletion rate 0.6% of the total productive forest area (Alam et al. 2012).

Use of woody biomass in producing biofuel is becoming a popular practice elsewhere in the world as agriculture grain based biofuel is facing food security critics (Elbehri et al. 2013). Production of biofuel as a stand-alone product from woody biomass is technically viable but financially may not be sustainable (Stephen 2013). A trade of between different co-products of biofuel and biochar is widely considered as one of the GHG emission reduction strategy as land application of biochar sequesters the carbon relatively in a very long time. Han et al. (2013) conducted a life cycle (well-to-wheel) assessment of fast pyrolysis woody biomass based biofuel and found that biofuels can reduce the GHG emission when co-produced biochar is applied to the soil.

An effective implementation of biochar as a climate-mitigating tool would require an application of vast quantities of biochar into the environment (Biederman and Harpole 2013), which may result in its exposure to non-target terrestrial and aquatic systems, as wind and water can erode up to 50% of applied biochar material during application (Major et al. 2010). Therefore, a comprehensive study of biochar-based bioenergy production and its subsequent application to land is required to assess its potential impacts on environmental and economic parameters of the region. Ideally, such a study should include every stage of production and utilization of the product in its life cycle. Woody biomass can be converted into bioenergy (heat or electricity) or energy carriers (char, oil or gas) by different thermochemical and biochemical conversion technologies (Van-Loo and Koppejan 2008). Life cycle assessment (LCA, also known as life-cycle analysis or ecobalance) is a standard technique (ISO 14040: 2006 series) to assess environmental impacts associated with all stages of a product's life from cradle-to-grave (i.e., from raw material extraction through materials processing,

manufacturing, distribution, use, repair and maintenance, and disposal or recycling) (Afrane and Ntiamoah 2011). LCA techniques have been widely applied to study the impacts of biofuel and bioenergy systems (Roberts et al. 2010; Steele et al. 2012; Rehl and Mueller 2011; Fantozzi and Buratti 2010; Kilpelainen et al 2011; Zhang et al. 2010) in different regions including Northwestern Ontario. A few studies have also used LCA to compare GHG mitigation and direct carbon sequestration potential of biochar produced from different feedstocks (Hammond et al. 2011; Roberts et al. 2010; Gaunt and Lehmann 2008; Woolf et al. 2010). Although these studies conclude that all biochar systems have GHG mitigation and direct carbon sequestration potential, there exists an inherent trade-off between bioenergy and biochar production (Fowles 2007). A recent review (Homagain et al. 2014) also suggested a thorough life cycle study of biochar-based bioenergy production.

Therefore, the general purpose of this paper is to collect and analyze background information using standard methods, and establish the context within which LCA of biochar and bioenergy co-production in Northwestern Ontario could be carried out. The specific objectives are: (1) to conduct a thorough life cycle inventory of biochar-based bioenergy production with the use of standard local and related global databases; (2) to calculate net energy and GHGs emission of the biochar-based bioenergy production system; (3) to conduct a life cycle environmental impact assessment for potential damage in different impact categories; and (4) to compare the potential environmental impact assessment results for conventional energy production with those for biochar based bioenergy production and its land application in Northwestern Ontario.

MATERIALS AND METHODS

In this paper, we use International Standards Organization's (ISO) 14040 series standard LCA methodology consisting of four major steps - goal and scope definition, inventory analysis, impact assessment, and interpretation (SAIC 2006).

Goal and Scope definition

The goal and scope of LCA for this study is to assess the net energy balance, greenhouse gas emissions and associated environmental impacts of a biochar-based bioenergy system and its utilization as a soil amendment to sequester carbon.

LCA System Boundary and Functional Unit

Figure 3.1 illustrates the life cycle study system boundary within the solid lines. The dotted lines represent the life cycle cost analysis (LCCA) boundary which is not covered in this paper. The unit of analysis is one tonne of biochar (and one megawatt of equivalent electricity that is generated) produced from woody biomass processed into wood pellets. The System boundary, depicted by the solid line in Figure 3.1, extends from raw material collection to the application of biochar to the forest, and includes different interdependent phases including collection, transportation, storage, processing and pyrolysis with and without land application. The extended system boundary, depicted by both solid and dotted lines, is used in the life cycle cost estimation phase and is not part of this paper.

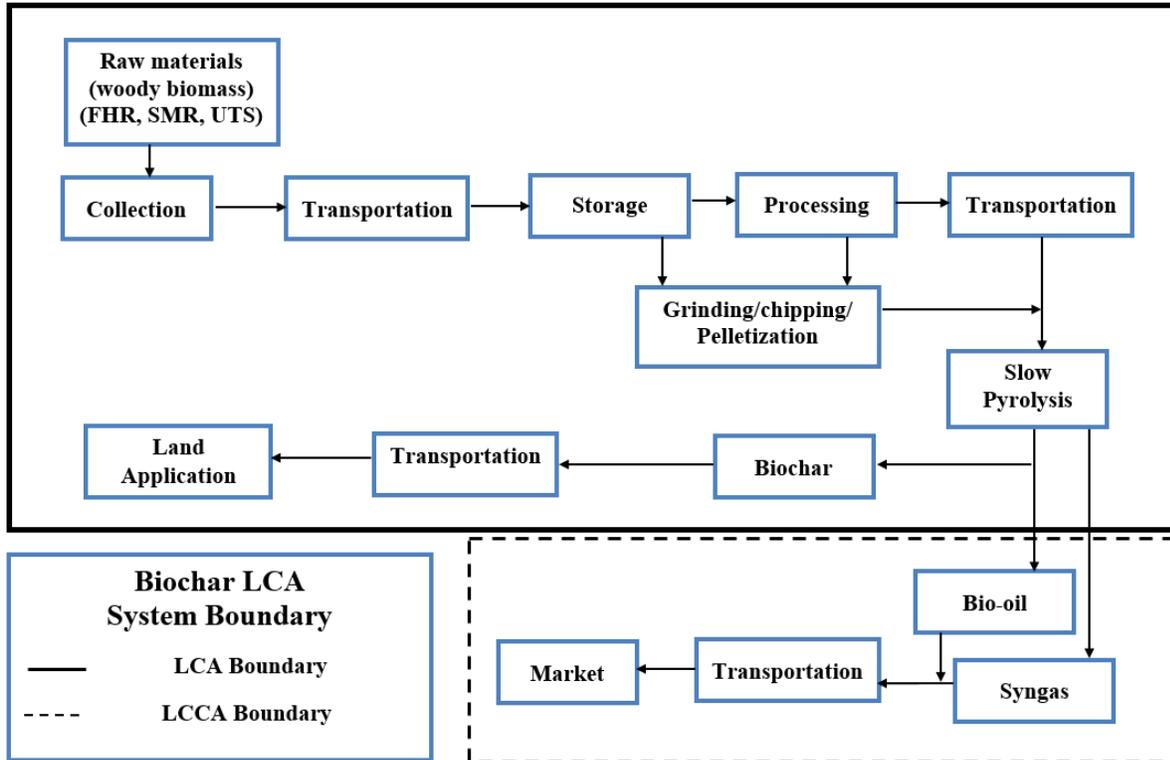


Figure 3. 1 System boundary for LCA of biochar-based bioenergy production

Study location and case assumptions

The study area lies in Northwestern Ontario Canada, where the Atikokan Generating Station (AGS) has been converted from coal to biomass (wood pellet) feedstock. Although AGS plans to use the combustion process for energy generation, our study uses a scenario where biomass feedstock will be converted to biochar using the best available pyrolysis process in order to illustrate the benefits of biochar-based bioenergy production. The input-output data for the system boundary and unit processes were obtained directly from the regional forest management unit, forest management plan, and personal communication with harvesters, transporters and other professionals.

Inventory analysis

An ISO standard inventory analysis was performed on material and energy inputs, air emissions (GHGs), and other environmental factors using SimaPro 8.1 LCA software. Inventory data of the built-in database (Ecoinvent and USLCI) of SimaPro 8.1 LCA software for input materials, equipment, processes and emissions was used in this paper (Table 3.1).

Raw material collection

Forest harvest residue (FHR), sawmill residue (SMR) and underutilized trees (UTS) are used as feedstock raw materials, with each source contributing equally in the feedstock mix. FHR and SMR are mostly composed of boreal softwoods (especially SPF-Spruce, Pine, Fir), whereas UTS consists of hardwoods (e.g. Poplars and Birch) and some Tamarack.

Transportation at different stages

Northern Ontario forest industry standards for transporting biomass feedstock from the forest management unit to storage (average 200 km one-way distance), processed feedstock from storage to the pyrolysis unit (20km), biochar from the pyrolysis unit to land application (100 km one-way), and biofuels from the pyrolysis unit to markets (100km) are used in the study. The average truck size is 40 tonnes (60m³) (Hammond et al. 2011) with a load factor of 75%. Regular gasoline is used as standard fuel type.

Biochar production

The standard biochar production process or “slow pyrolysis” occurs at 450° C with a 5-30 min vapor residence time (Brown 2009). The process of slow pyrolysis using standard wood pellets (moisture content less than 12%) is simulated within SimaPro 8.1 LCA software environment with the help of Ecoinvent and USLCl databases. A product yield of bio-oil 35%, syngas 30% and biochar 35% by weight of dry feedstock was used for this study (Brownsort 2009; Ronsee et al. 2013).

Storage

Two different storage stages are considered in the LCA: (i) storage of biomass feedstock before processing and pelletizing, and (ii) storage of pellets. Storage of biochar is not considered in this study, assuming that it will be applied to land immediately after production.

Land application

Land application of biochar is used to sequester carbon, and a weight loss of 10% is assumed during transportation and application. Application loss in could be as high as 30% depending on the type of biochar (Major 2010).

Impact assessment

Eco indicator 99 model of SimaPro 8.1 LCA software, one of the most widely used impact assessment methods in LCA (Cavalett et al. 2013), is used to assess

endpoint damage for each scenario in this study based on its scope (system boundary) and available life cycle inventory database (Goedkoop and Spriensma 2001). Impact categories analyzed in this study include damages to human health, damages to ecosystem quality, damages to resources and climate change in global warming potential terms (Afrane and Ntiamoah 2011). Damages to human health are caused by emissions of carcinogens, respiratory effects caused by the emission of organic and inorganic substances, climate change, ionizing radiation and ozone layer depletion. Impact assessment unit for this category is disability-adjusted-life-years (DALY). According to Jolliet et al. (2003) DALY characterizes the disease severity, accounting for both mortality (years of life lost due to premature death) and morbidity (the time of life with lower quality due to an illness, e.g., at hospital). Default DALY values of 13 and 1.3 (years/incidence) are adopted for most carcinogenic and non-carcinogenic effects, respectively. For example, a product having a human health score of 3 DALYs implies the loss of three years of life over the overall population not the person (Humbert et al. 2012). Damages to ecosystem quality are caused by ecotoxic emissions, combined effects of acidification and eutrophication, and land occupation and conversion. LCA unit for ecosystem quality damage assessment is Potentially Disappeared Fraction (PDF) of species over an area during a certain amount of time (PDF.m².yr) (Humbert et al. 2012). This represents the fraction of species disappeared on 1 m² of earth's surface during one year. For example, a product having an ecosystem quality score of 0.2 PDF.m².yr implies the loss of 20% of species on 1 m² of earth surface during one year (Jolliet et al. 2003). Damages to resources are caused by extraction of minerals and fossil fuels. Climate change impact in this study was assessed by the global-warming

potential (Afrane and Ntiamoah 2011) which is a relative measure of how much heat a greenhouse gas traps in the atmosphere. GWP compares the amount of heat trapped by a certain mass of the gas in question to the amount of heat trapped by a similar mass of CO₂. It is calculated over a specific time interval, e.g. 20, 100 or 500 years. GWP is expressed as a factor of carbon dioxide (whose GWP is standardized to 1).

Interpretation

The results from SimaPro 8.1 LCA software were normalized, weighted and interpreted in terms of defined impact categories within production stages of the System boundary. In order to understand the effect of changes in the availability of biomass raw material in future, a sensitivity analysis was carried out. It is likely that biomass feedstock for wood pellets will experience competition from other conventional uses. Therefore, the sensitivity analysis is designed to assess the overall impacts of low, medium and high availability of biomass feedstock.

Life cycle net energy analysis

Net energy of the system was calculated by deducting the energy output from the total energy input. Similar previous studies in different areas of biomass and bioenergy production (Hammond et al. 2011; Zhang et al. 2010; Paping et al. 2010) were followed to calculate the net energy of the system in each stages of production within system boundary.

Table 3. 1 Inventory data and general assumptions of study

Category	Component	Unit and Description	Remarks
Raw Material	Forest harvest residue (FHR)	33.3%	(SPF 80%, Others 20%)
	Sawmill residue (SMR)	33.3%	(SPF 80%, Others 20%)
	Underutilized trees (UTS)	33.4%	(HW 80%, Others 20%)
Collection	Standard roadside FHR	33.3%	This Study
	Average SMR	33.3%	This Study
	Cut and carry UTS	33.4%	This Study
	Transport truck	40 tonne (60 m ³)	(Hammond et al. 2011)
	Load factor	75%	This Study
	Emission factor	0.9 kg CO ₂ e	(DEFRA 2009)
	Fuel type	Standard gasoline	This Study
	Transportation distance for biomass feedstock	200km	Logging road and standard highway
	Transportation distance for land application	100 km	Forest road and standard highway
Storage	Standard shed	Not heated	This Study
	Moisture loss	33%	This Study
Processing	Grinding and chipping	Standard MC 20%	This Study
	Drying and pelletizing	Standard MC 10-12%	This Study
	Emissions from construction of pyrolysis plant	0.22 tonne CO ₂ /tonne of dry feedstock	(Elsayed and Mortimer 2001)
	Biochar to land transport vehicle	60m ³ capacity truck	(Mortimer et al. 2009)
	Transportation distance	100 km	This Study
	Biochar mean residence time (yrs.)	500	Expert judgment
	Biochar yield from pyrolysis	33.5%	(Brownsort 2009)
	Syngas yield from pyrolysis	31.9%	(Brownsort 2009)

Category	Component	Unit and Description	Remarks
	Oil yield from pyrolysis	34.6%	(Brownsort 2009)
	Syngas carbon content	30%	(Brownsort 2009)
	Syngas calorific value	11 MJ/t	(Brownsort 2009)
	Pyrolysis oil carbon content	45%	(Brownsort 2009)
	Pyrolysis oil calorific value	16 MJ/t	(Brownsort 2009)
	Biochar carbon content	75%	(Brownsort 2009)
	Biochar calorific value (if burnt)	26 MJ/t	(Brownsort 2009)
	Conversion of C to CO ₂	44/12	Scientific knowledge
	GWP CH ₄	25	(IPCC 2007)
	GWP N ₂ O	298	(IPCC 2007)
	Conversion of N to N ₂ O	44/28	Scientific knowledge
Electrical offsets	Coal	939 kg CO ₂ /MWh	(StatsCan 2012)
	Natural gas	405 kg CO ₂ /MWh	(StatsCan 2012)
	Grid average	501 kg CO ₂ /MWh	(StatsCan 2012)
	Kg of CO ₂ /liter of diesel	2.63	(StatsCan 2012)
	MJ/liter of diesel	38.6	(Hammond et al. 2011)
Biomass availability	High	Within 100km distance	This Study
	Medium	Within 200km distance	This Study
	Low	Within 300km distance	This Study

SPF= Spruce, Pine, Fir HW=Hardwood, MC= Moisture Content

RESULTS

Life-cycle inventory

Selected key environmental flows for the production stages of biochar, including land application, are presented in Table 3.2. Processing, pyrolysis and transportation, in that order, utilize the highest total amounts of primary fossil fuel inputs. Storage and land application account for less than half these amounts with collection at about 5% of processing. With respect to emissions, the order of the largest contributor changes to pyrolysis, transportation and processing with the other three stages accounting for less than 10% of the amount associated with pyrolysis. Of these emissions, nearly 100% are accounted for by CO₂, SO₂, SO_x, NMVOC, COD and phosphate for all stages but pyrolysis. Pyrolysis, which consists of several internal thermochemical processes converting biomass to char, gas and bio-oil, also results in the highest levels of CH₄, N₂O, NO_x and nitrate emissions.

Table 3. 2 Life-cycle inventory for production of 1 tonne biochar from forest biomass feedstock

Inventory	Collection	Transportation	Storage	Processing	Pyrolysis	Land Application
Primary fossil inputs						
Gasoline (GJ)	0.1253	2.0326	0.0015	0.9547	0.5633	1.0327
Natural gas (GJ)	0.0026	0.0195	1.2001	0.9862	1.7960	0.0022
Crude oil (GJ)	0.0025	0	0.0146	0.5630	0.0015	0.0001
Emissions						
CO ₂ (kg)	7.50	118.03	69.94	194.02	135.78	59.52
CH ₄ (kg)	0.47	0.28	0.58	0.54	12.24	0.06
N ₂ O (g)	0.01	0.05	0.03	0.03	25.36	0.96
NO _x (g)	0.05	0.56	0.01	0.02	10.23	0.86
SO ₂ (g)	5.56	0.19	0.02	1.89	120.23	1.12
SO _x (g)	1.26	101.22	0.96	0.56	98.63	0.99
NM VOC (g)	20.36	121.03	11.95	25.33	124.01	10.23
BOD (kg)	0.001	0.001	0.002	2.22	101.65	0.026
COD (kg)	0.001	0.001	0.001	1.22	186.44	0.025
Nitrate (g)	0.001	0.22	0.002	0.96	2.23	0.001
Phosphate (g)	0.001	0.011	0.002	0.88	90.23	0.002

*NMVOC =Non-methane volatile organic carbon, BOD=Biological Oxygen Demand, COD=Chemical Oxygen demand

Net energy and GHG emissions

Values for net energy and GHG emissions for the production stages of biochar do not differ based on the addition of land application. Net energy and GHG emissions per tonne dry feedstock with and without land application of biochar are therefore presented in Table 3.3 for comparison. Energy balance results show that about 1 GJ more energy is consumed when biochar is applied to the land however, emissions change from a source (-215 kg CO_{2e}) to a sink (68 kg CO_{2e}) when land application is included.

Table 3. 3 Net energy and GHG emissions per tonne dry feedstock with and without land application of biochar as compared to coal based energy production system

LCA Stages	Energy (MJ per unit)		GHGs (Kg CO _{2e} per unit)	
	Consumption	Generation	Emitted	Reduced*
Collection	1120.26	5015.36	196	201
Transportation	8236.23	-100.23	300	102.02
Storage	1269.23	-56.36	25.1	100.23
Processing	2153.36	123.23	150.32	25.4
Pyrolysis	5623.25	9623.25	96.01	123.98
Without Land Application	Net Gain/Loss	-3797.08	Emission change	-214.8
Land Application	592.36	-458.15	13.32	296.32
With Land Application	Net Gain/Loss	-4847.61	Emission change	68.19
	Gain if (+ve)		Emitted if (-ve)	

*when compared to coal

Transportation and pyrolysis are the largest consumers of energy while pyrolysis and collection are the largest generators of energy.

Environmental impacts

SimaPro results for biochar-based bioenergy production using pyrolysis with and without land application for potential environmental impacts and impact reduction by each impact category are compared with a conventional coal-based system and presented in Table 3.4. Negative percent variations indicate reductions from the reference scenario which means that there is a positive environmental impact. With or without land application, the biochar production scenario adversely impacts respiratory organics and inorganics, ionizing radiations, and aquatic acidification. However, the impact on aquatic acidification with land application scenario is less severe than in the pyrolysis alone scenario. Similarly, aquatic eutrophication changes with land application improving the situation substantially. The pyrolysis scenario alone leads to reductions in the impacts of 9 categories; inclusion of land application actually reduces this number to 8 with terrestrial ecotoxicity and acidification increasing while aquatic eutrophication declines. The negative impacts of global warming and non-renewable energy, respectively, are reduced from 18% to 21% and from 4% to 7% with land application.

Damage assessment and total impact single scores per tonne of biochar production within the system boundary are presented in Table 3.5. Both scenarios resulted in reduced impacts on all scores except DALY (disability adjusted life years). Land application nearly doubles the positive impacts on ecosystem quality and climate

change while improving resource use by approximately 30%. DALY (Disability adjusted life years) increases by 1.69% and 3.39% with and without land application, respectively.

Table 3. 4 Comparative environmental impact potential per tonne of biochar produced as compared to coal based energy production system

LCA Impact category	Unit	Conventional (Reference Case)	Biochar w/o Land Application	Difference ^a	Rank	Biochar w/ Land Application	Difference ^a	Rank
Global warming	kg CO ₂ eq	1.08E+00	8.85E-01	-18.02	1	8.53E-01	-21.06	1
Aquatic ecotoxicity	kg TEG water eq ^b	4.31E+01	4.07E+01	-5.49	2	4.16E+01	-3.40	5
Mineral extraction	MJ surplus	1.08E-03	1.02E-03	-5.48	3	1.02E-03	-5.21	4
Non-renewable energy	MJ primary	1.03E+01	9.90E+00	-3.89	4	9.57E+00	-7.11	3
Terrestrial ecotoxicity	kg TEG soil eq ^b	9.44E+00	9.17E+00	-2.89	5	9.78E+00	3.56	9
Terrestrial acidification	kg SO ₂ eq	1.60E-02	1.56E-02	-2.76	6	1.67E-02	4.23	11
Carcinogens	kg C ₂ H ₃ Cl eq	2.72E-03	2.65E-03	-2.54	7	2.65E-03	-2.63	6
Non-carcinogens	kg C ₂ H ₃ Cl eq	1.53E-02	1.50E-02	-1.90	8	1.51E-02	-1.02	7
Ozone layer depletion	kg CFC-11 eq	8.16E-09	8.07E-09	-1.06	9	8.16E-09	-0.03	8
Respiratory inorganics	kg PM _{2.5} eq	6.02E-04	6.10E-04	1.40	10	6.31E-04	4.81	13
Respiratory organics	kg C ₂ H ₄ eq	5.76E-05	5.95E-05	3.26	11	5.98E-05	3.89	10
Aquatic eutrophication	kg PO ₄ P-lim ^c	3.16E-06	3.32E-06	5.01	12	2.87E-06	-9.02	2
Aquatic acidification	kg SO ₂ eq	4.22E-03	4.44E-03	5.21	13	4.41E-03	4.62	12
Ionizing radiations	Bq C-14 eq	1.25E+00	1.34E+00	7.00	14	1.34E+00	7.20	14

a=percentage change in per unit of environmental impact compared with the conventional (reference) system (Huang et al. 2013); b=TEG water/soil: triethylene glycol into water/soil; c=P-lim: into a phosphorus-limited land.

Table 3. 5 Life cycle impact points of biochar-based bioenergy per tonne of biochar produced

Impact Category	Unit	Conventional (Reference system)	Pyrolysis	Difference ^a	Land Applicati on	Difference ^a
Human health	DALY ^b	4.72E-07	4.88E-07	3.39	4.80E-07	1.69
Ecosystem quality	PDF*m ² *yr ^c	9.78E-02	8.90E-02	-9.00	7.97E-02	-18.51
Climate change	kg CO ₂ eq	1.08E+00	9.91E-01	-8.24	9.09E-01	-15.83
Resources	MJ primary	1.03E+01	9.20E+00	-10.68	8.90E+0 0	-13.59
Total points ^d	pt	2.51E-04	2.23E-04	-11.28	2.14E-04	-14.92

a = Percentage change in per unit of environmental impact compared with reference system (conventional electricity); b = DALY: disability adjusted life years; c = PDF: potentially disappeared fraction of plant species; d = The total impact single scores of the normalized and weighted damage assessments.

Sensitivity analysis

Sensitivity analysis based on biomass availability was done to assess the damage for each impact category (Figure 3.2). Impacts decline as biomass availability increases and land application improves all impacts over pyrolysis alone.

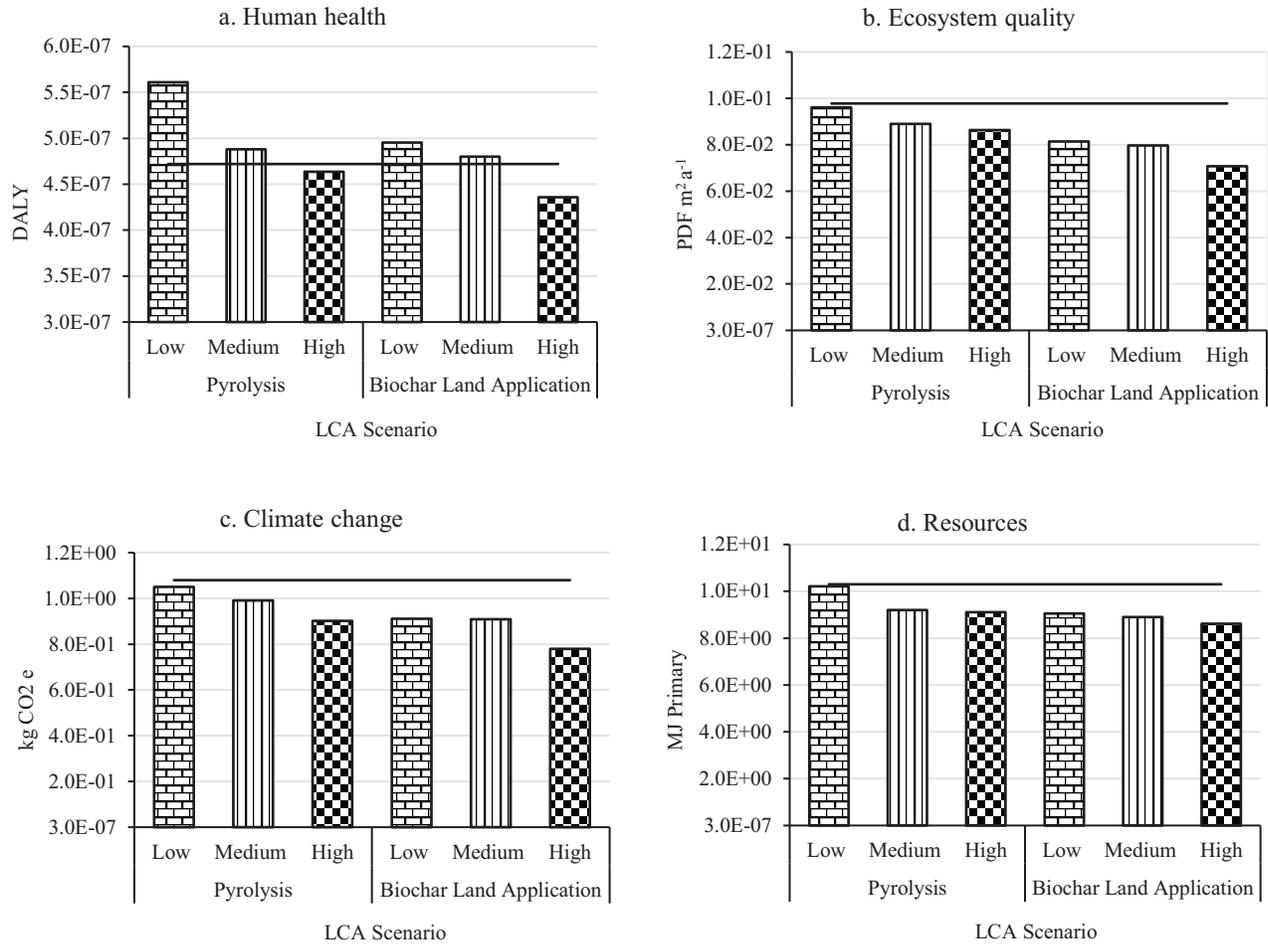


Figure 3. 2 Sensitivity analysis of biomass feedstock availability for different impact categories. [Horizontal line is the reference case]

DISCUSSION

Use of woody biomass for biochar-based bioenergy production is a relatively new initiative in Northwestern Ontario. Life cycle assessment inventory and impact assessment results presented in this paper are based on system boundary and the model assumptions made during the run. Production of biochar-based bioenergy and replacing it with conventional (Faaij et al. 1998) energy production system adds several activities that may not have been accounted for in our analysis. We have only

accounted for collection of raw materials (woody biomass), transportation in different stages, storage, processing (drying, grinding and pelletization), pyrolysis and land application of biochar in the system boundary defined for our analysis.

Our assumption of biochar-based bioenergy production is based on conventional forest biomass transportation, storage, processing and burning in a modern pyrolysis plant. Each of these operations requires major consumption of fossil fuel and has related GHG emissions (Paa et al. 2011; Magelli et al. 2009). The additional GHG emissions may be reduced by land application of biochar, which is stable for many years, and also by using bio-oil and syngas produced in the pyrolysis process to replace fossil fuel in power generation.

Net energy consumption warrants that the biochar-based bioenergy system is a net energy consumer, which uses more energy than it generates. But it will reduce GHG emissions significantly within the life cycle if biochar is applied to the land. Xu et al. (2011) also concluded that the thermal self-sustainability of lab based biochar production by pyrolysis can be energy negative but with the alternation in the system and use of advanced technology these losses can be reduced in the future. Our results of consumption of 3.7 GJ of more energy to sequester 214 kg of equivalent CO₂ is consistent with other studies (Hammond et al. 2011; Zhang et al. 2010).

Both positive and adverse environmental impacts of biomass burning are eminent. Among the different kind of biomass available for burning, forest based woody biomass are considered environmentally cleaner as they claim that they are being burned for the power generation instead of letting them decompose in the nature and they use less energy input in production. In our results, we found that most of the impact

categories are positively impacted by biochar production and land application. The most notable advantage is reduction of global warming potential by 18 and 21% with either scenario. Some notable adverse effects are mostly related to human health by exposing to carcinogenic emissions, respiratory organics and land pollution but which are pretty low in scale as compared to similar other disadvantages of burning coal. This adverse impact is mainly due to the new wood burning scenario and added biomass transportation in the system boundary which in the future might be reduced by proper personal protection instruments and improving pyrolysis plant and improving transportation efficiency. The damage assessment of the unit process as indicated by LCA and inventory is mostly positive for each impact category except in human health. With the improvement of ecosystem quality by 18% reducing climate impact by upto 15% and reducing non-renewable resource dependency by 15% in the life cycle of biochar can easily contribute to compensate this human health impact of 2-3% DALY. Similar increase of DALY was also reported by Huang et al. (2013). Our sensitivity analysis of availability of biomass also resulted in best performance when availability of biomass is high in the close area to the pyrolysis plant. It reflects directly with the reduced transportation and low loss of energy. It also supports the local use of biomass resource.

CONCLUSIONS

Life cycle assessment of biochar-based bioenergy production system with land application of biochar is conducted within a defined system boundary in Northwestern Ontario. It is found that i) biomass collection, transportation and pyrolysis processes are

most energy intensive and account for about 75% of the total GHG emissions of the system; ii) the net energy of the biochar-based bioenergy system is negative but it can reduce and GHG emissions with land application of biochar; iii) biochar-based bioenergy can have some adverse impact on human health but it significantly reduces the impact of climate change by improving ecosystem quality and reduction of dependence on non-renewable resources; and iv) pyrolysis and land application of biochar have most promising positive environmental impacts as compared with conventional coal based power generation system, if biomass availability is high. In this paper, we have only accounted for the environmental impact side of biochar-based bioenergy production, and did not consider the cost of production and GHG emissions reduction. Further research should focus on life cycle cost analysis of the biochar-based bioenergy system, as its economics are fundamental to the financial sustainability of the system.

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REFERENCES

(All references are arranged at the end of Chapter 5)

CHAPTER 4**PAPER 3: LIFE CYCLE COST AND ECONOMIC ASSESSMENT OF BIOCHAR-BASED BIOENERGY PRODUCTION AND BIOCHAR LAND APPLICATION IN NORTHWESTERN ONTARIO, CANADA**

Krish Homagain^{*1}, Chander Shahi¹, Nancy Luckai¹ and Mahadev Sharma²

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ABSTRACT

Background: Replacement of fossil fuel based energy with biochar-based bioenergy production can help reduce greenhouse gas emissions while mitigating the adverse impacts of climate change and global warming. However, the production of biochar-based bioenergy depends on a sustainable supply of biomass. Although, Northwestern Ontario has a rich and sustainable supply of woody biomass, a comprehensive life cycle cost and economic assessment of biochar-based bioenergy production technology has not been done so far in the region. Methods: In this paper, we conducted a thorough life cycle cost assessment (LCCA) of biochar-based bioenergy production and its land application under four different scenarios - 1) biochar production with low feedstock availability; 2) biochar production with high feedstock availability; 3) biochar production with low feedstock availability and its land application; and 4) biochar production with high feedstock availability and its land application- using SimaPro[®], EIOLCA[®] software

¹ Krish Homagain, khomagai@lakeheadu.ca

Faculty of Natural Resources Management, Lakehead University, 955 Oliver Rd. Thunder Bay, ON P7B 5E1 Canada

² Ontario Forest Research Institute, 1235 Queen Street E, Sault Ste. Marie, ON P6A 2E5 Canada

and spreadsheet modeling. Based on the LCCA results, we further conducted an economic assessment for the break-even and viability of this technology over the project period. Results: It was found that the economic viability of biochar-based bioenergy production system within the life cycle analysis system boundary based on study assumptions is directly dependent on costs of pyrolysis, feedstock processing (drying, grinding and pelletization) and collection on site and the value of total carbon offset provided by the system. Sensitivity analysis of transportation distance and different values of C offset showed that the system is profitable in case of high biomass availability within 200km and when the cost of carbon sequestration exceeds CAD \$60 per tonne of equivalent carbon (CO_{2e}). Conclusion: Biochar-based bioenergy system is economically viable when life cycle costs and environmental assumptions are accounted for. This study provides a medium scale slow-pyrolysis plant scenario and we recommend similar experiments with large-scale plants in order to implement the technology at industrial scale.

Keywords: LCA, LCCA, SimaPro, Biochar, Biomass, Pyrolysis, Bioenergy, Wood Pellets

INTRODUCTION

Biochar¹-based bioenergy production through slow pyrolysis² of sustainably produced biomass feedstock is one of the simplest and cheapest method among several carbon capture and storage (CCS) methods (Woolf et al., 2010). Production of biochar and bioenergy is gaining significant momentum worldwide over the last decade with a steady growth of 3% per year (IEA 2015, IBI 2016). Growing worldwide attention towards combating the adverse impacts of climate change, and the future courses of actions towards climate related issues were willfully agreed during the recent (2015) climate conference in Paris by different nations. Canada made a further commitment to achieve 30% reduction in CO₂ from 2005 levels by 2030 which basically lies within the provincial jurisdictions as management of natural resources is a provincial affair in Canada. The Province of Ontario further targeted to reduce 37% CO₂ from 1990 levels by 2030 (Lyman 2015, MOECC 2015). As a forest resource rich province, Ontario has the best opportunity to utilize its forest-based biomass to reduce carbon emission by reducing its dependency towards much debated fossil fuel. A significant step towards this has already begun in Ontario as the province legally banned coal burning for the power generation.

¹ Biochar is a highly porous and stable carbon-rich co-product of pyrolysis that has many uses including soil amendments and long term carbon sequestration. Although chemically similar, Biochar differs from charcoal in the sense that it is not used as fuel (Lehmann and Joseph, 2009).

² Pyrolysis is defined as a thermochemical decomposition process occurring in the absence of oxygen (Spokas et al. 2012).

In this paper we deal with biochar produced from woody biomass in a bioenergy plant using the slow pyrolysis technique, a process that maximizes production, at 300–500°C with a vapor residence time of 5–30 minute. (Please see details in Homagain et al. 2015).

Use of biomass-based feedstocks especially from agriculture and forestry has been popular in recent years. Northwestern Ontario (NWO), in particular, has a rich and sustainable source of woody biomass supply through the sustainable management of about 12 million ha of productive forest through 18 Forest Management Plans (MNR 2015). Several previous studies (Alam et al. 2012; Hacatoglu et al. 2011; Kennedy et al 2011; Wood and Layzell 2003) have also indicated that the NWO forests are capable of sustainably supplying enough biomass feedstock to generate electricity from power-generating stations, which used coal as feedstock until 2014. One of the limiting factors in the use of biomass feedstock for power generation is the energy density and its vast variability within different types of woody biomass. To overcome this limitation and to continue a sustained supply of the feedstock, the wood biomass raw materials are being processed and pelletized. Atikokan generating station (AGS-200MW) in NWO, a coal burning power plant recently converted to wood burning facility has already started using locally produced wood pellets to produce clean electricity. Although the production of bioenergy¹ is a fairly established technology, it is not economically competitive compared to the production of energy using fossil fuel, because of its high cost of production (Klinar 2016). The other secondary issue related to bioenergy production that is gaining momentum is landfilling with wood ash, which may contain heavy metals. If these issues are not properly addressed, bioenergy production may lose its competitive edge as a clean energy producing technology. Co-production of biochar with bioenergy, and applying biochar back to the land from where the biomass

¹ Bioenergy is the energy derived from the conversion of biomass where biomass may be used directly as fuel, or processed into liquids and gases.

feedstock originated is suggested as one of the most feasible solutions for GHG emissions and waste management issues (Lehmann and Joseph, 2009). Several life cycle analysis studies including our study (Homagain et al., 2015) have shown GHG emissions reduction with co-production (Sohi, 2013; McElligott et al., 2011; Roberts et al., 2010; Winsley, 2007). However, there is no study to our knowledge, which conducts a comprehensive life cycle cost assessment of the biochar-based bioenergy system, and accounts for every step of the production and use cycle.

Most of the related studies in literature focus on economic assessment of biochar systems (Galinato et al., 2011; Shackley et al., 2011; Yoder et al., 2011; Pratt and Moran, 2010; Roberts et al., 2010; McCarl et al., 2009). These studies typically found that the potential economic profitability of biochar production systems varies depending on the feedstock used (Cleary et al., 2015; Roberts et al., 2010), the conversion technology employed (Bruun et al., 2011; Pratt and Moran, 2010), or the inclusion of carbon sequestration subsidies or carbon credits¹ reflecting the social value of GHG mitigation (Galinato et al., 2011; Shackley et al., 2011; Pratt and Moran, 2010; Roberts et al., 2010). One study, modeling the trade-off between product yield and product quality as conversion temperature increases, has explored the implications of different production techniques and resulting variations in biochar properties for overall system performance (Yoder et al., 2011). Recent techno-economic assessments of slow-

¹ A carbon credit (often called a carbon offset) is a financial instrument that represents a tonne of CO₂ (carbon dioxide) or CO₂e (carbon dioxide equivalent gases) removed or reduced from the atmosphere from an emission reduction project, which can be used, by governments, industry or private individuals to offset damaging carbon emissions that they are generating.

pyrolysis biochar and heat production (Patel et al., 2016; Klinar, 2016) also showed that the biochar system can be profitable provided it is customized into the local production system. The size and scale of the biochar system affects the cost and its economic viability. Studies that compared the life cycle costs of different scale bioenergy systems with (Kulyk, 2012) and without (Cleary et al., 2015; Roberts et al., 2010) biochar land application found that production cost of large-scale plant is lower than smaller scale plant but the GHG mitigation cost for large-scale plant is very high as compared to the smaller plant. For the purpose of this paper, we define 'biochar-based bioenergy' as the energy (char, syngas and bio-oil) produced by slow pyrolysis of woody biomass in a pyrolysis plant in the absence of oxygen. Bio-oil and syngas is then converted into electricity and biochar is applied in the same forest land where the raw material was collected. In this paper we assess the life cycle cost of producing biochar-based bioenergy and its land application with high and low availability scenario of biomass feedstock in NWO, Canada.

METHODS

Life cycle cost analysis is a combination of life cycle environmental assessment, life cycle costing and economic analysis. We used a combination of LCA outputs, collected cost information for each analysis steps and scenario, created LCCA spreadsheet calculation tool, calculated net present value for each analysis scenario and conducted break-even analysis.

LCCA System Boundary, Study area and Analysis Scenarios

Life cycle cost analysis system boundary is presented in Figure 4.1. This is the same study area and system boundary that was used in life cycle assessment of biochar based bioenergy in our earlier paper (Homagain et al., 2015). The system boundary extends from raw material collection to the application of biochar to the forest including the co-products to the market, and covers different interdependent phases including collection, transportation, storage, processing and pyrolysis.

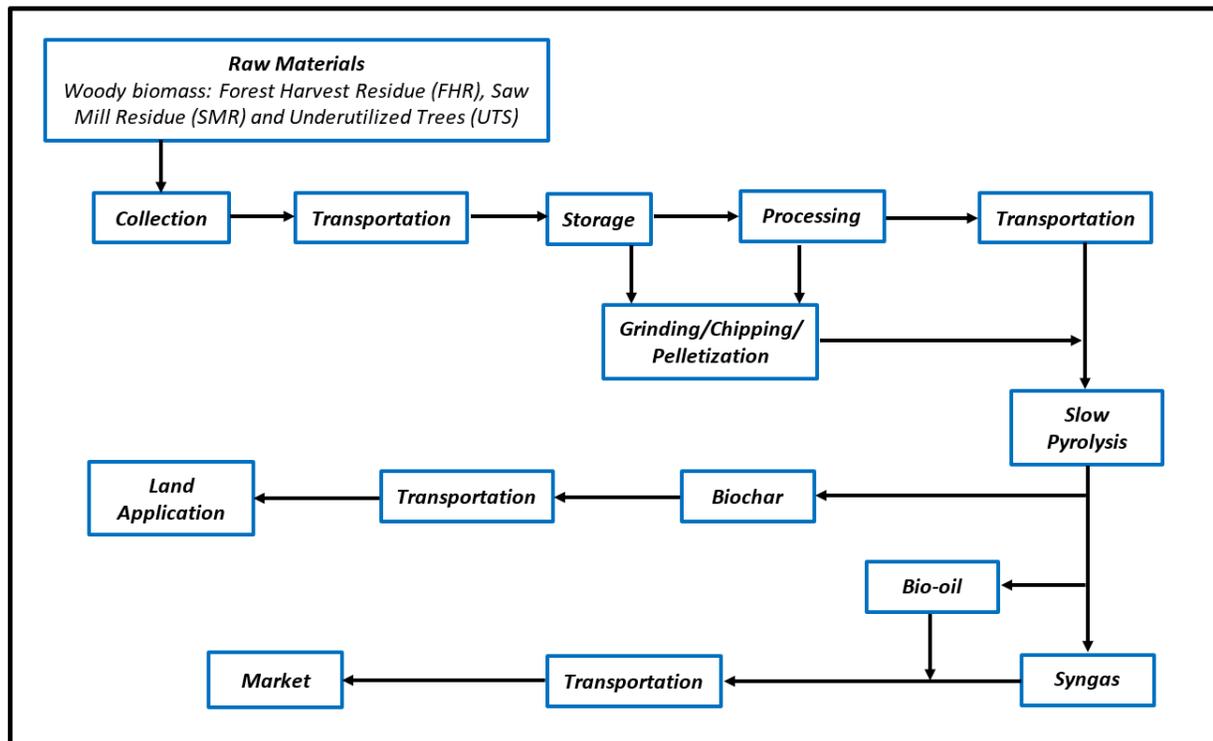


Figure 4.1 System boundary for LCCA of biochar-based bioenergy production

The study area lies in NWO Canada, where the Atikokan Generating Station (AGS) has been converted from coal to biomass (wood pellet) feedstock (OPG 2012). NWO has a vast amount of forest based woody biomass which can sustainably supply

biomass feedstock to recently converted power plant. Although AGS plans to use the combustion process for energy generation, our study uses different scenarios where biomass feedstock is converted into bio-oil, syngas and biochar using the normally available slow-pyrolysis machine in order to illustrate the cost assessment of biochar-based bioenergy production. The input-output data for the system boundary and unit processes were obtained directly from published literature, the NWO regional forest management units, forest management plans, and personal communications with harvesters, transporters and other professionals.

Our hypothetical biochar system is a medium sized (1 MWh) slow-pyrolysis system with fixed bed twin-fire pyrolyzer (Power Max 2015) with a life span of 25 years. We used four different cost analysis scenarios based on the availability of biomass feedstock, transportation distance and application of biochar back to the same forest land from where it was collected. Basic description of these scenarios is provided in Table 4.1. Same average transportation distance (300km for low availability and 100km for high availability) for biochar land application is used as feedstock transportation. Biochar land application rate is used as 50 tonne per ha which was set during the life cycle assessment in SimaPro[®] assumption (See Homagain et al. 2015 for details).

Table 4. 1 Life Cycle Cost Assessment Scenarios

Scenario	Feedstock Availability	Feedstock Transportation distance	Biochar Land Application	Project Period
1. Biochar Low	Low	More than 200 km Average 300 km	No	25 years
2. Biochar High	High	Less than 200 km Average 100 km	No	25 years
3. Land Application Low	Low	More than 200 km Average 300 km	Yes 50 t ha ⁻¹ at 300km	25 years
4. Land Application High	High	Less than 200 km Average 100 km	Yes 50 t ha ⁻¹ at 100km	25 years

Life Cycle Costing and Net Present Value

Following the life cycle environmental assessment (Homagain et al. 2015), we conducted a comprehensive life cycle cost assessment of each production stage within the system boundary using the following model (Eq. 1). Description of each variable and the sources of information are given in Table 4.2.

$$LCC_t = MSC_t + FCC_t + TC_t + SPC_t + PC_t + LAC_t \dots\dots\dots (1)$$

Where, LCC_t = Total life cycle cost at year t, MSC_t = Machine and setup cost at year t, FCC_t = Feedstock collection cost at year t, TC_t = Transportation cost at year t, SPC_t = Storage/processing cost at year t, PC_t = Pyrolysis cost at year t, and LAC_t = Land application cost at year t.

We used SimaPro® for life cycle assessment (Pre Consultants 2013) and Environmental Input and Output Life Cycle Assessment (EIO-LCA®) for detailed cost assessment (GDI 2010). We then developed a spreadsheet LCCA tool and calculated the whole life cycle cost of every stage of production. Revenue calculation included the equivalent electricity generated per kWh basis, and using the current market value for electricity, syngas and bio-oil. For non-land application scenarios (Scenario 1 and 2), the by-product biochar was again used as fuel in the system. Carbon sequestration benefit (Carbon credit) is also considered for land application scenarios. Similar transportation distance is assumed for market and land application of biochar as for feedstock transportation to processing site. A standard net present value model (Eq. 2) is used for the 15 year project period to calculate the NPV.

$$NPV_y = \sum_{t=1}^y (R_t - C_t) / (1 + r)^t \dots \dots \dots (2)$$

Where, NPV = Net present value, R = Revenue, C = Life cycle cost, r = Discount rate

Discount rate is a factor that takes into account the effect of time value of money. It is defined as the financial advantage of one investment when compared to a risk free annual rate of return (EPA 2010). Discount rate takes care of both the existing interest rate and inflation rate.

In general, the discount rate is calculated as: $r = i + f$ where, r is discount rate (nominal), i is interest rate, and f is inflation rate. The exact equation that links nominal and real interest rates is represented in (Eq. 3):

$$(1 + r) = (1 + i)(1 + f) \dots \dots \dots (3)$$

Ten year averages of real interest and inflation rates were used (Bank of Canada 2013). Year 2013 is considered the base year for the project for all four scenarios, defined in Table 4.1, and all future costs and revenues are discounted for this year. Value of carbon sequestration is considered as one of the important dependent variable for the net present value calculation of the system. We also conducted a sensitivity analysis of different values of carbon credit and used CAD 60 for each equivalent tonne of carbon sequestered, while biochar is applied to the soil.

Table 4. 2 Description of specific cost information

Variable	Description	Source
Total life cycle cost (LCC)	$LCC_t = MSC_t + FCC_t + TC_t + SPC_t + PC_t + LAC_t$	This study
Machine and Setup Cost (MSC)	<ul style="list-style-type: none"> • Planning - Feasibility study • Environmental Impact Assessment (EIA) and development services • Detailed Engineering Design • Industry renewal fee • Plant site Construction costs and maintenance in every 5 yrs. • Equipment base price and delivery • Plant Set Up and maintenance 	MOECC 2015, PowerMax 2015, <i>Pers. comm.</i>
Feedstock Collection Cost (FCC)	<ul style="list-style-type: none"> • Forest Harvest Residue (FHR) • FHR-Labor - and related • Saw Mill Residue (SMR) • SMR-Labor- and related • Underutilized trees (UTS) • UTS-Labor- and related 	AAFC 2008, Gautam et al 2010, <i>Pers. comm.</i> with harvesters, Upadhyay et al. 2012
Transportation Cost (TC)	<ul style="list-style-type: none"> • Feedstock Transportation to Storage • Transportation from storage to Pyrolysis Facility • Biochar Transportation to Land • Bio-oil Syngas Transportation to market 	AAFC 2008, Alam et al 2012, <i>Pers. comm.</i>
Storage/Processing Cost (SPC)	<ul style="list-style-type: none"> • Storage • Grinding/Pelletization Cost 	AAFC 2008, WPAC 2013 <i>Pers. comm.</i>
Pyrolysis Cost (PC)	<ul style="list-style-type: none"> • Cost of plant operation • Skilled labor/ Product Testing • Pyrolyzed Products storage 	NREL 2010, IRENA 2012
Land Application Cost (LAC)	<ul style="list-style-type: none"> • Material handling, tractor and fuel costs • Transportation and skilled labor costs • Other incidental cost (2%) 	<i>Pers comm</i> with independent applicators

RESULTS

Life cycle cost assessment tool (spreadsheets) with all assumptions and calculations are compiled in the appendix or as a supplementary document. A 25 year average annual cost inventory of the biochar-based bioenergy system of 1MWh plant (Figure 4.2) shows that cost of pyrolysis (\$ 381,536 yr⁻¹) is the most expensive stage of production followed by storage/processing (\$ 237,171 yr⁻¹) which includes pelletization. There is an extra cost of \$ 156,739 yr⁻¹ and \$ 133,228 yr⁻¹ for the land application of biochar for low and high availability of feedstock. Feedstock collection costs about \$ 134,053 yr⁻¹ (low availability) and \$ 113,945 yr⁻¹ (high availability). Transportation costs for low and high availability are \$ 97,962 yr⁻¹ and \$ 83,268 yr⁻¹, respectively. Pyrolyzer machine purchase, delivery, setup and environmental assessment costs as a whole averages \$ 82,727 yr⁻¹.

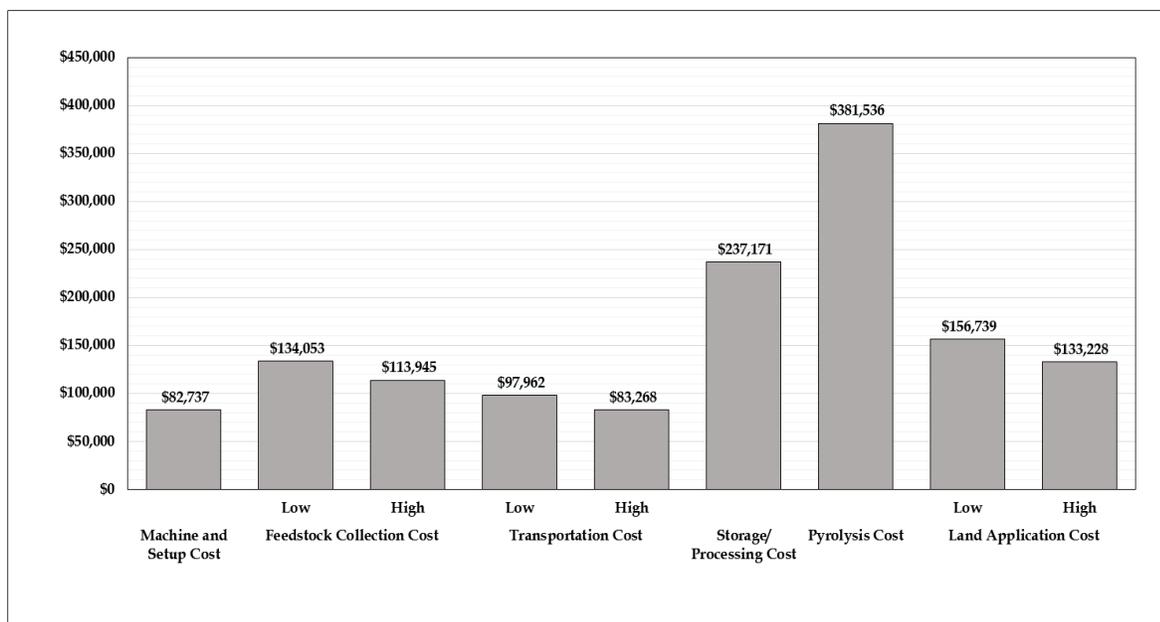


Figure 4. 2 Average annual life cycle cost inventory (undiscounted) for the biochar-based bioenergy system

Total inventory cost is further aggregated to calculate total annual cost of plant operation and its present value for each scenario and is presented in Figure 4.3. Total annual plant operation cost is high in land application with low feedstock availability (Scenario 3) followed by land application with high feedstock availability (Scenario 4), biochar with low feedstock availability (Scenario 1), and biochar with high feedstock availability (Scenario 2). Average annual cost of operation from all scenarios is \$ 988,550 with a present value of \$ 532,816 in 2013 dollar terms and a discount rate of 5.06%.

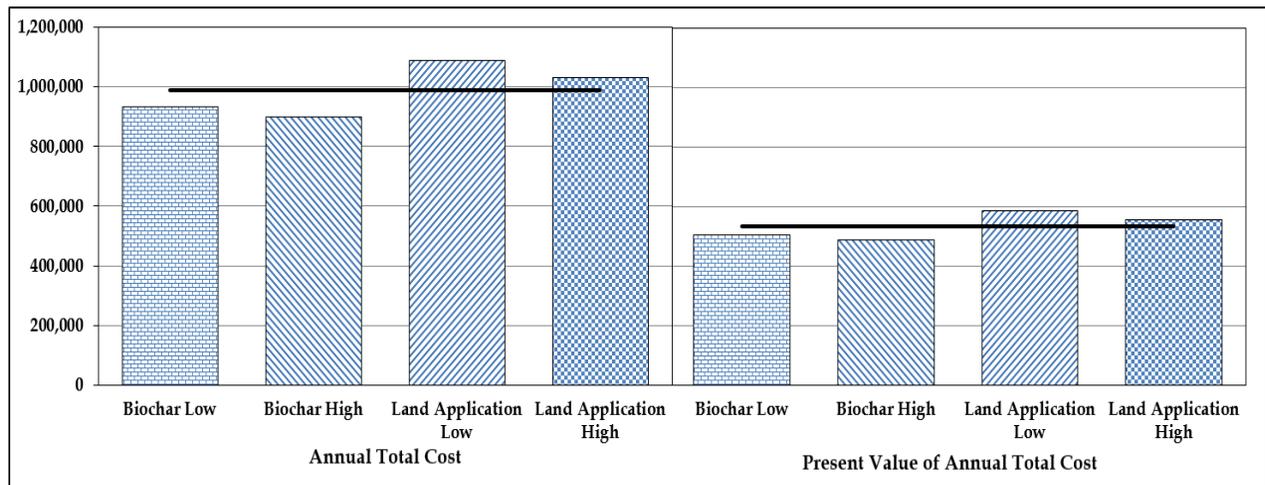


Figure 4. 3 Total annual (undiscounted) and present value (discounted) of biochar-based bioenergy production costs (\$) in different scenarios. (Horizontal solid line depicts the average)

A cumulative cost for all scenarios (Figure 4.4) shows that both land application scenarios costs more than 25 million.

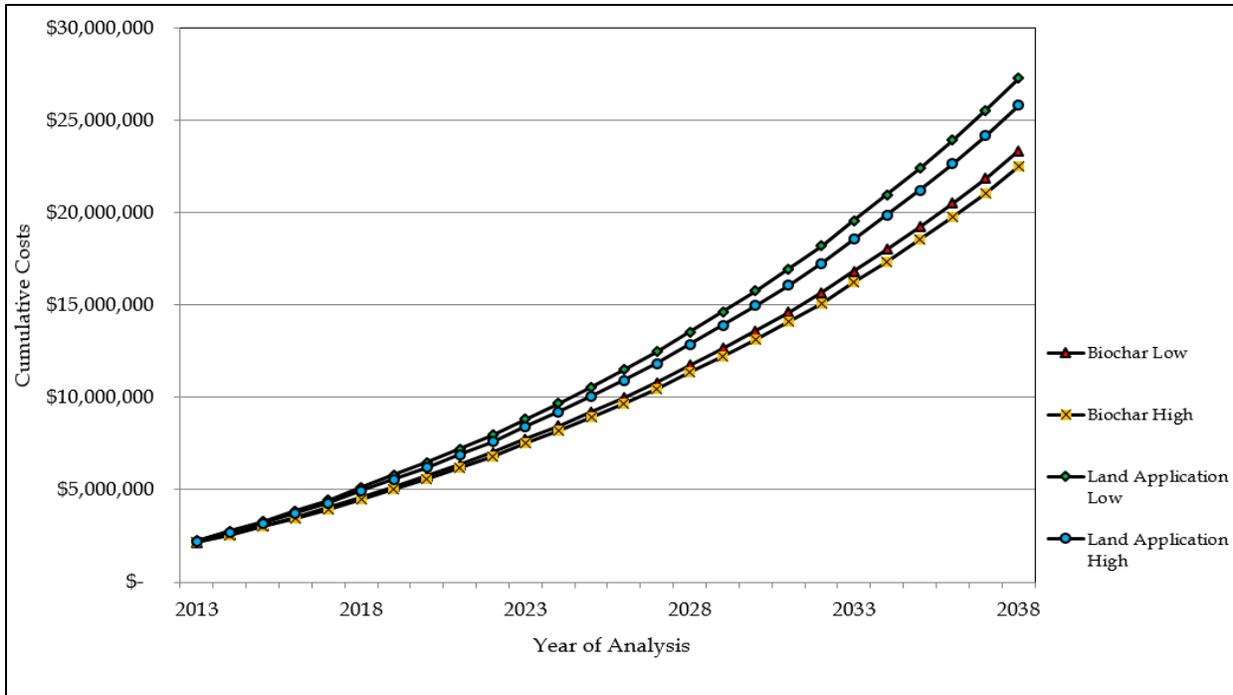


Figure 4. 4 Cumulative life cycle cost (undiscounted) for 25-yr project period

Sensitivity analysis of carbon credit provided for each tonne equivalent of CO₂ sequestration on rate of return of all four scenarios shows that both land application scenarios are profitable, but both biochar only scenarios are not profitable (Figure 4.5). The rate of return maximizes at 9% when per tonne of carbon is priced at CAD 60. This figure is used for entire calculation and economic assessment.

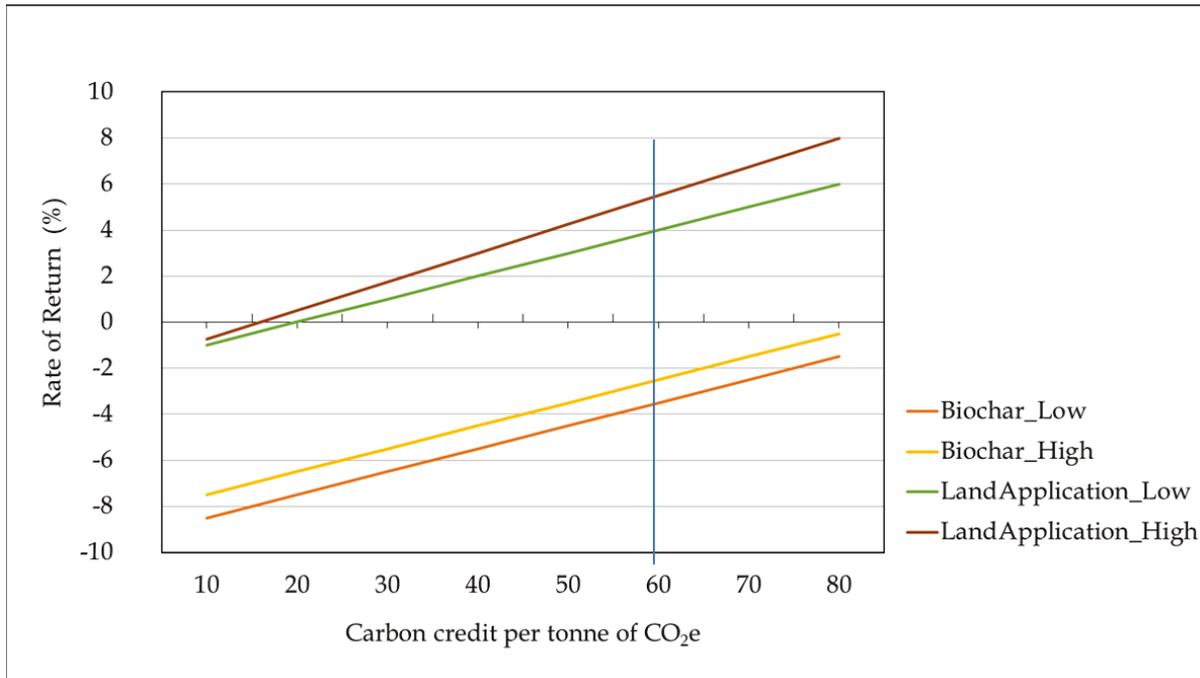


Figure 4. 5 Sensitivity of rate of return of a 25-yr biochar based bioenergy system based on carbon credits

We conducted a break-even analysis on the basis of 25 year revenue and cost at \$60 per tonne of CO₂e. The analysis is presented in Figure 4.6. It shows that scenario 4 (Land Application High) reaches into the break-even at about 12 years which has a return on investment (ROI) of 9%. Similarly scenario 3 (Land Application Low) reaches break-even after 13 years with a ROI of 5%. Scenario 2 (Biochar High) and scenario 1 (Biochar Low) reach break-even after 17 years with a negative ROI of -4% and -6% respectively.

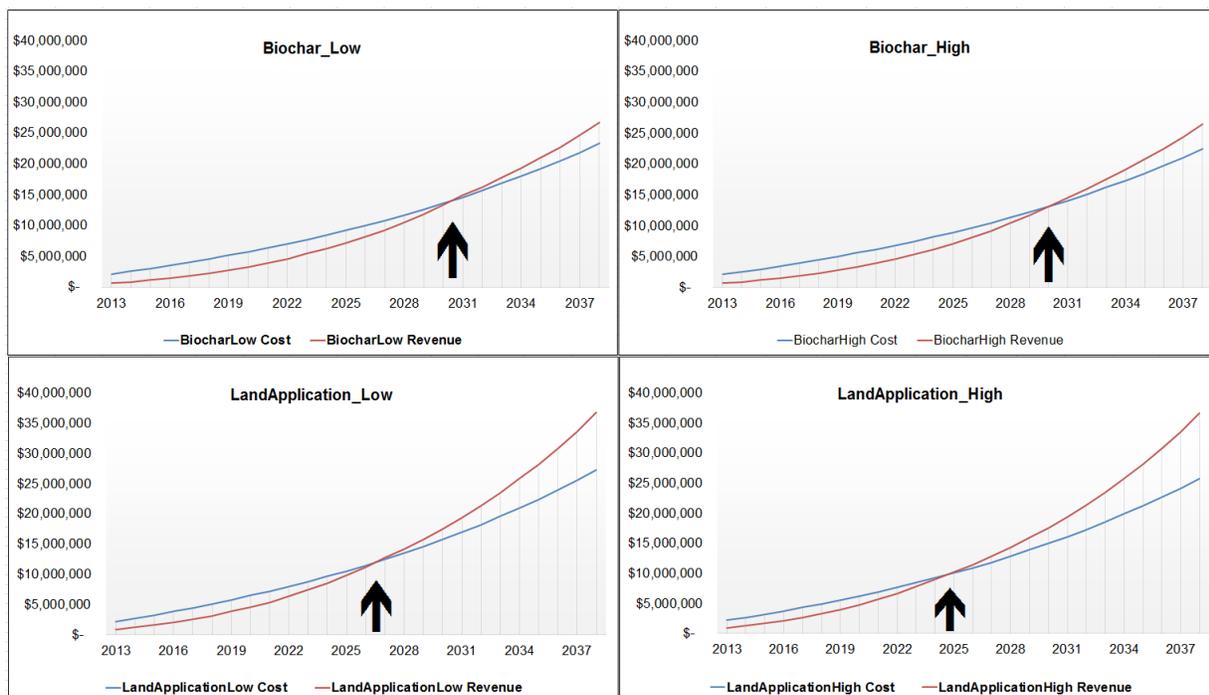


Figure 4. 6 Life cycle break-even analysis of 1-mwh biochar-based bioenergy system in 25-yr period

DISCUSSION

Biochar based bioenergy production is a costly investment. Our LCCA analysis shows that it warrants at least about a million dollar investment each year for a 25 year project. However, we noticed some thoughtful observation in our results.

Pyrolysis has the highest (36%) share of total cost

Pyrolysis is the most costly stage among all production stages in the life cycle of bioenergy production and accounts for 36% of the total cost of the system. Although pyrolysis is an old and established technology, there is a need to develop highly efficient and optimized machines. When producing biochar, bio-oil and syngas, the pyrolyzer consumes large amounts of energy and requires more skilled work force as compared

to other stages. The average annual cost for the 1-MWh pyrolyzer in our study is slightly more than a similar half-capacity portable pyrolyzer (Coleman et al. 2010), but is cheaper than bio-oil pyrolysis system used in the UK (Rogers and Brammer, 2012).

In a study on carbon market investment criteria for biochar projects conducted by California Energy Commission (CEC 2014), the authors also found that pyrolysis may be one of the most energy/resource expensive investments for biochar production. Although, pyrolysis biochar is becoming popular, it is still in research and development stage. If the demand for bioenergy production increases due to its environmental benefits, there will be more emphasis on developing highly efficient and cost effective system, thereby reducing the cost of pyrolysis.

Feedstock collection cost (12%) is higher than transportation cost (9%)

Our study uses three types of feedstock: forest harvest residue, saw mill residue and underutilized trees that are available in the study area of NWO. Collection of these materials would be a relatively new business and there are no established companies that can provide a sustainable supply of feedstock. On the other hand, there is an established forestry raw material transportation service provided by contractors on a competitive basis in the study area. Collection of these vast amounts of scattered feedstock is relatively labour and time intensive, and costs more than transportation. However, in other studies (Kaliyan et al., 2015; Ronsse et al., 2013; Kung et al., 2013; Zhang, 2010; Simon et al., 2010) where the feedstock was mainly agriculture or municipal waste, the transportation cost was always found to be more than raw material collection cost.

Land application cost (14%) is higher than feedstock collection and transportation cost (9%)

Biochar land application would be completely new business in the area. Land application in forest lands or in recently harvested area is a cumbersome job as compared to homogenous agriculture farming field. Our study used a rate of 50 t ha⁻¹ which is almost half of what is suggested in the cropping field (Major 2010). Land variability, distance and rate of application may have contributed to the high cost of land application. However, land application is considered as paying carbon back to the nature for a long-term sequestration so the carbon credit accrued from the sequestration ultimately offsets this cost in the long run.

Land application scenarios have early break even and more return

Both land application scenarios with high and low feedstock availability have early break even periods (12 and 13 years) as compared to non-land application scenarios where break-even is after 17 years. This is because of the revenue generated through the carbon credits earned through the land application of biochar and the cost associated with the application is low as compared to the cost of land application.

Limitation of the study

Biochar-based bioenergy is a new socio-economic intervention in the area where fossil fuel has been contributing in the past. Social dimensions of bioenergy system especially macro-economic demand and supply side effects cannot be ignored while

evaluating life cycle carbon and costs of the individual projects. This study did not consider this area, nor it did anything on the local job creation scenarios (direct, indirect and induces) as there are highly visible displacement effects and local job creation functions of the biochar-based bioenergy system.

This study was conducted during 2011-2013 (three year span) when most of the wood market was relatively slow and energy prices (especially petroleum) were high as compared to 2014 onwards. Collection of cost information in a longitudinally spanned time frame may have caused some deviations in the total costs but all the future values are discounted with national real and 10-yr average inflation rates.

All other related costs above and beyond the system boundary (Fig 4.1) are assumed to be constant throughout all study period and across all scenarios.

CONCLUSION

Canada has committed to achieving 30% reduction in CO₂ emissions from 2005 levels by 2030, while the province of Ontario in Canada has further committed to reducing CO₂ emissions by 37% from 1990 levels by 2030. As a result, Ontario has banned the use of coal and is utilizing its forest-based biomass instead for energy production. However, the slow pyrolysis process of biochar-based bioenergy production has not been tested so far in Ontario due to its uncertain environmental and economic impacts. In this study we conducted a comprehensive life cycle cost and economic assessment analysis of biochar-based bioenergy production and biochar land application in Northwestern Ontario, Canada using LCA assumptions from our previous study (Homagain et al., 2015). Within the biochar-based bioenergy production system

boundary and study assumptions, we found that pyrolysis process accounts for the highest share of 36% cost in the production system; whereas land application accounts for 14%, feedstock collection for 12%, and transportation cost for 9% of the total production cost. Land application scenarios are economically viable with 12 to 13 years of break-even time, when carbon sequestration is credited for at least CAD 60 per tonne of CO₂e. Therefore, if biochar and bioenergy are co-produced, these can not only provide an economic alternative to fossil fuel energy production, but also help in sequestering stable carbon for longer periods of time. However, utilization of forest biomass may warrant an improvement in the regional biomass harvesting policy.

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Authors' contributions

KH as a first author conducted all analyses, interpreted results and wrote and revised the manuscript. CS as a principal supervisor and NL & MS as academic committee members made substantial contributions to the layout and design of the study and interpretation of the results. All authors read and approved the final manuscript.

Authors' information

KH is a recent PhD graduate from Faculty of Natural Resources Management of the Lakehead University and currently working with Ontario Ministry of Natural Resources and Forestry (MNRF) as a Regional Analyst. CS (Socio economist) and NL (Ecologist) are both Professors at Lakehead University with multi-disciplinary forestry-ecology- economics and statistics background. MS is a Forest Growth and productivity research scientist in Ontario Forest Research Institute of MNRF.

Competing interests

The authors declare that they have no competing interests.

List of abbreviations and definitions

AAFC = Agriculture and Agri Foods Canada, a federal department.

AGS = Atikokan Generating Station. A 200 MWh power generating station owned by OPG. This is the largest wood pellet burning station in North America as of 2014 when it was converted from lignite coal burning to wood pellets.

C = Carbon

CAD = Canadian Dollar

CCS = Carbon capture and storage

CEC= California Energy Commission

CO₂ = Carbon dioxide

CO₂e= Carbon dioxide equivalent, is a standard unit for measuring carbon footprints to express the impact of each different greenhouse gas in terms of the amount of CO₂ that would create the same amount of warming. Carbon footprints of different greenhouse gases can be expressed as a single number as CO₂e.

EIOLCA® = Environmental Input and Output Life Cycle Assessment, a software developed by GDI

FCC = Feedstock collection cost

GDI= Green Design Institute. Developer of EIOLCA

GHG = Greenhouse Gas

IBI = International Biochar Initiative, USA

IEA = International Energy Agency, an autonomous intergovernmental organization established in the framework of the Organization for Economic Co-operation and Development (OECD) in 1974 in the wake of the 1973 oil crisis.

IRENA = International Renewable Energy Agency

LAC = Land application cost

LCC = Total life cycle cost

LCCA= Life cycle cost assessment

MNRF = Ministry of Natural Resources and Forestry, Ontario, Canada

MOECC = Ministry of Environment and Climate Change, Ontario, Canada

MSC = Machine and setup cost

MWh = Megawatt hour

NPV = Net Present Value. It is the difference between the present value of total revenue (cash inflows) and the present value of total cost (cash outflows) discounted for the entire investment period.

NREL = National Renewable Energy Laboratory of USA

NWO = Northwestern Ontario. A big section of Province of Ontario covering about 52 million ha area

OPG = Ontario Power Generation, a crown corporation owned by Province of Ontario.

PC = Pyrolysis cost

Pers. Comm. = Personal communication

ROI = Return on investment. It is the most common profitability ratio of a project which is usually expressed as a percentage of net profit and is typically used for financial decisions, to compare the efficiency of different investments.

SimaPro® = A LCA software developed by Pre Consultants, the Netherlands.

SPC = Storage and processing cost

TC = Transportation cost

WPAC = Wood Pellet Association of Canada

REFERENCES

(All references are arranged at the end of Chapter 5)

CHAPTER 5 BIOENERGY, BIOCHAR AND SUSTAINABILITY: A SYNTHESIS

Krishnahari Homagain*

* Lakehead University, Faculty of Natural Resources Management, 955 Oliver Road, Thunder Bay, Ontario, Canada P7B 5E1

THESIS SUMMARY

Biochar is ranked as one of the ten technologies to save the planet (Goodall 2010) and one of the 20 top green tech ideas of 2010 (TIME 2010). Biochar's well documented benefits of climate change mitigation, soil amendment, waste management, mine site reclamation and energy generation have been widely advocated by many researchers and scientists such as Gaia¹ theorist James Lovelock (Lovelock 2009) and NASA's James Hansen (Hansen et al. 2008). Despite of relatively short spanned research and practice history, biochar supporting institutions have evolved to promote its science, action-research and application in many parts of the world. For example, the International Biochar Initiative (IBI) was formed in 2006 with a mission to support the generation, review and dissemination of information on all aspects of biochar (IBI 2011).

Subsequent centers of biochar research have then evolved over the last decade, notably in Cornell University USA, the University of Zurich Switzerland, the UK Biochar Research Centre at Edinburgh University UK, Canadian Biochar Initiative in Canada, National Initiative for Biochar Research, Australia, etc. In general, the interest behind

¹ Gaia principle proposes that all organisms and their inorganic surroundings on Earth are closely integrated to form a single and self-regulating complex system, maintaining the conditions for life on the planet

biochar in the developed world is a result of its inherent appeal as a natural carbon sequestration technology that avoids the technological risks of other complex and expensive carbon capture and storage methods.

However, despite its theoretical charm, biochar requires a massive expansion to sequester volumes of carbon significant on the global scale. Several lines of debate are ongoing on current outbreak of activities and concerned observers and environmentalists are calling for greater caution before accelerating the scaling process. For example, George Monbiot launched a strong challenge to the idea that biochar can be produced on a global scale without resultant negative impacts on biodiversity and food systems (Monbiot 2009) in contrast to claims made by biochar academics (Woolf et al. 2010). Moreover, many NGOs warn that these risks will be further intensified if biochar becomes accepted for voluntary carbon market credits (Mainville 2011; Action Aid 2012; Biofuel Watch 2012).

Many initiatives to acquire carbon credit entitlement are ongoing (Biochar Protocol 2012). Despite carbon markets being a contentious topic since their inception (Lehmann 2010), it is broadly accepted that significant carbon finance (approximately US\$48/ton) will be required to scale biochar production to any meaningful size in developed countries (Lehmann 2007) like USA, UK, Australia and Canada. However, initial efforts to channelize a methodology for biochar achieve a Voluntary Verified Carbon Standard (VCS) have failed (VCS 2011).

More recently IBI submitted a request to American Carbon Registry (ACR) to list the Methodology for Emissions Reductions from Biochar. However, ACR reached the conclusion that there was insufficient scientific evidence to support the Test Method for

Estimating Biochar Carbon Stability (IBI 2015). One critical bottleneck is that a scientifically accepted system to measure carbon sequestered by biochar in the soil has yet to be validated in wider landscape. Long term research is essential in this regard.

Even in the absence of significant investment or carbon market finance, large-scale biochar production may continue in developed countries as an alternate carbon capture strategy. However, the story is very different in the developing world. In this context the scalability of biochar depends less on big industry turning a profit but relies on small farmers using biochar for its soil amendment and subsequent yield-increasing properties. Nevertheless, two important questions surround the concept of scaling biochar through smallholder farmer usage in developing countries. Firstly, will biochar produce significant yield increases to warrant its purchase and/or production by farmers? Secondly, can small farmers sustainably source sufficient quantities of biochar without increasing deforestation or emitting powerful greenhouse gases commonly associated with biochar creation in the developing world (Pennise et al. 2001)? This chapter summarizes the current research state of biochar, its life cycle environmental impacts on micro and macro level, economic aspects and overall sustainability of the system.

On the basis of overall biochar-based bioenergy review (Chapter 2), life cycle assessment of its production and land application (Chapter 3) and life cycle cost and economic analysis (Chapter 4) this synthesis (Chapter 5) summarizes the trends and development of bioenergy sector with respect to production and commercialization potential of biochar for its potential land application.

SPECIFIC CONCLUSIONS

1. Northwestern Ontario (Canada) has a sustainable and sufficient supply of woody biomass that can be used to produce biochar based bioenergy for household and industrial purposes. While several biochar based bioenergy plants are operating around the world, the switch to biomass based energy is relatively recent in Northwestern Ontario with the Atikokan Generating Station's conversion to biomass representing a new era in large scale forest based feedstock requirements. Current demand of biomass feedstock (including AGS) can be easily supplied and new entrants to the biomass bioenergy system will initially have a high availability. The late entrants in the system, depending on the location of the plant, may have to rely on low availability of biomass feedstock. However, AGS having the highest availability of biomass can run the current plant sustainably.
2. If biochar and bioenergy are co-produced, they will serve two immediate functions: i) to provide an alternative to fossil fuel energy and ii) to sequester stable carbon for longer periods of time. Biomass may be sourced from either harvesting waste or underutilized species. The former is usually piled at roadside and if not burned in situ used for fuel, its presence can inhibit regeneration for long periods of time. The “slash piles” can also pose a fire hazard. Harvesting of underutilized species or extension of harvesting to include coarse woody debris (CWD) has raised concerns about reduced soil nutrient inputs thereby altering forest site productivity. CWD also contribute to the structure, microhabitat diversity, and nutrient cycling of forests. In the current forest management plans

in the region, there are no provisions of harvesting underutilized trees and any of the harvest residues. With enough demand from industry side, plans can allocate to harvest the underutilized especially hardwoods and larch species as part of sustainable management within the available allowable harvest. Further, most of the piles of harvest residue left in the roadside can be recommended to utilize to produce bioenergy. There need to be a clear direction on how much CWD need to be retained in the harvest area so that portion of leftover in the cut block can also be collected.

3. Utilization of forest biomass may warrant an improvement in regional biofibre harvesting policy. Replacing fossil fuels with biomass for power generation would certainly change the regional ecosystem carbon budget through transportation, collection, processing, and pyrolysis of biomass, and possibly, land application of biochar. Ontario's current biofibre harvest policy [Forest Biofibre – Allocation and Use Policy FOR 03 02 01] (MNR 2013) supports the utilization of woody biomass from its approved management plan. But most of the allocations are already contracted to sustainable license holders which may limit the feedstock acquiring ability for new companies. These policies need to be improved to accommodate the need of new industries in future.
4. A comprehensive life cycle analysis of the biochar-based bioenergy production from raw material collection to biochar application within a defined system boundary in Northwestern Ontario found that i) biomass collection, transportation and pyrolysis processes are most energy intensive and account for about 75% of the total GHG emissions of the system; ii) the net energy of the biochar-based

bioenergy system is negative but it can reduce GHG emissions with land application of biochar; iii) biochar-based bioenergy can have some adverse impact on human health but it significantly reduces the impact of climate change by improving ecosystem quality and reducing the dependence on non-renewable resources; and iv) pyrolysis and land application of biochar have most promising positive environmental impacts as compared to conventional coal based power generation system, if biomass availability is high. Despite negligible human health issue, the net energy consumption of the system is negative and it reduces the GHG emission significantly. Therefore, it is recommended that there need to be more advancement in worker's safety and transportation and pyrolysis system developed in the future should be fuel efficient (Is that what you mean?). Hauling roads needs to be improved which reduces transportation sectors GHG emission and energy consumption. Use of bioelectricity to replace fossil fuel based energy also needs to be promoted.

5. Life cycle cost and economic assessment of biochar-based bioenergy production and biochar land application within the biochar-based bioenergy production system boundary revealed that: (i) pyrolysis process costs about 36% of the total cost, and has the highest share of cost in the production system; (ii) feedstock collection cost is 12%, which is higher than transportation cost (9%); (iii) land application cost (14%) is higher than feedstock collection and transportation cost; and (iv) both land application scenarios (with low and high feedstock availability) are economically viable with 12 and 13 years of break-even time, when CO₂ sequestration is credited at least CAD 60 per tonne of CO_{2e}. Pyrolysis process is

still expensive. Future modifications and advancement in the power plant technology and wider application (more demand) will offset some of the cost in this sector. Overall, the system is financially viable within a 25-year plant life cycle if carbon prices are kept at least to \$60 per tonne. Current Ontario's cap and trade and climate change policy supports this idea but needs more clarification on biochar's side. As Canadian Food Inspection Agency recently approved the use of biochar on land, Ontario may also need to subsidize the carbon permanently sequestered by biochar-based bioenergy and its land application.

GENERAL CONCLUSIONS

Ontario government recently released its long-awaited Climate Change Action Plan, which calls for up to \$8.3 billion in government spending on climate change initiatives from 2016 to 2020 (MOECC 2016). In line with the goal of achieving sustainability through its cap-and-trade system in the natural resource management sector, this Action Plan is intended to support the province's goal of reducing greenhouse gas emissions to 15% below 1990 levels by 2020, 37% by 2030, and 80% by 2050 (MOECC 2016). The term “sustainability” was introduced into the political (as well as public) discussion by the United Nation's World Commission on Environmental and Development (UNCED) in the well-cited report, *Our Common Future* (Brundtland Commission 1987). This document has projected the responsibility of humankind toward the future generations with an elegant definition that has had far-reaching acceptance from around the world including governments, NGOs, as well as private

organizations. The document also states “Sustainable development should meet the needs of present generation without compromising the ability of future generations to meet their own needs”.

Although this impressive claim was not easy to operationalize, it has been very successful in environmental politics as well as in resource mobilization. Indeed, the United Nations declared sustainability as the guiding principle for the 21st century at the World Conference in Rio de Janeiro and promoted a concrete action plan, Agenda 21 (United Nations Environment Program) (UNEP 1992). The confirmation of this concept introduced the life cycle aspect (of what?) in 2002 in Johannesburg South Africa. Furthermore, the joint UNEP–SETAC (the Society of Environmental Toxicology and Chemistry) Life Cycle Initiative was started just prior to the Johannesburg forum (Klopffer 2003). This initiative aims at a global promotion and use of life cycle thinking, life cycle assessment (LCA), and life cycle management (LCM) which is still a major UN-IPCC agenda after its Paris endorsement with a new target of limiting the global mean temperature increase at 1.5⁰C above pre-industrial level (UN COP 2015).

Achieving sustainability will require its quantification, the identification of appropriate and valid indicators, as well as associated thresholds in the long run. How this is achieved will be the topic of debate. However, there is widespread belief that sustainability will involve an economic axis that will require life cycle costing. The standard model which is well accepted universally often referred to as a 3-pillar interpretation of sustainability. Fundamentally, it states that environmental, economic, and social aspects must have to be adjusted and checked against each another.

$$\text{Sustainable Assessment} = \text{LCA} + \text{LCC} + \text{SLCA}$$

Here, LCA is the environmental life cycle assessment, LCC stands for environmental life cycle costing and SLCA stands for societal life cycle assessment. This thesis was not intended to cover the SLCA part. There are some prerequisites that have to be fulfilled in using the above equation. Among these, the consistency of the system boundaries of the three assessments is the most important. This means that all 3 pillars of sustainability assessment should use the same life cycle inventory scenario. Klopffer (2003) has explained why sustainability assessment methods (ELCC and SLCA) have to be life cycle because trade-offs between pillars can be recognized and compensated. So the life cycle thinking is the prerequisite of any sound sustainability assessment. It does not make any sense at all to improve (environmentally, economically, socially) one part of the system in one country or region in one step of the life cycle or in one environmental compartment if this “improvement” has negative consequences for other parts of the system which may outweigh the advantages achieved. Furthermore, the problems shall not be shifted into the future which may create an intergenerational justice issue (Brundtland Commission 1987). Life cycle thinking or approach alone is not enough in most cases. In order to estimate the magnitude of the trade-offs between resource sustainability and development, which are always contentious, assessment tools instruments (like LCA) have to be as quantitative as possible with sufficient local (regional) data. Since we are living in a global economy, the system boundaries used in the methods must also be global in the long run. But within this thesis context, we used a local Northwestern Ontario context which can further be scaled up based on its assumptions and life cycle inventory data availability.

SIGNIFICANCE OF THE STUDY

This is a unique study of its kind in Northwestern Ontario. The environmental impact assessment results developed through this study will help in reinforcing the confidence of industry partners in promoting biochar-based bioenergy and use of biochar as soil amendment in Northwestern Ontario. This study within the scope of its system boundary and study assumptions concludes that biochar-based bioenergy is environmentally sustainable and economically viable. This can be replicated in other regions or scaled up with incorporation of socio economic study in the future. This can serve to develop a life cycle database inventory of the region as Canada lacks its own Life Cycle Inventory database. With local database, future life cycle assessment studies will never rely on other regional databases.

REFERENCES

- AAFC Agriculture and Agri Food Canada 2008. Analysis of the logistical costs associated with second generation biofuel feedstocks modelled supply chain logistical costs associated with cellulosic ethanol production in Canada. <http://www.agr.gc.ca/eng/about-us/publications/economic-publications/alphabetical-listing/analysis-of-the-logistical-costs-associated-with-second-generation-biofuel-feedstocks-modelled-supply-chain-logistical-costs-associated-with-cellulosic-ethanol-production-in-canada/?id=1247181726624>.
- Action Aid 2012. Say No to Soil Carbon Markets. Accessed on 05 Jan 2012. Available at: http://www.actionaid.org/sites/files/actionaid/say_no_to_soil_carbon_markets_actionaids_policy_briefing_final_20_july_2011.pdf
- Afrane G and Ntiamoah A. 2011. Comparative life cycle assessment of charcoal, biogas, and liquefied petroleum gas as cooking fuels in Ghana. *Journal of Industrial Ecology*, 15(4): 539-549.
- Alam MB, Pulkki R, Shahi C. 2012. Woody biomass availability for bioenergy production using forest depletion spatial data in Northwestern Ontario. *Canadian Journal of Forest Research*, 42(3): 506-516.
- Anderson CR, Condrón LM, Clough TJ, Fiers M, Stewart A, Hill RA, Sherlock RR. 2011. Biochar induced soil microbial community change: Implications for biogeochemical cycling of carbon, nitrogen and phosphorus. *Pedobiologia*, 54(5-6): 309-320.
- Asai H, Samson BK, Stephan HM, Songyikhangsuthor K, Homma K, Kiyono Y, Inoue Y, Shiraiwa T, Horie T. 2009. Biochar amendment techniques for upland rice production in northern Laos 1. Soil physical properties, leaf SPAD and grain yield. *Field Crops Research*, 111(1-2): 81-84.
- Atkinson CJ, Fitzgerald JD, Hipps NA. 2010. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. *Plant and Soil*, 337(1-2): 1-18.
- Bank of Canada 2013. Selected historical interest rates for Canada. <http://www.bankofcanada.ca/rates/interest-rates/selected-historical-interest-rates/>
- BASF 2000. Life Cycle Assessment and Eco-Efficiency: Instruments for sustainable product development. Aktiengesellschaft 67056 Ludwigshafen Germany, <http://www.basf.de>.
- Basso AS, Miguez FE, Laird DA, Horton R, Westgate M. 2013. Assessing potential of biochar for increasing water-holding capacity of sandy soils. *GCB Bioenergy*, 5(2): 132-143.

- Beesley L, Moreno-Jimenez E, Gomez-Eyles JL, Harris E, Robinson B, Sizmur T. 2011. A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. *Environmental Pollution*, 159(12): 3269-3282.
- Biederman LA, Harpole, WS. 2013. Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. *GCB Bioenergy* 5:202-214
- BioCap 2008. Analyzing Ontario biofuel options: Greenhouse gas mitigation efficiency and costs. BIOCAP Canada Foundation, Queen's University, Canada
- Biochar Protocol 2012. Biochar Protocol website. Accessed on 02 Feb 2011. Available at: <http://www.biocharprotocol.com/>
- Biofuel Watch 2012. Biofuelwatch website. <http://www.biofuelwatch.org.uk/uk-campaign/>
- Blackwell P, Krull E, Butler G, Herbert A, Solaiman Z. 2010. Effect of banded biochar on dryland wheat production and fertilizer use in south-western Australia: an agronomic and economic perspective. *Australian Journal of Soil Research*, 48(6-7): 531-545.
- Boateng AA, Mullen CA, Goldberg NM, Hicks KB, Devine TE, Lima IM, McMurtrey JE. 2010. Sustainable production of bioenergy and biochar from the straw of high-biomass soybean lines via fast pyrolysis. *Environmental Progress and Sustainable Energy*, 29(2): 175-183.
- Brick S, Wisconsin M. 2010. Biochar: Assessing the promise and risks to guide US policy. Natural Resources Defense Council: NRDC Issue Paper, November 2010. http://www.nrdc.org/energy/files/biochar_paper.pdf. [Accessed on 17 Feb 2013].
- Brown R. 2009. Biochar production technology. In Lehmann J, Joseph S. (Eds.) *Biochar for Environmental Management: Science and Technology*, pp127–146
- Brown RA, Kercher AK, Nguyen TH, Nagle DC, Ball WP 2006. Production and characterization of synthetic wood chars for use as surrogates for natural sorbents. *Organic Geochemistry*, 37(3): 321-333.
- Brownsort P. 2009. Biomass Pyrolysis Processes: Performance Parameters and their influence on Biochar System Benefits. M.Sc. Dissertation, University of Edinburgh, UK
- Brundtland Commission. 1987. *Our common future*. Oxford (UK): World Commission on Environment and Development.
- Bruun EW, Ambus P, Egsgaard H, Hauggaard-Nielsen H. 2012. Effects of slow and fast pyrolysis biochar on soil C and N turnover dynamics. *Soil Biology and Biochemistry*, 46: 73-79.
- Bruun EW, Muller-Stover D, Ambus P, Hauggaard-Nielsen H. 2011. Application of biochar to soil and N₂O emissions: potential effects of blending fast-pyrolysis biochar with anaerobically digested slurry. *European Journal of Soil Science*, 62(4): 581-589.

- Butnar I, Rodrigo J, Gasol CM, Castells F. 2010. Life-cycle assessment of electricity from biomass: Case studies of two biocrops in Spain. *Biomass and Bioenergy*, 34(12): 1780-1788.
- Campbell JE, Lobell DB, Genova RC, Field CB. 2008. The global potential of bioenergy on abandoned agriculture lands. *Environmental Science and Technology*, 42(15): 5791-5794.
- Cavalett O, Chagas MF, Seabra JEA, Bonomi A: Comparative LCA of ethanol versus gasoline in Brazil using different LCIA methods. *International Journal of Life Cycle Assessment*, 18:647-658
- Chan KY, Van Zwieten L, Meszaros I, Downie A, Joseph S. 2007. Agronomic values of greenwaste biochar as a soil amendment. *Australian Journal of Soil Research*, 45(8): 629-634.
- Cherubini F, Bird ND, Cowie A, Jungmeier G, Schlamadinger B, Woess-Gallasch S. 2009. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resources Conservation and Recycling*, 53(8): 434-447.
- Cherubini F and Stromman AH. 2011. Life cycle assessment of bioenergy systems: State of the art and future challenges. *Bioresource Technology*, 102(2): 437-451.
- Cleary J, Wolf DP and Caspersen JP. 2015. Comparing the life cycle costs of using harvest residue as feedstock for small- and large-scale bioenergy systems (part II). *Energy* 86, 539-547.
- Clough TJ, Condon LM. 2010. Biochar and the nitrogen cycle: Introduction. *Journal of Environmental Quality*, 39(4): 1218-1223.
- Coleman, M., Page-Dumroese, D., Archuleta, J., Badger, P., Chung, W., Venn, T., Loeffler, D., Jones, G., and McElligott, K. 2010. Can portable pyrolysis units make biomass utilization affordable while using bio-char to enhance soil productivity and sequester carbon? Proceedings of the 2009 National Silviculture Workshop. RMRS-P-61. Fort Collins, CO: U.S. Department of Agriculture, Forest Service.
- Department for Environment, Food and Rural Affairs (DEFRA) 2009. Guidance on how to measure and report your greenhouse gas emissions. Department for Environment, Food and Rural Affairs UK
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69282/pb13309-ghg-guidance-0909011.pdf. [Assessed 10 May 2013]
- Dutta B and Raghavan V. 2014. A life cycle assessment of environmental and economic balance of biochar systems in Quebec. *Int. J Energy Environ Eng.*, 5:1-11

- Dwivedi P, Bailis R, Bush TG and Marinescu M. 2011. Quantifying GWI of wood pellet production in the southern United States and its subsequent utilization for electricity production in the Netherlands/Florida. *Bioenergy Research*, 4(3): 180-192.
- EC 2011. Environment Canada Website.
<http://www.ec.gc.ca/cc/default.asp?lang=En&n=E907D4D5-1> [Assessed on 5 Nov 2012]
- EC 2012. Environment Canada Website.
<http://www.ec.gc.ca/cc/default.asp?lang=En&n=E907D4D5-1> [Assessed on 5 Aug] 2013
- Elbehri A, Segerstedt A and Liu P. 2013. Biofuels and the sustainability challenge: A global assessment of sustainability issues, trends and policies for biofuels and related feedstocks. Food and agriculture organization of the United Nations (FAO) Rome. Pp175+xiii.
- Elsayed MA and Mortimer ND. 2001. Carbon and Energy Modelling of Biomass Systems: Conversion Plant and Data Updates. DTI http://www.pfpi.net/wp-content/uploads/2011/04/PFPI-biomass-carbon-accounting-overview_April.pdf [Assessed 27 May 2014]
- Environmental Protection Agency (EPA). 1993. Life Cycle Assessment: Inventory Guidelines and Principles. EPA/600/R-92/245. Office of Research and Development, Cincinnati, Ohio, USA.
- EPA Environment Protection Agency 2010. Guidelines for Preparing Economic Analyses. Environment Protection Agency USA. <https://www.epa.gov/environmental-economics/guidelines-preparing-economic-analyses>.
- Ericksen PJ, Ingram JSI and Liverman DM. 2009. Food security and global environmental change: emerging challenges. *Environmental Science and Policy*, 12: 373–377
- Faaij A, Meuleman B, Turkenburg W, van Wijk A, Bauen A, Rosillo-Calle F and Hall D. 1998. Externalities of biomass based electricity production compared with power generation from coal in the Netherlands. *Biomass & Bioenergy*, 14:125-147.
- Fantozzi F and Buratti C. 2010. Life cycle assessment of biomass chains: Wood pellet from short rotation coppice using data measured on a real plant. *Biomass and Bioenergy*, 34(12): 1796-1804.
- Fargione J, Hill J, Tilman D, Polasky S and Hawthorne P. 2008. Land clearing and the biofuel carbon debt. *Science*, 319(5867): 1235-1238.
- Finnveden G, Hauschild MZ, Ekvall T, Guinee J, Heijungs R, Hellweg S, Koehler A, Pennington D and Suh S. 2009. Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, 91: 1-21

- Fowles M. 2007. Black carbon sequestration as an alternative to bioenergy. *Biomass and Bioenergy*, 31(6): 426-432.
- Galinato SP, Yoder JK and Granatstein D. 2011. The economic value of biochar in crop production and carbon sequestration. *Energy Policy*, 39(10): 6344-6350. doi: 10.1016/j.enpol.2011.07.035.
- Gaskin JW, Steiner C, Harris K, Das KC and Bibens B. 2008. Effect of low-temperature pyrolysis conditions on biochar for agricultural use. *Transactions of the Asabe*, 51(6): 2061-2069.
- Gaunt JL and Lehmann J. 2008. Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. *Environmental Science and Technology*, 42(11): 4152-4158.
- Gautam S, Pulkki R, Shahi C and Leitch M 2010. Economic and energy efficiency of salvaging biomass from wildfire burnt areas for bioenergy production in northwestern Ontario: A case study. *Biomass & Bioenergy* 34, 1562-1572.
- GDI Green Development Institute 2010. Environmental input output life cycle assessment. <http://www.eiolca.net/>
- Glaser B, Lehmann J and Zech W. 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal: a review. *Biology and Fertility of Soils*, 35(4): 219-230.
- Goedkoop M and Spriensma R. 2001. The Eco-indicator 99: a damage oriented method for life cycle impact assessment-methodology report. PRe Consultants, Amersfoort, Netherlands
- Gonzalez-Garcia S, Berg S, Feijoo G and Moreira MT 2009. Comparative environmental assessment of wood transport models: a case study of a Swedish pulp mill. *Science of the Total Environment*, 407(11): 3530-3539.
- Goodall, C. 2010. *Ten Technologies to Save the Planet: Energy Options for a Low Carbon Future*. Greystone Books, D&M Publishers Inc. Vancouver/Toronto/Berkley. 310+p
- Granatstein D, Kruger C, Collins HP, Garcia-Perez M and Yoder J. 2009. Use of biochar from the pyrolysis of waste organic material as a soil amendment. Center for Sustaining Agric. Nat. Res. Washington State University, Wenatchee, WA. WSDA Interagency Agreement. C0800248. <http://www.ecy.wa.gov/pubs/0907062.pdf>. [Accessed on 25 Jan 2013]
- Gundale MJ and DeLuca TH. 2007. Charcoal effects on soil solution chemistry and growth of *Koeleria macrantha* in the Ponderosa pine/Douglas-fir ecosystem. *Biology and Fertility of Soils*, 43(3): 303-311.

- Hacatoglu K, McLellan PJ and Layzell DB. 2011. Feasibility study of a Great Lakes bioenergy system. *Bioresource Technology*, 102(2): 1087-1094.
- Hacatoglu K. 2009. Bioenergy systems in Canada: towards energy security and climate change solutions. Queen's University, Canada. pp. 149.
- Hammond J, Shackley S, Sohi S and Brownsort P. 2011. Prospective life cycle carbon abatement for pyrolysis biochar systems in the UK. *Energy Policy*, 39(5): 2646-2655.
- Han J, Elgowainy A, Dunn JB and Wang MQ. 2013. Life cycle analysis of fuel production from fast pyrolysis of biomass. *Bioresource Technology* 133, 421-428
- Hart S. 2013. Charcoal in North American boreal forests: Implications for carbon storage and management. PhD Thesis. Lakehead University, Thunder Bay, ON, Canada. 102 pp.
- Harter J, Krause HM, Schuettler S, Ruser R, Fromme M, Scholten T, Kappler A and Behrens S. 2014. Linking N₂O emissions from biochar-amended soil to the structure and function of the N-cycling microbial community. *The ISME Journal*, 8: 660-674. doi: 10.1038/ismej.2013.160.
- Hazlett PW, Gordon AM, Voroney RP and Sibley PK. 2007. Impact of harvesting and logging slash on nitrogen and carbon dynamics in soils from upland spruce forests in northeastern Ontario. *Soil Biology and Biochemistry*, 39: 43–57.
- Homagain K, Shahi C, Luckai N and Sharma M. 2014. Biochar-based bioenergy and its environmental impact in Northwestern Ontario Canada: A review. *Journal of Forestry Research*, 25(4):737-748.
- Homagain K, Shahi C, Luckai N and Sharma M. 2015. Life cycle environmental impact assessment of biochar-based bioenergy production and utilization in Northwestern Ontario, Canada. *J. For. Res.* 26(4):799-809.
- Hsu DD, Inman D, Heath GA, Wolfrum EJ, Mann MK and Aden A. 2010. Life cycle environmental impacts of selected US ethanol production and use pathways in 2022. *Environmental Science and Technology*, 44(13): 5289-5297.
- Huang YF, Syu FS, Chiueh PT and Lo SL. 2013. Life cycle assessment of biochar cofiring with coal. *Bioresource Technology*, 131: 166-171.
- Humbert S, Schryver AD, Bengoa X, Margni M and Jolliet O. 2012. Life Cycle Assessment IMPACT 2002+ User Guide. http://www.quantis-intl.com/files/8814/1198/3664/IMPACT2002_UserGuide_for_vQ2.21_30April2014a.pdf [Assessed 17 May 2014]
- Husk B and Major J. 2010. Commercial scale agricultural biochar field trial in Québec, Canada, over two years: Effects of biochar on soil fertility, biology, crop productivity and quality. BlueLeaf Inc. Quebec, Canada. 32pp.

- Ibarrola R, Shackley S and Hammond J. 2012. Pyrolysis biochar systems for recovering biodegradable materials: A life cycle carbon assessment. *Waste Management*, 32(5): 859-868. doi: 10.1016/j.wasman.2011.10.005.
- IBI International Biochar Initiative 2016. Biochar research and educational resources. <http://www.biochar-international.org/research/education> [Accessed 10 Dec 2015]
- IEA International Energy Agency 2012. *World Energy outlook 2012: Executive summary*. Paris, France.
- IEA International Energy Agency 2015. *World Energy outlook 2015: Executive summary*. Paris, France. IESO 2013. Independent Electricity System Operator New Release. 2013. http://www.ieso.ca/imoweb/media/md_newsitem.asp?newsID=6323 [Accessed 5 Jan 2013]
- Intergovernmental Panel on Climate Change (IPCC) 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC* http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4_wg1_full_report.pdf [Assessed 11 Dec 2012]
- International Biochar Initiative (IBI) 2013. Biochar research and educational resources. <http://www.biochar-international.org/research/education> [Accessed 10 Dec 2013]
- International Energy Agency (IEA) 2013. *World Energy outlook 2013: Executive summary*. Paris, France
- International Energy Agency (IEA) 2015. *World Energy outlook 2015: Executive summary*. Paris, France
- IRENA International Renewable Energy Agency 2012. *Renewable Energy Technologies: Cost Analysis Series. Biomass for power generation Volume 1*. https://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-BIOMASS.pdf
- ISO 1997. *Environmental Management - Life Cycle Assessment -Principles and Framework ISO 14040*.
- Iswaran V, Jauhri KS and Sen A. 1980. Effect of charcoal, coal and peat on the yield of moong, soybean and pea. *Soil Biology and Biochemistry*, 12: 191-192.
- Jeffery S, Verheijen FGA, van-der Velde M and Bastos AC. 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems and Environment*, 144(1): 175-187. doi: 10.1016/j.agee.2011.08.015.
- Jolliet O, Margni M, Charles RL, Humbert S, Payet J, Rebitzer G and Rosenbaum R. 2003. IMPACT 2002+: A new life cycle impact assessment methodology. *International Journal of Life Cycle Assessment*, 8:324-330

- Kaliyan N, Morey RV and Tiffany DG. 2015. Economic and Environmental Analysis for Corn Stover and Switchgrass Supply Logistics. *Bioenergy Research* 8, 1433-1448.
- Kameyama K, Shinogi Y, Miyamoto T and Agarie K. 2010. Estimation of net carbon sequestration potential with farmland application of bagasse charcoal: life cycle inventory analysis through a pilot sugarcane bagasse carbonization plant. *Australian Journal of Soil Research*, 48(6-7): 586-592.
- Kennedy M, Wong R, Vandenbroek A, Lovekin D and Reynolds M. 2011. Biomass sustainability analysis. An assessment of Ontario-sourced forest-based biomass for electricity generation. FINAL REPORT. Revision C. Pembina Institute, Alberta.
- Kilpelainen A, Alam A, Strandman H and Kellomaki S. 2011. Life cycle assessment tool for estimating net CO₂ exchange of forest production. *Global Change Biology Bioenergy*, 3:461-471
- Kishimoto S and Sugiura G. 1985. Charcoal as soil conditioner. *International Achievements for the Future*, 5: 12-23.
- Klinar D. 2016. Universal model of slow pyrolysis technology producing biochar and heat from standard biomass needed for the techno-economic assessment. *Bioresource Technology* 206, 112-120.
- Klopffer W. 2003. Life-cycle based methods for sustainable product development. *International Journal of Life Cycle Assessment*, 8 (3), 157–159.
- Koide RT, Petprakob K and Peoples M. 2011. Quantitative analysis of biochar in field soil. *Soil Biology and Biochemistry*, 43(7): 1563-1568.
- Kookana R. 2010. The role of biochar in modifying the environmental fate, bioavailability and efficacy of pesticides in soils: a review. *Australian Journal of Soil Research*, 48(6): 627-637.
- Kookana RS, Sarmah AK, Van Zwieten L, Krull E and Singh B. 2011. Biochar application to soil: Agronomic and environmental benefits and unintended consequences. In: Donald LS. (eds), *Advances in Agronomy*. 112. Academic Press, pp. 103-143.
- Kulyk N. 2012. Cost-Benefit Analysis of the Biochar Application in the U.S. Cereal Crop Cultivation. Technical Report # 12. 2012. Center for Public Policy and Administration University of Massachusetts, Amherst, MA USA. 1-1-2016.
- Kung CC, Mccarl BA and Cao XY. 2013. Economics of pyrolysis-based energy production and biochar utilization: A case study in Taiwan. *Energy Policy* 60, 317-323.
- Laird DA, Fleming P, Davis DD, Horton R, Wang B and Karlen DL. 2010. Impact of biochar amendments on the quality of a typical midwestern agricultural soil. *Geoderma*, 158(3-4): 443-449.

- Laird DA. 2008. The charcoal vision: A win-win-win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. *Agronomy Journal* 100(1): 178-181.
- Lal R and Pimentel D. 2007. Biofuels from crop residues. *Soil and Tillage Research*, 93:237-238.
- Lal R. 2007. World soils and global issues. *Soil and Tillage Research*, 97(1): 1-4.
- Larson ED. 2006. A review of life-cycle analysis studies on liquid biofuel systems for the transport sector. *Energy for Sustainable Development*, 10(2): 109-126. doi: 10.1016/S0973-0826(08)60536-0.
- Lehmann J, da Silva Jr JP, Steiner C, Nehls T, Zech W and Glaser B. 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. *Plant and Soil*, 249: 343-357.
- Lehmann J, Gaunt J and Rondon M. 2006. Biochar sequestration in terrestrial ecosystems - a review. *Mitigation and Adaptation Strategies for Global Change*, 11(2): 395-419.
- Lehmann J and Joseph S. 2009. Biochar for environmental management: An Introduction. In: Lehmann J, Joseph S (Eds.) *Biochar for environmental management science and technology*. Earthscan, London.Washington D.C., pp. 1-12
- Lehmann J and Rondon M. 2006. Biochar soil management on highly weathered soils in the humid tropics. In: Uphoff N, Ball AS, Fernandes E, Herren H, Husson O, Laing M, Palm C, Pretty J, Sanchez P, Sanginga N, Thies J. (eds), *Biological approaches to sustainable soil systems*. Boca Raton, FL: CRC/Taylor & Francis, pp. 517-530.
- Lehmann J. 2007. A handful of carbon. *Nature*, 447(7141): 143-144.
- Lemoine DM, Plevin RJ, Cohn, AS, Jones AD, Brandt AR, Vergara SE and Kammen DM. 2010. The climate impacts of bioenergy systems depend on market and regulatory policy contexts. *Environmental Science and Technology*, 44(19): 7347-7350. doi: 10.1021/es100418p.
- Magelli F, Boucher K, Bi HT, Melin S and Bonoli A. 2009. An environmental impact assessment of exported wood pellets from Canada to Europe. *Biomass and Bioenergy*, 33(3): 434-441.
- Mainville N. 2011. *Fueling a biomass: Why burning trees for energy will harm people, the climate and forests*. Greenpeace, Montreal, Quebec. Pp40
- Major J, Lehmann J, Rondon M and Goodale C. 2010. Fate of soil-applied black carbon: downward migration, leaching and soil respiration. *Global Change Biology*, 16:1366-1379

- Major J, Rondon M, Molina D, Riha SJ and Lehmann J. 2010a. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. *Plant and Soil*, 333(1-2): 117-128.
- Major J. 2010. Guidelines on practical aspects of biochar application to field soil in various soil management systems. International Biochar Initiative, IBI, USA. p20
- Mankasingh U, Choi PC and Ragnarsdottir V. 2011. Biochar application in a tropical, agricultural region: A plot scale study in Tamil Nadu, India. *Applied Geochemistry*, 26: S218-S221.
- McCarl BA, Peacocke C, Chrisman R, Kung CC and Sands RD. 2009. Economics of biochar production, utilization and greenhouse gas offsets. In: Lehmann J, Joseph S. (eds) *Biochar for environmental management science and technology*. London, Washington D.C.: Earthscan, pp. 341-358.
- McElligott K, Page-Dumroese D and Coleman M. 2011. Bioenergy production systems and biochar application in forests: potential for renewable energy, soil enhancement, and carbon sequestration. RN-46, 1-14. 2011. Fort Collins, CO, USDA Rocky Mountain Research Station.
- Mckechnie J, Colombo S, Chen JX, Mabee W and Maclean HL. 2011. Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environmental Science and Technology*, 45(2): 789-795.
- Ministry of Environment Ontario (MOE) 2010. Ontario's coal phase out plan 2010. <http://news.ontario.ca/mei/en/2009/09/ontarios-coal-phase-out-plan.html>. [Assessed 13 July 2014]
- MNRF Ontario Ministry of Natural Resources and Forestry 2015. Forest management units in Ontario. Ontario Ministry of Natural Resources and Forestry. <http://www.efmp.lrc.gov.on.ca/eFMP/home.do>
- MNR Ministry of Natural Resources 2014. Forest Resources of Ontario 2011. Ministry of Natural Resources Ontario <https://www.ontario.ca/environment-and-energy/forest-resources-ontario-2011> [Accessed 15 July 2014]
- MNR 2011. Forest Resources of Ontario 2011. Ministry of Natural Resources Ontario. http://www.mnr.gov.on.ca/stdprodconsume/groups/lr/@mnr/@forests/documents/document/stdprod_092922.pdf. [Accessed on 5 June 2012].
- MNR 2012. Forest Management Units in Ontario. Ministry of Natural Resources Ontario. http://www.mnr.gov.on.ca/en/Business/Forests/1ColumnSubPage/STEL02_163535.html. [Accessed on 6 Jan 2013].
- MNR 2013. Forest Management Directives and Procedures. Forest biofibre allocation and use policy. <https://www.ontario.ca/document/forest-biofibre-allocation-and-use>

- MOE 2010. Ontario's coal phase out plan. Ministry of Environment Ontario.
<http://news.ontario.ca/mei/en/2009/09/ontarios-coal-phase-out-plan.html>. [Accessed on 27 June 2012].
- MOE 2010a. Ontario Ministry of the Environment: Green Energy Act. 2010.
http://www.ene.gov.on.ca/environment/en/legislation/green_energy_act/index.htm. [Accessed on 28 Jan 2013]
- MOECC Ontario Ministry of Environment and Climate Change 2015. Ontario carbon target news release. Ontario ministry of environment and climate change.
<https://news.ontario.ca/ene/en/2015/05/ontario-first-province-in-canada-to-set-2030-greenhouse-gas-pollution-reduction-target.html>.
- MOECC 2016. Ontario Climate Change Action Plan 2016. Ministry of Environment and Climate Change, Ontario. <https://www.ontario.ca/page/climate-change-action-plan>.
- Mohan D, Charles U and Steele PH. 2006. Pyrolysis of wood/biomass for bio-oil: A critical review. *Energy Fuels*, 20(3): 848-889. doi: 10.1021/ef0502397.
- Monbiot G. 2009. Woodchips with everything. It's the Atkins plan of the low-carbon world. Accessed 15 Dec 2011. Available at:
<http://www.guardian.co.uk/environment/2009/mar/24/george-monbiot-climate-change-biochar>
- Moon JH, Lee JW and Lee UD. 2011. Economic analysis of biomass power generation schemes under renewable energy initiative with Renewable Portfolio Standards (RPS) in Korea. *Bioresource Technology*, 102(20): 9550-9557.
- Mortimer ND, Evans A, Shaw VL and Hunter AJ. 2009. Life Cycle and Techno-Economic Assessment of the North East Biomass to Liquids Project. North Energy Associates Limited, York, UK
- Nepal P, Grala RK and Grebner DL. 2012. Financial feasibility of increasing carbon sequestration in harvested wood products in Mississippi. *Forest Policy and Economics*, 14(1): 99-106.
- Novak JM, Lima I, Xing B, Gaskin JW, Steiner C, Das KC, Ahmedna M, Rehrah D, Watts DW, Busscher WJ and Schomberg H. 2009. Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. *Annals of Environmental Science*, 3:195-206. www.aes.northeastern.edu, ISSN 1939-2621.
- NRCan 2010. Is forest bioenergy good for the environment? Canadian Forest Service Science-Policy Notes. Natural Resources Canada, Canadian Forest Service, Ottawa. 3 p.
- NERL National Renewal Energy Laboratory 2010. Techno-Economic Analysis of Biomass Fast Pyrolysis to Transportation Fuels. National Renewal Energy

- Laboratory of the United States. Technical Report NREL/TP-6A20-46586 November 2010. p73.
- Obernberger I and Thek G. 2010. The Pellet Handbook. The Production and Thermal Utilization of Pellets. Earthscan, London. Washington, D.C., p. 549 + xxxii.
- Oguntunde PG, Abiodun BJ, Ajayi AE and van de Giesen N. 2008. Effects of charcoal production on soil physical properties in Ghana. *Journal of Plant Nutrition and Soil Science*, 171: 591-596.
- OPG Ontario Power Generation 2012. Atikokan Generating Station bio-mass fuel suppliers announced: meeting the needs of a growing economy in Northwestern Ontario.
http://www.opg.com/news/releases/121122Atikokan%20Fuel%20Contracts_FINAL.pdf [Assessed 13 July 2014]
- OPG Ontario Power Generation 2012a. Atikokan Generating Station bio-mass fuel suppliers announced: meeting the needs of a growing economy in NW Ontario.
http://www.opg.com/news/releases/121122Atikokan%20Fuel%20Contracts_FINAL.pdf [Assessed 13 July 2014]
- OPG 2011. Ontario Power Generation Biomass Sustainability Analysis Summary Report. Pembina Institute 2011.
- Pa A, Bi XTT and Sokhansanj S. 2011. A life cycle evaluation of wood pellet gasification for district heating in British Columbia. *Bioresource Technology*, 102(10): 6167-6177.
- Pa A, Craven JS, Bi XTT, Melin S and Sokhansanj S. 2012. Environmental footprints of British Columbia wood pellets from a simplified life cycle analysis. *International Journal of Life Cycle Assessment*, 17(2): 220-231.
- Palma MA, Richardson JW, Roberson BE, Ribera LA, Outlaw J and Munster C. 2011. Economic feasibility of a mobile fast pyrolysis system for sustainable bio-crude oil production. *International Food and Agribusiness Management Review*, 14(3):1-16
- Papong S and Malakul P. 2010. Life-cycle energy and environmental analysis of bioethanol production from cassava in Thailand. *Bioresource Technology*, 101:S112-S118
- Park JH, Choppala GK, Bolan NS, Chung JW and Chuasavathi T. 2011. Biochar reduces the bioavailability and phytotoxicity of heavy metals. *Plant and soil*, 348(1-2): 439-451.
- Patel M, Zhang XL and Kumar A. 2016. Techno-economic and life cycle assessment on lignocellulosic biomass thermochemical conversion technologies: A review. *Renewable & Sustainable Energy Reviews* 53, 1486-1499.

- Pedlar JH, Pearce JL, Venier LA and McKenney DW. 2002. Coarse woody debris in relation to disturbance and forest type in boreal Canada. *Forest Ecology and Management*, 158: 189-194.
- Pennise DM, Smith KR, Kithinji JP, Rezende ME, Raad TJ, Zhang J and Fan C. 2001. Emissions of greenhouse gases and other airborne pollutants from charcoal making in Kenya and Brazil. *Journal of geophysical research*, 106: 24143-24156.
- Pimentel D, Marklein A, Toth MA, Karpoff MN, Paul GS, McCormack R, Kyriazis J and Krueger T. 2009. Food versus biofuels: Environmental and economic costs. *Human Ecology*, 37(1): 1-12.
- PowerMax 2015. 1000kw Biomass pyrolysis/gasification system technical specification. http://powermax1234.en.ec21.com/Biomass_Gasifier_Power_Plant--7762130_7762661.html
- Pratt K and Moran D. 2010. Evaluating the cost-effectiveness of global biochar mitigation potential. *Biomass and Bioenergy*, 34(8): 1149-1158.
- PRé Consultants (2013) SimaPro Software for life cycle assessment. www.pre-sustainability.com/software. Accessed May 2014.
- Raupach MR, Marland G, Ciais P, Le Quere C, Canadell JG, Klepper G and Field CB. 2007. Global and regional drivers of accelerating CO₂ emissions. *Proceedings of the National Academy of Sciences of the United States of America* 104(24): 10288-10293.
- Rebitzer G and Hunkeler D. 2003. Life cycle costing in LCM: ambitions, opportunities, and limitations, discussing a framework. *International Journal of Life Cycle Assessment*, 8 (5), 253–256.
- Rehl T and Mueller J. 2011. Life cycle assessment of biogas digestate processing technologies. *Resources Conservation and Recycling*, 56:92-104
- RFP Resolute Forest Products 2012. Our view of sustainability. Annual sustainability report for 2011 performance. Resolute forest products. http://www.resolutefp.com/uploadedFiles/Media/Publications/Resolute_Sustainability_Report_2011.pdf. [Accessed on 20 July 2013].
- Roberts KG, Gloy BA, Joseph S, Scott NR, Lehmann J. 2010. Life cycle assessment of biochar systems: Estimating the energetic, economic and climate change potential. *Environmental Science and Technology*, 44(2): 827-833.
- Rockstrom J, Steffen W, Noone K, Persson A, Chapin FS, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, Nykvist B, de Wit CA, Hughes T, van der Leeuw S, Rodhe H, Sorlin S, Snyder PK, Costanza R, Svedin U, Falkenmark M, Karlberg L, Corell RW, Fabry VJ, Hansen J, Walker B, Liverman D, Richardson K,

- Crutzen P and Foley JA. 2009. A safe operating space for humanity. *Nature*, 461(7263): 472-475.
- Rogers JG and Brammer JG. 2012. Estimation of the production cost of fast pyrolysis bio-oil. *Biomass & Bioenergy* 36, 208-217.
- Rondon MA, Lehmann J, Ramirez J and Hurtado M. 2007. Biological nitrogen fixation by common beans (*Phaseolus vulgaris L.*) increases with bio-char additions. *Biology and Fertility of Soils*, 43: 699-708.
- Ronsse F, Van Hecke S, Dickinson D and Prins W. 2013. Production and characterization of slow pyrolysis biochar: influence of feedstock type and pyrolysis conditions. *GCB Bioenergy*, 5:104-115
- Scheer C. 2011. Effect of biochar amendment on the soil-atmosphere exchange of greenhouse gases from an intensive subtropical pasture in northern New South Wales, Australia. *Plant and soil*, 345(1-2): 47-58.
- Schlamadinger B, Apps M, Bohlin F, Gustavsson L, Jungmeier G, Marland G, Pingoud K and Savolainen I. 1997. Towards a standard methodology for greenhouse gas balances of bioenergy systems in comparison with fossil energy systems. *Biomass and Bioenergy*, 13(6): 359-375. doi: 10.1016/S0961-9534(97)10032-0.
- Scientific Applications International Corporation (SAIC) 2006. Life cycle assessment: Principles and Practice. 11251 Roger Bacon Drive, Reston, VA 20190 USA, p14
- Searchinger T, Heimlich R, Houghton R, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D and Yu TH. 2008. Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, 319(5867): 1238-1240.
- Sebastian F, Royo J and Gomez M. 2011. Cofiring versus biomass-fired power plants: GHG (Greenhouse Gases) emissions savings comparison by means of LCA (Life Cycle Assessment) methodology. *Energy*, 36(4): 2029-2037.
- Shackley S, Hammond J, Gaunt J and Ibarrola R. 2011. The feasibility and costs of biochar deployment in the UK. *Carbon Management* 2, 335-356.
- Simon D, Tyner WE and Jacquet F. 2010. Economic Analysis of the Potential of Cellulosic Biomass Available in France from Agricultural Residue and Energy Crops. *Bioenergy Research* 3, 183-193.
- Singh BP, Hatton BJ, Singh B, Cowie AL and Kathuria A. 2010. Influence of biochars on nitrous oxide emission and nitrogen leaching from two contrasting soils. *Journal of Environmental Quality*, 39(4): 1224-1235.
- Smith JL, Collins HP and Bailey VL. 2010. The effect of young biochar on soil respiration. *Soil Biology and Biochemistry*, 42: 2345–2347.

- Sohi S, Lopez-Capel E, Krull E and Bol R. 2009. Biochar's roles in soil and climate change: A review research needs. CISRO. Rep. Land and Water Science Report 05/09. 64pp.
- Sohi SP, Krull E, Lopez-Capel E and Bol R. 2010. A review of biochar and its use and function in soil. In Donald LS. (eds) *Advances in Agronomy*. Vol. 105. Academic Press, pp. 47-82.
- Sohi SP. 2013. Pyrolysis bioenergy with biochar production - greater carbon abatement and benefits to soil. *GCB Bioenergy* 5, i-iii.
- Solomon S, Plattner GK, Knutti R and Friedlingstein P. 2009. Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences of the United States of America* 106(6): 1704-1709.
- Sparkes J and Stoutjesdijk P. 2011. Biochar: implications for agricultural productivity. Australian Bureau of Agricultural and Resource Economics and Sciences. Rep. ABARES Technical Report No. 11.6.
- Spokas KA, Cantrell KB, Novak JM, Archer DW, Ippolito JA, Collins HP, Boateng AA, Lima IM, Lamb MC, McAloon AJ, Lentz RD and Nichols KA. 2012. Biochar: A synthesis of its agronomic impact beyond carbon sequestration. *Journal of Environmental Quality*, 41(4): 973-989.
- Spokas KA, Koskinen WC, Baker JM and Reicosky DC. 2009. Impacts of woodchip biochar additions on greenhouse gas production and sorption/degradation of two herbicides in a Minnesota soil. *Chemosphere*, 77(4): 574-581.
- Statistics Canada (StatsCan) 2012. The Energy statistics handbook First Quarter 2012 (2012) <http://www.statcan.gc.ca/pub/57-601-x/57-601-x2012001-eng.pdf> [Assessed 10 Feb 2014]
- Steele P, Puettmann ME, Penmetsa VK and Cooper JE. 2012. Life-cycle assessment of pyrolysis bio-oil production. *Forest Products Journal*, 62(4): 326-334.
- Steiner C, Teixeira WG, Lehmann J, Nehls T, MaceDo JLV, Blum WEH and Zech W. 2007. Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. *Plant and Soil*, 291: 275-290.
- Stephen JD. 2013. The viability of lignocellulosic ethanol production as a business endeavour in Canada. PhD Thesis, Faculty of Forestry, University of British Columbia, Canada. P225+xiv
- Taghizadeh-Toosi A, Clough TJ, Sherlock RR and Condon LM. 2012. Biochar adsorbed ammonia is bioavailable. *Plant and Soil*, 350(1-2): 57-69.
- Tang W, Tang AY. 2014. Transgenic woody plants for biofuel. *Journal of Forestry Research*, 25(2):225-236.

- Ter-Mikaelian MT, Colombo SJ and Chen JX. 2008. Fact and fantasy about forest carbon. *Forestry Chronicle*, 84(2): 166-171.
- Ter-Mikaelian MT, McKechnie J, Colombo SJ, Chen J and MacLean HL. 2011. The carbon neutrality assumption for forest bioenergy: A case study for Northwestern Ontario. *Forestry Chronicle*, 87(5): 644-652.
- Thomas S. 2013. Biochar and its potential in Canadian Forestry. *Silviculture Mag.* Winter 2013, P 4-6. <http://www.silviculturemagazine.com/sites/silviculturemagazine.com/files/issues/2013020712/Winter%202013.pdf>. [Accessed on 3 Mar 2013]
- Tilman D, Socolow R, Foley JA, Hill J, Larson, E, Lynd L, Pacala S, Reilly J, Searchinger T, Somerville C and Williams R. 2009. Beneficial biofuels: The food, energy and environment trilemma. *Science*, 325 (5938):270-271.
- TIME 2010. Top 20 GreenTech Ideas. Accessed on 11/11/2011. Available at: http://www.time.com/time/specials/packages/article/0,28804,2030137_2030135_2021656,00.html
- UN COP 2015. UN Climate resolution 2015. www.un.org
- UNEP 1992. United Nation's Environment Program. Agenda 21. www.unesco.org.
- Upadhyay TP, Shahi C, Leitch M and Pulkki R. 2012. Economic feasibility of biomass gasification for power generation in three selected communities of northwestern Ontario, Canada. *Energy Policy* 44, 235-244.
- Van-Zwieten L, Kimber S, Morris S, Chan KY, Downie A, Rust J, Joseph S and Cowie A. 2010. Effects of biochar from slow pyrolysis of paper-mill waste on agronomic performance and soil fertility. *Plant and Soil*, 327(1-2): 235-246.
- Van-Loo S and Koppejan J. 2008. *The Handbook of Biomass Combustion and Cofiring*. London, Washington, DC, p. 442+xii. Earthscan.
- VCS 2011. Verified Carbon Standards. Website accessed on 02/09/2013. Available at: <http://www.v-c-s.org/>
- Warnock DD, Lehmann J, Kuyper TW and Rillig MC 2007. Mycorrhizal responses to biochar in soil - concepts and mechanisms. *Plant and Soil*, 300(1-2): 9-20.
- Waters D, Zwieten L, Singh BP, Downie A, Cowie AL and Lehmann J. 2011. Biochar in soil for climate change mitigation and adaptation. In Singh BP, Cowie AL, Chan KY (eds) *Soil Health and Climate Change*. 29 ed. Springer Berlin Heidelberg, pp. 345-368.
- West TO and Marland G. 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. *Agriculture, Ecosystems and Environment*, 91: 217-232

- Wiebe S, Morris D, Luckai N and Reid D. 2012. Coarse woody debris dynamics following biomass harvesting: Tracking carbon and nitrogen patterns during early stand development in upland black spruce ecosystems. *International Journal of Forest Engineering*, 23(1): 25-32. doi: 10.1080/14942119.2012.10739957
- Winsley P. 2007. Biochar and bioenergy production for climate change mitigation. *New Zealand Science Review* 64, 5-10.
- Wood SM and Layzell DB. 2003. A Canadian Biomass Inventory: Feedstocks for a Bio-based Economy. Canada, BIOCAP Canada Foundation, Queen's University Ontario
- Woolf D, Amonette JE, Street-Perrott FA, Lehmann J and Joseph S. 2010. Sustainable biochar to mitigate global climate change. *Nature Communications* 1. Article No: 56 doi: 10.1038/ncomms1053
- WPAC Wood pellet association of Canada 2013. Canadian Wood Pellet production outlook 2013. Wood pellet association of Canada. <http://www.pellet.org/about/publications>.
- Xu R, Ferrante L, Hall K, Briens C and Berruti F. 2011. Thermal self-sustainability of biochar production by pyrolysis. *Journal of Analytical and Applied Pyrolysis*, 91:55-66.
- Yamato M, Okimori Y, Wibowo IF, Anshori S and Ogawa M. 2006. Effects of the application of charred bark of *Acacia mangium* on the yield of maize, cowpea and peanut, and soil chemical properties in South Sumatra, Indonesia. *Soil Science and Plant Nutrition*, 52(4): 489-495.
- Yoder J, Galinato S, Granatstein D and Garcia-Prez M. 2011. Economic tradeoff between biochar and bio-oil production via pyrolysis. *Biomass and Bioenergy* 35, 1851-1862.
- Zhang Y, McKechnie J, Cormier D, Lyng R, Mabee W, Ogino A and MacLean HL. 2010. Life cycle emissions and cost of producing electricity from coal, natural Gas and wood pellets in Ontario, Canada. *Environmental Science and Technology*, 44(1): 538-544.
- Zhang Y. 2010. Life Cycle Environmental and Cost Evaluation of Bioenergy Systems. ProQuest Dissertations and Theses, 209. 2010. Canada, University of Toronto, Canada.
- Zimmerman AR. 2010. Abiotic and microbial oxidation of laboratory produced black carbon (biochar). *Environmental Science and Technology*, 44(4): 1295–1301