Proceedings of the 59th International Convention of Society of Wood Science and Technology
March 6-10, 2016 – Curitiba, Brazil

Estimating GHG Emissions from the Manufacturing of Field-Applied Biochar Pellets

Richard D. Bergman[1 *] *– Hanwen Zhang*[2] *– Karl Englund*[2]
Keith Windell[3] *– Hongmei Gu*[1] *–*

[1] Research Forest Products Technologist, Research Forest Products Technologist, USDA Forest Service Forest Products Laboratory, Madison, WI, USA **Corresponding author*
rbergman@fs.fed.us, hongmeigu@fs.fed.us
[2] Research Assistant, Associate Research Professor Extension Specialist, Composite Materials & Engineering Center, Washington State University, Pullman, WA, USA *hanwen.zhang@wsu.edu, englund@wsu.edu*
[3] Project Leader, USDA Forest Service Missoula Technology & Development Center, Missoula, MT, USA
kwindell@fs.fed.us

Abstract

Biochar application to forest soils can provide direct and indirect benefits, including carbon sequestration. Biochar, the result of thermochemical conversion of biomass, can have positive environmental climate benefits and can be more stable when field-applied to forest soils than wood itself. Categorizing greenhouse gas (GHG) emissions and carbon sequestration profile are critical to the long-term sustainability of this practice. Using life-cycle assessment as a sustainable metric tool, this study evaluated the fuel consumed to pelletize, transport, and field-apply biochar produced from a novel thermochemical process from gate-to-gate on a per functional basis of one oven dry (OD) tonne. In the present study, pellet transport and field application were considered part of the manufacturing process. The fossil GHG emissions released from gate-to-gate manufacturing, 76.6 kg CO_2eq/OD t, was far exceeded by the amount of biogenic carbon sequestered long term at 2,430 kg CO_2eq/OD t, even considering the decay of biochar carbon over 100 years into biogenic CO_2. Biogenic CO_2 as part of the global carbon cycle does not contribute to climate change when the feedstock came from sustainably managed forests, as in this study. Quantifying global warming impact showed that consuming primary energy for field-applied biochar pellets had relatively small contributions to climate change relative to the carbon sequestration potential of the biochar pellets.

Key words: Life-cycle assessment, climate change, forest, biochar, spreading, sequestration

Introduction

Biomass as a sustainable feedstock for creating bioproducts has raised considerable attention (Ragauskas et al 2006; Guo et al 2007; Bozell and Petersen 2010). Biomass-derived fuels and products can reduce the need for petroleum imports while supporting the growth of agriculture, forestry, and rural economies (Roberts et al 2010; McKechnie et al 2011; Cowie and Cowie 2013). In particular, biochar as a bioproduct has received extensive consideration because of its carbon (C) sequestration potential and ability to boost soil productivity (Lehman et al 2006; Lorenz and Lal 2014). Thus, biochar as a byproduct of bioenergy production from biomass, including generation of heat, energy gas, and bio-oil, has the potential to reduce net greenhouse gas (GHG) emissions, improve local economies and energy security (Gaunt and Lehmann 2008; Homagain et al 2014), and possibly increase overall site productivity when added back to the soil.

Biochar application to forest soils can provide direct and indirect benefits as a soil amendment and through C sequestration (Sohi et al 2010; McElligott et al 2011). Biochar, the result of thermochemical conversion of biomass, can have positive environmental benefits and can be more stable when field-applied to forest soils than wood itself (Gaunt and Cowie 2009; Sohi et al 2010; McElligott et al 2011; Cowie and Cowie 2013; Schimmelpfennig et at 2014; USDOE EERE 2015).

Restoration treatments on western U.S. forests produce large quantities of woody biomass that can be used as feedstock for production of biofuels and other bioproducts. Producing bioenergy and bioproducts from such forest thinning or timber harvest byproducts would contribute to achieving broad national energy objectives, including the nation's energy security and reduction of greenhouse gas emissions from fossil fuels. The U.S. Department of Energy and the U.S. Department of Agriculture (USDA) are both strongly committed to expanding the role of biomass as an energy source and envision a 30% replacement of current U.S. petroleum consumption with biofuels by 2030 (Perlack et al 2005). One way to measure biochar's sustainability in the context of the abovementioned features is by conducting a life-cycle assessment (LCA).

LCA as a science-based tool is useful in assessing the claim that expanding bioenergy production from woody biomass has the potential to reduce net GHG emissions. Information provided by this analytical tool is essential for policy makers to make evidence-based judgments on expanding renewable energy production. LCA considers direct and related processes, flows of raw materials and intermediate inputs, waste, and other material and energy outputs associated with the entire product chain or system. Broadly, LCA can assess new products, new processes, or new technologies in an analytically thorough and environmentally holistic manner to guide more robust deployment decisions. LCA can calculate GHG and other emissions over part or all of the whole life cycle of a product.

For our study, we applied LCA to the pelletization and field application of biochar produced from a distributed-scale advanced biomass pyrolysis system, which will be referred to in this paper as the Tucker (developed by Tucker Engineer Associate, Locust,

NC) renewable natural gas (RNG) unit (Bergman and Gu 2014; Gu and Bergman 2015). This study is part of a larger USDA project developing and evaluating the Tucker RNG unit that could generate bioenergy and bioproducts for higher value markets. The Tucker RNG unit uses high-temperature conversion (>750 °C) in an extremely low oxygen environment to convert feedstock from forest thinning and mill residues into syngas that can be used for heat and electricity and into biochar for soil amendment or as a precursor in the manufacturing of activated carbon and other industrial carbon products. Syngas-generated electricity is intended to substitute a portion (marginal part) of grid electricity generated from fossil fuels, most commonly natural gas and coal. The system was specifically designed to generate a high-quality biochar to become activated carbon and not as a soil amendment, which sells at a lower price. However, LCA can focus on life-cycle stages that may not be considered once a process becomes commercialized but still in the development phase to evaluate what-if scenarios. In the present study, the what-if scenario was field application of pelletized biochar.

In this paper, LCA estimated the GHG emissions of field-applying biochar pellets in relation to its carbon sequestration potential. This is the first study to evaluate field application of pelletized biochar from a distributed-scale thermochemical conversion system in the United States. We answer the question of how much GHG emissions in kg CO_2-eq were generated from pelletizing biochar, transporting the pelletized biochar, and applying the pelletized biochar back to the forest where the raw material, wood, was harvested relative to the C sequestration potential found in the biochar.

Materials & Methods

The goal of this study was estimating the life-cycle impacts of field application of biochar pellets in relation to its C sequestration potential. To achieve this goal, the life-cycle inventory (LCI) for field-applying pelletized biochar, including processes of pelletizing biochar on a lab scale, transporting the pelletized biochar to the forest, and then field-applying the pelletized biochar, was modeled and conformed to the ISO 14040 and 14044 standards (ISO 2006a,b; ILCD 2010). LCI needs to be built before the impact analysis can be done. LCI, the data collection portion of a LCA, tracks and quantifies inputs and outputs of a system, including detailed resources, raw material, and energy flows.

Development of the LCI includes primary and secondary data. Primary data were collected on pelletization and field application of the pellets. Pelletizing biochar data came from lab runs. Application and spread rate data during field application of the pelletized biochar came from field work, and secondary data on estimates of fuel consumption for the machines used came from literature. As for transportation, the authors assumed that the pelletized biochar was field-applied roughly in the same forest where the feedstock was harvested to produce the biochar itself. The biochar was assumed to be produced at a sawmill located in St. Regis, MT, and then pelletized there at the sawmill as well before transporting to the forest. Secondary data on background processes, including (transportation) fuels and electricity, came from the U.S. LCI Database (NREL 2012).

Gate-to-gate manufacturing unit processes

Pelletization. A laboratory-scale pellet mill built by California Pellet Mill (CPM, Crawfordsville, IN, USA) and powered by a 1.5-kW motor densified the raw biochar. Inputs included raw biochar and electricity. Output was pelletized biochar at the lab. Off-site emissions came from grid electricity.

Transportation. Biochar pellets at the lab were transported 160 km to the forest for spreading. Inputs included biochar pellets and diesel for the pickup truck. Output was biochar pellets. Emissions included cradle-to-gate production and combustion of diesel.

Field-application. Biochar pellets were loaded on a diesel forwarder with a gasoline engine to run the spreader hydraulic system. For the present study, wood pellets were used as proxy because of the limited supply of biochar pellet. For the present paper, the authors used the term "biochar pellets" and not "wood pellets" when referring to field application. Inputs included biochar pellets, diesel, and gasoline. Output was biochar pellets on the forest floor.

The focus of this study was on the biochar product once produced. No upstream environmental impacts were assigned to the biochar before pelletization. In addition, the authors analyzed the biochar pellets for long-term carbon storage in soil (i.e., their carbon sequestration potential). Secondary data were drawn from peer-reviewed literature. With the material and energy inputs and reported emissions, the gate-to-gate LCI model for the field application of pelletized biochar was built in SimaPro 8 to estimate environmental outputs and cumulated energy consumption (PRé Consultants 2015). Within the SimaPro software, inventory data were compiled into the impact category indicator of interest, i.e., global warming (GW).

Scope

This study covers the partial gate-to-gate LCA of field application of pelletized biochar. The present LCA was classified as a partial LCA because the study covered only global warming and no other impact categories that are included in a full LCA. The U.S. electricity grid is composed of many regions with various energy sources (USEPA 2015). The U.S. Environmental Protection Agency (USEPA) has broken the U.S. electricity grid into "eGrids" (USEPA 2015).The eGrid system from the Northwest (NWPP) region included in the analysis is referred to as NWPP. The eGrid NWPP is representative of year 2012 mix of fuels used for utility electricity generation in the northwestern United States. Fuels include coal, biomass, petroleum, geothermal, natural gas, nuclear, hydroelectric, wind, and other energy sources. NWPP electricity grid covers area including Washington, Oregon, Idaho, Utah, most of Montana, Wyoming, Nevada, and northern parts of California, Arizona, and New Mexico.

Functional unit and declared unit

Functional unit is the reference unit used to quantify the environmental performance of a product system. It is also a reference related to inputs and outputs. A declared unit is used in instances where the function and the reference scenario for the whole life cycle of a product cannot be stated and includes only the quantity. For the present study, the authors

selected a functional unit, one oven-dry (OD) kg of field-applied pelletized biochar. All input and output data were allocated to the functional unit of product based on the mass of products and co-products in accordance with standards for conducting LCAs (ISO 2006b). Material flows, energy use, and emission data are standardized based on this functional unit within the system boundaries described in the following section. The present study does include grid losses (USEPA 2015).

Unit processes

To complete the life-cycle impact assessment (LCIA), the field-applied biochar pellet system was built from unit processes. LCI databases contain large lists of unit processes. In the product system, starting from the declared unit, related processes are called on and built into the process tree with inputs and outputs matched to the delivery of the declared unit. For the reference fossil fuel chains, GHG performance was calculated using secondary data from the U.S. LCI Database (NREL 2012).

For the present study, the mainstream model of this study, the gate-to-gate manufacturing of the field-applied biochar pellets, was downstream of the thermochemical conversion process. Bergman and Gu (2014) provided a detailed analysis of the Tucker RNG unit itself.

Compiling process data

Starting with the functional unit of 1 OD kg field-applied pelletized biochar, fuels and equipment use and transportation requirements were compiled in the SimaPro model to quantify GHG emissions to the environment. The model then relates them to the 100-year GW impact according to the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) method (IPCC 2007; Bare 2011; USEPA 2014). SimaPro software version 8 now includes the TRACI 2.1 method, which was used in the present study. In addition, biogenic CO_2 had no contribution in estimating GW impact for gate-to-gate manufacturing.

System boundary

Defining the system boundary selects the unit processes to be included in the system. Based on our goal to determine the environmental impacts of field-applied biochar pellets, the authors drew the system boundary to include 1) pelletization of raw biochar, 2) transportation of pelletized biochar, and 3) field application of pelletized biochar. Figure 1 shows the system boundary defined for this partial gate-to-gate LCA study. The cumulative system boundary includes both on- and off-site emissions for all material and energy consumed. Fuel and electricity consumed for pelletizing, transporting, and field-applying unit processes were included in the cumulative boundary (solid line) to calculate the total emissions. The on-site emissions were due to the processes within the dotted line (Fig 1). The off-site emissions resulted from the grid electricity production, transportation, and fuels produced off-site but consumed onsite.

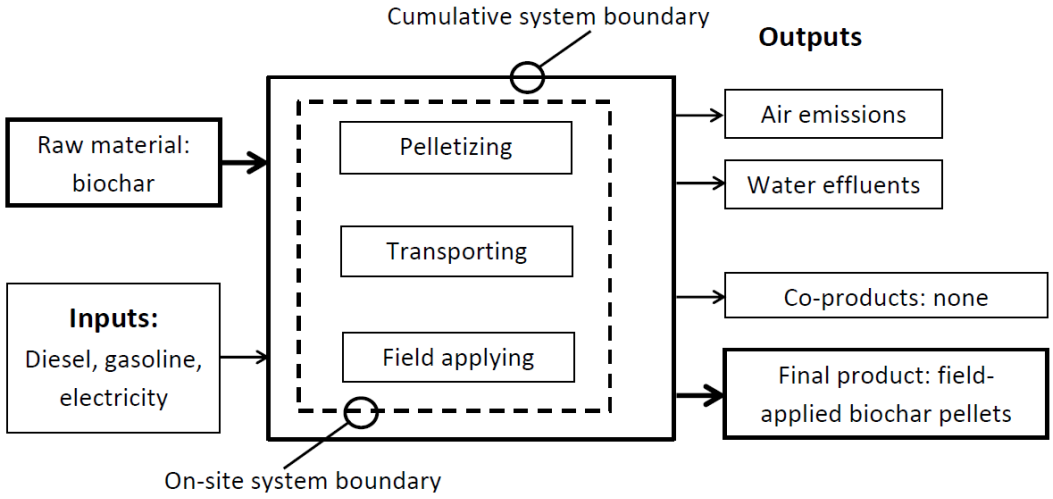

Figure 1. Gate-to-gate system boundaries for field-applying pelletized biochar

Results and Discussion

A lab-scale pellet mill and field application of pellets provided detailed primary data on mass flow, energy consumption, and fuel types. Primary data were modeled; estimates on environmental outputs (e.g., GHG emissions) were derived on a per 1.0 OD t basis.

Inputs and outputs

Pelletization. Several runs of 100% biochar were conducted using the CPM laboratory pellet mill powered by a 1.5-kW motor. On average, net electrical consumption was 44.60 ± 0.23 kWh/t at 27.45% moisture content (MC), which translated to 61.47 kWh/OD t at 0% MC.

Transportation. Pelletized biochar at 27.45% MC was transported 160 km to the forest using a diesel pickup truck. Moisture was considered when transporting the biochar.

Field application. Data were derived from six forest field runs that varied from 0.098 to 6.35 t/h biochar pellet application rate (Table 1). The average pellets applied were 6.35 ± 5.16 t/h. The authors assumed a 1-h run time for the six runs to develop an aggregate value of 25.4 t at 27.45% MC (18.5 OD t/h) and that the pellets were evenly distributed. The 82.1-kW forwarder hauling the biochar pellets consumed diesel fuel, and its consumption was estimated at 10.4 L/h using Brinker et al (2002, table 4). The 13.4-kW gasoline engine used for spreading the biochar pellets consumed 6.77 L/h.

Table 1. Data from field applying biochar pellets per tonne, 27.45% moisture content

Run	Application rate (t/hectare)	Spread rate (hectare/h)	Pellets applied (t/h)	
1	0.145	0.676	0.098	
2	0.997	2.871	2.864	
3	21.214	0.676	14.332	
4	1.793	0.957	1.716	
5	1.432	1.295	1.855	
6	3.008	1.520	4.572	**Stand Dev**
Total			25.436	
Average	4.765	1.332	6.349	5.159

Overall. Table 2 shows the SimaPro modeling inputs. Inputs for the three unit processes were shown with total diesel and gasoline consumption of 3.37 and 2.20 L/OD t of field-applied biochar pellets.

Table 2. Energy consumed per oven-dry t per hour of field-applied biochar pellets

Energy source	Unit	Pelletizing biochar	Biochar pellet transporting	Field applying biochar pellets	Total
Diesel	L	0.00	0.00	3.37	3.37
Gasoline	L	0.00	0.00	2.20	2.20
Electricity	kWh	61.47	0.0	0.0	61.5
Diesel truck	tkm	0	205	0	205

Life-cycle inventory

Cumulative energy consumption for pelletizing, transporting, and field-applying biochar pellets was 1,270 MJ/OD t, with diesel fuel accounting for about 59.0% of the total. Most of the diesel fuel was consumed during transportation. Coal (16.6%) and natural gas (12.4%) were the second and third most important energy sources.

Emission data produced through modeling found that estimated fossil CO_2, methane, and nitrous oxide (N_2O) emissions in kg/m^3 were 73.1, 0.120, and 0.00152 kg/t of field-applied biochar pellets (Table 3).

Table 3. Cumulative environmental outputs for producing 1oven-dry t of field-applied biochar pellets

Substance	(kg/OD t)
Water effluents	
BOD5 (Biological oxygen demand)	1.23E-02
Chloride	2.45E+00
COD (Chemical oxygen demand)	2.32E–02
DOC (Dissolved organic carbon)	2.77E–11
Oils, unspecified	1.55E–03
Suspended solids, unspecified	3.19E+00
Air emissions	
Acetaldehyde	6.84E–05
Acrolein	9.26E–06
Benzene	8.80E–05
Carbon monoxide (fossil)	6.20E–01
Carbon dioxide (fossil)	7.31E+01
Dinitrogen monoxide (N2O)	1.52E–03
Methane	1.20E–01
Formaldehyde	1.11E–04
Nitrogen oxides	5.96E–01
Non-methane VOC	3.33E–02
Particulate (unspecified)	1.53E–02
Phenol	2.54E–11
Propanal	6.03E–10
Sulfur dioxide	1.57E–01
Volatile organic compounds (VOC)	3.14E–02

GHG emission performance

GW impacts of field-applying biochar pellets in relation to its carbon sequestration potential were compared. There are two GHG emission sources: 1) from pelletizing, transporting, and field-applying (Table 4) and 2) from decay of biogenic carbon of the field-applied biochar pellets into CO_2 (Table 5). Based on Wang et al (2014), the authors calculated that 66.3% of the biochar pellets with an original moisture-free carbon content of 90% remained after 100 years (Gu and Bergman 2015). Carbon was converted to CO_2 by multiplying by 44/12. Therefore, the amount of biogenic carbon sequestered long term was estimated to be equivalent to 2,432 kg CO_2eq/OD t, far exceeding the fossil GHG emissions released from manufacturing, 76.6 kg CO_2eq/OD t. By contrast, far more biogenic CO_2 was emitted once the biochar pellets were field-applied.

Table 4. GHG emission gate-to-gate manufacturing performance of field-applied biochar pellets

Units	Pelletized biochar, at mill	Pelletized biochar, at forest landing	Pelletized biochar, field applied	Total manufacturing emissions
kg CO2eq/OD t	19.6	40.8	16.2	76.6
Percentage	25.5%	53.3%	21.1%	100.0%

Table 5. Stability and decay of field-applied biochar (biogenic) carbon

Units	Labile carbon[a]	Recalcitrant carbon[b]	Recalcitrant carbon[c]	Total carbon
kg CO2eq/OD t	330	538	2432	3300
Percentage	10.0%	16.3%	73.7%	100.0%

[a] Decayed away after 1 year
[b] Decayed away after 100 years
[c] Intact after 100 years

Conclusion

Categorizing GHG emissions from human activities such as biochar pellets helps in identifying contributions to climate change. Bioproducts, including biochar, can have a vital role in helping to mitigate GHG emissions. In the present study, gate-to-gate manufacturing of the field-applied biochar pellets had a relatively small contribution to climate change compared with the carbon sequestration potential.

Sequestering biochar carbon in forests (i.e., soils) does not necessarily stop decay of biochar. Thus, estimating decomposition of biochar (biogenic) carbon once applied turns out to have a far larger impact than the gate-to-gate manufacturing fossil GHG emissions. However, biogenic CO_2 as part of the global carbon cycle does not contribute to climate change when the original feedstock was derived from sustainably managed forests as it was in this case. In addition, quantifying decay of recalcitrant carbon, which depends on many factors (Gaunt and Cowie 2009; Sohi et al 2010; Lorenz and Lal 2014), shows it has a substantial contribution to climate change as well.

Study assumptions and limitations that may affect the final results include transportation distance of biochar pellets to the forest of wood origin, use of wood pellets instead of biochar pellets, and that the pellets applied in the forest were evenly distributed. In addition, the other major two GHG emissions were not included and may have an indirect impact on climate change.

Acknowledgements

The authors thank Drs. Sevda Alanya-Rosenbaum and Scott Bowe and Mr. Changlei Xia for their peer review of this paper. We gratefully acknowledge financial assistance for this research project provided by the U.S. Department of Agriculture (USDA) National Institute of Food and Agriculture Biomass Research and Development Initiative (BRDI) award no. 2011-10006-30357. BRDI is a joint effort between the USDA and the U.S. Department of Energy.

References

Bare J (2011) TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0. Clean Technologies and Environmental Policy, 13(5): 687-696.

Bergman RD, Gu H (2014) Life-cycle inventory analysis of bio-products from a modular advanced biomass pyrolysis system. In: Proceedings, Society of Wood Science and Technology 57th International Convention. June 23-27, 2014. Zvolen, Slovakia: 405–415.

Bozell JJ, Petersen GR (2010) Critical review: Technology development for the production of biobased products from biorefinery carbohydrates—the US Department of Energy's "Top 10" revisited. Green Chem 12(4):539-554.

Brinker RW, Kinard J, Rummer B, Lanford B (2002) Machine rates for selected forest harvesting machines. Table 4: Fuel consumption by machine type and transmission type. Circular 296 (revised). Alabama Agricultural Experimental Station. Auburn University. Auburn, AL. 31 pp.

Cowie AL, Cowie AJ (2013) Case Study - Rural Climate Solutions (University of New England/ NSW Department of Primary Industries) Life cycle assessment of greenhouse gas mitigation benefits of biochar. http://www.ieabioenergy-task38.org/publications/T38_Biochar_case_study.pdf. (28 April 2015).

Gaunt J Lehmann J (2008) Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. Environ Sci Technol 42(11): 4152–4158.

Gaunt JL, Cowie A (2009) Biochar for environmental management: science and technology. Chapter 18. Biochar, greenhouse gas accounting, and emissions trading. London, United Kingdom: Earthscan.

Gu H, Bergman RD (2015) Life-cycle GHG emissions of electricity from syngas by pyrolyzing woody biomass. In: Proceedings, Society of Wood Science and Technology 58th International Convention. June 7-12, 2015. Jackson Hole, Wyoming: 376-389.

Guo Z, Sun C, Grebner DL (2007). Utilization of forest derived biomass for energy production in the U.S.A.: Status, challenges, and public policies. Int Forestry Rev 9(3):748-758.

Homagain K, Shahi C, Luckai N, Sharma M (2014). Biochar-based bioenergy and its environmental impact in Northwestern Ontario Canada: A review. Journal of Forestry Research, 25(4), pp. 737-748.

ILCD (2010) International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment—Detailed guidance. EUR 24708 EN. European Commission–Joint Research Centre–Institute for Environment and Sustainability. Luxembourg. Publications Office of the European Union. 417 p.

IPCC (2007) The physical scientific basis. Contribution of working group to the fourth assessment report of the intergovernmental panel on climate change, edited by S. Solomon et al, Cambridge Univ. Press, New York.

ISO (2006a) Environmental management—life-cycle assessment—principles and framework. ISO 14040. International Organization for Standardization, Geneva, Switzerland. 20 pp.

ISO (2006b) Environmental management—life-cycle assessment—requirements and guidelines. ISO 14044. International Organization for Standardization, Geneva, Switzerland. 46 pp.

Lehmann J, Gaunt J, Rondon M (2006) Bio-char sequestration in terrestrial ecosystems – a review. Mitigation and Adaptation Strategies for Global Change, 11(2):403-427.

Lorenz K, Lal R (2014) Biochar application for climate change mitigation by soil organic carbon sequestration. J Plant Nutr Soil Sc 177(5):651-670.

McElligott K, Page-Dumroese D, Coleman M (2011) Bioenergy production systems and biochar application in forests: potential for renewable energy, soil enhancement, and carbon sequestration. Res Note RMRS-RN-46. USDA For Serv Rocky Mountain Research Station. Fort Collins, CO. 14 p.

McKechnie J, Colombo S, Chen J, Mabee W, Maclean HL (2011) Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuel. Environ Sci Technol 45(2):789-795.

NREL (2012) Life-cycle inventory database project. National Renewable Energy Laboratory. https://www.lcacommons.gov/nrel/search. (5 January 2016)

Perlack PD, Wright LL, Turhollow AF, Graham RL, Stokes RJ, Erbach DC (2005) Biomass as feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton: Annual supply. April 2005. A joint study sponsored by U.S. Department of Energy and the U.S. Department of Agriculture. http://www1.eere.energy.gov/bioenergy/pdfs/final_billionton_vision_report2.pdf (5 January 2016)

PRé Consultants (2015) Life-cycle assessment modeling software package. SimaPro Version 8. Amersfoort, The Netherlands.

Ragauskas AJ, Williams CK, Davison BH, et al (2006) The path forward for biofuels and biomaterials. Science 311(5760):484-489.

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. Environ Sci Technol 44(2):827-833.

Schimmelpfennig S, Müller C, Grünhage L, Koch C, Kammann C (2014) Biochar, hydrochar and uncarbonized feedstock application to permanent grassland—Effects on greenhouse gas emissions and plant growth. Agr, Ecosyst, & Environ 191(2014):39-52.

Sohi SP, Krull E, Lopez-Capel E, Bol R (2010) Chapter 2 – A review of biochar and its use and function in soil. Advances in Agronomy 105:47–82.

USDOE EERE (2015) Bioproducts to enable biofuels workshop summary report. United States Deprtment of Energy Office of Energy Efficiency and Renewable Energy. A Bailey, GJ Leong and N Fitzgerald, eds. DOE/EE-1294. Washington, DC. 35 pp.

USEPA (2014) Carbon dioxide emissions associated with bioenergy and other biogenic sources. United States Environmental Protection Agency. Washington, D.C. http://www3.epa.gov/climatechange/ghgemissions/biogenic-emissions.html (4 January 2016).

USEPA (2015) eGRID Year 2012 summary tables: Table 5. eGRID2012 subregion resource mix. United States Environmental Protection Agency. Washington, D.C. 13 p. http://www.epa.gov/sites/production/files/2015-10/documents/egrid2012_summarytables_0.pdf (16 December 2015).

Wang Z, Dunn JB, Han J, Wang MQ (2014) Effects of co-produced biochar on life cycle greenhouse gas emissions of pyrolysis-derived renewable fuels. Biofuels and Bioprod Bioref. 8:189–204.