BIOMASS TO ENERGY IN THE SOUTHERN UNITED STATES: SUPPLY CHAIN AND DELIVERED COST

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Supply chain and delivered cost models for seven feedstocks (loblolly pine, *Eucalyptus*, natural hardwood, switchgrass, *Miscanthus*, sweet sorghum, and corn stover) were built, simulating a supply of 453,597 dry tons per year to a biorefinery. Delivered cost of forest-based feedstocks ranged from $69 to $71 per dry ton. On the other hand, delivered cost of agricultural biomass ranged from $77.60 to $102.50 per dry ton. The total production area required for fast growing feedstocks was estimated as between 22,500 to 27,000 hectares, while the total production area for feedstocks with lower biomass productivity ranged from 101,200 to 202,300 hectares (corn stover and natural hardwood, respectively). Lower delivered cost per ton of carbohydrate and million BTU were found for loblolly pine, *Eucalyptus,* and natural hardwood. In addition, agricultural biomass had higher delivered costs for carbohydrate and energy value.

Keywords: Biomass; Pine; Hardwood; Eucalyptus; Switchgrass; Corn stover; Miscanthus; Sweet sorghum; Delivered cost; Supply chain; Bioenergy

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INTRODUCTION

Tax incentives and government mandates worldwide have resulted in a gradual increase in bioethanol production, primarily driven by Brazil and the USA, with a combined world market share of ca. 86% (RFA 2010). The United States alone has drastically increased bioethanol production by 210% since 2005 (RFA 2010; Gonzalez et al. 2011a). However, bioethanol production scale-up in the USA and Brazil relies on the use of corn and sugar cane (respectively) as the main feedstocks (Goldemberg et al. 2004; Goldemberg 2007). The use of food sources as feedstocks for fuel production has sparked an international debate, referred to as the “food vs. fuel” debate, and involves a wide variety of potential social, environmental, economic, and political problems (Erickson et al. 2007; Runge et al. 2007; Mitchell 2008; Tenenbaum 2008; Foust et al. 2009; Wu et al. 2010). Increased demand for food products has resulted in price pressures in markets either as direct pressure, through growing demand and changes in consumption patterns as incomes rise, or indirect, as alternative uses of food crops, such as for biofuels (OECD 2008). Nevertheless, there is no consensus on how large the impact of biofuels production is on food price increases (Mitchell 2008; OECD 2008; Mueller et al. 2011).

This debate is not just fueled by rising feed prices. Some authors support the claim that farmers will no longer grow less profitable food crops in favor of more profitable corn crops (Sullivan 2003; Leibtag 2008). In addition to the “food versus fuel debate," it is known that corn alone cannot supply the growing ethanol industry within the United States (Bohlmann 2006; Yacobucci et al. 2007). These findings have created and obvious need for an alternative to food-based raw material.

The search for new biofuel feedstocks has driven engineers and scientists towards cellulose-based plant materials. Cellulose is the most abundant polymer on earth and has been used as an energy source for heating since ancient times. As of 2004, this type of biomass contributed ca. 13.4% of the global energy supply (Sims et al. 2006; Heinimö et al. 2007). One of the main advantages of cellulosic biomass is its flexibility to be used to produce different forms of energy; it can be used in a solid state as raw material to generate heat, steam, and electricity, but it can also be further processed to produce liquid biofuels used for transportation (Jackson et al. 2010; Gonzalez et al. 2011a). In this sense, several authors anticipate an increase in the global demand for biomass to be used for bioenergy (Ericsson et al. 2004; Parikka 2004; Hillring 2006; Junginger et al. 2008). This increase in demand is mostly driven by legislation in countries such as the Netherlands, India, China, Thailand, New Zealand, Canada, and the U.S. (Sims et al. 2006). For example, the European Union (EU) has created targets requiring renewable energy to account for 20% of the total energy production by 2020, and with a specific 10% target for renewable energy in transportation (EU 2011). Moreover, some EU countries, such as Sweden, are requiring that 40% of their primary energy supply come from biomass by the year 2020 (Faaij 2006), while Finland has established a goal of 38% renewable energy (Tohka et al. 2009). As of May 2010, the Swedish Bioenergy Association reported that bioenergy provided 31.7% of the total energy used in Sweden in 2009, displacing oil to second position with 30.8% of the energy share (Focus 2010; Gibson 2010). For the U.S., the Environmental Protection Agency has announced ambitious goals in advanced biofuels and cellulosic biofuel production, with a target of 1 billion gallons of cellulosic biofuel by 2013 and 16 billion gallons by 2022 (EPA 2010).

Considering that, i) cellulosic feedstock is the major cost in biomass to bioenergy production (Tao et al. 2009; Pirraglia et al. 2010b; Gonzalez et al. 2011c), ii) marketplace economics, which include type and availability of biomass, should be considered to decide which conversion approach would be used (Faaij 2008; Blaschek et al. 2009; Mu et al. 2010), and iii) projects that are not endorsed with sufficient feedstock supply are likely to have a difficult time obtaining external funding (Johnson 2010a,b); extensive research in feedstock production and economics is justified. The best approach to lowering the delivered cost of biomass may include the use of fast growing species and highly productive perennial grasses (Gonzalez et al. 2009; Wu et al. 2010; Gonzalez et al. 2011d). Recently, many publications have analyzed biomass as feedstock for energy production, mostly based on productivities, chemical composition, and species adaptation to different sites. Despite the increasing number of papers surrounding biomass economics, it still remains a challenge to compare supply chain characteristics and the delivered cost of biomass between different publications, due to wide variations in study assumptions and financial indicators used. A more consistent supply chain and delivered cost structure is needed, in order to be able to compare biomass types under the same economic basis and conditions.

Since the concept of supply chain is centrally featured in this paper, it is important to include its definition. Supply chain has been defined as "a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances and/or information from a source to a customer"(Mentzer et al. 2001). The interface between supply chain issues and bioenergy is of great relevance, because the question how bioenergy systems are implemented crucially determines whether bioenergy projects are evaluated favorably or unfavorably (Gold et al. 2010; Gold 2011).

Objective

This study presents the supply chain and the delivered cost of biomass for six dedicated energy crops and one agriculture residue, comparing productivities, delivered cost, sourcing freight distance, supply chain challenges and land area required for an annual supply of 500,000 BDT (bone dry ton short ton) per year (453,597 dry metric tons per year equivalent) to a specific biorefinery.

MATERIAL AND METHODS

The structure of this manuscript is here disclosed to provide a better understanding for the different sections and information provided. In materials and methods, a section on *Feedstock Selection* describes the criteria used in the selection of potential candidates. In the *Feedstock Description* section a background is provided for each of the selected candidates, with information regarding biomass production and natural geographical occurrence. Then the *Chemical Composition* section provides a brief discussion about the types of carbohydrates found in those feedstocks (making also the distinction between first and second generation biofuels). The *Basis for Evaluation* section discusses the major assumptions considered for the comparison of the different feedstocks in terms of annual supply, percentage of covered area, biomass productivity, as well as how the economic analysis was performed. The costs of establishment, maintenance and harvesting are then presented followed by two sections on Freight and Storage and Biomass Loss.

Feedstock Selection

The selection of potential agricultural and forestry energy crops was based on an extensive literature review and interactions with specialists in the biomass and bioenergy arena. From this review, several key parameters were identified to select the feedstocks:

i. High biomass productivity per unit area, measured in dry tons (metric tons) per hectare per year.
ii. Lignocellulosic biomass not currently used for food or feed.
iii. High carbohydrate content in dry biomass basis, suitable for biochemical and thermochemical conversion into ethanol.
iv. Current availability of that biomass growing in the southeastern U.S.
v. Species with published information on biomass productivity, carbohydrate content, establishment and maintenance costs, and harvesting costs, as well as other biomass properties such as bulk density and moisture content when harvested. This published data will enable a more accurate economic analysis.

vi. Information on the performance of the biomass in existing and proposed conversion technologies for cellulosic ethanol production.

Based on the listed criteria, the following feedstocks were selected for further study: fast growing loblolly pine, *Eucalyptus*, mixed natural hardwood, switchgrass, *Miscanthus*, corn stover, and sweet sorghum. Biomass productivity (unless otherwise stated) is presented in dry (metric) tons. Eco-physiological characteristics and life cycle impact of potential feedstocks were not considered for this publication. It is important to mention that feedstock selection presented in this paper is mainly considered for Southern U.S.

FEEDSTOCK DESCRIPTION

Loblolly Pine

Loblolly pine (*Pinus taeda*) is an abundant softwood species in the southern U.S., covering almost 29 million acres (11.7 million ha) and accounting for 20% of the standing pine volume in 2007 (Baker et al. 2008). In addition, loblolly pine is an important source for saw timber and pulp wood. In 2002 this species provided nearly 73% of the total roundwood softwood volume in the southern U.S. (Johnson et al. 2003). It grows naturally from central Florida, to as far north as Delaware and New Jersey, and as far west as east Texas and southeast Oklahoma (Schultz 1999). In Georgia, intensively managed short rotation (10 to 12 years) loblolly pine plantations, with tree stand density between 608 to 652 trees per acre, have been reported to produce around 26.6 m^3/ha/year (12.8 dry $tons^{-1}$ ha $year^{-1}$) for pulpwood (Borders et al. 2001). Loblolly pine has been studied for alcohol production, and results showed that ethanol production from this species might be economically competitive, compared to ethanol from corn stover and other lignocellulosic materials (Frederick et al. 2008a). However, improvement in enzymatic hydrolysis and conversion of pentoses into monomeric reactable sugars still needs more research to insure technical and economic success (Frederick et al. 2008a; Frederick et al. 2008b).

Eucalyptus

Eucalyptus (*Eucalyptus* sp.) is among the fastest growing hardwood plantation genera in the world. In addition, eucalypts have been used for plantation-grown 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 as well. *Eucalyptus* plantations in the southern U.S. can be successfully established using improved seedlings that are freeze tolerant, grown in specific regions such as Florida, Georgia, Alabama, Texas, and South Carolina. In 2010 the Forest Nutrition Cooperative at North Carolina State University established freeze tolerant *Eucalyptus* trials to better understand biomass productivity and survival for several regions in the U.S. Rotation length and yields for pulpwood can be 5 to 8 years with a mean annual increment (MAI) of 8 to 16 green tons $acre^{-1}$ $year^{-1}$ (10 to 20 dry ton ha^{-1} $year^{-1}$). However, rotation length for energy crop biomass can be 3 to 4 years with MAI of 10 to18 green tons per acre per year (12.3 to 22.4 dry ton ha^{-1} $year^{-1}$) (Gonzalez et al. 2009). As an energy crop, this species has been researched for pellets and ethanol production (Ferrari et al. 1992; Gonzalez et al. 2011c,d).

Mixed Hardwood - Natural Regeneration

Mixed natural hardwood represents cellulosic biomass currently available for conversion across the southern U.S. As of 2007, the state of North Carolina alone had a total of 10.2 million acres (4.13 million hectares) of natural hardwood forests along with nearly 2.3 million acres (0.9 million hectares) of mixed hardwood and pine natural forests. Natural hardwood rotation length management may range from 30 to 50 years (Cassidy 2005). Growth rate and species composition varies according to soil types, climatic conditions, and age of the forest. Based on data obtained from the Forest Inventory Data Online, the natural hardwood forest growth rate in the state of North Carolina (as of 2007) was close to 0.9 dry ton ha^{-1} year^{-1}, only including trees with a diameter of more than 5 inches at breast height (USDA, 2010a). For transportation costs and distance calculations, total biomass growth per year was assumed at around 2.2 dry ton ha^{-1} year^{-1}. This assumption is based on the estimated native forest growth rate of 2.5 dry ton ha^{-1} year^{-1}, though this rate will depend on soil and climate characteristics, as well as species composition (SunGrant-BioWeb 2010a). Species composition of natural hardwood forests in North Carolina may include: white and red oaks, hard and soft maples, hickory, yellow birch, beech, sweetgum, tupelo, cottonwood, aspen, and yellow poplar (USDA 2010a).

Switchgrass

Switchgrass (*Panicum virgatum* L.) is a perennial grass native to North America. This species has been identified as a potential biomass feedstock for bioenergy and is currently being studied across the U.S. to understand its growing conditions and production costs (Cundiff et al. 1996; Epplin 1996; Wiselogel et al. 1996; McLaughlin et al. 2005; Kumar et al. 2007; Austin 2010a,b). 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 ton ha^{-1} year^{-1} (McLaughlin et al. 2005; Perrin et al. 2008; Austin 2010a,c). Harvesting period of switchgrass ranges from three to four months per year; currently studies are being developed to expand the harvesting windows to reduce storage costs. Switchgrass can be harvested in different seasons of the year, though studies are looking to understand the tradeoff of harvesting switchgrass in different seasons and its impact in long term productivity (Adler et al. 2006). The moisture content of switchgrass when harvested after the first freeze and early spring is ca. 16% (Haq 2002).

Miscanthus

Miscanthus sp. is a perennial plant native to tropical, subtropical, warm, and temperate parts of Southeast Asia and is related to sugar cane. Very limited research has been conducted regarding the characteristics of *Miscanthus* species in the Unites States. However, in Europe, *Miscanthus* has been studied for bioenergy production (SunGrant-BioWeb 2010b). When grown in Europe, *Miscanthus*' productivity has been estimated to be between 4.5 and 31.4 dry tons ha^{-1} year^{-1} (Lewandowski et al. 2000; Clifton-Brown et al. 2001). Biotechnology companies in the USA are developing material with better genetics and with expected productivity between 8 to 16 dry tons per acre per year

(White-Technology 2010). Rotation length in the U.S. may vary from 10 to 25 years; however, the tradeoff between productivity and rotation length must be further studied. If harvested in April/May, the moisture content of *Miscanthus* can range between 12% and 15% (Kristensen 2003); however, this delayed harvest in late spring may reduce dry biomass yields, but improves biomass quality, as moisture content is drastically reduced, making feedstock drying unnecessary (Dopazo et al. 2010). U.S. rotation length has been suggested at 10 years, with average productivities ranging from 22.4 to 36 dry ton ha^{-1} year^{-1} (Heaton et al. 2004).

Sweet Sorghum

Sweet sorghum (*Sorghum sp.)* is a biomass crop similar to sugar cane in regards to its sugar content. The plant has high sucrose content and offers additional carbohydrate material in the bagasse. The sucrose contained in its juice is a fermentable sugar that requires minimum pretreatment for ethanol production (Gnansounou et al. 2005; Reddy et al. 2005; Prasad et al. 2007; Almodares et al. 2009). Additionally, sweet sorghum has been identified as a possible ethanol feedstock due to biomass productivity and the concentration of readily fermentable sugars, as previously mentioned. Yet, due to a short harvest window and poor post-harvest storage characteristics, the use of sweet sorghum has been limited (Bennett et al. 2008, 2009). This crop has a rotation length of approximately 4 months, with harvesting windows of approximately 3 months (Rajvanshi 1996; Stotts 2008). When harvested, sweet sorghum cane moisture content is around 70% to 75% (Jasberg et al. 1983; Prasad et al. 2007). Due to its short growing time, it is possible to grow two cycles of sweet sorghum per year, depending on climate conditions (Brekke 2005; Reddy et al. 2005; Mattews 2009; Veal 2010a). However, expected biomass yield per crop cycle may be reduced with biannual harvests. For annual harvests in the southern U.S., typical dry matter production varies from around 13.5 to 22.4 dry ton ha^{-1} year^{-1} (Irvin et al. 2001; Bennett et al. 2008, 2009). In addition, the production of sugar per acre in a sweet sorghum plantation is positively correlated with dry biomass production (Bennett et al. 2008, 2009). For this analysis it was assumed that sweet sorghum is simultaneously harvested and chopped in field and transported to the biorefinery for sugar extraction. After sugar extraction the resulting residues (bagasse) are expected to be stored for further processing for alcohol or power production.

Corn Stover

Corn stover is the residue left after corn grain harvesting. When harvested, corn stover has low moisture content (16% to 20%) with a low bulk density (8.1 lb per ft^3) (Womac et al. 2005; Glassner et al. 2008; Dopazo et al. 2010). Corn stover supply economics, pretreatments, and enzymatic hydrolysis have been studied to determine the feasibility of utilizing corn stover as feedstock for ethanol production (Aden et al. 2002; Kadam et al. 2003; Kim et al. 2005; Öhgren et al. 2007; Wilhelm et al. 2007; Petrolia 2008). Corn stover production per acre is related to the production per acre of corn grain. To estimate corn stover availability, a ratio of 1:1 corn grain to corn stover (on a dry basis) is commonly used (Perlack et al. 2003; Lee et al. 2007). In North Carolina, an average corn grain productivity of 5.9 dry ton ha^{-1} year^{-1} was estimated with data from the National Agricultural Statistics Service for 2009 (USDA 2010c). Using a conservative scenario with grain–to-stover ratio of 1:0.8, an average of 4.6 dry ton ha^{-1}

year^{-1} of corn stover might be available per acre, with minimum and maximum values between 1.8 to 7.9 dry ton ha^{-1} year^{-1}. This study did not consider the minimum amount of corn stover that should be left out on the ground after harvesting to maintain soil carbon and reduce erosion.

Chemical Composition

The chemical composition for each feedstock is illustrated in Table 1. Carbohydrate content was calculated from average values found in the literature. Forest feedstocks including loblolly pine, *Eucalyptus*, and natural mix hardwood show higher carbohydrate content compared to those found in corn stover, *Miscanthus*, and switchgrass. Sweet sorghum is the only listed feedstock that readily provides monomeric sugars for fermentation. These sugars account for approximately 48% of total dry biomass, and can be sent directly to fermentation without additional costs for pretreatment. This monomeric rich stream can be extracted using a squeeze operation. The resulting solid residue called sweet sorghum bagasse can provide heat (through burning) or can be pretreated for further hydrolysis and fermentation. The availability of monomeric sugars represents a significant advantage to the conversion process; however, due to the reduced harvesting windows and high moisture content, supply chain issues arise when handling this type of raw material.

Table 1. Chemical Composition for the Forest and Agriculture Feedstock

Components	Loblolly Pine [1]	Eucalyptus [2]	Natural hardwood [3]	Switchgrass[4]	Miscanthus[5]	Sweet sorghum [6]	Corn stover [7]
Glucose						48%	
Glucans	43.6%	46.7%	42.6%	33.3%	44.0%	20.0%	35.5%
Xylans	6.6%	12.3%	15.1%	21.9%	19.0%	12.0%	19.2%
Galactans	2.2%	0.7%	1.0%	1.1%	0.0%	0.4%	0.9%
Mannans	10.8%	0.6%	2.1%	0.3%	0.0%	0.1%	0.5%
Arabinans	1.6%	0.2%	0.5%	2.9%	0.0%		2.3%
Uronic acid	3.7%	4.4%	4.7%	1.7%	0.0%		3.2%
Acetyl	1.1%	2.8%	2.7%	0.0%	0.0%		0.0%
Lignin	26.8%	29.4%	28.3%	18.1%	17.0%	10.0%	18.7%
Resins Extractives	3.2%	3.1%	2.5%	13.2%	2.5%	7.7%	5.4%
Ash	0.4%	0.1%	0.3%	5.5%	2.5%	0.9%	11.6%
Total Carb.	69.6%	67.7%	68.7%	61.2%	63.0%	80.5%	61.5%

Source: [1] (Frederick et al. 2008a), [2] (Gomides et al. 2006), [3] (Tunc et al. 2008) , [4] (DOE 2010) , [5] (Murnen et al. 2007), [6] (Prasad et al. 2007), [7] (DOE 2010).

Biofuels obtained from sweet sorghum are considered to be part of the so-called first generation biofuels, while those obtained from lignocellulosic materials (loblolly pine, switchgrass, etc.) belong to the category of second generation biofuels. First generation biofuels rely on the conversion of starch, sugar, and fat-based material into liquid fuels. Such feedstocks (also used as human feed) are cheaper for conversion, compared to second generation biofuels. On the other hand, second generation biofuels produced from plant biomass mainly refers to lignocellulosic feedstocks (considered to be cheap, abundant nonfood feedstocks). Due to the natural resistance of lignocellulosic material to be hydrolyzed (recalcitrance), current conversion processes are so far not cost effective, because of a number of technical barriers that need to be overcome (Naik et al. 2010; Gonzalez et al. 2011a; Gonzalez et al. 2011b; Gonzalez et al. 2011c). Data regarding the energy content for each feedstock (in BTU/lb) were obtained from previous studies (Ghetti et al. 1996; DOE 2010; Pirraglia et al. 2010a).

Basis for Evaluation

The delivered cost of biomass for a biorefinery with an annual capacity to process 453,597 dry metric tons per year (500,000 dry short ton) was the assumed annual supply for this study, as this can represent an average size of facilities processing biomass. For all feedstocks, a covered area of 5% was assumed (this percentage of covered area varies depending upon the type of feedstock and geographic location, a standard covered area was assumed to compare the feedstocks under the same basis). This percentage reflects the portion of area around the biorefinery growing that specific biomass. Economic spreadsheets for each feedstock considering biomass growing costs, harvesting, freight, storage (where applicable), and storage loss (where applicable) were developed. Results from these economic spreadsheets were integrated into supply chain models, considering biomass productivity (dry ton ha^{-1} year^{-1}), rotation length, and harvesting windows for each feedstock, as indicated in Table 2. Delivered cost for each feedstock is dependent on several variables. For dedicated energy crops and plantations such as loblolly pine, *Eucalyptus*, switchgrass, *Miscanthus*, and sweet sorghum, total delivered cost is composed of biomass payment to the farmer (stumpage), harvesting cost (paid to a harvesting contractor), and freight cost (paid to a freight service company). For natural hardwood biomass, the delivered cost is similar, however, a value of 80% of the market price of pulp wood stumpage is assumed.

For corn stover, biomass cost was assumed based on recent reported market values, while harvesting and freight costs were estimated using the same methodology as for switchgrass and *Miscanthus* (Edwards 2007; Kumarappan 2009). In the case of agriculture biomass such as switchgrass, *Miscanthus*, corn stover, and sweet sorghum, additional costs in storage and biomass loss during storage were considered. Biomass payment to the farmer was estimated assuming a 6% internal rate of return (IRR), harvesting cost was estimated assuming 8% IRR, freight cost were estimated assuming market values, and storage cost was estimated assuming 6% IRR profit for the business unit, plus an extra 3% cost for biomass loss during storage. For all cases, dollar values are expressed as of the first quarter of 2010. For the estimation of the IRR, a 30 year financial evaluation was considered. In the case of switchgrass, *Miscanthus*, and sweet sorghum, it was assumed crop land was leased by a farmer who was attracted to grow the bioenergy crop for a financial return, at a cost of \$135 ha^{-1} (USDA 2010b). Neither inflation nor increases in biomass price were considered. For further detail see the methodology used by Gonzalez et al. (2011b). Delivered costs were estimated based on biomass productivity values listed in Table 2, and establishment and maintenance costs illustrated in Table 3.

Table 2. Biomass Productivity, Rotation Length, and Harvesting Window

Feedstock	*dry ton ha^{-1} yr^{-1}	Rotation length (moths)	Harvesting window
[1] Loblolly pine	17.1	132	Year round
[2] *Eucalyptus*	20.2	48	Year round
[3] Natural hardwood	2.2	480	Year round
[4] Switchgrass	15.7	12	3 months
[5] *Miscanthus*	20.2	12	3 months
[6] Sweet sorghum cane	16.8	4	3 months
[7] Corn stover	4.5	4	3 months

Based on: [1]simulation using Loblolly pine decision support system (Amateis et al. 2001), [2](Hinchee et al. 2009; Gonzalez et al. 2011d), [3](USDA 2010a), [4] (McLaughlin et al. 2005; George et al. 2008; Perrin et al. 2008; Austin 2010b; Conable et al. 2010), [5] (Lewandowski et al. 2000; Clifton-Brown et al. 2001; White-Technology 2010), [6](Irvin et al. 2001; Gnansounou et al. 2005; Bennett et al. 2008; Almodares et al. 2009; Bennett et al. 2009), [7] (Kadam et al. 2003; Perlack et al. 2003; USDA 2010c).

Table 3. Trees per Hectare, Establishment, Maintenance Cost, and Harvesting Cost for the Different Feedstocks

Feedstock	Trees (per ha)	Establishment cost ($ per ha)	Maintenance cost ($ per ha)	Harvesting cost ($ per dry ton) [f]
[a]Loblolly pine	2,690	[a]1459	130	34.3
[b] *Eucalyptus*	1,271	[b]1244	135	34.3
Natural hardwood	n/a	n/a	n/a	34.3
[c] Switchgrass	n/a	[c]531	242	13.2
[d] *Miscanthus*	n/a	[d]746	242	13.2
[e]Sweet sorghum cane	n/a	[e]408	n/a	13.3
Corn stover	n/a	n/a	n/a	26.2

Source: [a and b] (Dougherty 2009; ArborGen 2010; De La Torre et al. 2010; Gonzalez et al. 2011d), [c and d] (Lewandowski et al. 2000; Duffy et al. 2001; Kumar et al. 2007; Duffy 2008; CERES 2009; Rizzon 2009; Conable et al. 2010; Veal 2010b; White-Technology 2010), [e] (Bennett et al. 2008; Bennett et al. 2009; Rizzon 2009; Veal 2010a), [f] based on harvesting models developed at NC State University 2010.

Establishment, Maintenance Cost, and Harvesting Cost

Establishment costs were estimated based on available publications and through consultation with forestry and agriculture specialists. A harvesting model developed for forestry biomass, grasses, and agriculture residues was used to estimate harvesting costs. An 8% IRR for the harvesting contractor was assumed for this model. These estimated establishment, maintenance, and harvesting costs are shown in Table 3. In the case of forestry feedstock, the biomass was delivered in the form of chips with a moisture content of ca. 45%. In the case of corn stover, switchgrass, and *Miscanthus*, biomass was delivered in form of square bales with a moisture content of ca. 16%. Sweet sorghum bagasse was delivered in the form of chopped cane with a moisture content of ca. 74%.

Freight

Freight distance was estimated using the average biomass productivity listed in Table 2 and a covered area of 5%, meaning 5% of the area around the facility was dedicated to grow that specific energy crop or plantation. Based on the annual supply, biomass productivity (dry ton ha^{-1} yr^{-1}) and percentage of covered area, the maximum freight distance to achieve sufficient biomass supply was estimated. The methodology was the same as the one used by CERES (2009) and Gonzalez et al. (2011c). Sourcing distance and market fees as of 2010 were used to estimate a freight cost of $0.13 per short green ton per mile of loaded truck, plus an additional $30 per hour of loading and unloading (NCAPL 2010). It was assumed that forestry biomass is limited by weight to 26 green short tons per truck (23.6 green metric tons), while corn stover, switchgrass, and *Miscanthus* were limited by volume, using a bulk density 8.11 lb per ft^3 (Sokhansanj et al. 2002; Scurlock 2005; Sokhansanj et al. 2006; Edwards 2007; Kaliyan et al. 2009). Sweet sorghum cane was assumed to be limited by weight to 24 tons per truck (21.8 green metric tons), due to the fact that wet bulk density of sweet sorghum is high, with values between 310-400 Kg/m^3 or 19.3-25 lb/ft^3, mainly due to its high moisture content (ca. 74% MC) (Shinners et al. 2003; Webster et al. 2004).

Storage and Biomass Loss

Storage cost and biomass loss were considered for agriculture energy crops, including switchgrass, *Miscanthus*, corn stover, and sweet sorghum. Storage cost was calculated to be $13.30 per dry ton for every type of agricultural energy crops. This estimate assumed a separate business unit achieving a 6% IRR based on an annual supply of 453,597 dry ton $year^{-1}$, with the assumption that 60% of the biomass will be stored. This biomass storage cost was similar to previously reported storage costs calculated in a similar manner by Cundiff et al. (1996) and Duffy (2008). Considering a covered storage, the cost of lost biomass was estimated by assuming an average of 3% biomass loss per year (Cundiff et al. 1996; Sanderson et al. 1997; Shinners et al. 2003; Sokhansanj et al. 2006). This percentage was then multiplied by the delivered cost of biomass and divided by the total volume per year, to calculate the total dollars lost due to storage loss ($ per dry ton).

Biomass pretreatments such as drying, pelletization, torrefaction and pyrolysis were not included in this analysis. Thought these pretreatments could improve biomass handling and energy densification that might benefit specific bioenergy conversion processes (Uslu et al. 2008; Gold et al. 2010), these pretreatments also increase the cost of the delivered biomass.

RESULTS AND DISCUSSION

Annual Productivity and Total Required Area for Production

Total production area required to supply an annual volume equivalent to 453,597 dry tons directly depends on the biomass productivity, measured in dry ton (metric) per hectare per year. Assuming an average loblolly pine biomass productivity of 17.1 dry ton ha^{-1} year^{-1} and a rotation length of 11 years, the net annual harvest area was around 2, 416 hectares (see Fig. 1) (2,416 hectares x 11 years rotation length x 17.07 dry ton ha^{-1} year^{-1} ≈ 453,597 dry ton).

This value represents the net area required to supply the targeted volume in a specific year. For continuous production, the total net area required was 26,576 hectares (2,416 hectares year^{-1} x 11 years rotation length). Based on this, it is expected that highly productive feedstocks such as *Eucalyptus*, switchgrass, and loblolly pine would require less area, when compared to less productive biomass, such as natural hardwood and corn stover.

It is worth noting that these calculations considered only net production area, where the total area would be 25% to 30% bigger, due to roads, facilities, and natural forests. Net production areas varied from 22,500 to 28,900 hectares for the fast growing species, to a more extensive production surface area between 101,200 and 202,300 hectares for corn stover and natural mixed hardwood, respectively. When more hectares are required to achieve an annual biomass supply, more land mechanization, increased plantation-crop establishment, harvesting, CO_2 emissions, and greater sourcing distances are necessary.

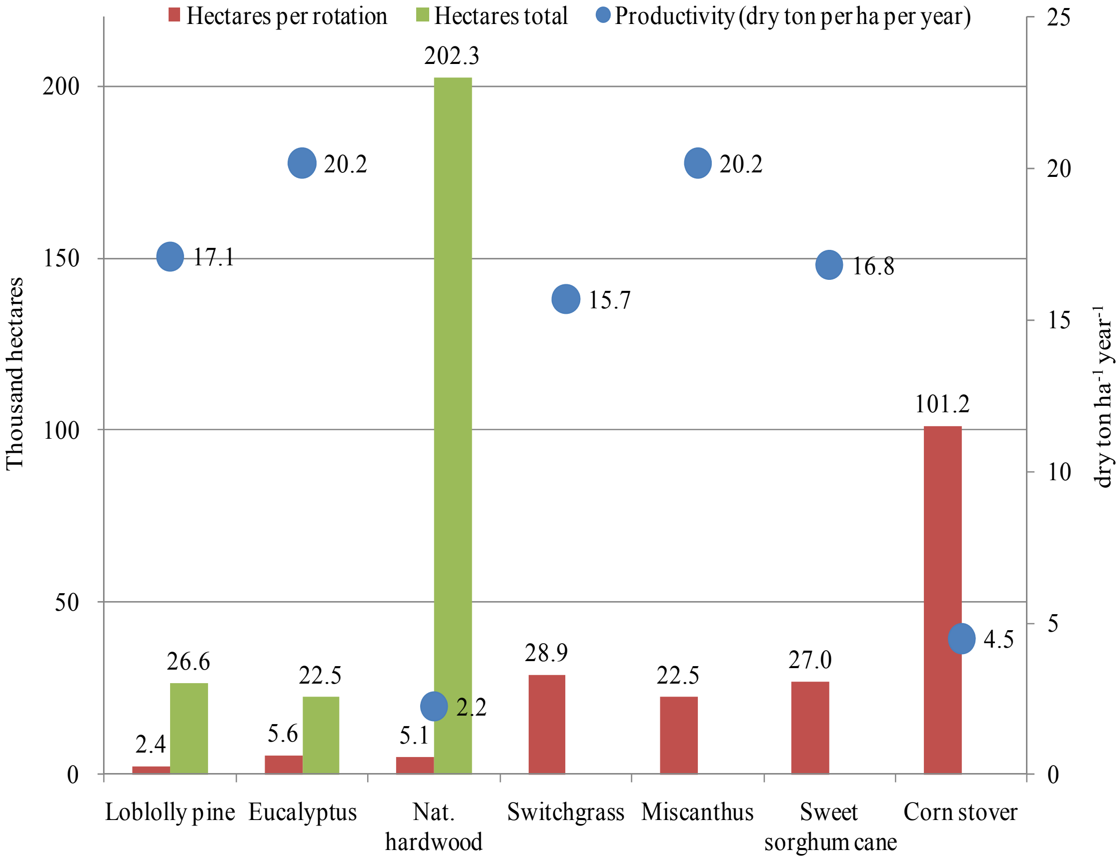

Fig. 1. Biomass productivity and hectares required for production to supply 453,597 dry ton yr^{-1}

Sourcing Freight Distance

As previously mentioned, sourcing freight distance is highly dependent on biomass productivity and the percentage of area growing that specific biomass. Changes in biomass productivity (dry ton ha^{-1} yr^{-1}), percentage of covered area, and annual biomass supply (dry tons per year) will affect feedstock sourcing radius distance. For example, loblolly pine had a productivity of 17.1 dry ton ha^{-1} yr^{-1} and a maximum radius distance of 41.1 km to achieve the targeted biomass supply (assuming 5% loblolly pine covered area around the facility, exclusively supplying 453,597 dry tons per year to the biorefinery). In Fig. 2, lower sourcing radius can be observed for highly productive feedstocks, including *Eucalyptus*, *Miscanthus*, and loblolly pine, with freight distances ranging from ca. 38 to ca. 41 km. On the other hand, feedstocks with lower biomass productivity, such as corn stover and natural mixed hardwood, require higher sourcing freight distances, ranging from ca. 80 to ca. 114 km.

Because higher freight distance will result in higher freight costs, this might level off the delivered cost of biomass of agriculture residues to the delivered costs of dedicated energy crops. In the case of corn stover, biomass payment to the farmer might be lower compared to the payments required to compensate investment to grow dedicated energy crops, such as switchgrass, *Miscanthus*, and *Eucalyptus*. Considering that agriculture residues such as corn stover have low biomass availability per hectare, the result would be higher freight costs to supply a specific biomass volume.

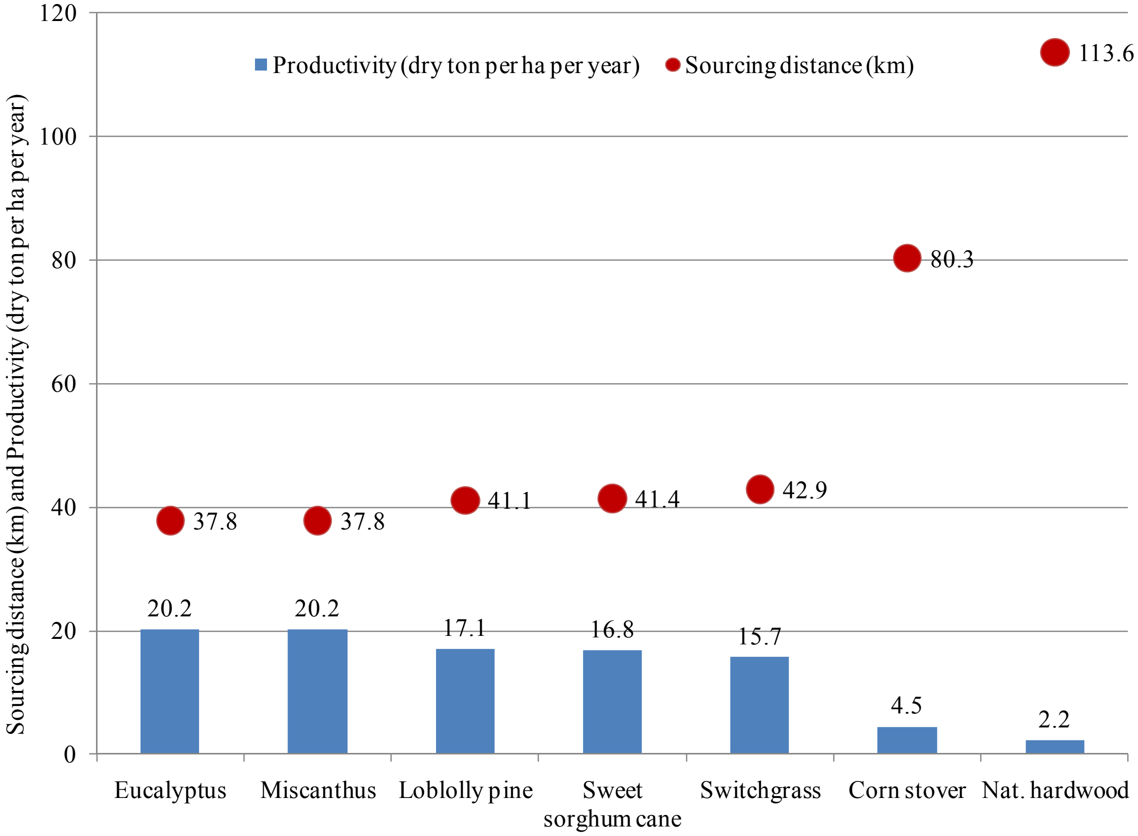

Fig. 2. Sourcing distance (km) and productivity (dry ton ha^{-1} yr^{-1}) for the different feedstocks

Delivered Cost

Though there are huge expectations to achieve a delivered cost of biomass below \$40 per dry ton, studies show that the target is not yet achievable. Based on the information given in the methodology section using average establishment, maintenance, harvesting, and freight costs, as well as average reported biomass productivity, delivered cost of biomass for any of the seven feedstocks considered in this research does not even fall below \$65 per dry ton. For forestry feedstocks, the main cost driver is harvesting, follow by stumpage (payment to the farmer), with the exception of natural hardwood, where the second most important cost driver is freight (due to higher sourcing distance). Strategies to reduce delivered costs for forestry feedstocks include the establishment of plantations with high tree stand density (exclusively for biomass production) and the use of harvesting equipment specifically developed for forest biomass (Volk et al. 2006; Spinelli et al. 2009). Delivered cost of biomass for the modeled energy plantation feedstocks ranged from \$69.40 to \$71 per dry ton, as shown in Fig. 3. Delivered cost of switchgrass, *Miscanthus*, sweet sorghum, and corn stover includes additional costs in storage and biomass loss during storage. *Miscanthus* had the lowest delivered cost, followed by switchgrass and corn stover (\$77.60, \$85.90 and \$87 per dry ton, respectively). Though delivered cost of sweet sorghum cane was higher than the other feedstocks considered in this analysis, it has the advantage of readily available monomeric sugars for fermentation, requiring no additional costs in pretreatments (for this fraction of the biomass). This cost savings can be better appreciated in a complete conversion model (into alcohol) comparing each of the feedstocks. Increases in biomass productivity and higher percentage of covered area with the desired feedstock will reduce harvesting and freight costs, with a favorable impact to the biorefinery.

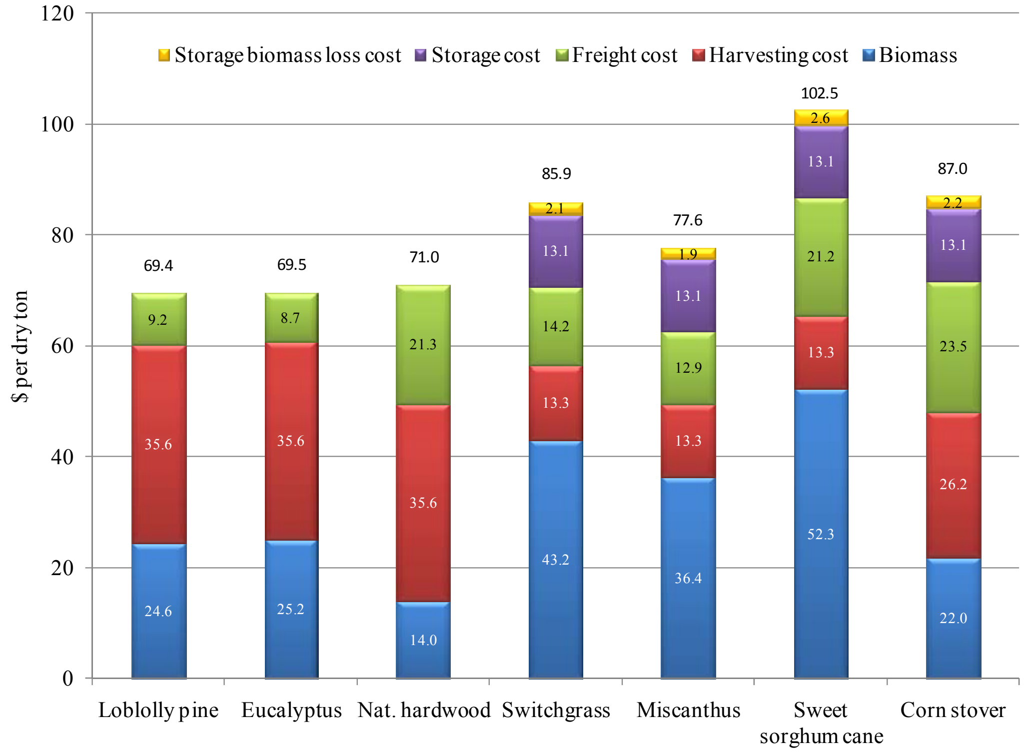

Figure 3. Delivered cost of biomass for each of the feedstock, assuming a 5% covered area and annual supply of 453,597 dry ton year^{-1}

Carbohydrate and Delivered Cost of Energy

Delivered cost of biomass is an important indicator that makes it possible to understand raw material costs, and also allows comparing different feedstocks available in a given region. Moreover, there are two indicators that provide more useful information, taking into consideration carbohydrate and energy content. These indicators are delivered cost of carbohydrate (dollar per ton of carbohydrate) and delivered cost per energy unit (dollars per million BTU), as illustrated in Fig. 4. Delivered cost of carbohydrate was lower in more recalcitrant feedstocks, such as loblolly pine and *Eucalyptus* (resulting from a combination of lower delivered cost and high carbohydrate content). Carbohydrate cost in dedicated energy crops and agriculture residues range from $123.10 to $141.40 per dry ton. In terms of heating content, lower delivered costs are found in loblolly pine ($3.7 per million BTU) and *Miscanthus* ($4.4 per million BTU), while higher delivered costs are found in sweet sorghum and corn stover ($6.3 and $5 per million BTU, respectively).

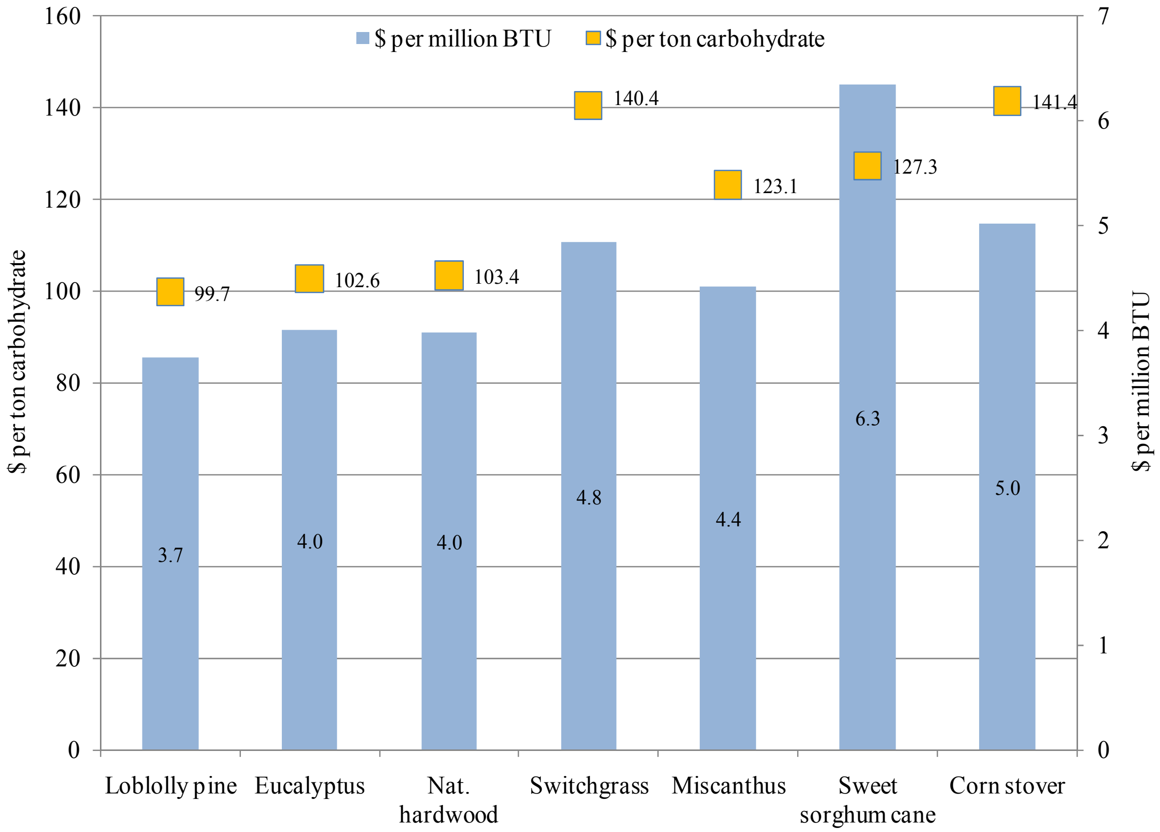

Figure 4. Delivered cost per ton of carbohydrate and dollars per million BTU

Supply Chain

Woody biomass offers many advantages over agricultural crops and harvest residues (Gonzalez et al. 2011a,d), including (a) efficient and well developed machinery for harvest; (b) storage in the field is not an issue, since trees continue to grow until they are ready for harvest; and (c) wood is dense enough to load trucks to a weight limit, thus minimizing transportation costs. Additionally, wood chips store well at a plant site and do not experience degradation and loss of chemical value at the processing plant (when compared to agricultural biomass). Almost none of those advantages exist for non-wood crops and the following are their disadvantages:

a. Harvesting equipment is typically adapted from other commercially available designs;
b. Baling is required for corn stover and switchgrass. Bale storage location can be in the field or at the plant site, but in either case, insurance and ownership must be addressed (Uslu et al. 2008; Gold et al. 2010).
c. Storage is problematic. Though we assumed 3% loss in storage, other issues include accelerated degradation dependent on local weather and means of storage. Some plant design concerns arise when considering accumulating a year's volume of raw material supply in the short (3-4 months) harvest window period. The land requirement for storage at a central location is prohibitive, so decentralized storage is often specified.
d. Crop failure, at least for corn and sweet sorghum, is known to occur; switchgrass experience is not extensive enough at present to assess such a risk.
e. Following harvest and baling, most reports suggest compaction prior to transport to a plant site (Uslu et al. 2008; Gold 2011). In most cases, trucks are filled only to a volume limit, rather than the more economic weight limit, due to low (< 10) bone dry pounds per cubic foot, a value approximately 3 times the bulk density of wood chips.

CONCLUSIONS

Delivered costs of seven feedstocks (loblolly pine, *Eucalyptus*, natural hardwood, switchgrass, *Miscanthus*, sweet sorghum, and corn stover) were analyzed using supply chain and economic models to deliver 453,597 dry tons per year to a biorefinery, while considering the most recently published costs and biomass productivity data. Lower freight distance can be achieved by establishing high yield energy crops including loblolly pine, *Eucalyptus*, switchgrass, *Miscanthus,* and sweet sorghum. The delivered cost of biomass for forestry feedstock ranges from $69 to $71 per dry ton; however, the delivered cost of agricultural biomass ranges from $77.60 to $102.50 per dry ton. The total production area for fast growing biomass was estimated to be between 22,500 and 27,000 hectares, while the total net area for less productive feedstocks ranged from 101,200 to 202,300 hectares (corn stover and natural hardwood, respectively). Loblolly pine, *Eucalyptus*, and natural hardwood were predicted to have the lowest delivered cost per ton of carbohydrate and million BTU for all the feedstocks evaluated, while agricultural biomass showed the highest delivered costs of carbohydrate and BTU. In terms of supply chain, forest feedstocks present competitive advantages over agricultural biomass, those competitive advantages translates to lower risk in biomass sourcing.

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