Economics, Environmental Impacts, and Supply Chain Analysis of Cellulosic Biomass for Biofuels in the Southern US: Pine, Eucalyptus, Unmanaged Hardwoods, Forest Residues, Switchgrass, and Sweet Sorghum

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The production of six regionally important cellulosic biomass feedstocks, including pine, eucalyptus, unmanaged hardwoods, forest residues, switchgrass, and sweet sorghum, was analyzed using consistent life cycle methodologies and system boundaries to identify feedstocks with the lowest cost and environmental impacts. Supply chain analysis was performed for each feedstock, calculating costs and supply requirements for the production of 453,592 dry tonnes of biomass per year. Cradle-to-gate environmental impacts from these modeled supply systems were quantified for nine mid-point indicators using SimaPro 7.2 LCA software. Conversion of grassland to managed forest for bioenergy resulted in large reductions in GHG emissions due to carbon uptake associated with direct land use change. By contrast, converting forests to cropland resulted in large increases in GHG emissions. Production of forest-based feedstocks for biofuels resulted in lower delivered cost, lower greenhouse gas (GHG) emissions, and lower overall environmental impacts than the agricultural feedstocks studied. Forest residues had the lowest environmental impact and delivered cost per dry tonne. Using forest-based biomass feedstocks instead of agricultural feedstocks would result in lower cradle-to-gate environmental impacts and delivered biomass costs for biofuel production in the southern U.S.

Keywords: Biomass; Economics; Environmental Impacts; Supply chain; Delivered cost; Life cycle assessment

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INTRODUCTION

The U.S. government's goals for the production and use of bioenergy have catalyzed unprecedented incentives for research and development (R&D) of second-generation biofuels and other bio-based products (EPA 2012). Cellulosic biofuels are expected to reduce the nation's dependence on foreign energy sources, improve rural economies, and reduce greenhouse gas (GHG) emissions, compared to conventional transportation fuels (Demirbas 2008, 2009).

To ensure GHG reductions and a sustainable bioenergy industry, the Energy Independence and Security Act (EISA) established life cycle GHG reduction thresholds (against gasoline) compared to a 2005 baseline. The EISA dictates 20% reductions for renewable fuels, 50% for advanced fuels, 50% for biomass-based fuels, and 60% for cellulosic biofuels (EPA 2012). The feedstock type plays a central role in determining

GHG emissions and the financial and technological feasibility of biofuel production. Previous studies have revealed feedstock production and delivery as the single largest contributor to the financial feasibility of bioenergy technologies, accounting for 35 to 45% of the total production cost (Tao and Aden 2009; Gonzalez *et al.* 2011a, b, d; Pirraglia *et al.* 2012). Private firms have conducted R&D in search of technological processes capable of converting lignocellulosic biomass to liquid biofuels and bioproducts at lower operational costs and capital expenditures (CAPEX) (Frederick *et al.* 2008b; Gonzalez *et al.* 2011a,d). Significant research and funding have focused on understanding the relationship between biomass productivity, supply system costs, conversion technology CAPEX, operation, and yield of bioenergy and biofuel products. Confirmed by unsuccessful commercial facilities, high feedstock and conversion costs have been identified as a major barrier to the commercial success of advanced (second generation) biofuels. Consequently, the success and sustainability of the bioenergy industry critically depends on the optimization of the biomass supply system and effective use of capital investments.

In this study, supply chain logistics, delivered cost (the price a biomass processing facility would pay for delivered biomass), and environmental burdens of these feedstocks were qualified and quantified from cradle-to-gate for eucalyptus, loblolly pine, unmanaged hardwood, forest residues, switchgrass, and sweet sorghum. Delivered cost per million BTU (LHV), cost per tonne of carbohydrate, and cost per bone-dry tonne (equivalent) are the main cost metrics reported herein, reflecting important information for specific conversion pathways (Gonzalez *et al.* 2011a, c).

The pulp and paper industry has proven the feasibility of forest-based biomass supply systems by optimizing infrastructure and methodologies to provide consistent and cost-effective biomass supplies to facilities. The infrastructure and supply system are less developed for agricultural energy crops. The agricultural biomass supply chain is more complex due to reduced harvesting windows, generally lower biomass density compared to forestry feedstock (often limiting transportation capacity by volume instead of weight), year-round storage requirements to provide a consistent supply due to narrower harvest windows, and associated costs related to biomass degradation and working capital during storage (Jackson *et al.* 2010; Gonzalez *et al.* 2011a, c). To better understand and improve the biomass supply systems, integrated analysis of the supply chain, delivered cost, and environmental impacts must be conducted.

Previous studies have compared biomass supply systems for bioenergy production based on financial, logistical, and environmental assessments for feedstocks including switchgrass, willow, corn stover, corn grain, sugarcane and sugarcane bagasse, soybeans, and microalgae (Keoleian and Volk 2005; Kim and Dale 2005; McLaughlin and Kszos 2005; Botha and von Blottnitz 2006; Sanderson *et al.* 2006; Volk *et al.* 2006; Kumar and Sokhansanj 2007; Lardon *et al.* 2009; Mani *et al.* 2010; Morey *et al.* 2010; Roberts *et al.* 2010; Singh *et al.* 2010; Sokhansanj *et al.* 2010; Campbell *et al.* 2011; Mobini *et al.* 2011; Yang *et al.* 2011). These studies present delivered cost estimates for biomass ranging from \$81 to \$90 per metric tonne of biomass. A comparison between data from the literature and the results from supply systems modeled in this study reveals a similarity between the cost data, though previous studies show less detailed financial analysis and do not integrate environmental burden data. The Billion Ton Study presented delivered costs ranging from \$33 to \$111 per dry tonne of feedstock (Perlack

2011). However, these costs did not include all costs up to the conversion facility gates, as are included in this work.

Previous studies have also compared non-food lignocellulosic and agricultural biomasses to conventional energy sources, such as coal and natural gas (Wu *et al.* 2006; Mu *et al.* 2010; Zhang *et al.* 2010; Guest *et al.* 2011). However, life cycle scope and assumptions were not consistent between studies and did not integrate financial, supply chain, and environmental analyses. Consequently, feedstock comparisons were not possible through a literature review prior to this study. While it is beneficial to determine which feedstock has the lowest delivered cost, most feasible supply chain system, and lowest environmental burden, a detailed discussion of which processes contribute most to the cost or environmental burden is also presented.

The goal of this work is to present data and recommendations to guide policy-makers, bioenergy producers, and feedstock producers in policy and investment decisions. Using consistent study assumptions, biomass types with the lowest delivered costs and environmental burdens are identified and recommended for use in the appropriate conversion technologies. Environmental "hot spots or process stages with significant environmental impacts are discussed.

MATERIAL AND METHODS

Supply Chain Systems

This study analyzed six biomass supply systems: plantation loblolly pine (*Pinus taeda)*, bioenergy-grown eucalyptus (*Eucalyptus* sp.*)*, mixed unmanaged hardwoods, forest residues, and the bioenergy crops switchgrass and sweet sorghum. Financial indicators, energy usage, and environmental impact for each type of biomass were calculated up to the point of delivery to a processing facility.

Feedstocks

This study examines several feedstocks with industrial processing potential in the southern United States, as identified through extensive literature review and communications with bioenergy and biomass experts. Each biomass supply system was extensively modeled in a production scenario including the activities associated with the production, harvest, storage, and transportation of each feedstock. Characteristics considered integral to the selection of regional bioenergy feedstocks for this analysis (Gonzalez *et al.* 2011a) include:

1. High biomass productivity, measured in dry metric tonnes per hectare per year
2. High carbohydrate content sufficient for biochemical conversion of sugars to ethanol
3. Current and consistent regional availability of published plant characteristics data (productivity, carbohydrate content, bulk density, moisture content at harvest) and cost of establishment, maintenance, and harvest
4. Reasonable performance data for existing and proposed cellulosic ethanol conversion technologies

A review of literature and industry data identified biomass feedstock species meeting these criteria grown in the Southern U.S. In addition to these identified feedstocks, forest residues and unmanaged hardwoods were also investigated. A brief description of each is presented here; more detail can be retrieved from Gonzalez *et al.*'s work (2009, 2011a).

Loblolly pine

Loblolly pine (*Pinus taeda*) is the most prominent commercial forest species in the southern U.S., covering almost 29 million acres (11.7 million ha) and accounting for over 50% of the standing pine volume in 2007 (Baker and Langdon 2008). In 2002, this species provided nearly 73% of the total roundwood softwood volume produced in the southern U.S. (Johnson *et al.* 2003). Loblolly pine grows naturally from central Florida, north to Delaware and New Jersey, and west to east Texas and southeast Oklahoma (Schultz 1999). In Georgia intensively managed short-rotation (10 to 12 years) plantations with stand densities between 608 and 652 trees per acre have been reported, producing approximately 26.6 m^3 ha^{-1} $year^{-1}$ (12.8 dry tonnes ha^{-1} $year^{-1}$) of pulpwood (Borders and Bailey 2001). In another study, the FASTLOB model was used by Gonzalez *et al*. (2011a) resulting in a yield of 17.1 tonnes ha^{-1} $year^{-1}$ (Amateis *et al*. 2001). It has been suggested that commercial ethanol production from loblolly pine may be more economically viable than ethanol from corn stover and other lignocellulosic materials (Frederick *et al.* 2008b). Improvement in enzymatic hydrolysis and conversion of polysaccharides into monomeric fermentable sugars in the presence of high lignin contents found in pine (for biochemical conversion) still requires more research to ensure technical and economic success commercially (Frederick *et al.* 2008b).

Eucalyptus

Eucalyptus (*Eucalyptus* sp.) is among the fastest growing hardwoods in the world and has been used for bioenergy and fiber production in numerous countries, such as Australia, USA (Hawaii), South Africa, Brazil, Uruguay, Portugal, and Venezuela (Lopes *et al.* 2003; Gonzalez *et al.* 2008, 2009; Hinchee *et al.* 2009; Keffer *et al.* 2009). The native habitat of eucalyptus is primarily Australia, with a few species native to Indonesia and Papua New Guinea. Eucalyptus plantations in the southern U.S. can be successfully established using freeze-tolerant seedlings. They are typically grown in regions such as Florida, Georgia, Alabama, Texas, and South Carolina, where appropriate climate conditions exist.

Rotation length and yield for pulpwood can be 5 to 8 years with a mean annual increment (MAI) of 8 to 16 green tonnes $acre^{-1}$ $year^{-1}$ (10 to 20 dry tonne ha^{-1} $year^{-1}$). MAI is the annual productivity per acre per year calculated by dividing the above-ground biomass per hectare at time of harvest by the age of the biomass. The rotation length between eucalyptus harvesting can be 3 to 4 years with a MAI of 10 to 18 green tonnes per acre per year (12.3 to 22.4 dry tonne ha^{-1} $year^{-1}$) (Gonzalez *et al.* 2009, 2011a). In addition to ethanol production, eucalyptus has been investigated for pellet production for bioenergy purposes (Ferrari *et al.* 1992; Gonzalez *et al.* 2011a, b).

Unmanaged hardwood

Unmanaged hardwood forests are known for low productivity and high biomass cost. They were studied in this work to provide a full spectrum of biomass options. Unmanaged hardwood forests were modeled to have a rotation length of 50 years and stand productivities of approximately 2.2 dry tonne ha^{-1} $year^{-1}$ (Gonzalez *et al*. 2011a). As a result of the low productivity, larger collection areas are needed to provide an adequate biomass supply compared to other, more productive feedstocks. With a larger collection area, larger biomass transportation distances are required, which result in increased delivered costs. The increased transportation costs and environmental burdens are, in part, offset by the lack of the establishment and maintenance costs. Despite the low productivity and large collection area, use of such feedstocks for first rotation length may be necessary prior to the establishment of intensively managed plantations or energy crops. Additionally, unmanaged hardwoods are more easily converted to ethanol than softwoods using the biochemical conversion process. Cellulosic bioethanol produced using unmanaged hardwoods is not considered a renewable fuel, according to the latest renewable fuel standards (EISA 2007).

Forest residues

Forest residues, consisting of tops, small branches, and leaves of harvested trees, are often left on the ground after harvesting. This non-commercial feedstock can only be removed at the time of harvest or after harvesting and represents around 20% of the above-ground biomass of softwood, specifically loblolly pine (Daystar *et al*. 2012). Thus the supply forest residue (no burdens) system feedstock scenario does not include any activities prior to collection of the residues. Depending on the forest characteristics and machinery technology, 50-65% of the total residues can be expected to be collected (Perlack *et al.* 2005). The percent of residues collected and biomass chemical composition will depend both on the tree species and the age of the forest stand. It is important to emphasize that the availability of forest residues is dependent on biomass harvesting, which may be limited by stumpage costs, wood product prices at market, and other factors influencing a landowner’s decision to sell. A typical yield of 1.0 metric dry tonnes hectare^{-1} year^{-1} was assumed for forest residues based on the loblolly pine yield, the ratio of above-ground biomass left as forest residues, and the expected percentage of residues collected (Gonzalez *et al*. 2011a, USDA 2012).

Switchgrass

Switchgrass (*Panicum virgatum* L.), a perennial grass native to North America, has been identified as a potential biomass feedstock for bioenergy and has been extensively studied to understand optimal growing conditions and production (Cundiff and Marsh 1996; Epplin 1996; Wiselogel *et al.* 1996; McLaughlin and Kszos 2005; Kumar and Sokhansanj 2007; Austin 2010). For this study, no annual tilling activities were administered for the modeled supply systems (Parrish and Fike 2005; Rinehart 2006; Sanderson *et al.* 2006); however, tilling was included in the initial establishment of the energy cropland. The best commercial varieties have been managed successfully with a 10 year rotation, resulting in growth yields ranging from 5.6 to 22.4 dry tonne ha^{-1} year^{-1} (McLaughlin and Kszos 2005; Perrin *et al.* 2008; Austin 2010, Gonzalez *et al*. 2011a);). For annual harvests in the southern U.S., typical dry matter production varies from around 13.5 to 22.4 dry tonne ha^{-1} year^{-1} (Sanderson *et al.* 2006; Bennett and Anex 2008; Bennett and Anex 2009).

Sweet sorghum

Sweet sorghum (*Sorghum* sp.*)*, an annual biomass crop, has a sugar monomeric content similar to that of sugarcane. This high sucrose (sugar) content can be combined with cellulosic carbohydrate material in the bagasse for biofuel conversion. The sucrose within the pressed sweet sorghum juice can be fermented to ethanol with minimal pretreatment (Gnansounou *et al.* 2005; Reddy *et al.* 2005; Prasad *et al.* 2007; Almodares and Hadi 2009). Yet, due to a short harvest window and significant biomass degradation during post-harvest storage (~14% dry matter loss), the use of sweet sorghum for bioenergy applications has been limited (Bennett and Anex 2008, 2009). Sweet sorghum is assumed to yield 15.7 metric dry tonnes of biomass hectare^{-1} year^{-1} (Irvin *et al*. 2001; Bennett *et al*. 2008; 2009; Gonzalez *et al*. 2011a). Past studies have confirmed this value with a reported range in yield between 10 and 20 metric dry tonnes hectare^{-1} year^{-1}, depending on region and intensity of maintenance (Bennett and Anex 2009; Wortmann *et al.* 2010). For this study, annual tilling activities were modeled as part of normal cropland maintenance (Rajagopal and Zilberman 2007; Srinivasa *et al.* 2009; Smith 2011; Salvino and Messing 2012), as opposed to switchgrass, for which no soil disturbance was assumed other than in establishment.

Feedstock chemical composition

Chemical compositions and energy contents for all analyzed feedstocks are listed in Table 1. The chemical compositions were used to calculate the percentage of carbohydrate in the biomass, delivered costs, and the environmental burden of delivering one tonne of carbohydrates of each feedstock. Additionally, the heating value (in million BTU) per dry tonne was used to calculate cost and environmental burden per million BTU.

Table 1. Chemical Compositions and Energy Values [Lower Heating Value (LHV)] for the Biomass Feedstocks on a Dry Basis. (Note: compositions not summing to 100% were normalized to sum to 100%)

Chemical Composition	Loblolly Pine [a]	Eucalyptus [b]	Unmanaged Hardwoods [C]	Forest Residues [d]	Switchgrass [e]	Sweet Sorghum [f]
Glucose (%)						48
Glucan (%)	44	45	43	39	33	20
Arabinan (%)	2	0.3	0.5	2	3	0
Xylan (%)	7	13	15	12	22	12
Mannan (%)	11	0.5	2	10	0	0
Galactan (%)	2	0.5	1	3	1	0
Uronic acid (%)	4	7	5	0	1	0
Extractives (%)	3	4	3	5	13	8
Ash (%)	1	0.3	0.3	1	5	1
Lignin (%)	27	30	28	29	18	10
Total Carbs (%)	70	66	67	66	60	80
Carbon (%)	51.6	51	49.7	50.2	47	44.9
LHV (BTU/kg)	3,770	3,748	3,736	3,957	3,541	3,692
LHV (MJ/kg)	19.3	19.2	19.2	20.3	18.2	18.9

Sources: a = Frederick *et al.* 2008a, b, DOE 2010; b = Gomides *et al.* 2006, Gonzalez *et al.* 2011a, DOE 2010; c = Tunc and van Heiningen 2008, DOE 2010; d = Kadam *et al.* 2000, DOE 2010; e = DOE 2010; f = Prasad *et al.* 2007, Carrillo *et al*. 2013

Supply Chain and Delivered Cost

A supply chain can be defined as a set of organizations or individuals directly involved in the flow of products, services, finances, and information from a source to a customer (Mentzer *et al.* 2001). The effective integration of supply chain systems and bioenergy production facilities is critical to the economic success of a cellulosic biomass processing facility or biorefinery (Gold and Seuring 2011; Gonzalez *et al.* 2011c,d). With supply chain system analysis it is possible to identify stakeholders and weigh their relative importance to project success. Additionally, technical and economic limitations can be identified and addressed to avoid disruptions across the supply chain. For each biomass supply system, establishment and maintenance of the cropland or plantation forestry operations, harvest, storage (when required), and transportation were considered. However, for unmanaged hardwood and forest residues, no forest establishment was required. Figure 1 depicts the three supply systems modeled in this study.

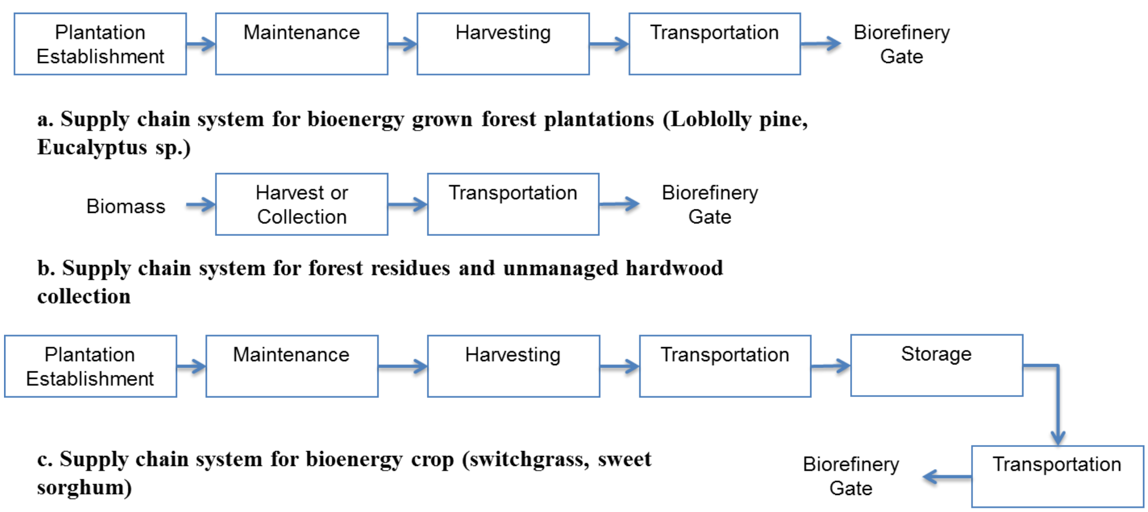


Fig. 1. Biomass supply systems for forest and agricultural feedstocks. Process stages not inside a box were not included in this study.

Annual supply

A constant biomass supply of 500,000 bone dry short tons (equivalent [BDT]) year $^{-1}$ (453,592 metric tonnes year^{-1}) was assumed for all biomass delivery systems. The functional unit was set to one bone-dry tonne delivered to the biorefinery for each feedstock scenario. This supply level has been shown to be financially feasible in a mid-sized conversion facility (Gonzalez 2011). Collection area, land use, transportation distance, land use change, and other aspects of each scenario were calculated based on a supply rate of 500,000 BDT annually delivered to a biorefinery.

Delivered cost

Integrated supply chain and financial models facilitated the calculation of the delivered cost, biomass transportation distance, hectares of land used for continuous supply, and other variables for each of the supply chain systems. Figure 2 presents the major model input and output variables. Major assumptions and values used to estimate feedstock delivered costs are presented in the Biomass Productivity and Management section.

Loblolly pine and eucalyptus delivered cost

The minimum revenue selling price per green metric tonne (and price per BDT) for stumpage was calculated by integrated biomass supply chain and economic models. Stumpage costs were paired with harvesting and freight costs models to determine delivered biomass costs.

Supply chain operation costs were obtained from personal communication with current logging companies and forest managers in the southern U.S. (D. Dougherty 2009; D. Duncan 2009; M. Mark 2009), as well as from published references (Bradfield and Levi 1984; De La Torre and Abt 2010). Establishment and maintenance costs were simulated based on yearly free cash flow with a project life of 30 years. These costs were the result of the following activities for the first year of the plantation: land preparation, chemical weed control, seedling cost, plantation establishment, fertilization, and mechanical weed control. Plantation maintenance for the second year included both mechanical and chemical weed control. The financial analysis was performed based on short tons and acres as well as dry metric tons (dry tonne equivalents) and hectares.

Forest residues and unmanaged hardwood delivered cost

The delivered cost of the forest residues was based on the cost per green tonne [cost of biomass at the biomass loading point for transportation to the bioprocessing facility, or free on board (FOB)] and transportation cost using average values from the third quarter 2010 and second quarter 2011 data from Timber Mart South (TMS 2011). The estimated average delivered cost was similar to the price paid for hog fuels in several locations in the southern U.S. as of the third quarter 2011 as reported by industry contacts.

Switchgrass and sweet sorghum delivered cost

The delivered cost for switchgrass and sweet sorghum included payment to the farmer for growing and harvesting the biomass, transportation costs, storage costs, and biomass degradation cost during storage. The financial evaluation for switchgrass was carried out for 10 years (which coincided with the rotation length for this crop) and the cash flow evaluation for sweet sorghum was one year (the first year incurred all costs and revenues, resulting in positive cash flows).

Harvesting costs

A harvesting cost of \$24.80 metric tonne^{-1} (dry equivalent) was used for loblolly pine and eucalyptus. This harvest cost is an average cost supplied by active logging companies in the southern U.S., obtained from Timber Mart South (TMS) as of 2011 and scaled to 2012, using a 2% per year inter-annual multiplier (TMS 2011). Switchgrass and sweet sorghum harvesting costs were taken from the literature (Vadas *et al.* 2008; Bennett and Anex 2009; Mooney *et al.* 2009; Larson *et al.* 2010; Kim and Day 2011). Unmanaged hardwood harvest costs were based on adjustments to the TMS value for loblolly pine. Harvesting times per hectare were assumed to be the same for loblolly pine and unmanaged hardwoods, resulting in similar equipment and labor costs for harvesting (Nesbit *et al.* 2011; Gonzalez *et al.* 2012). Forest residues have no harvest cost, however, a collection cost was calculated (Junginger *et al.* 2001; Koch 2008; Dirkswager *et al.* 2011; Khachatryan *et al.* 2008).

Freight costs

Transportation costs were based on freight distance (estimated from percentage of covered area with the specified feedstock, biomass productivity per hectare, and rotation length), as well as vehicle operation costs (Gonzalez *et al.* 2011a). Covered area, an important parameter for transportation distance, represents the percentage of planted land surrounding the biorefinery that is available for biorefinery use at a point in time. Transportation costs were obtained from Timber Mart South (TMS 2011). Tortuosity values (a value that accounts for the winding nature of roadways) were incorporated into the maximum collection radius (a radius of a simple circular collection area based on land use and covered area values) and together accounted for the natural transportation routes. Ravula (2007) determined that the average tortuosity factor had a standard deviation of 0.17, with a minimum value of 1.00 and a maximum value of 1.98 for the southern U.S. The average of these calculations provided the 1.31 tortuosity multiplier with a standard deviation of 0.17, which was used in this study (Ravula 2007).

For all feedstocks except switchgrass, a minimum haul rate (minimum fee for transportation of biomass to the facility even if the transportation distance was lower than this threshold) of $0.13 per green short ton-loaded mile was used, with an incremental haul rate (the fee per ton-mile for all distances exceeding the minimum haul rate) of $0.12 per green short ton-loaded mile. For switchgrass, a minimum haul rate (fee per short green ton-loaded mile) of $0.26 was used, with an incremental haul rate of $0.24 per short green ton-loaded mile as indicated by personal communication with S. Jackson (personal communication, Jackson 2011). Switchgrass had higher transportation costs due to volumetric loading constraints, as opposed to mass limited per truck as modeled for the other scenarios. For all supply systems, an average minimum haul distance of 61 kilometers (equivalent to approximately 38 miles) was used (TMS 2011).

Storage costs

Storage costs were estimated for sweet sorghum and switchgrass, as these feedstocks are grown seasonally and therefore require storage to ensure a year-round supply to the year-round operations of a conversion facility. A tarped hoop storage structure was modeled, based on specifications and costs obtained from Duffy's work (2008). It was assumed that only 70% of the original biomass required year-round storage (30% was consumed during harvesting time and used as backyard biomass inventory). The CAPEX of the tarped hoop was assumed to be \$12 square foot^{-1} (Duffy 2008) and depreciation was estimated on a 10 year straight line schedule with a financial evaluation horizon of 15 years. Land rent cost was estimated at \$50 per acre and assumed to increase 2% year^{-1}. The minimum storage cost was back-calculated to achieve an 8% internal rate of return (IRR) on the overall storage operations. The storage fee estimated per tonne (estimated for 70% of the total biomass delivered) was then distributed to 100% of the annual supply input.

Biomass degradation costs

The cost of biomass degradation during storage was calculated through adjusted yield as additional green biomass purchased to maintain the 459,532 metric tonne (500,000 BD ton) annual feedstock supply. Degradation was assumed to occur for agricultural feedstocks due to long storage times; however, it was not modeled for woody biomass as the storage times were much shorter, preventing large degradation losses. The percentage of biomass loss due to degradation was 7% for switchgrass and 14% for sweet sorghum.

Biomass Productivity and Management

Biomass productivity (dry tonne equivalent per hectare), rotation length, plantation/crop management data for each of the biomass systems are listed in Table 2.

Table 2. Feedstock Productivity, Management, and Moisture Content, Assuming Medium Productivity and 10% Covered Area

Description	Loblolly pine [a]	Eucalyptus [b]	Unmanaged hardwoods [c]	Forest residues [d]	Switchgrass [e]	Sweet sorghum [f]
Productivity (dry tonne ha^{-1} $year^{-1}$)	17.1	17.6	2.2	1.0	17.9	15.7
Rotation length	12	4	50	n/a	n/a	n/a
Harvesting window	Year-round	Year-round	Year-round	Year-round	Three months	Three months
Moisture content	45%	45%	45%	45%	16%	74%
Delivery form	Logs	Logs	Logs	Chips	Square bales	Cane
Trees per ha	2,965	1,400	n/a	n/a	n/a	n/a
Establishment cost ($/ha)	638	552	n/a	n/a	182	416
Maintenance cost ($/ha)	62.4 [1]	62.4 [1]	n/a	n/a	85.3 [2]	n/a

1 = Second year of plantation; 2 = Maintenance cost per year, year 2 through 10

Sources: a = Amateis *et al*. 2001, Gonzalez *et al*. 2011a; b = Gonzalez *et al*. 2011a; c = SunGrant-Bio Web 2008, USDA 2012, Gonzalez *et al*. 2011a; d = Gonzalez *et al*. 2011a; e = McLaughlin and Kszos 2005, Sanderson *et al*. 2006, Perrin *et al*. 2008, Austin 2010a, b, Gonzalez *et al*. 2011a; f = Irvin *et al*. 2001, Bennett and Anex 2008, 2009, Gonzalez *et al*. 2011a

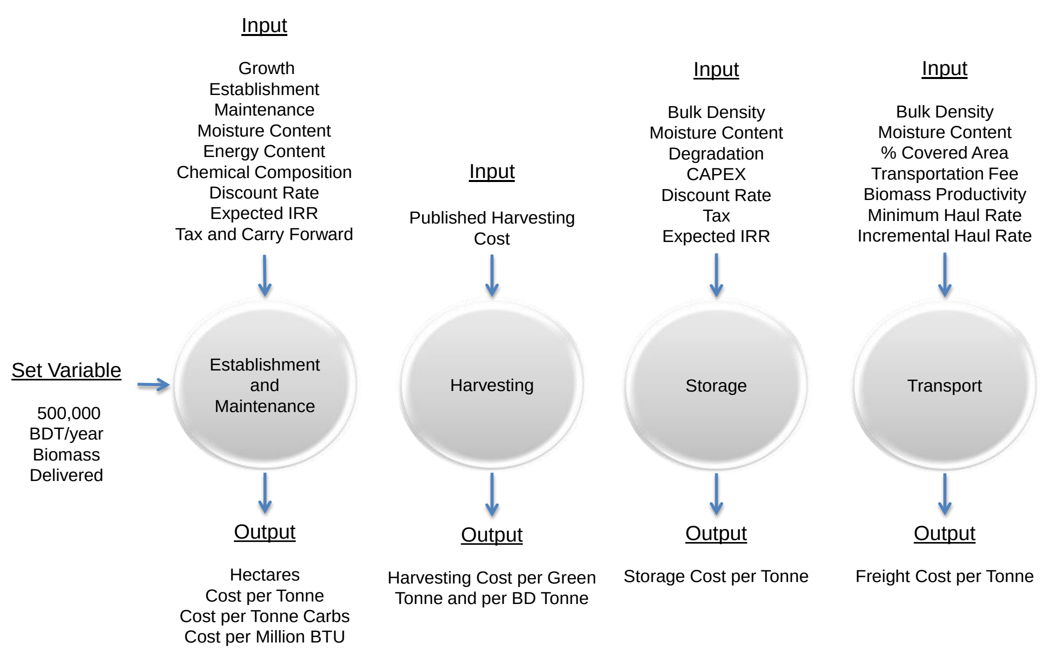


Fig. 2. Inputs and outputs of the biomass supply chain model

Financial Analysis Methodology

The structure of the income statement, central to the financial analysis, includes income after taxes or EBIT (earnings before interest and taxes) less taxes. The following financial terms and indicators were used in this study to determine the financial feasibility of the various scenarios (Fazzari and Petersen 1993; Edmonds *et al.* 2007):

1. Landowners received revenue for selling biomass (stumpage costs).
2. An 8% internal rate of return (IRR) for landowners was used to calculate the delivered biomass price.
3. Direct costs for feedstock production, including payroll, depletion, and rent for cropland or farmland not owned directly by the biomass supplier were sourced from industry-supplied best estimates.
4. The indirect costs that were modeled included research and development and other fixed costs.
5. The difference between the revenue and total cost was represented as EBIT.
6. Both state and federal taxes (15% for forest biomass and 35% for agricultural biomass) were modeled including depletion and 'tax carry forward' incentives (holding over losses from CAPEX and research and development as a tax write-off in later years).
7. EBITDA (earnings before interest, taxes, depreciation, depletion, and amortization) was used to measure the earnings, including non-cash costs (Edmonds *et al.* 2007).
8. New fixed capital and deferred charges included investments in new plantations. However, they were not counted as a cost for that current taxable period.
9. Cash flow reported the EBIT plus non-cash costs, including depreciation, amortization, and depletion.
10. The net cash flow available per year for new investments was represented as the free cash flow, which was calculated by the difference between cash flow and deferred charges, to pay debts or to pay dividends. Free cash flow was used to measure the internal rate of return (IRR) because it is the real available cash per year in the project.

A sensitivity analysis was performed for different biomass productivity levels using three different multipliers: low (0.75), medium (1.00), and high (1.25), relative to a central assumption of biomass productivity per hectare per year. Biomass productivity is presented here in metric tonnes (dry tonnes) and in some cases, data is also presented as bone dry short ton equivalent.

The economic indicators used to compare growth and investment scenarios were measured in U.S. dollars per dry metric tonne delivered and internal rate of return (IRR) as a percentage. The IRR financial indicator was calculated based on the free cash flow for each project scenario (Brealey and Myers 1996). The delivered cost per dry tonne included the cost of growing the biomass (also called depletion), profit for the farmer (estimated at 8% IRR), harvesting cost, and freight cost. The price per dry tonne delivered was calculated to achieve a specific IRR, which ensured a profit for the landowner.

The IRR as used here is the rate of return on investment (CAPEX and R&D) that produces a zero net present value (NPV) for a proposed project or investment (Edmonds *et al.* 2007). An 8% IRR was used for all feedstock supply chain models. The NPV is the difference between capital invested and the current worth of future cash inflows at the specified discount rate (Edmonds *et al.* 2007). The discount rate (the opportunity cost of using capital for a specific investment, often called the 'hurdle rate') used in the analysis was 8% (Brealey and Myers 1996; Ross *et al.* 2004). The base year for the analysis, prices (real dollars), and costs were based on the first quarter 2012.

For the forestry biomass except unmanaged hardwood (loblolly pine and eucalyptus), two scenarios were analyzed. One included land rent and the other did not (rentless assumptions evaluate scenarios for which the investor owns the land used for biomass production).

Life Cycle Assessment Approach

The goal of this study was to identify feedstocks with the lowest environmental burdens and delivered costs. An attributional life cycle assessment was performed to determine the environmental impacts of each supply system. Additionally, process stages producing the largest environmental burdens were identified. Many ISO 14044 standard methods were followed to enable comparison to other life cycle assessments and to ensure accuracy of the data. LCA software SimaPro 7.2 was used as a tool to compile database records, perform uncertainty analyses, and perform impact assessments (Pré 2010).

System boundary

A cradle-to-gate (crop establishment to raw materials delivered at conversion facility gate) boundary was used. Upstream emissions of raw materials as well as direct emissions due to biomass production were included within these boundaries. System boundaries for each biomass scenario are indicated by the dashed line perimeters in Figs. 3, 4, and 5 for forestry biomass, forest residues, and agricultural biomass, respectively.

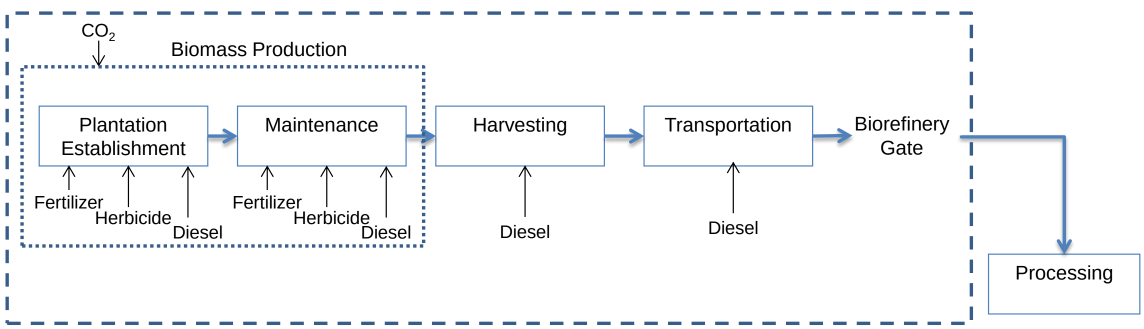


Fig. 3. Production stages and system boundary of forestry biomass production and delivery

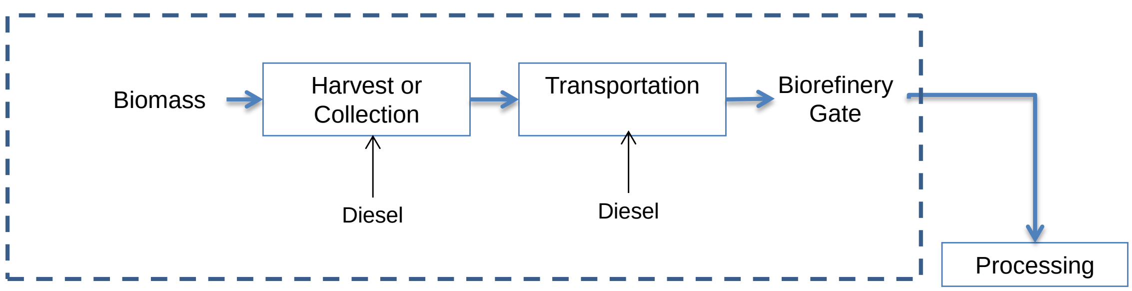


Fig. 4. Production stages and system boundary of forest residue collection and delivery

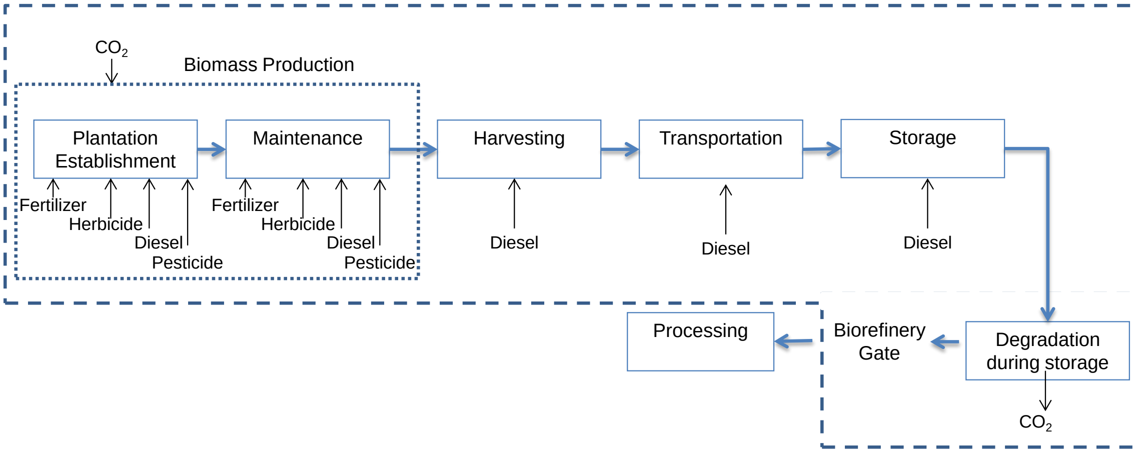


Fig. 5. Production stages and system boundary of agricultural biomass production and delivery; note: degradation emissions and CO_2 uptake during growth are shown separately for clarification

Carbon uptake during biomass growth

During the growth of biomass, carbon in the form of CO_2 is absorbed from the atmosphere through photosynthesis. This carbon can be stored in the above-ground biomass, forest litter, or below-ground biomass (root system). Only the carbon harvested from above-ground biomass was counted as a credit or a negative emission for this study (Rabl *et al.* 2007). However, it is worth noting that if the studied biomass is to be used for energy, this carbon will eventually be released back into the atmosphere.

The biomass percent carbon and molecular weight ratios were used to convert dry biomass to tonnes of CO_2 absorbed during photosynthetic growth. Equation 1 was used to convert biomass loss to CO_2 emissions during degradation, as well as carbon uptake from biomass growth with the fractional carbon content denoted [Carbon].

$$CO_2\ Emissions = \ Biomass\ (tonnes) \times [Carbon] \times \frac{3.67\ tonnes\ carbon\ dioxide}{tonne\ carbon} \qquad (1)$$

Land use change

Previous studies suggest that effects of land use change can represent a substantial share of life cycle burdens for biomass to bioenergy systems (Walsh 2003; Gnansounou *et al.* 2009; Mathews and Tan 2009; Malca and Freire 2012). Many bioenergy LCA studies provide some analysis of the impact of land use change (LUC). These studies, however, do not distinguish between LUC of different feedstocks nor do they model before and after scenarios in great detail (Farrell 2006; Adler *et al.* 2007).

The Integrated Biomass Supply and Logistics (IBSAL) biomass model (Sokhansanj *et al.* 2006, 2009; Sokhansanj and Hess 2009) is effective for techno-economic analysis; however, it does not incorporate biogeochemical inputs, which are necessary for effective analysis of soil CO_2 loss due to cultivation and vegetation removal. The Suppose model, produced by the U.S. Forest Service as a forest vegetation simulator, does not model pre- and post-conversion species to the resolution achieved in this study (Dixon 1999). Some studies avoid detailed LUC modeling and simplify land use change CO_2 loss equations by estimating a single value for the amount of CO_2 lost from the soil during land clearing (Guo and Gifford 2002; Murty *et al.* 2002; Searchinger *et al.* 2008).

Herein, 20 LUC scenarios were modeled using the Forest Industry Carbon Assessment Tool (FICAT; NCASI, 2011) to develop a better understanding of the range of possible impacts that land use change could have on the net life cycle burdens (Parigiani *et al.* 2011). The values used for land use change in FICAT are based on the Intergovernmental Panel on Climate Change data (IPPC, 2007). A 100 year time period was used to model these impacts in FICAT. Additionally, to be consistent with the LUC burden time scope, feedstock environmental burdens were quantified per hectare over 100 years. Table 3 provides values and assumptions used in the FICAT models. The results of LUC analysis are reported in terms of tonnes of CO_2 emitted per hectare over 100 years, due to the land use change and resulting soil disturbance, quantity of standing biomass, and amount of carbon dioxide removed from the air during photosynthesis. The LUC GHG emissions are recognized to occur soon after the land use conversion; however, these impacts are normalized over a production period of 100 years, the time during which GHGs are considered to be persistent in the environment (IPCC 2007). Biomass produced in the year of land use change may have higher GHG emissions. However, when the land use changed impacts are normalized over a 100 year time period, the increased impacts per year were reduced and reported in the results section.

Table 3. Assumptions Used for the FICAT Land Use Change Emissions Model

BD tonnes per year	453,592	Atmospheric moisture	Humid
Carbon content (%)	See Table 1	Soil type	Highly active clay
Moisture content (%)	See Table 1	Soil moisture	Humid
Scope of analysis (years)	100	Low uncertainty multiplier	0.5
Collection area (Ha)	See Table 7	High uncertainty multiplier	1.75
Climate type	Temperate - warm		

Four pre-conversion scenarios were considered: 1) from cropland, 2) from grassland, 3) from deciduous natural forest, and 4) from coniferous natural forest. These scenarios were chosen because they represent much of the land in the southern United States (Lubowski *et al.* 2006). These scenarios were analyzed for all feedstocks except forest residues because the latter are a byproduct of other forestry operations.

Establishment, maintenance, harvest, and transportation

Emissions related to forest establishment and maintenance, harvesting, and collection were calculated using U.S. LCI data. Data used to create these records were based on softwood in the southern U.S.; however, these emission factors were also applied to eucalyptus and unmanaged hardwood. To check data consistency, U.S. LCI emissions factors used in this study were compared to recent literature (Rajagopal and Zilberman 2007; Nesbit 2008; Smeets *et al.* 2009; de Vries *et al.* 2010; Luo *et al.* 2010; Gonzalez-Garcia *et al.* 2012).

Emissions resulting from switchgrass and sweet sorghum cropland cultivation, maintenance, harvest, and collection were calculated using diesel fuel use data for each scenario and U.S. LCI data for combustion emissions. Fuel consumption rates, harvest, transport, and storage costs, as well as commodity prices for switchgrass were based on experimental data from University of Tennessee at Knoxville and personal communication with S. Jackson (personal communication, Jackson 2011), commodity average spot prices (EIA 2012), and peer-reviewed literature sources (TMS 2011). Sweet sorghum composition data was referenced from Prasad *et al.* (2007). Diesel fuel combusted in industrial equipment and the average U.S. diesel fuel mixture from U.S. LCI records (NREL 2003) were used to calculate emissions resulting from the use of diesel in cultivation machinery.

Transportation data was sourced from Timber Mart South (TMS 2011) and used in SimaPro to determine emissions for each scenario. The U.S. LCI combination diesel truck emission values were used to calculate transportation emissions. Table 4 outlines the energy content and emissions associated with forest operations and transportation fuel usage.

Table 4. Heating Value and Combustion Emissions of Fuels Used for Transportation and Forest Operations

Fossil Fuel Data	Energy Content MJ/L	Global Warming Potential kg CO_2/L	Source
Diesel	36.3	3.9	1,2
Gasoline	35	2.75	1,2

1: EV World 2004, 2: NREL 2003

Environmental burdens associated with upstream chemical consumption emissions (fertilizers, herbicides, and pesticides) were included for all feedstocks except forest residues and unmanaged hardwoods. The emission factors in Table 5 are based on the U.S. Life Cycle Inventory (NREL 2003; You *et al.* 2012) and the ecoinvent database (Curran 2006; Sonne 2006; ecoinvent Centre 2007; Neupane *et al.* 2011), where electricity usage was changed from European sources to world average to reflect production from different locations around the world.

Table 5. Fertilizer and Pesticide Emission Factors and Energy Usage

Chemical	kg CO_2/kg Chemical	Energy MJ per	Unit	Source
Glyphosate	16.86	221	kg	1
Herbicide	7.93	221	kg	2
Lime	0.01	7.3	kg	2
Pesticide	7.93	224	l	2
Phosphorus	2.29	5.8	kg	2
Potassium	0.37	5.8	kg	2
Potash	0.37	5.8	kg	2
Pursuit	7.90	7.3	l	2
Urea	14.90	5.8	kg	2
Dipel	7.93	224	l	2
Alzarine 90 DF	7.93	221	l	2

Sources: 1: SCLCI 2010, 2: NREL 2003

Life Cycle Inventory Inputs

A life cycle inventory was compiled for each feedstock scenario based on the inputs and outputs of the supply system (Table 6). All inputs are expressed based on the functional unit: dry tonne of biomass delivered. A second functional unit was used for additional analysis purposes incorporating land use efficiency: one managed hectare over 100 years. The life cycle inventory data was used as input data for the SimaPro modeling software, which calculated direct and indirect emissions due to chemical use, transportation, electrical use, and storage emissions (Glew *et al.* 2012; Gonzalez-Garcia *et al.* 2012; You *et al.* 2012). The ecoinvent database (ecoinvent Centre 2007, Neupane *et al.* 2011) and the U.S. Life Cycle Inventory database (You *et al.* 2012) were used to calculate a cradle-to-gate life cycle inventory. In future research this cradle-to-gate model will be combined with biochemical and thermochemical conversion models, fuel distribution systems, and combustion emission values to produce full cradle-to-grave life cycle assessments.

Biomass storage

With seasonal growing periods, sweet sorghum and switchgrass crops must be stored to provide a year-round supply to a biorefinery. During this storage period, the biomass' aerobic and anaerobic decomposition releases GHGs. In this study, only aerobic decomposition was considered, as little data exits describing emissions related to anaerobic biomass decomposition during storage (Wortmann *et al.* 2010). It is recognized that biomass handling practices will influence the decomposition of the materials, possibly resulting in anaerobic decomposition and methane emissions, but this was not considered in the scope of this study (Wang *et al.* 2002; Palviainen *et al.* 2004; Vavrova *et al.* 2009).

The feedstock-specific biomass carbon content was used to calculate the GHG emissions. Molecular weight ratios were used to convert biomass loss to carbon loss and carbon dioxide emissions (Equation 1).

Life Cycle Impact Assessment Approach

The Tool for the Reduction and Assessment of Chemical and other Environmental Impacts 2.0 (TRACI 2) impact assessment method (Bare 2002; Bare *et al.* 2003; Jolliet *et al.* 2004; Bare 2011) was used to analyze global warming potential, acidification, eutrophication, carcinogens, non-carcinogens, respiratory effects, ozone depletion, eco-toxicity, and smog. The global warming equivalents for methane and dinitrogen monoxide were updated to the most recent IPCC report values for global warming equivalency to CO_2 (IPCC 2010).

In the TRACI 2 life cycle assessment results, corn grain was included as a baseline against which to compare the modeled biomass supply scenarios. These impacts were calculated using the TRACI 2 method and the ecoinvent dataset modified with the United States electricity data (ecoinvent Centre 2007). The exact record used for this analysis, "Corn, at field/kg NREL/US," was modified to allow a more equal comparison with the biomass feedstock scenarios herein. The corn data record accounted for direct field emissions to the soil and air. However, the study herein did not account for nutrient runoff and direct emissions from the field, other than CO_2 and N_2O. Due to the study limitation herein, all direct emissions from the field were removed from the corn grain LCI except for CO_2 and N_2O. It is noted that nutrient runoff and emissions from the field would likely be higher for the corn scenario than the biomass scenarios due to higher levels of nutrients and chemical applications. Additionally, all impacts of the corn grain process were attributed to the corn grain alone, even though stover was produced as a by-product. A 50 km transportation distance was used for the baseline corn grain scenario.

Table 6. Life Cycle Inventory Inputs for Establishment, Maintenance, Harvest, and Transportation for Low (L), Medium (M), and High (H) Productivity Scenarios Assuming 500,000 BDT/year (453,592 metric tonnes) and 10% Covered Area

	Loblolly Pine			**Eucalyptus**			**Unmanaged Hardwood**			**Forest Residues**			**Switchgrass**			**Sweet Sorghum**		
Productivity level →	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
Fuel use	Liter per dry tonne			Liter per dry tonne			Liter per dry tonne			Liter per dry tonne			Liter per dry tonne			Liter per dry tonne		
Fuel consumption, collection	-	-	-	-	-	-	-	-	-	0.05	0.04	0.03	-	-	-	-	-	-
Plantation establishment and maintenance, diesel	0.86	0.65	0.52	2.47	1.85	1.48	-	-	-	0.61	0.45	0.36	-	-	-	-	-	-
Plantation establishment and maintenance, gasoline	0.04	0.03	0.03	0.12	0.09	0.07	-	-	-	8.0	6.0	4.8	3.93	2.95	2.36	-	-	-
Harvesting, diesel	10.1	7.58	6.06	10.1	7.58	6.06	10.1	7.6	6.1	-	-	-	6.02	4.51	3.61	4.13	3.1	2.48
Storage													0.6	0.6	0.6	0.84	0.84	0.84
Transportation	Dry tonne*km			Dry tonne*km			Dry tonne*km			Dry tonne*km			Dry tonne*km			Dry tonne*km		
Forest to facility	79	69	62	78	67	60	219	190	170	327	283	253	-	-	-			
Farm to storage	-	-	-	-	-	-	-	-	-	-	-	-	51	44	39	175	152	136
Storage to facility	-	-	-	-	-	-	-	-	-	-	-	-	9.5	9.5	9.5	31	31	31
Fertilizer	kg per dry tonne			kg per dry tonne			kg per dry tonne			kg per dry tonne			kg per dry tonne			kg per dry tonne		
Urea	2.1	1.6	1.3	2.9	2.2	1.7	-	-	-	0.13	0.1	0.08	-	-	-			
Phosphorus	-	-	-	-	-	-	-	-	-	-	-	-	1.6	1.2	0.96	3.43	2.57	2.06
Potassium	-	-	-	-	-	-	-	-	-	-	-	-	15.83	11.88	9.5	1.7	1.27	1.02
Lime	-	-	-	-	-	-	-	-	-	-	-	-	62.28	46.71	37.37	-	-	-
Nitrogen	-	-	-	-	-	-	-	-	-	-	-	-	8.47	6.36	5.08	8.50	6.37	5.10
Herbicide	kg per dry tonne			kg per dry tonne			kg per dry tonne			kg per dry tonne			kg per dry tonne			kg per dry tonne		
General herbicide, glyphosa	0.03	0.01	0.01	0.08	0.04	0.03	-	-	-	0.002	0.001	0.001	-	-	-	-	-	-
Pursuit	-	-	-	-	-	-	-	-	-	-	-	-	2.36	1.77	1.41	-	-	-
MSO	-	-	-	-	-	-	-	-	-	-	-	-	3.31	2.48	1.99	-	-	-
2,4-D	-	-	-	-	-	-	-	-	-	-	-	-	1.14	0.85	0.68	-	-	-
Alzarine 90 DF	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.19	0.14	0.11
Dipel ES	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.2	0.15	0.12

Uncertainty Analysis

Data used in LCA studies are often drawn from databases, literature, and expert opinions that are prone to uncertainty. The uncertainty within this study was addressed in two ways. The biomass productivity (variations in rate of growth and resulting available biomass) uncertainty was addressed by applying 0.75 and 1.25 multipliers to all medium productivity scenario costs and emission values for each feedstock, representing low and high productivity, respectively. The uncertainty surrounding productivity was thus taken into account by the creation of error ranges for all cost and environmental impact values.

Pedigree analysis (Huijbregts *et al.* 2001; Heijungs and Huijbregts 2004) was used to categorize data and generate standard deviation values. Pedigree analysis ranks the data source quality and categorizes sources using a score of 1 to 5, one being low accuracy data sources and five being the most accurate data sources. Using this method, ecoinvent life cycle inventory data were analyzed to generate environmental impact standard deviation values, included with the ecoinvent database (ecoinvent Centre 2007). A uniform uncertainty distribution was used for chemical usage and feedstock yields, modeled in SimaPro. These uncertainty values were used for a Monte Carlo uncertainty analysis in SimaPro.

RESULTS AND DISCUSSION

Maximum Transportation Distance for Feedstock Delivery

The maximum transportation distance used in each of the supply chain systems was estimated for two levels of feedstock-covered area, 10% and 25% (Fig. 6). For each productivity scenario (low, medium, and high for each feedstock), a distinct maximum transportation distance value was calculated. The maximum transportation distances were calculated using a spatial diameter of biomass collection, using radius values as one-way transportation distances and assuming the conversion facility is located at the center of the circular collection area. The collection area is the spatial scope of harvest and collection activities that is necessary to ensure the appropriate supply of biomass to the conversion facility year-round. The area required to supply 500,000 BD short tons per year (Table 7) was used to calculate transportation distances.

Transportation distances ranging from 20 to 40 kilometers were required for loblolly pine, eucalyptus, switchgrass, and sweet sorghum. Forest residues and unmanaged hardwood required the longest transportation distances, ranging from 45 to 180 kilometers (almost four times greater than the other feedstock supply scenarios). These maximum distances were calculated using a tortuosity factor of 1.31 (Ravula 2007).

Required Area

Land required for each feedstock production system at low, medium, and high productivity levels is presented in Table 7. Forest residues and unmanaged hardwoods required the largest areas, ranging from 145,700-242,800 hectares (360,000-600,000 acres), mainly due to the low biomass yield (0.70 and 2.24 bone dry tonnes per hectare per year for forest residues and unmanaged hardwoods, respectively) (Gonzalez *et al.* 2011a). Loblolly pine, eucalyptus, switchgrass, and sweet sorghum production areas were lower due to higher biomass productivity.

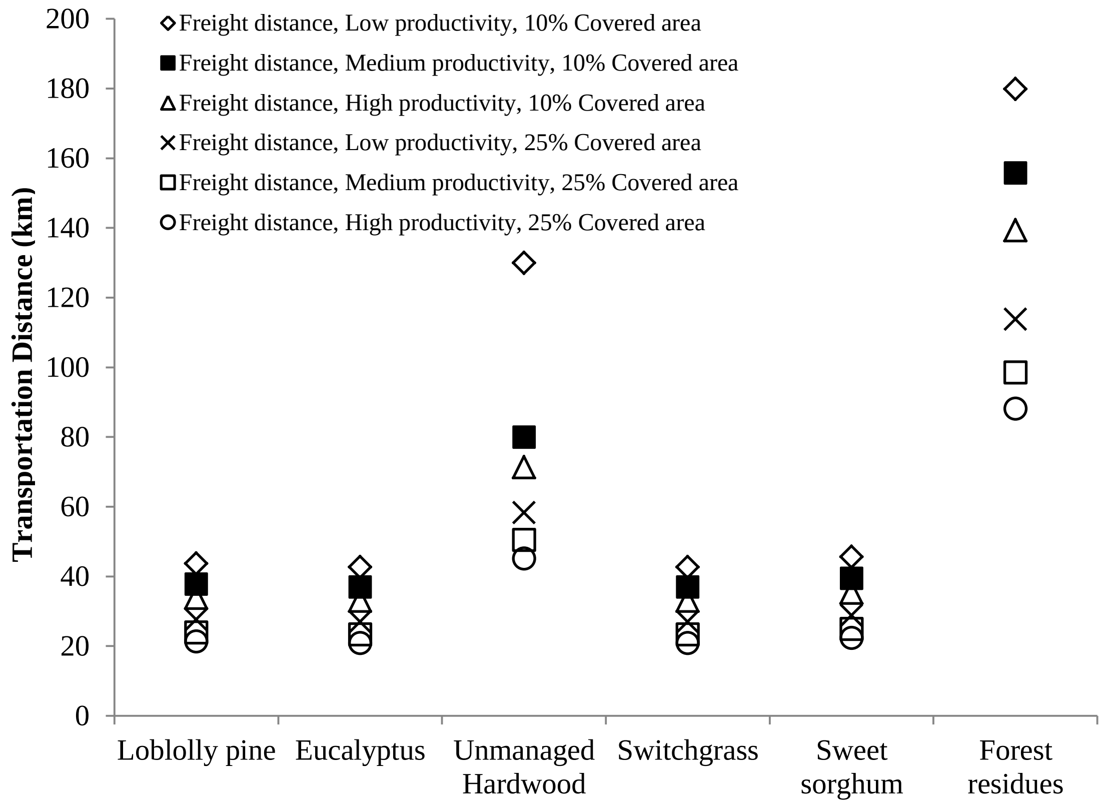


Fig. 6. Maximum freight transportation distances from biomass source to processing facility, assuming 500,000 BDT/year (453,592 metric tonnes/year), feedstock-specific productivity, and covered area values as indicated. All transportation distances include a tortuosity factor of 1.31 km transported per linear km of distance from point of biomass harvest to biorefinery (Ravula 2007).

Table 7. Feedstock Production Land Use Requirements (in hectares) for Delivering 500,000 BDT (453,592 metric tonnes) for Low, Medium, and High Productivity, Assuming 10% Covered Area

Description	Loblolly Pine	Eucalyptus	Unmanaged Hardwood	Switchgrass	Sweet Sorghum	Forest Residues
Total (low)	35,300	33,700	269,900	33,700	38,600	599,800
Per rotation (low)	2,900	8,400	5,400			24,000
Total (medium)	26,500	25,300	202,400	25,300	28,900	449,800
Per rotation (medium)	2,200	6,300	4,000			18,000
Total (high)	21,200	20,200	162,000	20,200	23,100	359,900
Per rotation (high)	1,800	5,100	3,200			14,400

Delivered Costs

The calculated biomass delivered cost was reported using three different units: cost per dry metric tonne of biomass, cost per million BTU, and cost per tonne of carbohydrates. The delivered cost per dry metric tonne of biomass is pertinent to fiber processing and thermochemical conversion facilities (*e.g.*, MDF, particle board, and pellet facilities and thermochemical conversion to bioethanol). The delivered cost per million BTU is pertinent to biomass-to-energy production facilities (such as bio-power and wood-pellet producers). The delivered cost per tonne of carbohydrate is pertinent to bio-chemical conversion pathways that utilize carbohydrates to produce fermentable sugars.

Delivered cost per bone dry tonne

The delivered cost per dry tonne equivalent (at the moisture content listed in Table 2) was calculated for each of the productivity levels (low, medium, and high), as shown in Fig. 7. Forest residues had the lowest delivered cost, ranging from \$51.20 to \$56.70 BD $tonne^{-1}$, followed by loblolly pine with values ranging from \$51.30 to \$61.40 BD $tonne^{-1}$.

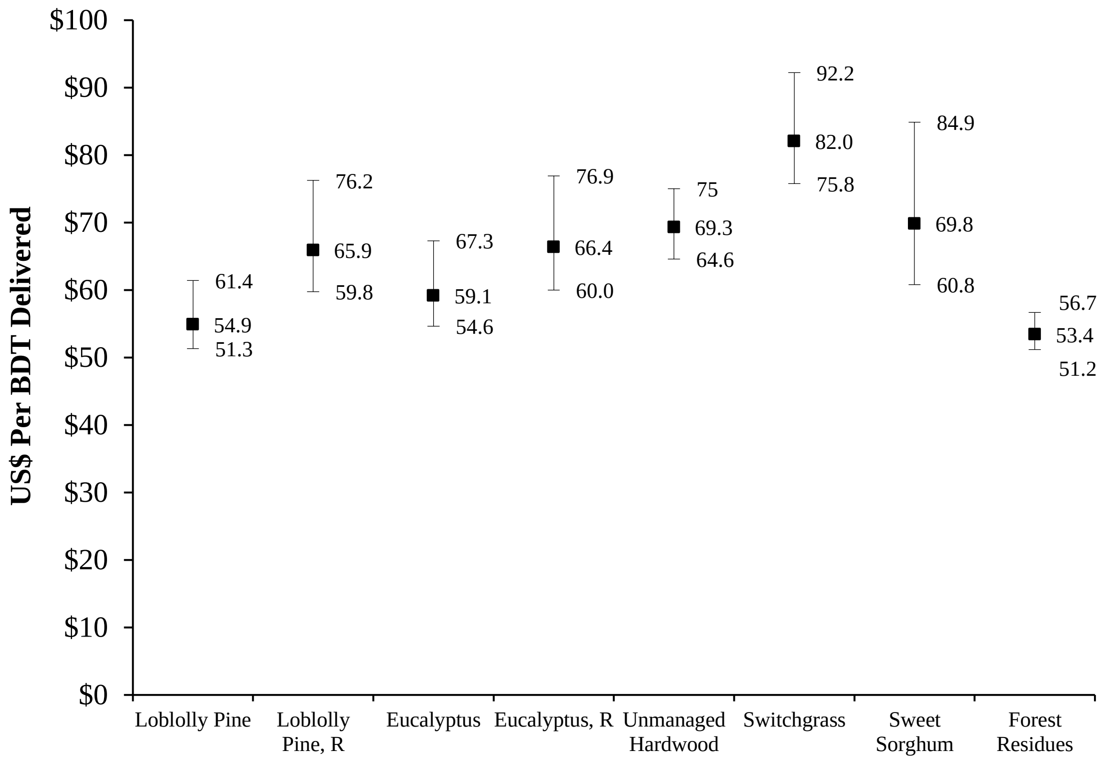


Fig. 7. Delivered cost per BDT for all feedstock scenarios, displaying the low, medium, and high productivity spread for each feedstock, assuming 500,000 BDT/year (453,592 metric tonnes/year) and 10% covered area. R denotes that the land has a rental cost.

Despite the higher transportation costs of forest residues, the delivered cost was lower due to no establishment and maintenance costs and lower biomass costs. For example, renting the land for biomass growth increased the pine and eucalyptus delivered costs by 10 to 20%, compared to the no-rent scenario. These values are similar to those found in the literature, which do not incorporate financial analysis calculations such as internal rate of return (IRR), net present value (NPV), discount rate, *etc.* (Eriksson and

Gustavsson 2008; Schnepf 2010). Schnepf (2010) calculated a delivered cost per ton of \$40 to \$56 for corn stover, another potential biomass source for biofuels, and these values are similar to or higher than the values determined in this study.

Sweet sorghum and switchgrass supply systems had larger delivered costs per BD tonne than forest biomass feedstocks. Duffy (2007) determined that switchgrass has a cradle-to-gate delivered cost of \$103.11 $tonne^{-1}$, which is higher than the low productivity switchgrass delivered cost of \$92.20 $tonne^{-1}$.

Delivered cost per tonne of carbohydrate

Delivered cost per ton of carbohydrate for each of the supply systems is presented in Fig. 8.

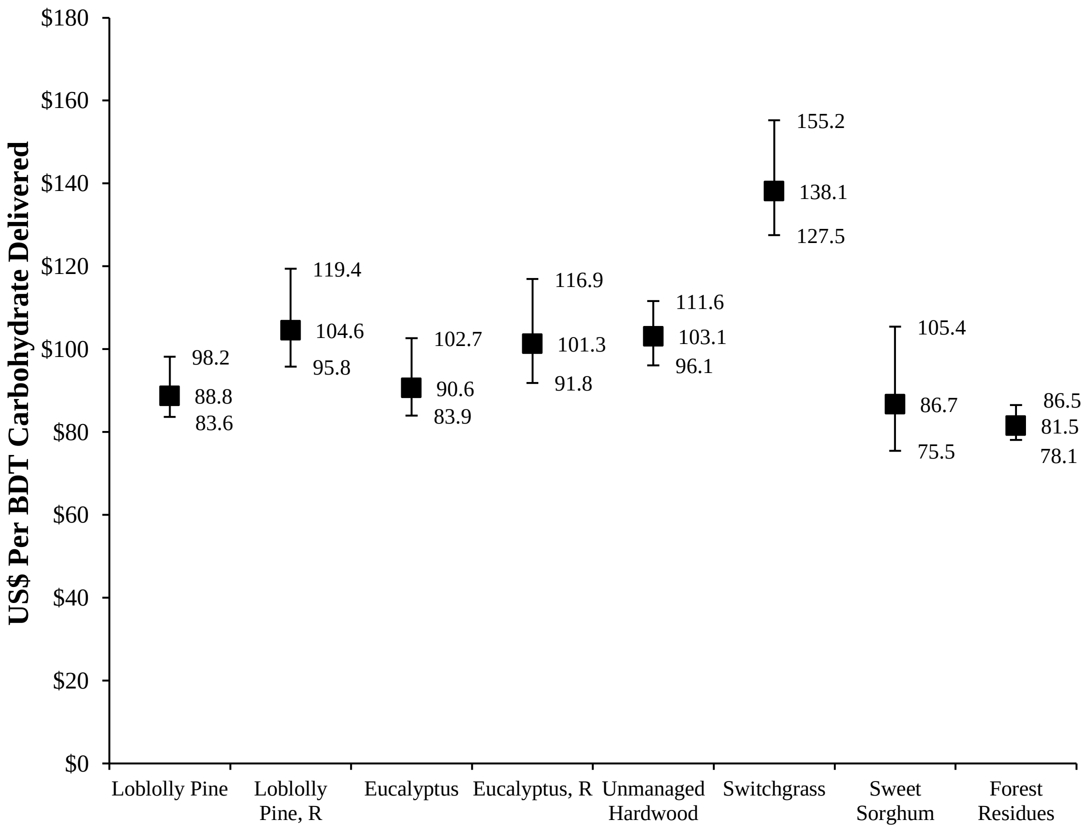


Fig. 8. Delivered cost per BDT of carbohydrate for all feedstock scenarios, displaying the low, medium, and high productivity spread for each feedstock, assuming 500,000 BDT/year (453,592 metric tonnes/year) and 10% covered area. R denotes that the land has a rental cost.

The same trends seen in Fig. 7 for delivered cost per BD tonne were observed here, with the exception that the cost per tonne of carbohydrates for sweet sorghum was comparable to the cost per tonne of carbohydrate for forest biomass scenarios, mainly due to the high carbohydrate content of sweet sorghum (80%). It is also noteworthy that the carbohydrate content of forest resources is almost entirely made of polysaccharides (difficult for enzymes to hydrolyze), whereas sweet sorghum has a combination of polysaccharides and monomeric sugars (readily hydrolyzed by enzymes). Conversely, the cost per tonne of carbohydrates from switchgrass was larger, despite a similar delivered cost per dry tonne, due to the low carbohydrate content (Mani *et al.* 2004; Li *et al.* 2005; Zhan *et al.* 2005).

Delivered cost per million BTU

The delivered cost per million British thermal units (MMBTU) for each of the supply chain systems is presented in Fig. 9. Forest-based feedstocks have a lower cost per MMBTU due to greater heating values and lower delivered cost per bone-dry tonne relative to agricultural biomass scenarios (Mani *et al.* 2004; Li *et al.* 2005; Bennett and Anex 2009; Sokhansanj *et al.* 2009; Carpenter *et al.* 2010; Gonzalez *et al.* 2011a). Forest residue is clearly the most inexpensive BTU source and a likely candidate for combustion applications.

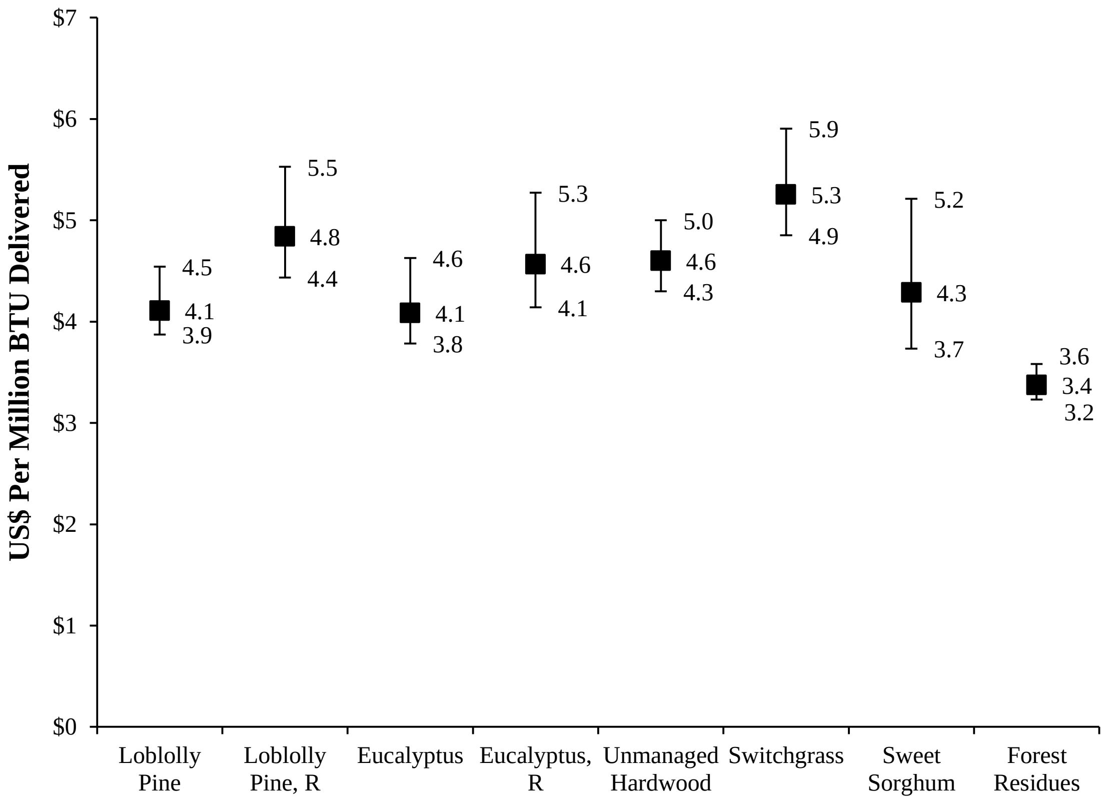


Fig. 9. Delivered cost per MMBTU for all feedstock scenarios, displaying the low, medium, and high productivity spread for each feedstock, assuming 500,000 BDT/year (453,592 metric tonnes/year) and 10% covered area. R denotes that the land has a rental cost.

The delivered costs per MMBTU for all supply systems were compared to the values of Henry Hub natural gas spot prices in Fig. 10, using the 2011 average price ($4.00 per MMBTU) for comparison to the six analyzed biomass feedstocks (EIA 2012). The Henry Hub natural gas prices have shown extreme volatility over the past decade, which indicates likelihood for volatility in natural gas prices in the future. Due to natural gas price volatility (ranging from $2 to $20 per MMBTU), comparing biomass delivered cost per MMBTU to an average natural gas delivered price is more meaningful. Here, the mean value of annual natural gas daily spot prices was used for the average price value. The average Henry Hub natural gas price is in a range that spans the calculated biomass cost per MMBTU in Fig. 9. However, the delivered energy content based on heating value does not incorporate combustion efficiency and moisture content, factors that would increase the cost of energy produced from the biomass if calculated for a cradle-to-grave cost analysis. Further, there are advantages in the handling, combustion, and transportation of gaseous fuel over solid fuels which are not reflected in the costs. In several studies, moisture content was identified as an important factor in thermochemical conversion and combined heat and power processes due to an increased heat of vaporization (Caputo *et al.* 2005; Phillips *et al.* 2007; Laser *et al.* 2009; Dutta *et al.* 2011; Gonzalez *et al.* 2012; Verma *et al.* 2012).

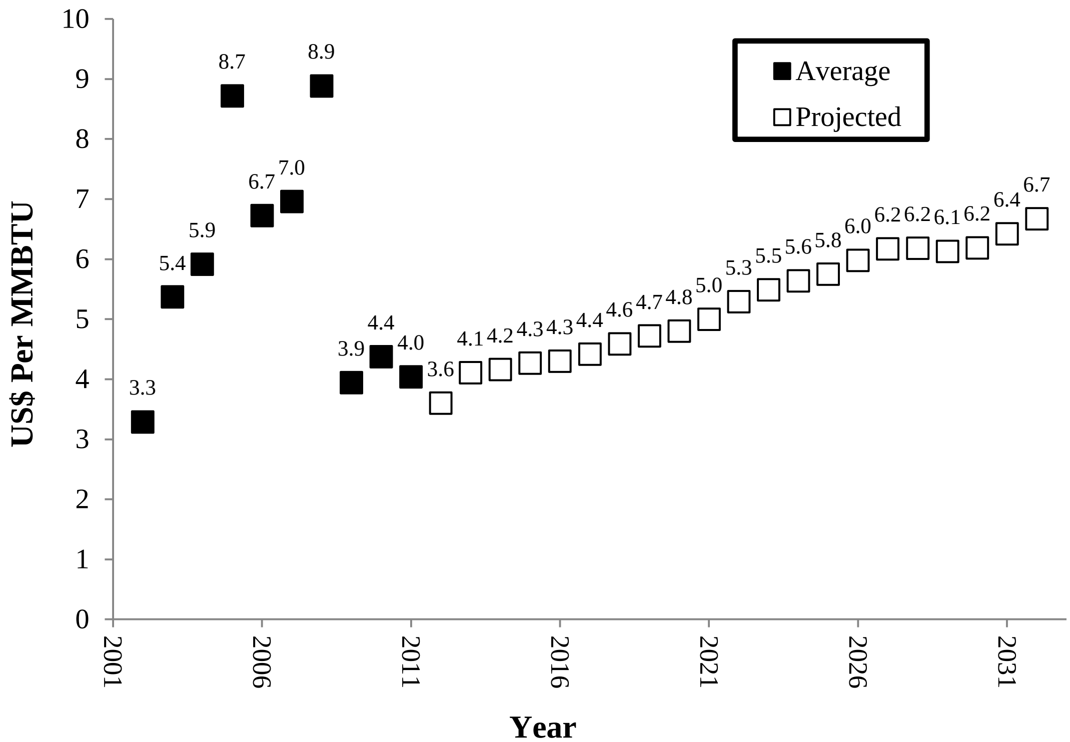


Fig. 10. Henry Hub natural gas spot prices per MMBTU for 2002-2012 and projected prices through 2032 (EIA 2012)

Forest *versus* Agricultural Biomass Supply Chain Summary

Woody biomass feedstocks are expected to have fewer supply chain issues relative to agricultural feedstocks. This is partially because optimized supply chains already exist for forest biomass. In contrast, energy crops, such as sorghum and switch-grass, are not as optimized or commercially operated. Additionally, storage of forest biomass is not an issue.

For annually grown and harvested agricultural crops, biomass degradation results in decreased cost efficiency and emissions. Forest-based feedstocks have a higher density than agricultural feedstocks, resulting in mass-limited rather than volume-limited transportation (switchgrass is volume-limited) and therefore lower transportation costs and emissions.

Greenhouse Gas Analysis

Greenhouse gas emissions on a cradle-to-gate basis were calculated for each biomass product stage, including establishment and maintenance, biomass growth, harvest and storage, and transportation (Fig. 11 and Table 8).

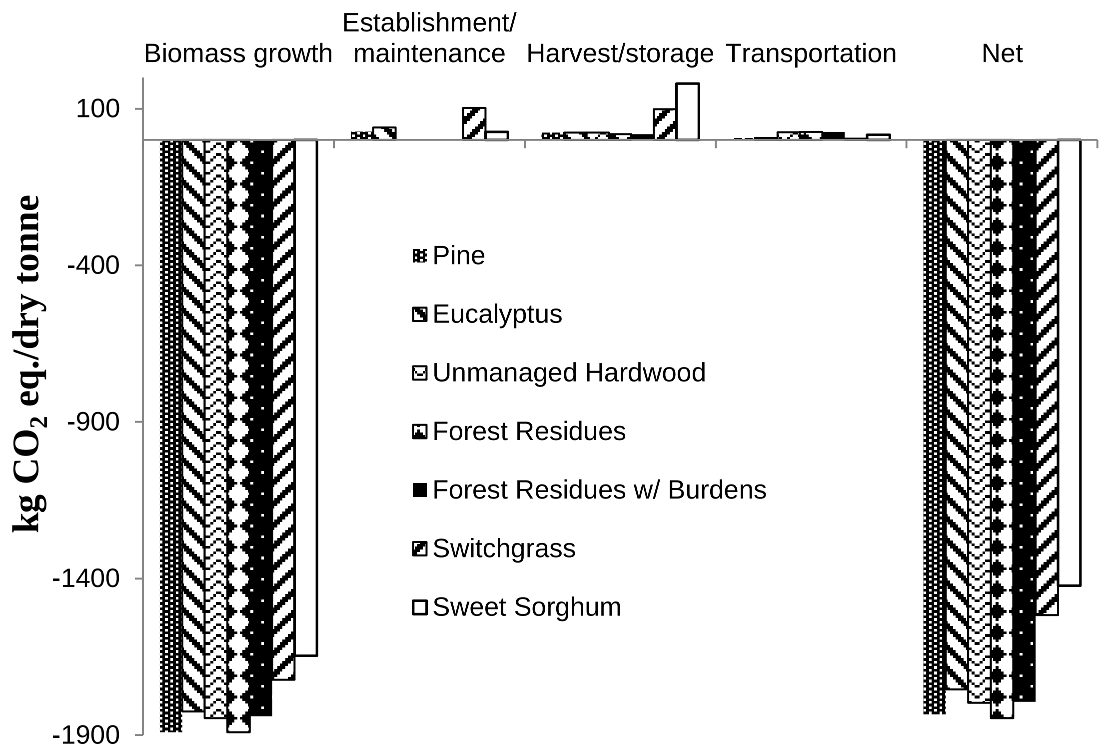


Fig. 11. Greenhouse gas emissions per product stage for biomass feedstocks delivered at a rate of 500,000 BDT/year (453,592 metric tonnes/year), assuming medium productivity and 10% covered area

Table 8. Global Warming Potential (GWP) Life Cycle Stage Contribution (All Values In %) Assuming Delivered Quantity of 500,000 BDT/Year (453,592 Metric Tonnes/Year), Medium Productivity, and 10% Covered Area

Feedstock	Biomass Growth	Establishment/ Maintenance	Harvest/Storage	Transportation
Pine	-103	1.47	1.32	0.35
Eucalyptus	-104	2.22	1.34	0.35
Unmanaged hardwood	-103	0.00	1.35	1.39
Forest residuals	-102	0.00	1.04	1.43
Forest residuals w. burdens	-103	0.09	1.07	1.43
Forest feedstock avg.	-104	1.84	1.33	0.35
Switchgrass	-114	6.78	6.48	0.33
Sweet sorghum	-116	1.85	12.71	1.20
Agricultural feedstock avg.	-115	4.31	9.59	0.76

The sum of all these product stages represents the net carbon released, minus the carbon absorbed from the atmosphere. The TRACI 2 impact assessment method (Bare 2002, 2003, 2011), updated with the Intergovernmental Panel on Climate Change (IPCC) global warming potential values, was used to calculate the CO_2 equivalents for each product stage. The global warming potential impact is a measure of how much thermal energy is trapped in the troposphere by a standardized volumetric quantity of a specific gas, thus increasing the global climate temperature (IPCC 2007).

Because biomass feedstocks are typically sold by mass, a functional unit of one metric tonne of dry-equivalent biomass was used (Kline *et al.* 2008; Galik *et al.* 2009; Swanson *et al.* 2010; Langholtz *et al.* 2012). During biomass growth, atmospheric CO_2 is taken up through photosynthesis to create plant matter. The uptake of CO_2 during biomass growth for all analyzed scenarios contributed a large negative GHG emission in the overall life cycle (Gnansounou *et al.* 2009; Lippke *et al.* 2011; McKechnie *et al.* 2011). Since the carbon (more specifically CO_2) taken up during growth was based on the chemical composition (percent carbon) of each species, the forest-based feedstocks with higher carbon contents captured more carbon per dry tonne than the agricultural biomass feedstocks.

Biomass establishment and maintenance GHG emissions are a function of rotation length and chemical resources used to plant, fertilize, and manage biomass production. The life cycle inventory for this study outlines the direct emissions from feedstock production activities in Table 6. Forest-based feedstocks, which have rotation lengths of 4 to 12 years, require less fertilizer and energy than the annually planted and harvested sweet sorghum and even the perennial switchgrass scenarios (Malmsheimer *et al.* 2008; Schmer *et al.* 2008; Wortmann *et al.* 2010). Establishment and maintenance emissions for pine and eucalyptus were similar; however, forest residues and unmanaged hard-woods were significantly lower and zero. Emissions from forest residue production were calculated on a no burden basis (attributes no emissions from establishment and maintenance to forest residues) and a mass allocated burden basis (allocates establish-ment and maintenance burdens at 11%, based on a 20% mass ratio between main tree stem biomass, the forest residues, and residue collection rates of 50%). In both allocation scenarios, forest residue establishment and maintenance emissions were insignificant compared to the net GHG emissions. On average, establishment and maintenance of forest-based feedstocks, representing 1 to 2% of the net GHG emissions, were not a differentiating factor when comparing different scenarios for biomass supply.

Agricultural feedstock (switchgrass and sweet sorghum) establishment and maintenance emissions were greater than forest-based feedstocks due to annual agricul-tural practices requiring increased energy, fertilizer, herbicide, and pesticide inputs. This resulted in establishment and maintenance emissions which were, on average, 5.7% of the total life cycle emissions, compared to 1 to 2% for the forest feedstocks.

Feedstock harvest and storage GHG emissions contributed less than 2% of the overall emissions for all feedstocks except switchgrass and sweet sorghum. Forest-based feedstocks harvested year-round do not require the long-term storage that switchgrass and sweet sorghum require to ensure a constant biomass supply. Sweet sorghum harvest and storage GHG emissions represented 11.3% of the net emissions. This analysis, however, assumes that only sweet sorghum would be fed to processing facilities, enduring long storage times; this might be alleviated through the use of a conversion process, utilizing multiple biomass types. Switchgrass decomposition (7% loss by dry mass) was less than that of sweet sorghum (14% loss by dry mass) due to lower moisture content and slower decomposition rates, in agreement with findings by Sanderson *et al.* (2006), Cherubini and Jungmeier (2010), Robertson *et al.* (2011), and Balan *et al.* (2012).

Transportation GHG emissions were a minor component in the overall GHG emissions for analyzed feedstocks. Transportation emissions were dependent on biomass productivity (tonnes biomass produced per hectare per year), biomass moisture content, transportation distance, feedstock production level (500,000 bone dry tons or 453,592 metric tonnes), truck capacity (truck volume limitations occur in the switchgrass scenario), and covered area (Srinivasa *et al.* 2009; Sokhansanj *et al.* 2009; Sokhansanj and Hess 2009; Banerjee *et al.* 2010; Inman *et al.* 2010; Miao *et al.* 2011; Perlack and Stokes 2011; Gonzalez *et al.* 2011a; Miao *et al.* 2012). Pine, eucalyptus, and switchgrass had lower transportation GHG emissions, while forest residues, unmanaged hardwoods, and sweet sorghum had higher transportation GHG emissions (Fig. 11) due to lower productivity values and moisture contents (Table 2). Forest residue and unmanaged hardwood transportation GHG emissions were 1.43% and 1.39%, respectively, of the net GHG emissions as a result of low land productivity and increased transportation distances required to collect the biomass.

Greenhouse gas emissions per hectare over 100 years

When GHG emissions per area are considered, the productivity of the land that produces the biomass of interest directly impacts the net GHG (kg CO_2 eq.) per hectare managed for 100 years. Using a kg CO_2 eq. dry tonne^{-1} functional unit does not directly incorporate the land-use benefits of enhanced biomass productivity. The biomass productivity does influence the transportation distance, but the effect is very small – less than 1.5% of the net GHG emissions.

The net GHG emission values per hectare per 100 years for each feedstock are shown in Fig. 12. GHG emissions for all biomass scenarios (except unmanaged hardwoods) were large and negative when using this functional unit. The negative emissions value from biomass growth dominates the net life cycle GHG emissions. The unmanaged hardwood scenario was still negative, but significantly smaller, as the productivity per hectare was about five times lower in the other five feedstock scenarios (Table 2). The "forest residues with pine" scenario, which combined residues from plantation loblolly pine (with no burdens from establishment and maintenance assumed) and the main pine stem for bioenergy production, resulted in the largest GHG capture in the biomass growth stage due to high biomass productivity, collection rates, and high carbon content. The eucalyptus and pine scenarios followed closely with a similarly large net negative GHG emission value from cradle-to-gate. Sweet sorghum had a less negative net GHG emission than switchgrass due to lower productivity. However, both agricultural scenarios had less negative emissions than the forest-based feedstocks, with the exception of unmanaged hardwood.

These results indicated that the production of high productivity biomass (plantation forestry) can significantly reduce the net GHG emissions relative to low productivity biomass production (unmanaged hardwood). Environmental factors apart from GHG emissions, however, may play an increased role in net environmental burdens when productivity is increased per hectare through higher intensity management practices, due to increases in energy or chemical inputs for biomass production. This is discussed in more detail in the Life Cycle Impact Assessment section.

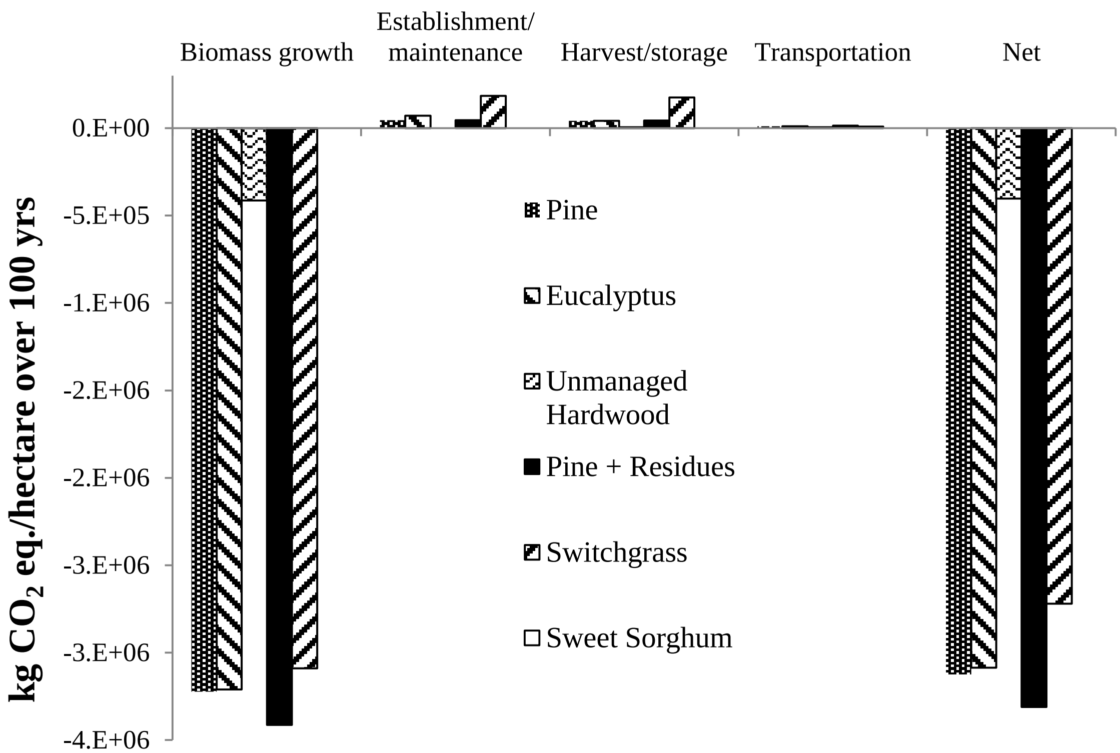


Fig. 12. Net GWP (kg CO_2 eq.) per hectare over 100 years organized by life cycle stage for all biomass feedstock scenarios, assuming 500,000 BDT/year (453,592 metric tonnes/year), medium productivity, and 10% covered area

Land Use Change Impacts

Previous studies have shown that land use change (LUC) impacts, such as volatilization of soil carbon and soil nutrient stock depletion, should be taken into account when quantifying the net environmental burden of a biomass supply system (Fargione *et al.* 2008; Searchinger *et al.* 2008; Lapola *et al.* 2010). Pre-conversion scenarios were modeled for each feedstock scenario except forest residues, because no LUC was assumed for that scenario. The LUC emissions calculation methodology used in this study is similar to that of Parigiani *et al.* (2011) and is described in more detail in the Land Use Change Methods section of this paper. When converting cropland and grassland to forest-based biomass land, all scenarios resulted in a negative emissions contribution and increased land and soil carbon stock, as shown in Fig. 13. When converting from deciduous or coniferous managed forestland to any of the analyzed feedstock species, the land use change resulted in a large, positive emission contribution. When converting deciduous or coniferous natural forestland to pine and eucalyptus, the land use change impact was negative. Conversion to unmanaged hardwood, switchgrass, or sweet sorghum species from deciduous or coniferous natural forestland resulted in a positive emissions contribution.

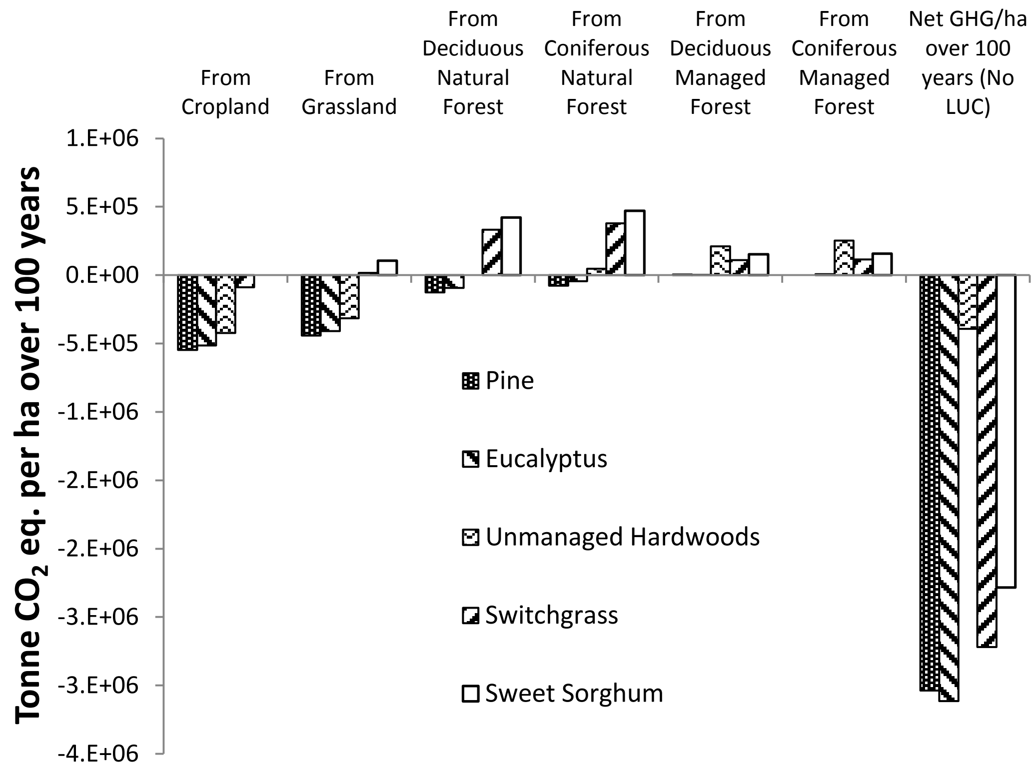


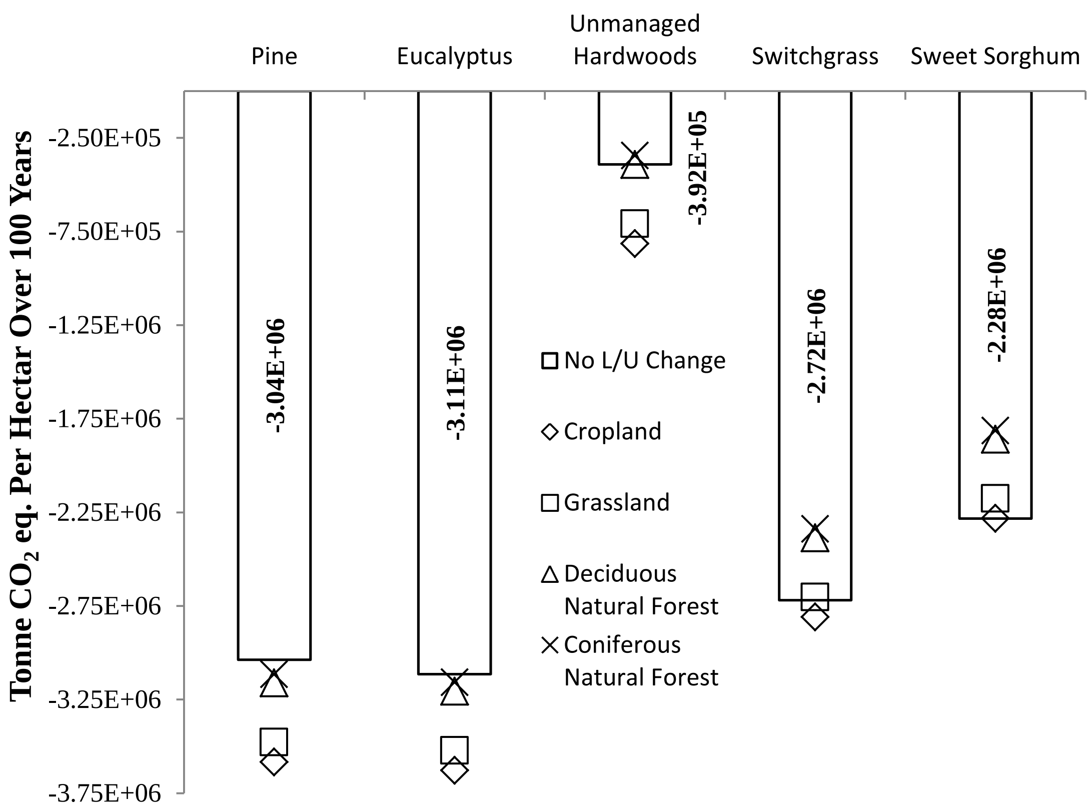
Fig. 13. Land use change GHG emissions from converting one hectare of land to biomass feedstock growth for bioenergy over 100 years. Also shown to the right is the net life cycle GHG emissions for each feedstock scenario with no LUC impacts considered, assuming 500,000 BDT/year (453,592 metric tonnes/year), medium productivity, and 10% covered area.

Land conversion from cropland to pine and eucalyptus production resulted in the largest negative emission contribution due to the large increase in root and plant material deposition, creating a long-term carbon sink. Converting previous forest to agricultural biomass production systems resulted in positive GHG emissions due to decreasing underground carbon and decreasing forest litter carbon. Additionally, tillage activity releases root soil carbon in agricultural systems. From all the scenarios, it was determined that converting natural coniferous forests to switchgrass and sweet sorghum resulted in the largest increase in net GHG emissions.

The land use change emissions, as previously indicated, can be significant in relation to the overall GHG emissions from the production of a biomass feedstock. Figure 14 incorporates LUC into the overall GHG emissions from the production of specified feedstocks for 100 years per hectare. The bars show the net GHG emissions from biomass delivery without taking into account the LUC impacts. The symbols represent the net GHG emissions for each of the LUC scenarios: from grasslands, from croplands, from natural deciduous forest, and from natural coniferous forest. Both the absolute values of the GHG emissions and the percent change relative to the no LUC considered cases are shown for the different LUC scenarios. The conversion of agricultural land, such as tobacco fields, which are common in the southern U.S., to pine and eucalyptus plantations results in the largest negative GHG emissions over a hectare for 100 years.

LUC impacts reduced GHG emissions for pine and eucalyptus by up to 18% compared to the no LUC net GHG emissions.

The cradle-to-gate GHG emissions value for unmanaged hardwoods was very sensitive to LUC emissions, which influenced the overall impact by as much as -108%, relative to the net GHG emissions without LUC considerations. This was mainly due to the low productivity of unmanaged hardwoods. Switchgrass and sweet sorghum net GHGs were basically unchanged when grassland or cropland were converted. However, increases of approximately 15 to 20% in net GHGs were observed when converting from forestland to these feedstock scenarios. It is clear that LUC is significant in many cases and should be considered in developing land use policies.



Post-Conversion Scenarios (all values in %)

Pre-Conversion ↓ Scenarios	**Loblolly Pine**	**Eucalyptus**	**Unmanaged Hardwoods**	**Switchgrass**	**Sweet Sorghum**
× Coniferous Natural Forest	-3	-1	12	14	21
△ Deciduous Natural Forest	-4	-3	0	12	19
□ Grassland	-15	-13	-81	1	5
◇ Cropland	-18	-17	-108	-3	0

Fig. 14. Land use change implications for the net GHG emissions per hectare over 100 years of biomass feedstock growth for bioenergy. The table included with the figure displays the percent change of considering LUC effects for the calculations of net GHG emissions per hectare over 100 years for all biomass feedstocks. Assumptions: 500,000 BDT delivered/year (453,592 metric tonnes/year), medium productivity, and 10% covered area. Values included in the bar graph portion of Figure 14 represent the No-L/U Change data.

Net Energy Ratio

The ratio of fossil energy consumed to lower heating value (LHV) inherent in the produced biomass (NER) was determined for all six feedstock scenarios to examine the energy efficiency of biomass delivery (Fig. 15). Previous biofuel and bioenergy studies have determined that NER is an effective method to compare feedstocks and account for efficiency of energy input to output (Tilman *et al.* 2006; Schmer *et al.* 2008; Liska *et al.* 2009; Lopez *et al.* 2010). The NER of unmanaged hardwood was the lowest, since no establishment or maintenance activities occurred. It was determined in this study that for woody biomass feedstocks (pine, eucalyptus, unmanaged hardwood, and forest residues), the NER was approximately 1:49. Sweet sorghum followed closely with 1:24 and switchgrass represented the worst-case scenario with an NER of approximately 1:8.

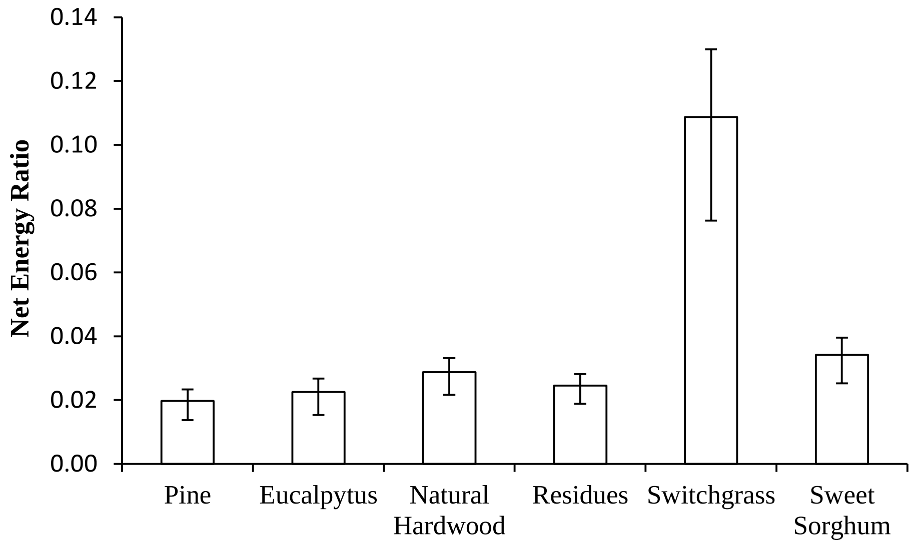


Fig. 15. Net energy ratio (fossil energy inputs to biomass energy delivered) for each feedstock, assuming 10% covered area and 500,000 BDT delivered/year (453,592 metric tonnes/year). Error bars display the range due to differences in feedstock productivity and yield.

Unmanaged hardwood resulted in the lowest fossil fuel energy to delivered biomass energy ratios; however, the transportation distance was higher than other feedstock scenarios due to the low yield per hectare. The low NER results for unmanaged hardwood should be tempered against the extremely low productivity and cost. Switch-grass has the least ideal energy ratio, due to the increased establishment and maintenance activities, low heating value, and broadly elevated environmental burdens across the life cycle (Mooney *et al.* 2009; Sokhansanj *et al.* 2009; Larson *et al.* 2010). Switchgrass is a more appropriate candidate for carbohydrate production than for energy (MMBTU) value, relative to forest resources.

Life Cycle Impact Assessment

Environmental and human health burdens due to each feedstock supply system extend beyond global warming potential. They were separated into eight additional impact categories using the TRACI 2 method (Bare 2002, 2003, 2011) determined as shown in Table 9 and plotted in Fig. 16. Table 9 gives the mid-point impacts for each of the nine TRACI 2 impact categories for each feedstock supply scenario modeled herein.

Table 9. Life Cycle Impact Assessment for Biomass Feedstocks Assuming 500,000 BDT Delivered/Year (453,592 Metric Tonnes/Year), Medium Productivity, and 10% Covered Area. All Values Are Reported Per Dry Tonne of Biomass.

Impact Category	Unit	Loblolly Pine	Eucalyptus	Unmanaged Hardwood	Forest Residues	*Forest Residues	Switchgrass	Sweet Sorghum
Global warming	kg CO_2 eq	-1833	-1753	-1797	-1845	-1793	-1517	-1423
Acidification	H+ moles eq	24	28	27	24	24	45	25
Carcinogenics	kg benzene eq	0.03	0.04	0.02	0.02	0.02	0.11	0.06
Non carcinogenics	kg toluene eq	359	432	351	323	328	1105	870
Respiratory effects	kg PM2.5 eq	0.03	0.04	0.03	0.03	0.03	0.12	0.06
Eutrophication	kg N eq	0.03	0.04	0.03	0.02	0.02	0.48	0.43
Ozone depletion	kg CFC-11 eq	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity	kg 2,4-D eq	13	16	10	9	9	21	12.87
Smog	kg NOx eq	0.54	0.61	0.61	0.53	0.53	0.62	0.36

*With burden scenario allocates emissions associated with the production and growth of the primary biomass product to the residues left behind

To compare feedstocks in each impact category, the results were expressed as a percent of the highest emissions in each category (the feedstock with the highest emissions was expressed as 100%) (Fig. 16).

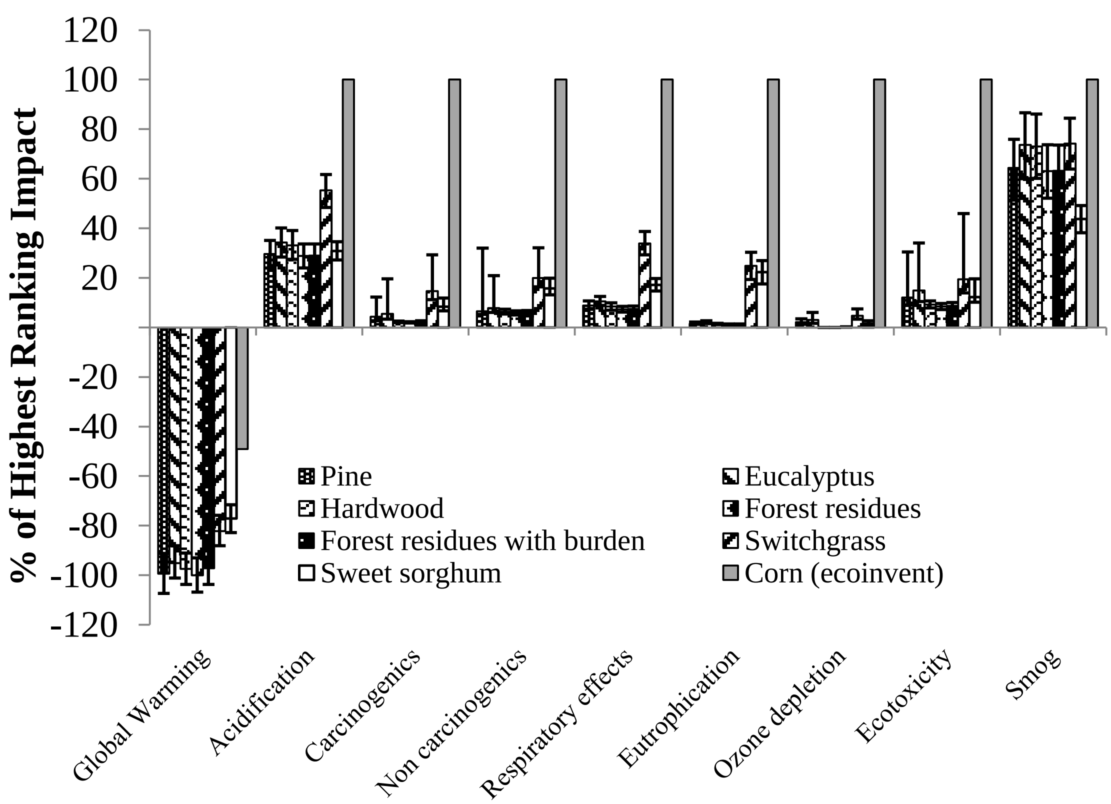


Fig. 16. Environmental and human health impacts from SimaPro using the TRACI 2 impact assessment method for biomass feedstocks relative to the feedstock scenario with the highest impact for each impact category. Assumptions: 500,000 BDT/year (453,592 metric tonnes/year) delivered to a single facility, medium biomass productivity, and 10% covered area

When displaying results in this way, however, it is difficult to gauge relevancy of the differences in each impact category. To judge relevancy, Fig. 16 should be interpreted with the magnitude or value of each impact category in mind, as listed in Table 9 relative to the global, national, regional, or per capita emissions of each category, but is not performed herein. As a comparison to a baseline feedstock, delivered corn production was compared with the analyzed feedstock scenarios. Corn has been the primary feedstock for first generation ethanol and serves as a baseline. Since this study did not account for nutrient runoff and other emission due to field application of chemicals, the corn scenario from the ecoinvent database (ecoinvent Centre 2007) was modified by removing nutrient runoff and direct air emissions. However, the N_2O GHG emission for corn was not removed, as this emission was also accounted for in the other biomass scenarios.

All of the studied biomass scenarios were determined to have lower environmental impacts than the corn baseline scenario in all categories. For the examined biomass scenarios, forest-based feedstocks had similar impacts in all categories. The minor differences in the impacts of forest-based feedstocks were considered to be within the range of uncertainty. This uncertainty was determined through Monte Carlo analysis within a SimaPro model. The growth of agricultural feedstocks, switchgrass, and sweet sorghum resulted in larger impacts in all categories compared to forest-based feedstocks, except for smog, which was similar to forest-based feedstocks. Higher fertilizer, pesticide, herbicide, and machinery fuel usage required for agricultural feedstocks resulted in increased impacts across most categories relative to forest-based feedstocks (Fu *et al.* 2003; Kim and Dale 2005; Goglio *et al.* 2012).

Because data surrounding nutrient runoff for these cultivation practices were not present in literature and are site dependent, nutrient runoff was not incorporated in this model. If these impacts were included, the eutrophication impact of agricultural feedstocks is expected to increase by a larger percentage than forest feedstocks, due to the higher fertilizer application rates and more frequent soil disturbances (Schneider and McCarl 2003; West and Marland 2003; Reijnders and Huibregts 2009; de Vries *et al.* 2010).

Greenhouse Gases and Delivered Cost

Agricultural feedstocks, such as switchgrass and sweet sorghum, were determined to have a higher delivered cost per BDT and higher net GHG emissions compared to pine, eucalyptus, and forest residues (Figure 17). Unmanaged hardwood was determined to have similar net GHG emissions and a delivered cost per BD tonne as the managed forest-based biomass scenarios. For sweet sorghum, both GHG emissions and project financial performance were significantly diminished by biomass storage losses and establishment and maintenance operations and costs. If net GHG emissions are based on per land per time functional units, as shown in Fig. 18, the less productive unmanaged hardwood captured less carbon (as CO_2) than the other feedstocks during feedstock production.

Conversion facilities that use carbohydrates often compare viable feedstock sources on a cost per tonne of carbohydrates basis to account for conversion efficiency. The delivered cost per tonne of carbohydrates and net GHG emissions are plotted in Fig. 19. In this comparison, switchgrass had a higher delivered cost per tonne of carbohydrate than all other biomass scenarios.

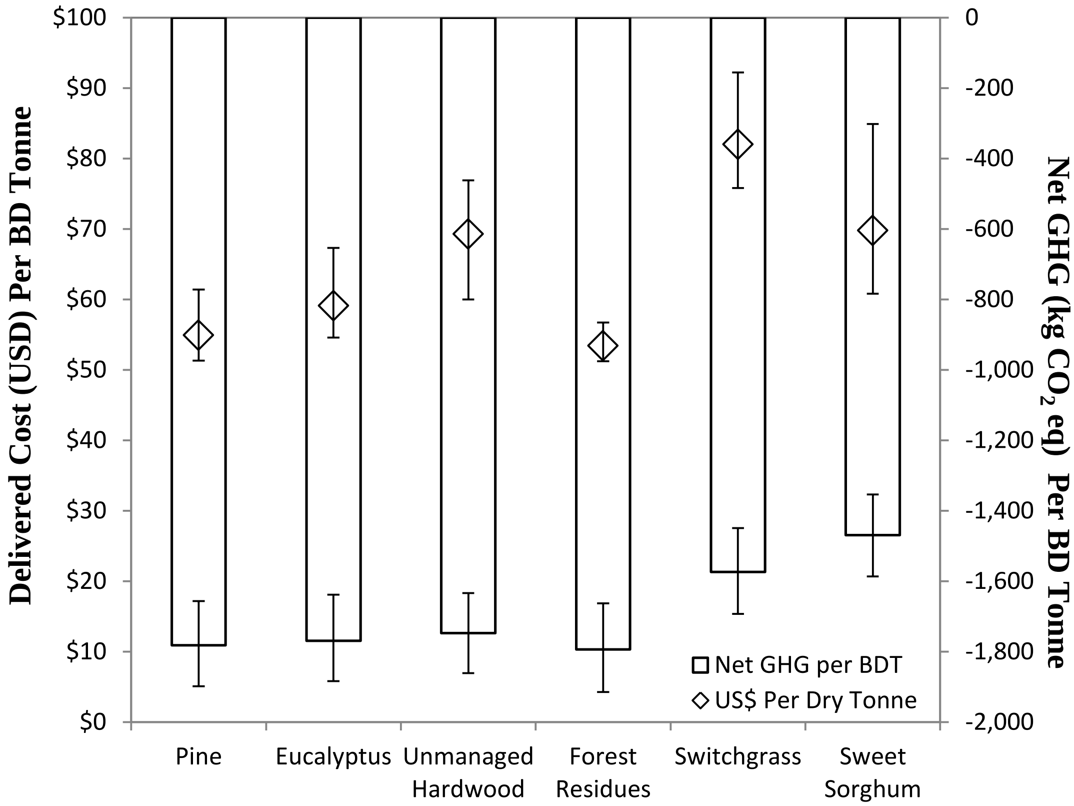


Fig. 17. Delivered biomass cost for 500,000 BDT (453,592 metric tonnes) per year and GHG captured per tonne of biomass, assuming medium productivity and 10% covered area. The error bars represent the range of uncertainty due to feedstock productivity (low, medium, and high).

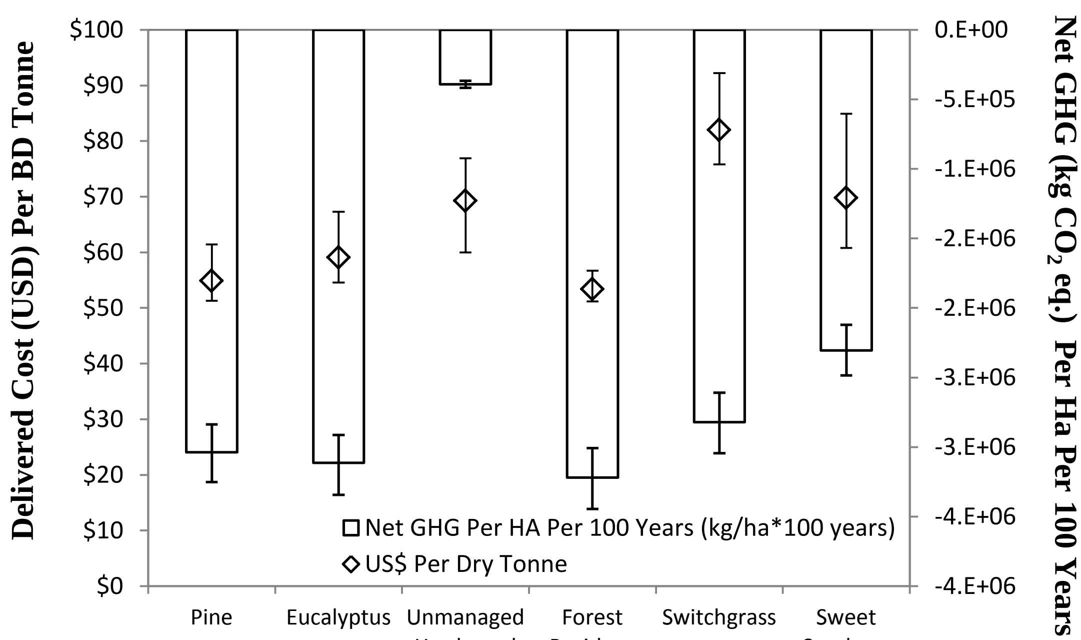


Fig. 18. Delivered biomass cost per BD tonne and net GHG (kg CO_2 eq.) per hectare over 100 years, assuming 500,000 BDT (453,592 metric tonnes) delivered per year, medium productivity, and 10% covered area. The error bars represent the range of uncertainty due to feedstock productivity (low, medium, and high).

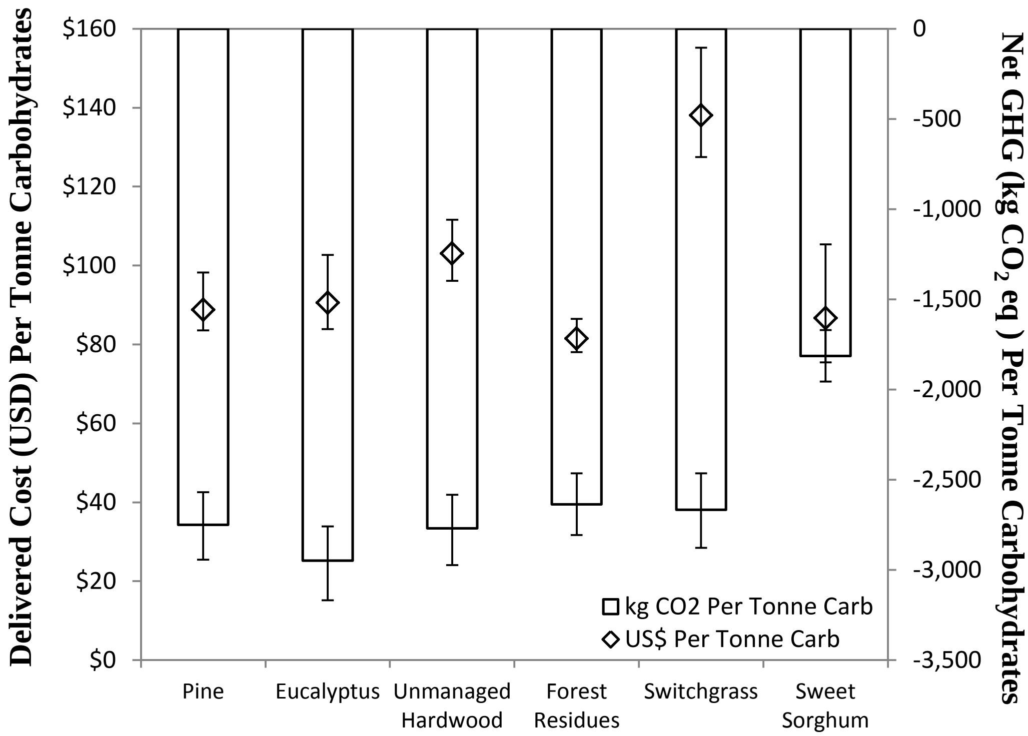


Fig. 19. Delivered cost and net GHG (kg CO_2 eq.) per BD tonne of carbohydrate assuming 500,000 BDT (453,592 metric tonnes) per year and carbon captured per hectare over 100 years, assuming medium productivity and 10% covered area. The error bars represent the range of uncertainty due to feedstock productivity (low, medium, and high).

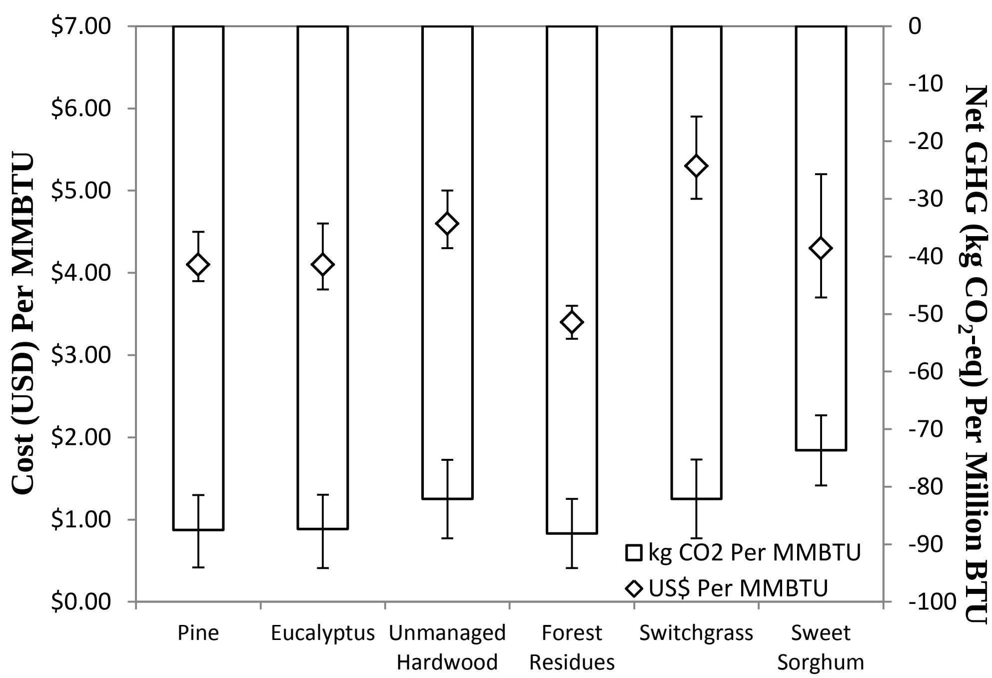


Fig. 20. Delivered cost and net GHG (kg CO_2 eq.) per MMBTU assuming 500,000 BDT (453,592 metric tonnes) per year and carbon captured per hectare over 100 years, assuming medium productivity, and 10% covered area. The error bars represent the range of uncertainty due to feedstock productivity (low, medium, and high).

Sweet sorghum had higher net GHG emissions because it is an annual energy crop requiring annual establishment and maintenance activities, whereas forest-based feedstocks, and even switchgrass, require fewer or less frequent establishment and maintenance activities.

The comparison of delivery cost and net GHG emissions per MMBTU of energy is shown in Fig. 20. The switchgrass scenario had the highest delivery cost, primarily due to a lower heating value (Table 1) and higher per dry tonne cost.

Cellulosic biomass compared to other fuel sources

Other carbohydrate and energy sources are currently commercially available. For biochemical ethanol conversion, corn (in the USA) and sugarcane (in Brazil) have been successfully utilized on a commercial scale as carbohydrate sources to produce ethanol (Liska *et al.* 2009; Seabra *et al.* 2011). These feedstocks have been compared to the lignocellulosic and agricultural feedstocks from this study in Fig. 21 with a plot of delivered cost per tonne carbohydrates *versus* GHG emissions per tonne carbohydrates. The bottom left quadrant represents the most ideal characteristics of feedstocks- low cost and low emissions. The upper right quadrant represents the worst performance, with high emissions and delivered cost. Feedstocks other than sweet sorghum are closely grouped, displaying similar results on a per tonne carbohydrates basis. The sweet sorghum scenario delivers carbohydrates at a significantly lower price but with greater GHG emissions.

Corn and sugar cane delivered cost values were calculated using data from Kim and Day (2011), and the cradle-to-gate emissions for corn were calculated in Kim and Dale (2005). Sugar cane emissions were modeled in SimaPro using the ecoinvent inventory database (ecoinvent Centre 2007). Other corn and sugarcane costs and GHG emissions were found in the literature and were used here for a basis of comparison (Kim and Dale 2005; Petrolia 2008; Pimentel and Patzek 2008; Vadas *et al.* 2008; Wang *et al.* 2009; Crago *et al.* 2010; Mani *et al.* 2010; Morey *et al.* 2010; Sokhansanj *et al.* 2010; Seabrea *et al.* 2011).

Due to regional biomass growth characteristics, sugarcane would not be a suitable potential biomass for the southern U.S. Given these geographical restrictions, sugarcane production yields, delivered costs, and GHG emissions were similar to sweet sorghum. Not accounting for uncertainty of data, the sugarcane carbohydrates appeared to be slightly cheaper with larger GHG emissions. Corn, widely used for bioethanol production in the USA, had the highest cost per tonne of carbohydrate and also produced the largest GHG emissions per tonne carbohydrates.

Many previous LCA studies and net energy calculations have shown that the corn feedstock production process often produces higher life cycle emissions than an equivalent volume or energy output of conventional fuel, such as gasoline (Berthiaume *et al.* 2001; Pimentel 2001; Graboski 2002; Shapouri *et al.* 2002; Pimentel 2003; Schneider and McCarl 2003). The sugarcane feedstock production system has been studied less than the corn production system; however, Macedo (1998) did calculate life cycle emissions and net energy ratio (NER) for the production system. The calculated NER for Brazilian sugarcane was 7.9, whereas the NER for American corn production (cradle-to-gate) was 1.3 at best. For comparison, American corn stover has an NER of 5.2 and Indian bagasse has an NER of 32 (von Blottnitz and Curran 2007).

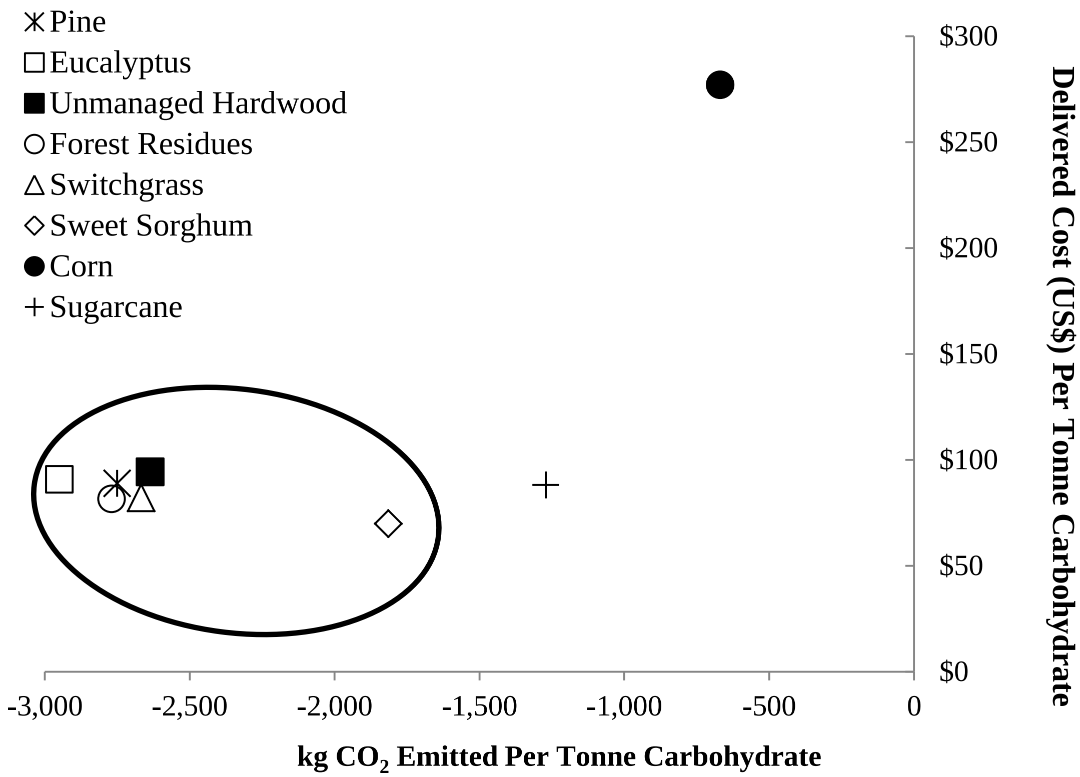


Fig. 21. Delivered cost and CO_2 emitted per tonne of carbohydrate for biomass feedstocks and literature references for corn and sugarcane carbohydrates (soluble sugars and lignocellulosic carbohydrates), assuming 500,000 BDT/year (453,592 metric tonnes/year), medium productivity, and 10% covered area. Note: land use change impacts are not included in this figure.

Biomass for electrical production is commercially viable in some locations in the USA, such as the Craven County, North Carolina waste biomass-to-heat facility. It is dependent on the biomass heating value (McKendry 2002; Caputo *et al.* 2005). Since thermochemical conversion processes are also sensitive to heating values, a comparison of feedstocks by heating value can provide valuable information about the feasibility of feedstock use for thermochemical conversion to ethanol. Figure 22 compares pine, eucalyptus, unmanaged hardwoods, forest residues, and switchgrass to traditional fuel types, including natural gas and coal. This analysis only quantifies the incoming heating value of the dry biomass. The actual production of electricity will depend on moisture content and other biomass properties.

Pine, eucalyptus, switchgrass, and forest residues all resulted in similar GHG emissions per MM BTU. The delivered cost for switchgrass was significantly higher than the forest-based feedstocks, whereas forest residues were the cheapest. Biomass delivered cost per MM BTU was much higher than coal and similar to natural gas, ranging from one dollar more expensive than natural gas (switchgrass) to nearly one dollar cheaper than natural gas (forest residues). Natural gas, on the other hand, had significant positive GHG emissions in comparison to the negative GHG emissions for biomass feedstocks. Though the GHG emissions for coal were less than natural gas, they were still positive and much higher than the biomass feedstocks. Also, since the fossil fuels are not the end product, such as heat or electricity, combustion efficiencies and emissions must be considered when determining fuel sources with the overall lower impact.

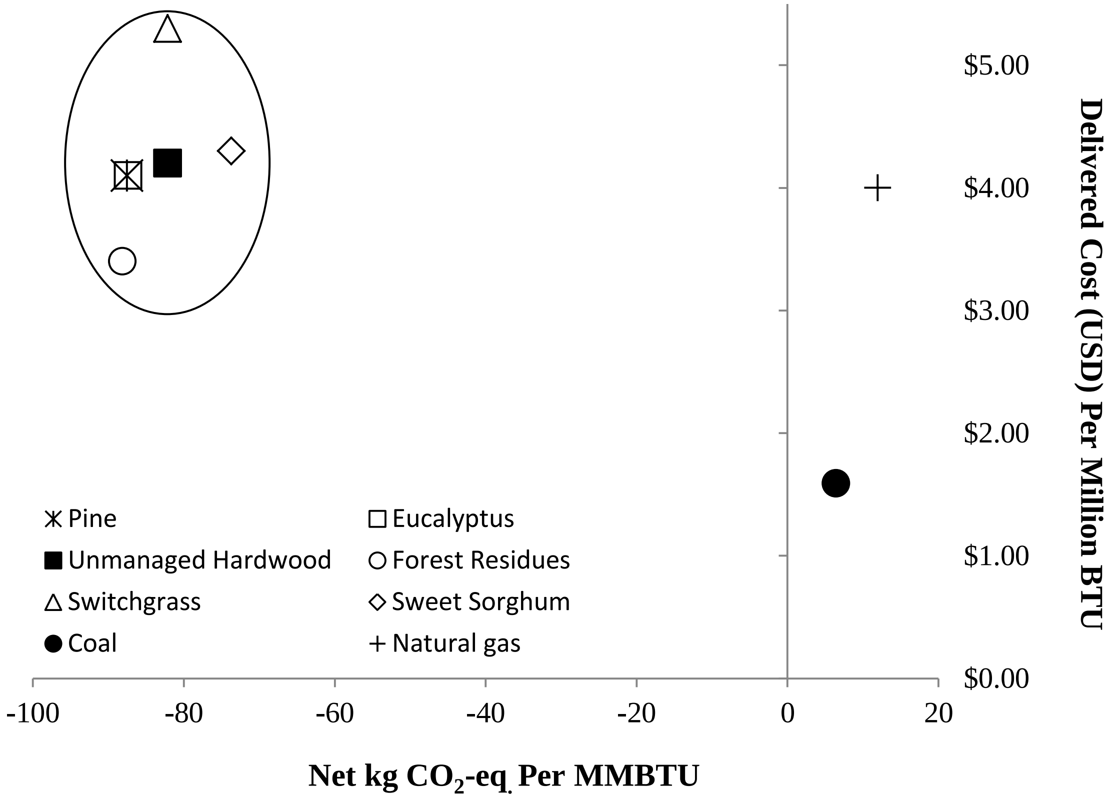


Fig. 22. Delivered cost and CO_2 emitted per MM BTU for analyzed biomass feedstocks and comparable fossil fuels (coal and natural gas based on NREL 2003 emissions data), assuming 500,000 BDT/year (453,592 metric tonnes/year), medium productivity, and 10% covered area

SUMMARY

Six non-food, cellulosic feedstock supply systems were analyzed for supply chain, delivered cost, and environmental life cycle burdens. A supply chain analysis included establishment and maintenance, harvest and storage, as well as transportation. A robust financial analysis model was created for each feedstock scenario, taking into account the cost of establishment and maintenance, herbicide and fertilizer inputs, harvest and collection activities, storage facility specifics, and transportation distance and truck type. Environmental life cycle burdens were analyzed for all six feedstock supply scenarios using LCA software and inventory data.

Supply Chain

The steps included in the biomass supply chain are critically important to the supply chain and the financial feasibility of each feedstock scenario. The agricultural biomass feedstocks had a higher delivered cost than the wood-based feedstocks due, in part, to a longer storage period, more frequent establishment and maintenance activities, and degradation of the biomass during storage.

Delivered Cost

Table 10 was developed to better analyze the relative feasibility of the studied feedstocks for continuous supply to bioethanol and biopower producers in the southern U.S. From this comparison, it was evident that forest residues production was the lowest cost feedstock scenario for all three cost metrics, followed by loblolly pine and eucalyptus. The sweet sorghum production scenario resulted in higher values in the metrics of dry tonne cost, delivered energy cost, and environmental burdens. This relative comparison does not consider conversion costs which can be lower for sweet sorghum due to high soluble sugar concentrations suitable for biochemical conversion to ethanol. Forest residues appear to fulfill all requirements for being considered a good candidate for ethanol and power production, but the volume of feedstock available, cost, environmental impact, and convertibility of the feedstock must also be considered.

Table 10. Scoring of Analyzed Feedstocks for Delivered Costs and Net GHG Emissions from Lowest (Top) to Highest (Bottom)

	US$ / Dry Tonne	US$ / Tonne Carb	$ / MMBTU	kg CO_2 eq./ Tonne
Lower -->	Forest Residues	Forest Residues	Forest Residues	Forest Residues
	Pine	Sorghum	Pine	Pine
	Eucalyptus	Pine	Eucalyptus	Eucalyptus
	Hardwood	Eucalyptus	Sorghum	Hardwood
	Sorghum	Hardwood	Hardwood	Switchgrass
Higher -->	Switchgrass	Switchgrass	Switchgrass	Sorghum

Loblolly pine, eucalyptus, and forest residues can be supplied at a lower delivered cost per tonne than unmanaged hardwood, switchgrass, and sweet sorghum. Of the feedstocks analyzed, forest residues were determined to have the lowest delivered cost per dry tonne, per ton carbohydrate, and per MMBTU, and were the most financially attractive feedstock for bioethanol and bio-power production.

All forest-based and agricultural lignocellulosic feedstocks had similar biomass growth and collection area, except for unmanaged hardwood and forest residues due to lower yield and productivity per hectare. Therefore, all feedstocks had a similar transportation distance except for forest residues and unmanaged hardwoods.

Feedstock chemical compositions greatly differentiated agricultural feedstocks from lignocellulosic feedstocks, as was evident when the delivered cost per tonne of carbohydrate was compared. Forest-based feedstock production allowed for lower delivered cost per carbohydrate and energy content. Switchgrass had the highest cost, due to lower carbohydrate content in the biomass and higher per tonne delivery costs. It is important to consider chemical composition alongside yield and productivity factors when predicting the cost per delivered tonne of carbohydrate. The same is true of cost per delivered MMBTU, since chemical composition plays a large role in the heating value of a feedstock.

Environmental Life Cycle Burdens

This study determined that wood-based biomass feedstocks can lower impacts and emit less net GHG than agricultural biomass feedstocks (cradle-to-gate) when used for renewable energy production. It is also evident that increased productivity due to intensive management greatly reduces the cost and GHG emissions of a biomass supply system over 100 years of management. Land use change impacts further reduce the environmental burden of forest-based lignocellulosic biomass supply systems, whereas land use change impacts for agricultural biomass supply systems increase net life cycle impacts.

While distinction between feedstocks for the establishment, maintenance, harvest, storage, and transportations stages is possible, the sum of these biomass life cycle stages on net GHG emissions represents a minimal fraction of the net life cycle emissions, due to the relatively large quantity of CO_2 taken up during biomass growth. Additionally, land use change represents a significant portion of the net GHG emissions for all feedstock scenarios. Yield and productivity are much more important to the delivered cost and net GHG emissions in a feedstock scenario than the transportation distance, harvest time, and degradation upon storage.

CONCLUSIONS

1. Forest-based feedstocks, especially forest residues, can be delivered at a lower cost and with a lower environmental burden than agricultural feedstocks.
2. Agricultural feedstock storage resulted in significant GHG emissions and increased overall cost of feedstock production.
3. Sweet sorghum, with a low delivered cost per ton of carbohydrate and soluble sugar content, is an advantageous feedstock choice for biochemical conversion pathways.
4. Replacing fossil-based energy and fuel feedstocks with cellulosic biomass feedstocks would greatly reduce cradle-to-gate greenhouse gas emissions.
5. All studied biomass scenarios had lower TRACI 2 environmental impacts than the corn baseline comparison.
6. Agricultural biomass scenarios resulted in higher values than forest-based biomass in most TRACI 2 impact categories; however, there was some uncertainty determined, and many of these differences were not significant. When comparing agricultural to forest biomass types, the impact categories of eutrophication, global warming, respiratory effects, and acidification (switchgrass) were most significantly different.
7. Agricultural feedstocks require higher levels of chemical inputs, fossil fuel, and storage requirements than forest-based biomass, and these additional requirements increase environmental impacts and costs.
8. These findings can be combined with a full cradle-to-grave LCA of biomass-to-biofuel production systems, such as biochemical conversion, thermochemical conversion, and combustion for power, to inform stakeholders about the economic, social, and environmental costs of renewable energy feedstock options for commercial facilities.

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