LIFE CYCLE ANALYSIS OF BIOCHAR

Waste to Wisdom: Subtask 4.6.5

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ABSTRACT

All products including bioproducts have an impact on the environment by consuming resources and releasing emissions during their production. Biochar has received considerable attention because of its potential to sequester carbon in soil while enhancing productivity. In addition, using a renewable source of feedstock to make the biochar is more likely to be sustainable. In this chapter, we discuss the environmental impacts of producing biochar using a holistic method called life-cycle assessment (LCA) or more generally life-cycle analysis. LCA is an internationally accepted method that can calculate greenhouse gas (GHG) and other emissions for part or all of a product life cycle. One huge benefit is that LCA provides metrics to compare alternative substitutable products. For example, using the metrics estimated from a LCA study such as impacts of climate change for a new and current product, LCA outcomes can show which product has less impact on the environment and human health and is more likely to be sustainable. LCA can be thought of as an approach similar to financial accounting but instead focused on the environment. Generally, the following chapter will show how LCA can assess impacts of the entire supply chain associated with all steps of the biochar system, from biomass harvesting to soil amendment with a focus on the biomass thermochemical conversion step. Specifically, a description of how the LCA method was developed and is used will be shown in the context of biochar production. Conducting LCA can capture many direct and indirect effects from the production of fuels and materials used in product production. We will also describe a new advanced pyrolysis technology developed in the United States and used to process waste woody biomass, thus exploring biochar LCA from a forestry perspective. Therefore, this chapter will present LCA mostly from a forestry perspective, although agricultural activities will be discussed. The new pyrolysis technology produces biochar, along with synthesis gas, and we will discuss its environmental performance based on the LCA research conducted so far.

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INTRODUCTION

Biomass as a feedstock for producing bioproducts has raised substantial attention (Guo *et al.*, 2007). Biomass-derived fuels and products are one approach to reduce the need for oil and gasoline imports while supporting the growth of agriculture, forestry, and rural economies (Roberts *et al*., 2010; McKechnie *et al.*, 2011). In particular, biochar as a bioproduct has received considerable attention because of its carbon (C) sequestration potential and ability to enhance soil productivity (Lehman *et al*., 2007; Lorenz and Lal, 2014). Thus, biochar as a byproduct of bioenergy production from biomass, including production of heat, energy gas and bio-oil, has the potential to reduce net greenhouse gas (GHG) emissions, improve local economies and energy security (Homagain *et al*, 2014), and may increase overall site productivity when added back to the soil.

Life-cycle assessment (LCA) can be used to evaluate alternative scenarios for their GHG emissions. Categorizing GHG emissions have become crucial to assessing the sustainability of manufactured products. Scenarios include using wood residues such as logging slash or mill residues for feedstock to make biochar. However, there are alternative forest management practices for disposing of logging slash instead of as collecting it for use as raw material of fuel. These include leaving the residues to decompose in the forest, thereby releasing GHG emissions or, worse yet from an emission standpoint, burning logging slash along the ground or in piles to either dispose of waste biomass or reduce impacts of potential wildfires. These practices tend to have worse emissions impacts because prescribed burning not only consumes the logging slash but also much of the down and dead wood on the forest floor, which releases unchecked GHG emissions and particulate matter in the form of smoke. Furthermore, incomplete combustion associated with open burning produces higher levels of methane and NOx, which have higher global warming potentials (US EPA, 1995; NETL, 2013; Loeffler and

Anderson, 2014; Pierobon *et al*., 2014). In the USA, wildfire-prevention policy objectives exist to drive the use of prescribed burning to reduce fuel loads, but open burning is also widely practiced in silviculture to open grown space for regeneration and in agriculture dispose of crop residues and prepare field for planting. LCA, as a widely- accepted scientific method, can be used to capture these climate change impact differences for the various uses of wood residues and thus enable practitioners and policy-makers to make sound decisions based on science. LCA can be thought of an approach similar to financial accounting but instead accounting for environmental costs and benefits to show what approach would cause the least negative impact.

Four phases of life-cycle assessment

LCA measures the holistic environmental impacts of a product, including resources consumed and emissions released along with the associated environmental impacts. A LCA can cover the life of a product from extraction of raw materials to product production point (i.e., "cradle-to-gate") or through distribution, use, and to its final disposal point (i.e., from "cradle-to-grave") ([Figure 0.1) (ISO 2006a; 2006b; ICLD 2010). This approach is nicely aligned with the supply chain management (SCM) used in manufacturing (Chapter 2), but includes more detailed treatment of emissions, effluents, and waste.

[Figure 0.1. goes here]

LCAs are comprised of four phases (components) as defined by the International Organization of Standardization (ISO): (1) goal and scope definition, (2) life-cycle inventory (LCI) analysis, (3) life-cycle impact assessment (LCIA), and (4) interpretation (Figure 3.2). An LCA study includes all phases, but an LCI study does not include stage 3.

[Figure 0.2. goes here]

An LCI measures all raw material and energy inputs and the associated environmental outputs to manufacture a particular product, process, or service on a per unit (functional) basis within carefully defined system boundaries. LCIAs as part of an LCA study can use LCI flows to calculate impacts in four areas: human health, social health, resource depletion, and ecosystem function. In the interpretation stage, alternative actions to reduce impacts are systematically evaluated after environmental 'hotspots' have been identified (ISO, 2006a; 2006b; ILCD, 2010). Some impact categories related to energy and material consumption are easier to calculate than others. The following sub-sections will discuss the four phases of LCA in more detail.

Goal and scope

The goal and scope definition provide the study framework and explain how, and to whom, results are to be communicated. There are several important items to address during this phase. First, the functional unit is defined for the product system to provide a way to allocate raw material consumption, air emissions, water effluent, and solid waste generated during product production and to enable product comparison. The functional unit similar to a production unit and can be defined as a quantity of a product serving a particular function for a set time. An example of a functional unit is one square meter of installed flooring with a service life of 100 year. This functional unit for the installed flooring can be met from renewable products such as wood or bamboo or nonrenewable products like vinyl and enable a product comparison on their environmental performance. Secondly, a system boundary for the product is selected by setting what unit processes will be included in the analysis. The system boundary tracks the environmental inputs and environmental outputs crossing the boundary as shown in Figure 3.1. The system boundary may cover the whole-life cycle of a product or just a single part of the life-cycle from gate-to-gate. Thirdly, to address the most relevant life-cycle stages, cut-off criteria are determined. In a practical sense, the cut-off criteria enable the LCA practioner to complete the project in reasonable time by omitting inconsequential life-cycle stages or life-cycle stages typically omitted. Lastly, a protocol is described on how the collected primary data will be validated. Primary data are measured and collected in-person and on-site-for the study. For product LCAs, a mass balance is typically performed to aid in this endeavor. In addition, a common practice is to calculate the process energy consumption on a production unit basis (e.g. a cubic meter of dry sawn lumber) and then compared the results to a similar product or products found within secondary data sources such as peer-reviewed literature (ISO, 2006a; 2006b; ILCD, 2010).

Life-cycle inventory analysis

The life-cycle inventory phase is the most time- and data-intensive part of conducting a LCA, primarily because primary data must be collected to develop LCI data or flows for the product system being evaluated. Data collection can occur at any stage of the life cycle such as during extraction of raw materials, product production, or use phase depending on the project goal and scope. As for data quality, certain requirements must be met, and the outcome reliability from LCA studies (i.e. LCIAs) highly depends on the degree to which these data quality requirements are met.

Once the primary data are collected, the data are validated and related to the functional unit to produce the aggregation of results (i.e. LCI flows or results). For industry products, a typical aggregation is by the production of the individual company where data collected from the largest company carry the most weight in reporting. LCI flows include the raw material consumed, emissions to air and water, and solid waste generated per functional unit. An intricate step in this calculation process is the allocation of LCI flows e.g., releases to air and water. Complications exist because most existing product systems yield multiple products. As discussed in Chapter 2, the difference between a waste, byproduct, and co-product is variable by discipline, but LCA provides definition based on assigning environmental impacts: waste products have disposal costs, byproducts have marginal costs and marginal value relative to primary products, and co-products are manufactured jointly and use joint product costing in accounting. The complication with this definition is that the same material can be a waste, a byproduct, or a co-product depending on its value and costs, but it is useful do draw a clear line between waste as a material with net costs, especially for disposal, and production outputs that have market value and the potential to generate revenue.

For example, sawmills not only produce sawn lumber as a product (i.e. the final product) but also produce chips, sawdust, bark, and shavings as co-products. As mentioned in Chapter 2 (Part 2.5.1), these ‘co-products’ in context of SCM would be considered by-products and not co-products as they are the LCA context because they have some economic value although little in some circumstances. Therefore, the environmental outputs must often be allocated (i.e. assigned) to the different products and co-products. Waste products like boiler ash are considered the same in the LCA and SCM context. The following allocation is recommended for allocation in order of preference. One, wherever possible, allocation should be avoided by using system expansion. Two, where allocation is not avoidable, environmental inputs and environmental outputs should be partitioned between different functions or products in a way that corresponds to the underlying physical relationships between them, such as mass and energy. Three, if 1 or 2 are not viable, allocation should be carried out based on other existing relationships (e.g. in proportion to the revenue of the various products and co-products (ISO, 2006a; 2006b; ILCD, 2010).

Life-cycle impact assessment

Life-cycle impact assessment aims to show the potential environmental impacts by using LCI flows found in phase 2. The ISO14040 suggests a LCIA include the following mandatory elements. The first is a selection of impact categories, category indicators, and characterization models. The second is classification, which is the assignment of individual inventory factors to impact categories. For example, CO_2 and N_2O are assigned to the global warming impact category. Other common impact categories are photo oxidant formation, eutrophication, ozone depletion, and acidification. The third mandatory element is characterization, which is the conversion of LCI flows to common units within each impact category, so the LCI flows can be aggregated into category indicator outputs. For example, CO_2 and N_2O are commonly emitted during burning of fossil fuels during transportation. However, though CO_2 is emitted at far greater levels than N_2O, CO_2 has less impact to climate change on a mass basis than N_2O. In addition, another complicating factor is that each GHG gas decays at different rates in the atmosphere. Therefore, each emission must be considered separately for the quantity emitted along with its impact on the individual category indicator output being estimated. Overall, a LCIA provides a systematic approach for sorting and characterizing environmental impacts (ISO, 2006a; 2006b; ILCD, 2010). In the United States, a midpoint-oriented LCIA method referred to as the Tool for the Reduction and Assessment of Chemical and other environmental Impacts' (TRACI) was developed by the U.S. Environmental Protection Agency specifically using input parameters consistent with U.S. locations (Bare 2011). Limits and assumptions of the LCA study are listed to enable reproducibility of the results.

Interpretation

The object of the interpretation phase is to reach conclusions and recommendations in line with the defined goal and scope of the study. Results from the LCI and LCIA are combined together and reported to give a comprehensive, transparent, and unbiased account of the study. The interpretation is to be made iteratively with the other three phases.

The life cycle interpretation of an LCA or an LCI comprises three main elements: 1) identification of the significant problems based on the outcomes of the LCI and LCIA phases of a LCA; 2) evaluation of outcomes, which considers completeness, sensitivity and consistency checks; and 3) conclusions and recommendations (ISO, 2006a; 2006b; ILCD, 2010).

Types of LCA

There are two main types of LCA along with various hybrid, dynamic, and streamlined methods. We will only discuss the two basic types here.

Attributional

Attributional LCA (ALCA) uses a process-modeling method to find the critical environmental impacts for a particular product referred to as “cradle-to-grave” (raw material extraction to waste disposal) analysis. This is the method that was discussed above. ALCA is a linear approach. Therefore, the magnitude of the functional unit (m^3 or thousand m^3 of biochar applied, for example) does not affect the LCIA outputs (Pennington *et al*., 2004). For example, one could state that for the global warming impact a value of 10 kg CO_2-eq/m^3 or 10,000 kg CO_2-eq/thousand m^3 of biochar and they would be equal. Using the LCIA results, an ALCA can locate environmental “hot spots” for a given product system (cradle-to-gate) to provide information for manufacturers (decision makers) regarding process improvements and design (Thomassen *et al*., 2008, Gaudreault *et al*., 2010). It is common for ALCA to use other allocation methods besides system expansion listed in section 3.2.1.2 if the LCA practioner is unable to divide unit processes sufficiently to track impacts. These allocation methods assign environmental burdens to products and co-products. Common allocation methods include mass, energy, and revenue allocations (ISO 2006a; 2006b).

Consequential

Consequential LCA (CLCA) is similar to ALCA in that it is a process-modeling method but is used to describe the (indirect) consequences of a particular decision. CLCA estimates system-wide changes in (material and energy) resource flows and environmental burdens that result from different production levels of the functional unit based on a decision. It is the decision that alters the technology activity (Ekvall and Weidema, 2004; Ekvall and Andrae, 2006). CLCA studies use system expansion to describe the consequences instead of allocation by mass, energy, or revenue. This method examines the effects on marginal electricity consumption for a change in production whereas ACLA evaluates environmental impacts based on modeling average technologies to create a “composite” technology. However, CLCA is not capable within the product system of locating “hot spots” as an ALCA is (Pennington *et al*., 2004; Thomassen *et al*., 2008; Gaudreault *et al*., 2010). Additionally, conducting a CLCA versus an ALCA usually results in greater uncertainty to an individual study reducing its usefulness. Even so, some of the benefits of biochar production are indirect, such as substitution for non-renewable products yielding emissions offsets, making it a relevant method for biochar LCA. Other benefits that could be captured indirectly are: displacement of carbon intensive agricultural inputs through both direct substitution and increased efficiency and carbon sequestration resulting from higher productivity leading to greater soil carbon.

Differences

An ALCA stays within carefully defined boundaries whereas a CLCA does not. CLCA activities may fall outside the original system boundary. For example, a sawmill produces sawn lumber as its final product while producing co-products such as sawdust (Bergman and Bowe, 2012). The sawdust is burned for fuel on-site to generate thermal energy for drying the sawn lumber or it is sold off-site. In an ALCA, material is not tracked once it crosses the system boundary and leaves the system. In the case of Bergman and Bowe (2012), sawdust from sawn lumber is not tracked beyond the system boundary, which is the sawmill gate. Its use as either fuel or as raw material for manufactured wood panels by another mill, does not impact the ALCA. An ALCA looks at a moment of time or a “snap-shot” whereas the basis for a CLCA could be to evaluate a market decision. For example, a sawmill may decide to sell sawdust to wood panel manufacturers rather than use it as fuel and use natural gas to fire the boilers to dry sawn lumber because sawdust has more value as a raw material than as a fuel. CLCA attempts to capture the potential environmental effects of selling the sawdust instead of burning it on-site at the sawmill for thermal energy. Depending on the goal and scope of the LCA study, both attributional and consequential methods are useful.

LIFE-CYCLE STAGES FOR BIOCHAR

As mentioned previously, LCAs can address environmental performance of biochar including categorizing GHG emissions along the entire life cycle of a product including carbon sequestration of the biochar when applied to the soil (Figure 3.3). The life-cycle stages include: 1) raw material extraction (i.e. feedstock production), 2) raw material (feedstock) logistics, 3) thermochemical conversion, 4) biochar logistics, and 5) product end uses including soil carbon sequestration. However, for a more complete description of the supply chain, the previous chapter (Chapter 2) provides a detailed view of biochar systems in a supply chain context. This section will deal primarily with the thermochemical conversion process from a LCA perspective.

[Figure 0.1. goes here]

Raw material extraction

The raw material extraction stage for biochar involves interaction with agricultural and natural systems. In the case of biochar, the raw material is biomass, most often biomass from herbaceous and woody plants. Raw material extraction may include forest or agriculture activities involving cultivation, harvesting, collection, handling and processing including in-woods grinding and chipping and screening. In-woods grinding and chipping are dominated by diesel fuel use. Inputs can include diesel, fertilizer, pesticides, and herbicides and outputs can include fossil CO_2 and N_2O air emissions along with possible nitrogen fertilizer run-off. In the United States and other parts of the world, industrial timberlands tend to have greater inputs of nursery seedlings, herbicides, pesticides and fertilizers than naturally regenerating forests managed by non-industrial landowners. In this case it is clear that management practices can have direct impacts on product attributes and corresponding LCA.

Raw material logistics

The second life-cycle stage is raw material (i.e. feedstock) logistics. For biochar, feedstock transportation typically includes a diesel tractor trailer hauling the feedstock generated at the harvesting site from the landing to the thermochemical conversion facility. Inputs include diesel and outputs include fossil CO_2, volatile organic compounds, and particulate emissions. Raw material logistics may also include multi-stage, multi-mode transportation that includes intermediate facilities to store, concentrate or process biomass. From a LCA perspective, dispersed feedstocks incur higher costs for collection and transportation, which translates to higher emissions from logistics stage.

Thermochemical conversion

Thermochemical conversion life-cycle stage involves the production of biochar from biomass via gasification and pyrolysis or some similar process. These thermochemical conversion technologies are similar to traditional charcoal kilns but under much tighter control to prevent the release of N_2O, CH_4, and particulate emissions associated with the older technology (Woolf *et al*., 2010). These systems produce biochar, synthesis gas, and pyrolysis oil in different percentages. For pyrolysis systems, these systems always produce some biochar (Gaunt and Lehman, 2008). The intent is to convert the incoming dry feedstock under a controlled environment while preventing the introduction of air (i.e. oxygen) into the system. Typically, the product production life-cycle stage consumes the most energy and materials and thus has the highest environmental impact (Bergman and Gu, 2014; Dutta and Raghavan, 2014). Therefore, finding a mass balance and energy consumption at this stage is of utmost significance to accurately quantify LCI flows and the subsequent LCIA outputs. In addition, incoming feedstock with high moisture content (i.e. “green” feedstock) and large, heterogeneous particles may have to be dried, reduced, and screened before thermochemical conversion, which can have large environmental impacts.

Feedstock preparation can be determined separately or be part of the thermochemical conversion life-cycle stage but its impacts must be captured. There are several reasons for these large impacts associated with the incoming green feedstock. First, mechanical size reduction by chipping, hammering and grinding and the subsequent screening required to ensure uniform size are energetically intensive activities. Second, feedstock drying to the appropriate moisture for the selected technology also has high energy demands. The sizing and moisture specification are highly dependent on the thermochemical conversion technology selected to optimize production. This processing ensures the feedstock is properly prepared before thermochemical conversion, but it comes at a price in terms of the energy consumed and its associated environmental impacts. Energy for drying feedstock can come from renewable or non-renewable sources, while the electricity for on-site grinding and chipping and handling comes primarily from grid power, which is dominated by fossil fuels in many locations. If woody biomass is burned as fuel for drying (as in common practice in the forest products industry), the drying process emits biogenic CO_2 emissions directly. However, boiler systems although burning woody biomass as fuel still consume grid power thus emit fossil CO_2 emissions indirectly.

It is noted that in addition to the direct effects of burning fuel for energy on-site and grid electricity captured within a LCA, but the indirect effects of its cradle-to-gate production are also considered. Therefore, geographical location of the biochar production plant has substantial effect on the environmental impacts, especially if the energy source for generating electricity has a high portion of fossil fuels such as coal and natural gas, which is common in the eastern United States. Inputs include biomass, electricity, and fossil fuels and outputs include CO_2 and particulate emissions.

Biochar logistics

Once the biochar has been produced, it can be packaged and transported to the application site by a tractor trailer and applied to the soil in several different ways, including manually, by logging equipment or by modified agricultural equipment. Application sequesters black carbon (biochar) on or within the soil, depending on application method. Inputs include diesel and outputs includes fossil CO_2, volatile organic compounds, and particulate emissions.

Soil carbon sequestration

Soil carbon sequestration is the process of transferring CO_2 from the atmosphere into the soil through agricultural crop (i.e., corn or wheat stover) or forest residues (i.e., logging slash), and other organic solids, including biochar (Lal, 2004). These systems can provide GHG mitigation by storing atmospheric CO_2 in live biomass, organic matter, and in the mineral soil (DeLuca and Aplet, 2008; McKechnie *et al*., 2011). In addition, biomass-derived black carbon (biochar), which is produced as a byproduct of pyrolysis, offers a large and long-term carbon (C) sink when applied to soils (Lehmann *et al*., 2006). Although large-scale application of biochar to soils in agricultural and forest systems is still in its infancy, the potential exists to provide environmental services to that improve nonproductive or degraded soils and sequester C (Ippolito *et al*., 2012). Although some biochars contain bioavailable C, it is generally more stable in soil than the C in the original biomass (Ippolito et al., 2012). While biochars will vary, those produced under moderate to high temperatures have stable C that will likely persist for hundreds of years (Ippolito *et al*., 2012). Stable C can be considered permanently sequestered after 100 years (Wang *et al.*, 2014). However, the impact of biochars on greenhouse gases (GHG) is influenced by plant productivity, mineralization of the char, and emissions of methane (CH_4) and nitrous oxide (N_2O). Several studies have shown that biochar-amended soil CO_2 losses are inversely related pyrolysis temperature (Brewer *et al*., 2012; Kamann *et al*., 2012; Yoo and Kang, 2012).

Feedstocks used to produce biochar influence the physical, chemical, and biological characteristics of biochar and therefore, care must be taken to optimize feedstock selection and pyrolysis production techniques and conditions (Spokas *et al*., 2012). Biochar can have positive, negative, or neutral effects on plant growth. For example, hardwood biochar applied once to a desert soil in the western United States produced no changes in corn growth 1 yr following application, but a 36% yield decline was noted in year 2 (Lentz and Ippolito, 2012). In a forest stand in central Ontario the short-term impact of adding biochar was an increased calcium and phosphorus and long-term impacts are expected to be achieved when the biochar becomes incorporated into the mineral soil (Sackett *et al*., 2014). As illustrated in Chapter 15, in the western US, tree growth after biochar additions can also be positive or neutral, but to date no detectable negative effects have been noted. One way to highlight the environmental “hotspots” is to evaluate a new thermochemical conversion technology for its environmental impacts.

LCA of an advance pyrolysis system

A new thermochemical conversion technology, an advanced high-temperature pyrolysis system called the Tucker Renewable Natural Gas (RNG) thermal conversion unit, is under development by Tucker Engineering Associate (TEA), North Carolina, US. The unit is designed to produce high yields of medium-energy synthesis gas that can be used in heat and power applications, or be converted to liquid fuels by catalysis. The system produces a biochar co-product at 10 to 20% yield by dry input weight. This biochar can be used in is raw form, or activated by steam or chemicals to make activated carbon (AC) for liquid and gas filtering applications. In some uses, renewable bio-based AC would substitute for AC made from fossil coal.

Operation

Feedstock production and logistics

Logs harvested from Montana, US, were processed into wood chips at a western Montana sawmill. The chips are a co-product of the mill's lumber production operations or produced directly by chipping poor-quality whole trees. An 812 kW_e chipper was used for whole-tree chipping, while a 108 kW_e screener operated in conjunction to produce the specified size. These chips were then dried in a saw dust dryer to a moisture content of about 10% to meet the Tucker RNG unit system requirements. The sawdust dryer was fueled by a bark and wood fuel mixture during the drying operation which released biogenic CO_2 emissions. Primary data for the whole-tree chipping, screening and drying processes were collected directly from the mill to help develop the LCI flows.

Advanced pyrolysis

Tucker RNG unit is an advanced pyrolysis system comprised of active and passive sections (i.e. chambers). Figure 3.4 shows the life-cycle stages that fall within the system boundary. Feedstock logistics is embedded within the thermochemical conversion stage. The unit is engineered to maximize synthesis gas (syngas) output in a very low-oxygen reaction chamber at a high temperature between 760°C and 870°C. At these temperatures, the system is endothermic, requiring net inputs of energy, propane to maintain the reaction. Three propane burners provide continuous active heating for the reaction. The residence time for biomass feedstock in the Tucker RNG unit is estimated at 3 minutes for the complete reaction, with equal 1.5 minutes residence time in each section. Wood chip feedstock is sent through an air-locked auger system into the active section for high temperature heating. After passing through the active section, the partially converted biochar and hot syngas are transferred in an enclosed auger to the passive section, which uses the residual heat transferred from the active section through a vent system. After transferring heat from the combustion exhaust gases to the passive section, the exhaust gases from burning propane are released directly to the air. The biochar moves through augers inside the passive section of Tucker unit, whereby additional conversion from higher molecular gases into methane occurs. The temperatures measured at the passive heating section are between 510 and 760 °C. After leaving the passive section, the syngas is cleaned and cooled to remove tar.

[Figure 0.2. goes here]

Syngas leaving the passive section is cooled in a tar condenser to help remove impurities. The tar condenser has a mechanism to remove buildup of tar from the condensing of tars caused by the cooling of the syngas. After cooling, the medium-energy syngas goes through a misting chamber that removes oil and tars before leaving the Tucker RNG unit to an outside storage tank. The two primary products from the system – biochar and medium-energy syngas are collected at separated outlets. The syngas is intended to combusted for electricity onsite. In this system, biochar is intended to be activated with steam to make AC, but can also be used in its raw form as a soil amendment or a coal replacement. Pyrolysis often produces residual tars which can be a useful output or an undesirable waste product, depending on production objectives. In the Tucker RNG system, the tar can be retorted back to the active heating chamber to produce a low-energy syngas for use as a propane substitute at about 30% of heating demand. However, in this study, the tar/water mixture was considered a waste in the analysis.

Two product components

Synthesis gas. The advanced pyrolysis system generates syngas, a medium-energy type. The medium-energy syngas will be burned to generate electricity for the grid. Medium-energy syngas will be referred to as syngas for the remainder of the chapter. The density of syngas is calculated at 1.08 kg/m^3. The higher heating value (HHV) was measured at 19.5 MJ/m^3 and the lower heating value (LHV) at 18.0 MJ/m^3. Electricity is intended to be produced from burning the

Tucker RNG syngas in a commercial 1.6 MW_e Caterpillar generator derated to 1.2 MW_e because the syngas's relatively low energy density compared to natural gas. Currently, the Tucker RNG unit will need to produce about two times amount of syngas to generate the same electricity as natural gas does, since the HHV of the produced syngas is one half of the natural gas HHV, 38.3 MJ/m^3. The main components by mass of the syngas are CO (55.5%), CO_2 (20.1%), and CH_4 (9.2%).

Biochar. The pyrolysis unit also generates a solid product, biochar but at a much smaller portion. Biochar on a dry basis has the following properties: 1) a fixed carbon content of about 89% and 2) an energy content of 32.1 and 31.9 MJ/kg for HHV and LHV, respectively. The energy content for biochar is about 50 percent higher on a dry basis than wood (Ince 1979; FPL 2004).

3.1.1 Four phases of Tucker RNG unit life-cycle assessment

Goal and scope

The goal was to evaluate the critical environmental impacts of the bioenergy (syngas electricity) and bio-product (AC) converted from forest or mill residues using an advanced pyrolysis system (Figure 3.4). The scope of the study is to cover the cradle-to-grave life cycle of generating syngas electricity and AC by the advanced pyrolysis system and make comparison with fossil-fuel alternatives. Biochar is a precursor to making AC. The focus of the analysis only covered biochar production and not AC production. The functional unit was 1.0 ovendry (OD) kg of incoming wood chips. OD units do no indicate that the feedstock was dried to 0% moisture content, but rather is used as a standardized unit that facilitates comparisons between feedstock with different moisture content.

Life-cycle inventory

Mass balance. A mass balance was performed and verified data quality provided during a production run. Thermochemical conversion turned the feedstock into syngas (65.5%), biochar

(13.9%), and tar/water mixture (20.7%) by mass. The tar/water mixture is primarily water. Although the pyrolysis unit currently produces the tar/water mixture that could be converted to a low-energy syngas, this gas was not used as a propane substitute in the present analysis. Therefore, the low-energy syngas via residual tars is considered a waste under this study's LCA framework. Thus, the only products that have environmental inputs and environmental outputs (i.e., LCI flows) assigned to them are the syngas and biochar. These allocations can occur either by mass or energy. Allocations are 82.5% and 17.5% by mass and 70.8% and 29.2% by energy for the medium-energy gas and the biochar, respectively.

Cumulative energy consumption. Evaluating products for their cumulative energy consumption can be conducted through a LCA. Table 3.1 shows the cradle-to-gate cumulative energy of 16.6 MJ consumed from pyrolyzing 1.0 OD kg of incoming wood chips to produce syngas and biochar. In addition, Table 3.1 shows the various fuels that contribute to this 16.6 MJ value. Propane was the major contributor at 44.1%, and wood was second at 22.7%. Propane was burned to maintain the high temperatures during pyrolysis, while wood was burned to generate thermal energy to dry the incoming green feedstock.

Table 0.1. Cradle-to-gate cumulative energy consumption from pyrolyzing 1.0 ovendry kg wood chips

			Higher heating values		Energy	
Fuel	Unit	Quantity	(MJ/m^3)	(MJ/kg)	(MJ)	(%)
Natural gas (proxy for propane)	m^3	0.1898	38.4		7.288	44.1%
Wood residue (ovendried)	kg	0.180		20.9	3.759	22.7%
Natural gas	m^3	0.054	38.4		2.068	12.5%
Crude oil	kg	0.04		45.5	1.811	11.0%
Coal	kg	0.055		26.4	1.461	8.83%
Nuclear	kg	3.66E-07		332000	0.121	0.73%
Biomass	MJ	0.021			0.021	0.13%
Hydro	MJ	0.014			0.014	0.08%
Wind	MJ	0.0008			0.0008	0.005%
Total					16.6	100%

Emissions to air and water. Table 3.2 shows some of the cradle-to-gate environmental outputs (e.g., emissions to the air and water) from wood pyrolysis. Fossil CO_2 emissions of 542 kg CO_2/OD kg of incoming wood chip came mostly from propane burning to maintain the endothermic reaction. Biogenic CO_2 emissions of 330 kg CO_2/OD kg came from burning wood residues as the heating source for the boiler used to dry the wood chips (i.e., green incoming feedstock). The total emission of each item is allocated to the two primary products based on the mass ratio of the two. Note that the total environmental outputs for the system listed in the last column in Table 3.2 will not change regardless of the allocation procedure used.

Table 0.2. Cradle-to-gate environmental outputs from pyrolyzing 1.0 ovendry kg wood chips, mass allocation

		Quantity		
Substance	Unit	Syngas	Biochar	Total
Air emission				
Carbon dioxide, fossil	g	447	94.9	542
Carbon dioxide, biogenic	g	272	57.8	330
Sulfur dioxide	g	3.82	0.81	4.64
Methane	g	1.77	0.38	2.15
Nitrogen oxides	g	1.18	0.25	1.43
Carbon monoxide	g	0.83	0.18	1.01
Particulates, > 2.5 um, and < 10um	g	0.73	0.16	0.89
Carbon monoxide, fossil	g	0.61	0.13	0.74
Methane, fossil	g	0.34	0.07	0.41
VOC, volatile organic compounds	g	0.13	0.03	0.15
Water effluent				
Suspended solids, unspecified	g	26.93	5.72	32.65
Chloride	g	21.50	4.57	26.07
Sodium	g	6.069	1.29	7.35
BOD5, Biological Oxygen Demand	g	2.81	0.60	3.41
Calcium	g	1.91	0.41	2.32
Lithium	g	0.614	0.13	0.74
COD, Chemical Oxygen Demand	g	0.17	0.04	0.21
Industrial waste				
Bark	g	1.19	0.253	1.44
Tar	g	35.1	7.5	42.6

Life-cycle impact assessment for syngas electricity

Syngas produced from the Tucker RNG unit is intended to fuel an internal combustion generator to provide electricity to the power grid. Based on generating 0.732 kg (0.676 m^3) of syngas from 1.0 OD kg of incoming wood chips, 1.26 kWh of electricity was generated. For comparison, a wood power plant burning logging slash generates 1.14 kWh/OD kg (Bergman *et al.*, 2013). Table 3.3 shows the values for the 10 impact categories to produce 1 kWh of syngas electricity. A GW impact of 0.525 kg CO_2-e/kWh of syngas electricity was estimated without biochar carbon sequestration being considered.

Table 0.3. Cradle-to-gate life-cycle impacts assessment of generating 1 kWh of syngas electricity

Impact category	Unit	Quantity
Global warming	kg CO2 eq	0.525
Ozone depletion	kg CFC-11 eq	5.09E-08
Smog	kg O3 eq	0.081
Acidification	kg SO2 eq	0.006
Eutrophication	kg N eq	3.64E-04
Carcinogenics	CTUh	7.05E-08
Non carcinogenics	CTUh	3.88E-08
Respiratory effects	kg PM2.5 eq	4.30E-04
Ecotoxicity	CTUe	0.699
Fossil fuel depletion	MJ surplus	1.158

In Table 3.3, note all environmental impacts were applied to the syngas electricity and none to the biochar. This was because the biochar will be applied to the soil for carbon sequestration. This means all the impacts tied to feedstock production and logistics and thermochemical conversion life-cycle stages were assigned to the syngas electricity. Furthermore, the system boundary stopped at the gate of the conversion facility so the analysis did not include the impacts of transporting or applying the biochar in the field or in the forest. Of course, because of the additional fuel needed to transport and apply the biochar, adding these impacts would increase the quantity of GHG emissions released.

To calculate the permanent carbon sequestration benefit, the stable C portion of biochar was estimated at 80% at the end of 100 yr. In Figure 3.5, GW impacts for the various electricity sources were calculated using LCA modeling software. GW impact from the cradle-to-gate production of syngas electricity showed a notably lower value (0.163 kg eq CO_2/kWh) compared to electricity generated from bituminous coal (1.08 kg eq CO_2/kWh) and conventional natural gas (0.720 kg eq CO_2/kWh), when including carbon sequestration from biochar.

[Figure 0.3. goes here]

Interpretation

The LCA on the Tucker RNG unit provides insight into its environmental performance as well as that of other pyrolysis systems. Most notable, the interplay between primary products and co-products is important. This system, which was engineered to produce high-quality syngas from a broad range of waste feedstocks, has relatively high environmental burdens for electricity compared to wood combustion as noted in Figure 3.5 even though the GWI from syngas electricity was substantially lower than the other forms of electricity. Furthermore, if producing high-quality biochar for field application is the main objective, there are many types of thermochemical conversion technologies that use less energy to create this form of biochar, many of which are exothermic and do not require energy inputs to maintain pyrolysis. However, in this case additional processing was performed for the Tucker RNG unit because the biochar produced by this system is meant to be used a precursor for producing AC, thus more energy was required to meet the specific processing requirements of the AC. Perhaps, most important, using biochar products as a soil amendment can significantly improve the GW profile of bioenergy technologies (Figure 3.5). Sequestering the biochar co-product in the soil as a GHG sink definitely lowers systems impacts on climate change compared to other options, such as using it as a fuel (Gaunt and Lehmann, 2008; Roberts *et al*., 2010).

To fully analyze the environmental impacts of the biochar to be used as a soil amendment, a more detailed analysis across multiple potential use scenarios needs to be performed. Figure 3.6 from Hammond *et al.* (2011) provides an excellent framework for exploring a more detailed

LCA. For example, the Tucker RNG unit LCIA results included only the direct carbon sequestration effect of applying biochar to the soil, whereas there are several indirect effects as noted earlier that should be considered, such as changes in net primary productivity and soil organic carbon, soil N_2O emission suppression, and fertilizer utilization. Indirect effects attributable to efficiency gains and various product substitutions, especially fossil fuel, can then be incorporated into the LCA as described in more detail below.

[Figure 0.4. goes here]

As with SCM considerations, LCA considerations for biochar used primarily to meet climate change mitigation objectives can be more complicated than the other end uses discussed in Chapter 2. Gaunt and Cowie (2009) identified six specific characteristics of biochar application that can result in net reductions of GHG emissions attributable to biochar systems: 1) sequestration of moderately stable carbon in the soil; 2) avoided emissions of carbon dioxide and methane related to alternative disposal methods such as biomass combustion and decomposition; 3) suppression of methane and nitrous oxide emissions related to changes in soil processes especially for intensively fertilized, irrigated cropland; 4) displacement of carbon-intensive agricultural inputs through direct substitution and increased plant efficiency; 5) carbon sequestration resulting from higher productivity leading to greater soil carbon accumulation; and 6) displacement of fossil fuels from biochar co-products. Only the first one, carbon sequestration in the soil, is a direct effect. The other benefits, though supported by research, are indirect and rely on assumptions about the changes in soil processes and characteristics, fate of waste biomass, and market substitutions for fertilizer, fossil fuels, and other carbon-intensive inputs.

Lastly, in conjunction with end uses and what was stated above, most biochar research has focused on short-term impacts of biochar applications on soil chemical, physical, and biological properties. However, future work on biochar additions to forest sites should focus on long-term field research that determines changes to nutrient availability, microbial community changes, net

GHG emissions, and net C sequestration. Furthermore, to produce a sustainable supply of biochar derived from wood, sustainable production of the feedstock (i.e., raw material) itself must be considered. In the next chapter, Chapter 4, the authors will discuss providing a sustainable feedstock using plantation forests.

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