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REVIEW ARTICLE

Biochar-based bioenergy and its environmental impact in Northwestern Ontario Canada: A review

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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 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, CO_2, carbon sequestration, greenhouse gas emissions, soil amendment.

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Introduction

The earth has sustained hazardous and rapid climate change patterns due to anthropogenic carbon dioxide (CO_2) 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 CO_2 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 CO_2) has already exceeded the safe limit (350ppm of CO_2) 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℃ 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 CO_2 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 (Fig. 1).

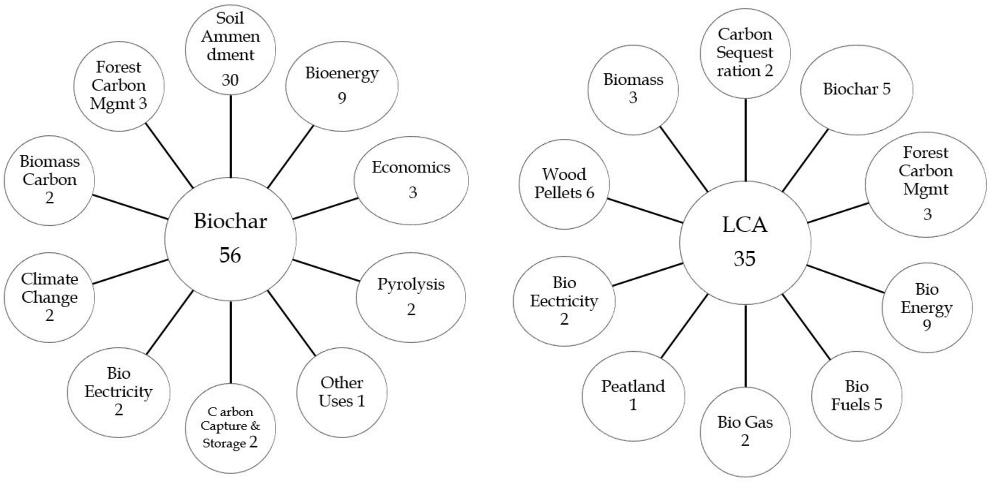

Fig. 1: Study spectrum and number of studies covered in this paper

The extent of papers reviewed is more or less global, with one third focusing on studies related to the USA (Fig. 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.

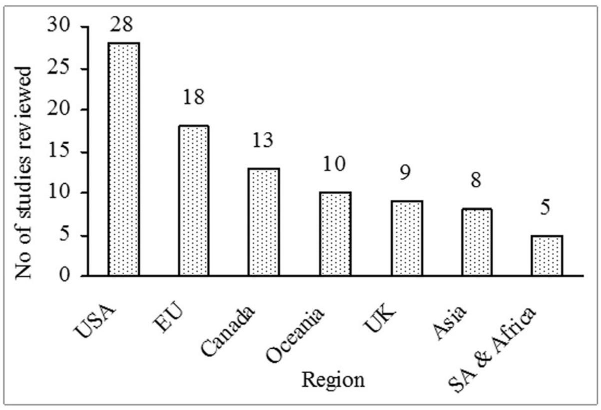

Fig. 2: Number of studies reviewed in different regions

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 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 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).

Table 2: Properties of biochar produced from fast and slow pyrolysis techniques. Fast - Moderate temperature (~600^{0}C), short vapor residence time (<2 sec); Slow - Low temperature (~400^{0}C), long vapor residence time (>30 min)

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

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 herabeceous plants and agricultural waste is presented in Table 3 (Tillman et al. 2009).

Table 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_2O_3	3.55	4.51	3.80
CaO	45.46	5.60	8.80
Fe_2O_3	1.58	2.03	1.80
P_2O_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 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 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	Temp ^{0}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 t·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 5).

Table 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%	
15 Mg·ha^{-1} wood-char	Decreased yield to 29%	
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%	
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	
without added N	No effect	
90 g·kg^{-1} biochar	Increased biomass production by 46%	Rondon 2007
60 g·kg^{-1} biochar	Increased biomass production by 39%	
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·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·ha^{-1} compared to the control under fertilized conditions. With pine chip biochar application, yield reductions occurred at both 11 and 22 t.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 6.

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.

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

Plant-Soil System	Climate Change adaptation	Climate Change Mitigation
• Improve soil air and water storage	• Enhance agriculture input efficiencies	• Increase stable soil C pool
• Improve soil structure	• Enhance soil water use	• Reduce soil greenhouse gas emissions
• Increase soil CEC, pH, C and nutrients	• Improve water quality	• Reduce soil degradation
• Increase soil microbial activity and diversity	• Reduce nutrient leaching and runoff	• Reduce N fertilizer use
• Enhance plant growth conditions	• Enhance global food security	• Reduce CH_4 emissions from biomass decay
	• Increase ecosystem resilience	

Environmental impacts and life cycle assessment of Biochar

Soil carbon is one of the major sources of GHG emissions (Lal 2007). Carbon Dioxide (CO_2), Methane (CH_4) and Nitrous Oxide (N_2O) 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 N_2O emissions over time (Table 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 N_2O from soil were observed in the short term (Clough and Condron 2010). N_2O, 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 N_2O emissions remain unknown (Van Zwieten et al. 2010). The effectiveness of biochar application in reducing soil N_2O 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 7.

Table 7: Environmental impacts of biochar application

Beneficial Environmental impacts		Reference
Reduced	Improved	
Bacterial Plant Pathogens; N_2O emission	Phosphate solublising bacteria	Anderson et al. 2011
Ammonium leaching; N_2O 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_2O 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 CO_2 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 CO_2 t^{-1} of feedstock consumed. A review of life cycle studies with a brief finding from each study is presented in Table 8.

Table 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_2e GHG is released for every ton 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 were 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
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.

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