Environmental LCA and Financial Analysis to Evaluate the Feasibility of Bio-based Sugar Feedstock Biomass Supply Globally: Part 1. Supply Chain Analysis

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Chemical production from crude oil represents a substantial percentage of the yearly fossil fuel use worldwide, and this could be partially offset by renewable feedstocks such as woody biomass and energy crops. Past techno-economic and environmental analyses have been conducted for isolated feedstocks on a regional or national scope. This study encompasses complete supply chain logistics analysis, delivered cost financial analysis, national availability, and environmental life cycle assessment (LCA) for 18 selected cellulosic feedstocks from around the world. A biochemical conversion route to monomeric sugars is assumed for estimated sugar yields and biosugar feedstock cost analysis. US corn grain was determined to have the highest delivered cost, while rice hulls in Indonesia resulted in the lowest cost of the feedstocks studied. Monomeric sugar yields from literature ranged from 358 kg BDMT^{-1} for US forest residues to 700 kg BDMT^{-1} for corn syrup. Environmental LCA was conducted in SimaPro using ecoinvent v2.2 data and the TRACI 2 impact assessment method for mid-point impacts cradle-to-incoming biorefinery gate. Carbon absorption during biomass growth contributed most substantially to the reduction of net global warming potential. Rice hulls and switchgrass resulted in the highest global warming potential, followed closely by corn and Thai sugarcane bagasse. Contribution analysis shows that chemical inputs such as fertilizer use contribute substantially to the net environmental impacts for these feedstocks.

Keywords: Biomass supply feasibility; Supply chain analysis; Life cycle assessment; Delivered cost

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INTRODUCTION

Bio-based chemicals are poised to play an integral role in the chemical industry at large and to contribute to decreasing the net climate change impacts through reductions in the use of petroleum feedstocks for chemical production. Production of non-fuel chemicals from crude oil currently represents roughly 5.5% of petroleum use in the U.S. (EIA 2015). A few key factors to consider when commercializing the products of such a chemical production system include chemical product choice, conversion pathway, the location of the biorefinery, biorefinery scale, and feedstock choice. These scenario conditions are instrumental to the feasibility of the modeled production system and competitiveness of a bio-based product entering an existing market. Many academic and industry studies have analyzed end product choice (Jang *et al.* 2012; Liao and Hu 2012), compared conversion pathways (Baskar *et al.* 2012; Shabbir *et al.* 2012; Tay and Ng 2012), optimized biorefinery location (Stephen *et al.* 2013), and supply chain logistics (Akgul *et al.* 2012; Awudu and Zhang 2012; Čuček *et al.* 2012), and have determined the most appropriate biorefinery scale (Argo *et al.* 2013). Other biomass-to-bioproducts studies have been conducted (Kim *et al.* 2011), though typically for a single country (Gonzalez-Garcia *et al.* 2009; Yu and Tao 2009; Stephen *et al.* 2010; Gonzalez *et al.* 2011; Daystar *et al.* 2014), for limited feedstock options (Giarola *et al.* 2011; You *et al.* 2012), or for other than a biorefinery scale (U.S. DOE 2001).

In the literature, there is an explicit gap in models that practically and objectively compare biomass feedstocks in an integrated manner, including technical, financial, and environmental concerns for a bio-based chemical refinery across multiple continents, irrespective of conversion pathway. This research would be helpful for those intending to construct and operate a biomass-to-monomeric sugar biorefinery to understand the impact of biomass type, biorefinery scale, location, and other parameters on the feasibility of successful biosugar commercialization. Additionally, a complete financial analysis would identify major cost drivers and a single feedstock delivered cost per bone-dry metric tonne (BDMT) for pertinent biomass feedstocks, biorefinery locations (country), and biorefinery scales.

Herein, we compared 18 biomass feedstocks from three different continents, calculated the delivered cost and environmental impacts per BDMT, provided estimated feedstock-specific monomeric sugar yields assuming a biochemical conversion process, and estimated the regional biomass availability. While the range of biomass feedstocks surveyed herein is by no means exhaustive, this study includes those feedstocks most commonly explored in the literature. The comparison of these biomass feedstocks using such measures enabled the authors to compare feedstocks objectively, to identify the parameters of each feedstock supply chain that could be optimized, and to discuss the realistic feasibility of commercialization of a bio-based economy.

METHODS

Biomass feedstock supply chain models were developed to determine the techno-economic and environmental feasibility of supplying a centralized biorefinery with biomass for a biomass-to-sugar production platform. Feedstocks analyzed were chosen based on preliminary research that indicated high potential availability and adequacy for conversion (Table 1). A biorefinery production scale of 500,000 BDMT yr^{-1} was chosen for analysis (Daystar *et al.* 2014; Reeb *et al.* 2014). The time horizon for supply chain and financial analysis was thirty project years and environmental impacts were analyzed on a 100-year time frame. US dollar values are presented as inflation-adjusted 2014 dollars.

The technical results include the form of delivery, biomass density, embodied energy content, chemical composition, and moisture content. The transport distances were calculated based on estimates of covered area and feedstock yield per hectare. The delivered cost includes the cost of biomass purchase or production, the cost of loading, transport to the biorefinery, and storage, as well as yield losses due to biomass degradation during storage. Environmental impacts of the cradle-to-gate feedstock supply chain were calculated by modeling necessary chemical, fuel, fertilizer, herbicide, pesticide and irrigation inputs and wastes for the establishment, maintenance, harvest, collection, loading, transport, and storage of the biomass feedstocks prior to the biorefinery gate

(Khanchi 2012). The system boundary includes upstream and downstream impacts of mass and energy inputs, but no infrastructure impacts. Mass allocation was used for all scenario co-products (Appendix Table A3, Reeb *et al.* 2014).

Table 1. Overview of Biomass Feedstocks Chosen for Analysis, the Country Assumed for Each Biomass Type, and the Primary Literature Sources Used for Data Collection

Feedstock	Country	Sources
Corn Grain	USA	Kim *et al.* 2009; Holzmueller and Jose 2012; Vadas and Digman 2013
Corn Syrup	USA	Allan *et al.* 2005; Rausch and Belyea 2006
Corn Stover*	USA	Glassner *et al.* 1998; Perlack and Turhollow 2003; Petrolia 2008; Vadas *et al.* 2008; Hess *et al.* 2009; Shinners *et al.* 2011; Huang 2013; Vadas and Digman 2013
Genera Corn Stover	USA	Tiller 2015
Softwoods	USA	Daystar *et al.* 2014
Eucalyptus	USA	Daystar *et al.* 2014
Unmanaged Hardwoods	USA	Daystar *et al.* 2014
Forest Residues*	USA	Daystar *et al.* 2014
Switchgrass	USA	Daystar *et al.* 2014
Genera Switchgrass	USA	Tiller 2015
Sweet Sorghum	USA	Daystar *et al.* 2014
Genera Biomass Sorghum	USA	Tiller 2015
Empty Fruit Bunch*	Malaysia	Reeb *et al.* 2014
Rice Hulls*	Indonesia	Chungsangunsit *et al.* 2004; Ou *et al.* 2007; Roy *et al.* 2007; Bergqvist *et al.* 2008; Vidal *et al.* 2009; Finkbeiner 2011; Kasmaprapruet *et al.* 2009; Schmidt *et al.* 2011; Thao *et al.* 2011; Shafie *et al.* 2012
Thai Bagasse*	Thailand	Wibulswas and Tamnanthong 1988; Wakamura 2003; Garivait *et al.* 2006; Nguyen *et al.* 2008; Nguyen and Gheewala 2008; Contreras *et al.* 2009; Groot and Boren 2010; Lois-Correa *et al.* 2010; Nguyen *et al.* 2010; Nguyen and Gheewala 2011; Sakdaronnarong and Jonglertjunya 2012
Brazilian Sugarcane	Brazil	Bauen 1999; Lens *et al.* 2005; Cavalett *et al.* 2012; Munoz *et al.* 2013
Brazilian Bagasse*	Brazil	Bauen 1999; Holtzapple *et al.* 1999; Hamelinck *et al.* 2005; Lois-Correa *et al.* 2010; Sakdaronnarong and Jonglertjunya 2012
Brazilian Eucalyptus	Brazil	Betters *et al.* 1991; Cromer *et al.* 1993; Hislop and Hall 1996; Azar and Larson 2000; Dube *et al.* 2002; Rosillo-Calle 2006; Diaz-Balteiro and Rodriquez 2006; Wright 2006; Cubbage *et al.* 2007; Gonzalez *et al.* 2008; Laclau *et al.* 2008, 2010; Soares *et al.* 2010; Couto *et al.* 2011; Fontan *et al.* 2011; Stephen *et al.* 2013

*Indicates a residue co-product biomass type

Feedstock Supply Chains

Excel-based feedstock supply chain models were used to systematically model biomass production inputs, feedstock characteristics, and supply chain parameters. All data were collected from literature as referenced in Table 1. In order to facilitate more objective comparisons between scenarios, feedstock supply chains were separated into life cycle stages, including: land use change, establishment, maintenance, harvest, transportation, and storage. Feedstocks classified as 'residues' do not include land use change, establishment, maintenance or harvest life cycle stages as these impacts and costs are allocated to the main product of biomass production, though collection of the residues was modeled. The life cycle stages, major inputs and outputs to the system, and system boundary for each feedstock are outlined in Fig. 1.

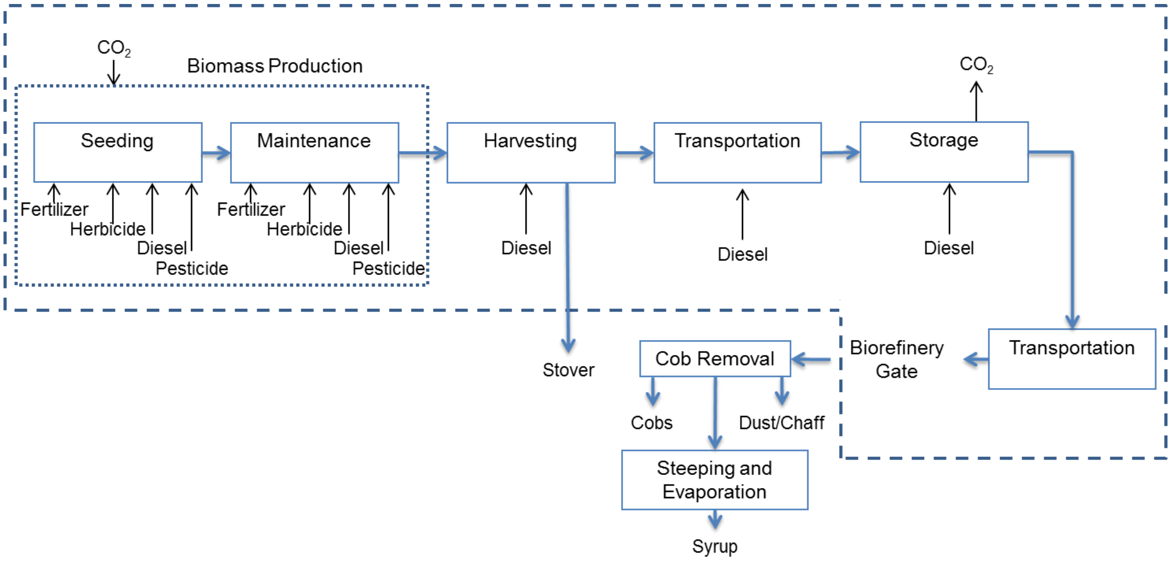

Fig. 1a. Supply system scope and boundary for corn grain, corn syrup, corn stover, and Genera corn stover

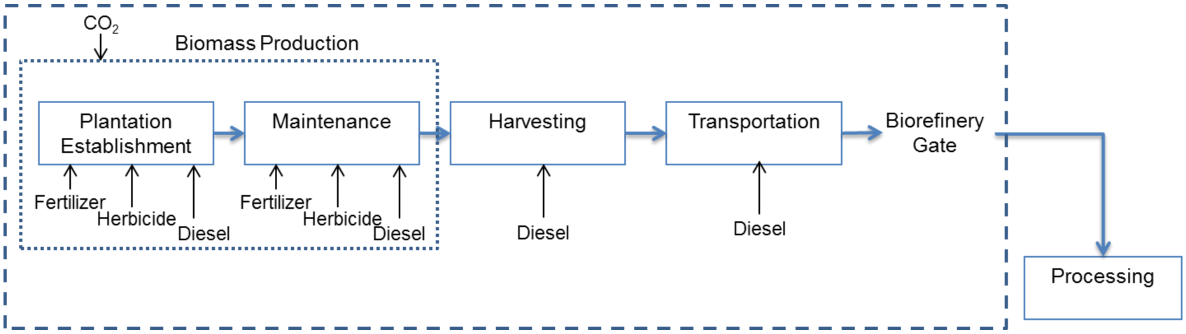

Fig. 1b. Supply system scope and boundary for softwoods, US eucalyptus, and Brazilian eucalyptus. Adapted from Daystar *et al.* (2014)

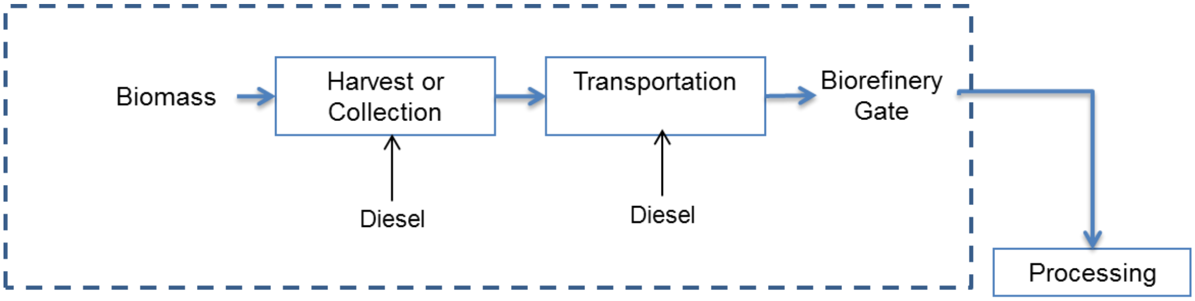

Fig. 1c. Supply system scope and boundary for unmanaged hardwoods, forest residues, and Indonesian rice hulls. Adapted from Daystar *et al.* (2014).

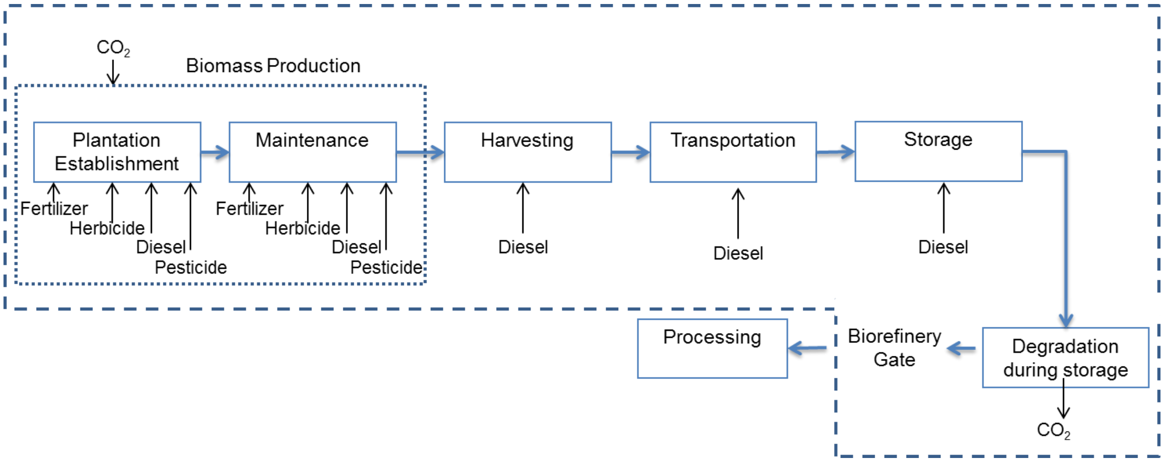

Fig. 1d. Supply system scope and boundary for switchgrass, sweet sorghum, Genera biomass sorghum, and Genera biomass sorghum. Adapted from Daystar *et al.* (2014).

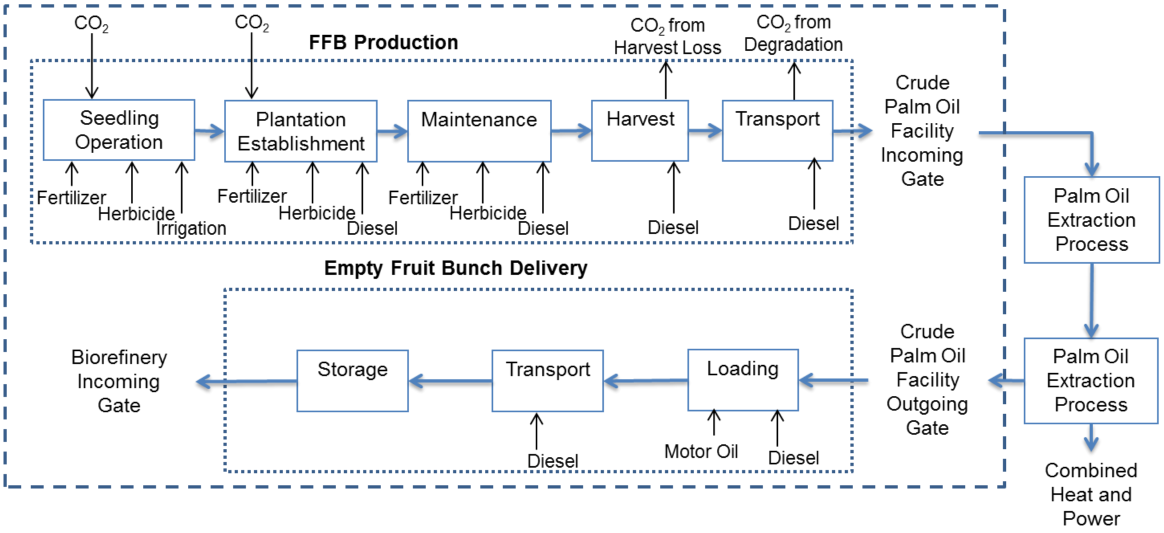

Fig. 1e. Supply system scope and boundary for Malaysian empty fruit bunches

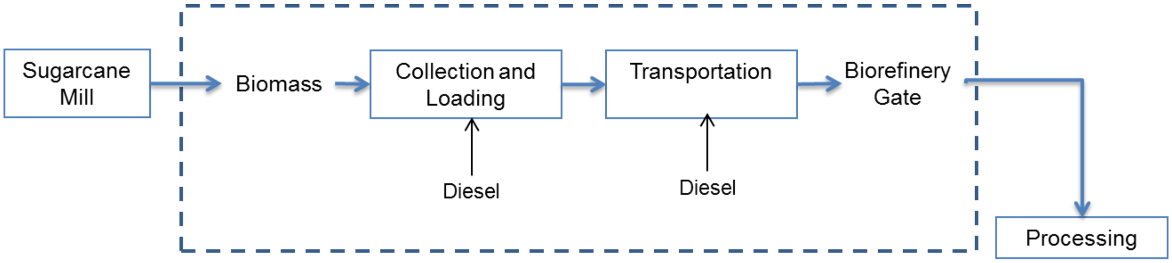

Fig. 1f. Supply system scope and boundary for Thai sugarcane bagasse

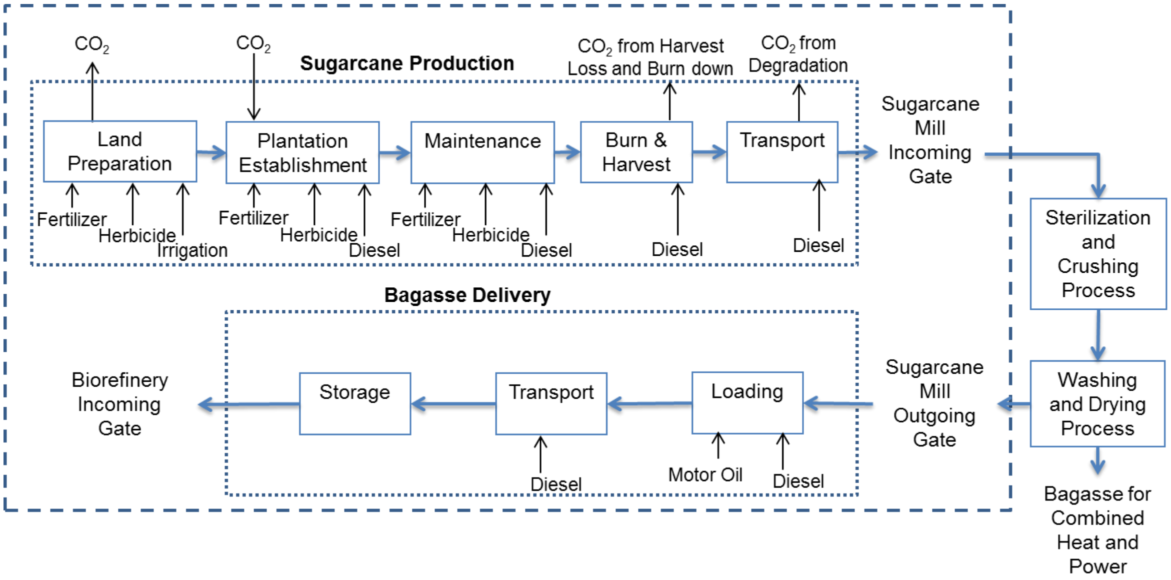

Fig. 1g. Supply system scope and boundary for Brazilian sugarcane and Brazilian sugarcane bagasse

Delivered Cost

The major outputs of the supply chain analysis include delivered cost and the feedstock production life cycle inventory (all material and energy consumption and production along with emissions). Delivered cost was calculated as the sum of establishment, maintenance, harvest, biomass purchase, loading and transportation, as applicable for each feedstock. The bases of feedstock cost were US$ per BDMT of biomass delivered, per metric tonne of carbohydrates delivered, per million British Thermal Units (MBTU) delivered, and per metric tonne of monomeric sugars subsequently produced. A more complete discussion of the methodology used for calculating the delivered cost is provided by Daystar *et al.* (2014) and Reeb *et al.* (2014).

Life Cycle Assessment

Greenhouse gas (GHG) accounting was accomplished through the use of a carbon balance and reported using a carbon dioxide equivalency (CO_2-eq.) based upon the Intergovernmental Panel on Climate Change (IPCC 2013) 100-year timeframe characterization factors for equivalency between CO_2 and other GHG molecules to the CO_2 baseline impact factor of 1.00. With respect to GHG accounting, plant growth was treated as a negative emission based on the proximate and ultimate analysis of each biomass type, and assuming a 3.667 carbon to CO_2 stoichiometric balance (Daystar *et al.* 2014; Reeb *et al.* 2014). The bases of analysis for GHG accounting and for life cycle assessment include a mass basis (per BDMT), a carbohydrate basis (per MT carbohydrates), and a biosugar basis (per MT monomeric sugar).

In addition to GHG accounting for the cradle-to-gate biomass feedstock life cycles, a full life cycle inventory (LCI) was developed and the life cycle impact assessment (LCIA) was conducted using SimaPro 7.3 (PRé 2013), ecoinvent v2.2 (Frischknecht *et al.* 2005), and the LCA methodology outlined by the International Organization for Standardization (ISO 2010). In order to maintain a basis for comparison between the feedstocks analyzed, the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts 2, version 3.01 (TRACI, Bare *et al.* 2002) was used to consistently calculate mid-point environmental impacts for the different biomass types (Table 2).

Table 2. Table of TRACI Impact Categories and Acronym Used

Impact Category	Acronym	Units
Global Warming	GWP	kg CO_2-Eq
Acidification	AC	moles of H+-Eq
Eutrophication	EU	kg N
Ecotoxicity	EC	kg 2,4-D-Eq
Ozone Depletion	OZ	kg CFC-11-Eq
Photochemical Oxidation	PO	kg NO_x-Eq
Carcinogenics	CA	kg benzene-Eq
Non-Carcinogenics	NC	kg toluene-Eq
Respiratory Effects	RE	kg $PM_{2.5}$-Eq

TRACI was used for all LCAs because it is of great importance to compare feedstocks consistently, though not all feedstocks are produced in the US and non-US LCI data was used for non-domestic feedstock supply models. Details about the GHG accounting method used and the LCA method, TRACI impact assessment method, and other parameters of the environmental assessment were outlined in detail by Reeb *et al.* (2014). Mass allocation data for coproducts are described in Appendix Table A3 and Appendix Figure A1.

RESULTS AND DISCUSSION

Supply Chain Analysis

The supply chain logistics for eighteen biomass feedstocks of interest for the potential bio-based economy were modeled at commercial scale. The characteristics of the selected biomass types that contribute to their selection include high carbohydrate content, relatively high yield, low cost, and sufficient availability (existing or projected) for the proposed biorefinery scale of 500,000 bone-dry metric tonnes (BDMT). Relevant assumptions about the analyzed biomasses and the modeled supply chains are further detailed in Table 3. A breakdown of the feedstock dry-mass composition is provided in Fig. 2 and in the Appendix (Table A2). These supply chain assumptions are important to take into account when comparing the biomass feedstocks because differences in delivered cost between feedstocks can likely be explained by yield differences, transport distances, required storage due to harvest window differences, covered area, and other factors.

Another factor which may impact the appropriateness of a biomass type for commercial-scale biorefinery feedstock supply is the availability of this feedstock within a financially-feasible transportation distance. In the case of some North American feedstocks the covered area is 10%, which, when coupled with low yields such as for unmanaged hardwoods, can contribute to very high maximum transportation distances. Assumptions about covered area and transport distance can be found in Table 3 and the results of the availability study in Table 4.

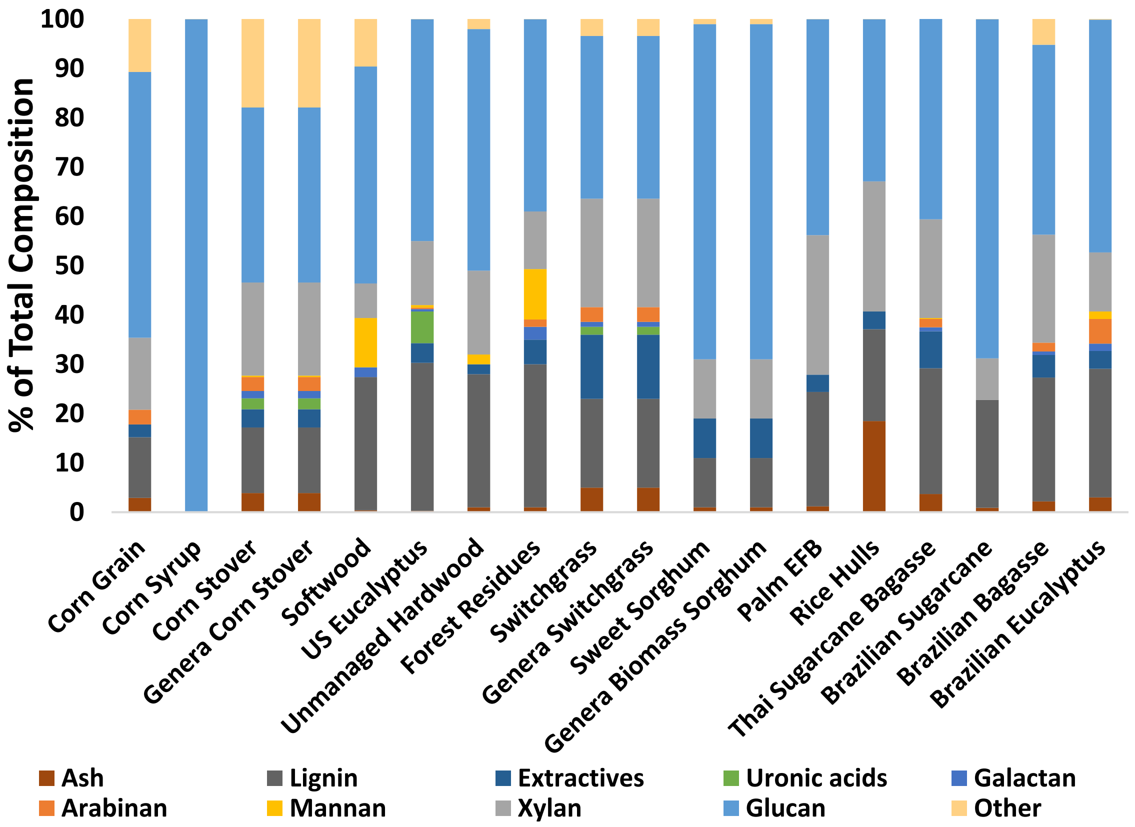

Fig. 2. Biomass feedstock composition on a dry-mass basis for the biomass types analyzed

Composition and supply chain logistics vary greatly for the various biomass types, as shown in Table 3 and Fig. 1. Other important factors and assumptions drawn from the literature include transportation distance (Gonzalez *et al.* 2011; Daystar *et al.* 2014; Reeb *et al.* 2014), a 1.31 tortuosity factor (Ravula 2007; Sultana and Kumar 2014), compositional analysis (Reeb *et al.* 2014; Daystar *et al.* 2015), and moisture content (Daystar *et al.* 2013). National biomass feedstock availability was estimated from literature and national agricultural production databases for each feedstock in each country of analysis (Table 4). Other important sources used throughout this study include: Allan *et al.* (2005), Rausch and Belyea (2006), Nguyen and Gheewala (2008), Lois-Correa *et al.* (2010), Couto *et al.* (2011), Prasera-A and Grant (2011), Shinners *et al.* (2011), Thao *et al.* (2011), Bolin (2012), Cavalett *et al.* (2012), Sakdaronnarong and Jonglertjunya (2012), Shafie *et al.* (2012), Munoz *et al.* (2013), Stephen *et al.* (2013), Vadas and Digman (2013), Daystar (2014), Daystar *et al.* (2014), and Reeb *et al.* (2014). Primary data regarding the three Genera feedstocks (corn stover, switchgrass, and biomass sorghum) were collected through personal communication with Genera Energy (Tiller 2015).

Table 3. Overview of Biomass Feedstock Options Chosen for Analysis and Relevant Feedstock Characteristics

	Units	Corn Grain	Corn Syrup	Corn Stover	Genera Corn Stover	Softwood	Eucalyptus	Unmanaged Hardwood	Forest Residues	Switchgrass	Genera Switchgrass	Sweet Sorghum	Genera Biomass Sorghum	Empty Fruit Bunch	Rice Hulls	Thai Bagasse	Brazilian Sugarcane	Brazilian Bagasse	Brazilian Eucalyptus
Delivery form		Whole kernels	Liquid	Square Bales	Square Bales	Logs	Logs	Logs	Chips	Square bales	Square bales	Canes	Chips	Whole Fiber	Bagged husk	Chips	Bales	Chips	Logs
Yield	BDMT ha^{-1} yr^{-1}	11.5	6.95	11.8	3.7	17.1	17.6	2.2	1.0	17.9	18.5	15.7	29.7	0.63	0.82	16.5	82.7	27.3	109
Rotation length	Years	1	1	1	1	12	4	50	12	7	25	1	1	25	1	6	6	6	10
Harvest window	Mo. yr^{-1}	2	2	2	1.5	12	12	12	12	3	4.5	3	3	12	12	12	12	12	12
Covered area	%	15	15	15	70	10	10	10	10	10	40	10	40	70	50	80	80	80	60
Higher Heating Value	MJ kg^{-1}	19.7	15.6	18.1	18.1	19.2	19.2	20.3	20.3	19.1	19.1	18.9	18.9	19	15.2	19.4	7.5	19.4	19.2
Delivered Quantity	BDMT yr^{-1}	5.0E+5	5.0E+5	5.0E+5	5.0E+5	5.0E+5	5.0E+5	5.0E+5	5.0E+5	5.0E+5	5.0E+5	5.0E+5	5.0E+5	5.0E+5	5.0E+5	5.0E+5	5.0E+5	5.0E+5	5.0E+5
Annual Harvest Area	Ha yr^{-1}	2.2E+5	3.6E+5	2.4E+5	3.3E+5	1.6E+5	1.6E+5	1.3E+6	2.8E+6	2.3E+5	6.7E+4	8.3E+4	4.2E+4	6.2E+5	1.1E+6	1.9E+4	9.1E+2	1.1E+4	3.7E+3
Total Plantation Area	Ha	2.2E+5	3.6E+5	2.4E+5	4.8E+5	1.9E+6	6.3E+5	6.3E+7	3.3E+7	1.6E+6	1.6E+4	8.3E+4	1.0E+5	1.6E+7	1.10+6	1.1E+5	5.4E+3	6.9E+4	3.7E+4
Average round-trip transport	t*km	81	81	81	130	138	134	380	566	107	77	366	366	160	34	75	34	66	92

Table 4. National Annual Availability Estimate for Each Biomass Feedstock Type Analyzed

Feedstock	Country	Estimated Biomass Available BDMT year^{-1}	Sources
Corn Grain	USA	4.46E+07	Singh 2007; Zych 2008; USDA 2014
Corn Syrup	USA	5.06E+06	Schwietzke *et al.* 2009
Corn Stover	USA	2.03E+07	Kadam and McMillan 2003; Bonner *et al.* 2014; Schmer and Dose 2014
Softwoods	USA	8.69E+07	USCB 2012; Meier 2014
Eucalyptus	USA	4.17E+05	Gonzalez *et al.* 2011a,b; Cunningham and Tamang 2014
Unmanaged Hardwood	USA	5.05E+09	Alvarez *et al.* 2007; Gonzalez *et al.* 2011b; Daystar *et al.* 2014
Forest Residues	USA	4.49E+07	USDA 2007; Mabee *et al.* 2011
Switchgrass	USA	1.88E+08	Sharp 2013; Zhuang *et al.* 2013
Sweet Sorghum	USA	4.92E+06	USDA 2014
Empty Fruit Bunch	Malaysia	7.00E+06	Reeb *et al.* 2014
Rice Hulls	Indonesia	1.17E+07	Lingga 2009; Prasara-A and Grant 2011
Sugarcane Bagasse	Thailand	1.39E+07	Laopaiboon *et al.* 2010; Prasertsri 2013
Sugarcane	Brazil	7.55E+07	Singh 2007; de Moraes Rocha *et al.* 2011
Sugarcane Bagasse	Brazil	1.15E+08	Singh 2007; de Moraes Rocha *et al.* 2011
Eucalyptus	Brazil	5.53E+07	Sarlls and Oladosu 2010; Stape *et al.* 2010; Couto *et al.* 2011

Delivered Cost

The delivered cost can be defined as the sum of land preparation, planting, maintenance, harvesting, loading, and transport costs for feedstocks that are a primary product in their system. Alternatively, delivered cost can be defined as the sum of biomass purchase price in the "field," cost of collection, loading costs, and transport costs for feedstocks which are a waste co-product of their system. Values for chemical use, yield, irrigation, harvest activities, transport distance, and other cost drivers were calculated using the methods more extensively outlined by Daystar *et al.* (2014) and Reeb *et al.* (2014). Table 5 gives a breakdown of costs by life cycle stage and the aggregate delivered cost per metric dry tonne of biomass and per metric tonne of carbohydrates. Cost data per metric tonne of carbohydrates and the total annual carbohydrate delivery potential for each feedstock within each studied country are provided below (Table 5 and Fig. 3).

Table 5. Total Delivered Cost Per BDMT, Per Metric Tonne (MT) of Carbohydrates and Per Million British Thermal Units (MBTU) Embodied Energy for Each Biomass Feedstock Type by Life Cycle Stage

	Units	Corn Grain	Corn Syrup	Corn Stover	Genera Corn Stover	Softwood	Eucalyptus	Unmanaged Hardwood	Forest Residues	Switchgrass	Genera Switchgrass	Sweet Sorghum	Genera Biomass Sorghum	Empty Fruit Bunch	Rice Hulls	Thai Bagasse	Brazilian Sugarcane	Brazilian Bagasse	Brazilian Eucalyptus
Establish	\$ BDMT^{-1}	50										26	14				2		10
Maintain	\$ BDMT^{-1}	22															8		
Biomass Purchase	\$ BDMT^{-1}		184	13	13	31	25	13	32	27	27			12	1	28		48	
Harvest	\$ BDMT^{-1}	10		5	5	31	28	39		14	14						3		8
Loading	\$ BDMT^{-1}	1		14	14						8			5					12
Storage	\$ BDMT^{-1}	17		3	3					17	16	4	4		7				
Transport	\$ BDMT^{-1}	14		13	21	9	9	21	22	20	12	19	31	28	7	26	28	7	19
Loss	\$ BDMT^{-1}			5	5					4	5	5	5			4	8	4	
Total Del. Cost	\$ BDMT^{-1}	113	184	53	61	71	62	73	53	82	80	54	53	45	15	58	49	59	49
Carb Content	%	80	100	75	75	70	66	69	65	63	63	81	63	72	59	63	77	66	67
Carb Del. Cost	\$ MT^{-1}	141	184	71	81	102	94	105	82	131	127	66	84	63	25	91	64	88	72
Energy Content	MBTU BDMT^{-1}	19	15	17	17	18	18	19	19	18	18	18	18	18	14	18	7	18	18
Energy Del. Cost	\$ MBTU^{-1}	6	12	3	4	4	3	4	3	5	4	3	3	3	1	3	7	3	3

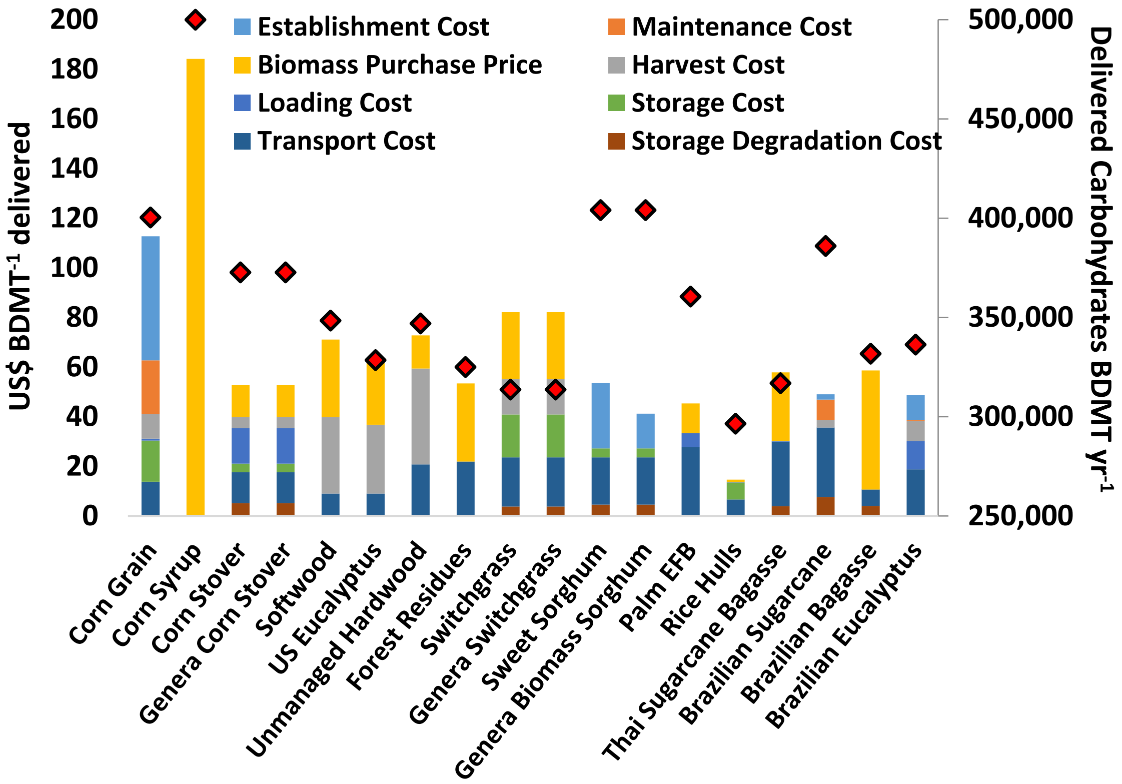

Fig. 3. Biomass feedstock delivered cost per MT carbohydrates and major cost drivers for each feedstock, assuming 500,000 BDMT yr^{-1}. Where biomass purchase price is not available, it is taken as equal to establishment, maintenance, and harvest costs for that biomass type.

As Brazilian sugarcane bagasse does not currently occupy an organized, consistent market as a biomass type, valuation of a market average price, spot price, or other purchase price equivalent was not possible. Therefore, the embodied energy content was used to calculate the expected electricity production potential from burning bagasse in an industrial power boiler. The value of that electricity in the Brazilian electricity grid was calculated using a 2014 average price per kWh in 2014 US dollars. This lack of market price data means that the estimate herein of \$59 BDMT^{-1} might be higher than what biorefineries would encounter under actual contract terms at commercial scale.

It is clear from delivered cost calculations that South American and Southeast Asian biomass types can be supplied to a biorefinery at a lower cost than most North American biomass types. This is primarily due to the high purchase price of biomass in North America and the high cost of feedstock harvesting in the case of woody biomass types. Corn also requires a substantial agrochemical investment for establishment and maintenance of the prepared, planted field. The feedstocks that will deliver the most carbohydrates for the least cost, not taking into account the monomeric sugar conversion rate of these feedstocks, are, in descending order, rice hulls, empty fruit bunch, Brazilian sugarcane, sweet sorghum, corn stover, and Brazilian eucalyptus. Depending upon the unit of measure for delivered cost, some biomass types might not seem as financially feasible relative to other biomass types that are cheaper on a per unit mass basis. Accounting for carbohydrate content and hypothetical biosugar yield can help identify the tradeoffs between biomass types more pragmatically from the perspective of the biorefinery.

While these delivered cost values are specific to the 500,000 BDMT yr^{-1} biorefinery scale, the increase or decrease in refinery scale does not greatly impact scale-equivalent technology comparisons. Although bio-refinery CAPEX and other *pro forma* financial values would likely be impacted by scale changes, biosugar conversion economics are not examined herein. This nth-year financial analysis shows that non-North American feedstocks can provide a lower cost biomass carbohydrate supply to a biorefinery. These biomass types include rice hulls, Genera biomass sorghum, corn stover, Genera corn stover, Malaysian empty fruit bunch, and all Brazilian biomass types studied. This analysis does not account for biosugar yields, or bio-based chemical yields, or biorefining costs.

In addition to the availability, delivered cost, and environmental impacts caused by biomass feedstock supply, the monomeric sugar biochemical conversion yield for each biomass type was also explored. Dilute acid pretreatment was assumed for initial disaggregation followed by enzymatic hydrolysis to facilitate the production of dilute monomeric sugars in solution. A review of literature provided conversion efficiency factors used for analysis of the technical feasibility of biochemical conversion for each feedstock (Table 6). These values were validated using WinGEMS biochemical conversion models.

It is important to note that rice hulls, and to some extent switchgrass and Genera switchgrass, are higher in ash content and lower in carbohydrate content, which reduces the attractiveness of these biomass types as feedstock for monomeric sugar production through biochemical conversion. Some feedstocks, such as corn, corn syrup, switchgrass and Genera switchgrass have a high carbohydrate cost, while others, such as forest residues, Brazilian sugarcane, and Brazilian sugarcane bagasse, have a lower sugar cost due in part to high sugar yield and low delivered cost. Switchgrass has both a low carbohydrate concentration and therefore a higher carbohydrate cost, but also a low carbohydrate-to-monomeric sugar yield, which results in a high estimated feedstock cost per tonne of monomeric sugar produced.

Table 6. Carbohydrate Cost and Content, Monomeric Sugar Yield, and Calculated Feedstock Cost Per Tonne of Sugar Produced for Each Feedstock Type, Based on Conversion Efficiency Estimates

	Carbohydrate Cost (US$/MT)	Carbohydrate Content (%)	Sugar Yield (kg/BDMT)	Feedstock Cost (US$/MT Sugar)	Sources for Sugar Yield Data
Corn Grain	$141	80	626	$225	Van Eylen *et al.* 2011; Scott *et al.* 2012
Corn Syrup	$184	100	700	$263	Singh *et al.* 2010
Corn Stover	$71	75	551	$129	Lloyd and Wyman 2005; Zhou *et al.* 2014; Zhang *et al.* 2015
Genera Corn Stover	$81	75	551	$147	Same as Corn Stover
Softwood	$102	70	570	$179	Phillips *et al.* 2013; Sun 2013
Eucalyptus	$94	66	611	$154	Li *et al.* 2013a
Unmanaged Hardwood	$105	69	615	$171	Lim and Lee 2013
Forest Residues	$82	65	358	$230	Zhang *et al.* 2012; Janzon *et al.* 2014
Switchgrass	$131	63	493	$266	Garlock *et al.* 2011; Shi *et al.* 2011; Li *et al.* 2013b
Genera Switchgrass	$127	63	493	$258	Same as Switchgrass
Sweet Sorghum	$66	81	654	$102	Xu *et al.* 2011; Banerji *et al.* 2013; Marx *et al.* 2014; Bernardes *et al.* 2015
Genera Biomass Sorghum	$84	63	530	$158	Corredor *et al.* 2009
Empty Fruit Bunch	$63	72	649	$97	Ling *et al.* 2013; Cui *et al.* 2014
Rice Hulls	$25	59	460	$54	Cabrera *et al.* 2014
Thai Bagasse	$91	63	550	$166	Pattra *et al.* 2008; Benjamin *et al.* 2013
Brazilian Sugarcane	$63	77	617	$102	Kim and Day 2011; Jung *et al.* 2013
Brazilian Bagasse	$88	66	504	$175	de Moraes Rocha *et al.* 2011
Brazilian Eucalyptus	$72	67	626	$116	Li *et al.* 2013a

Note: Brazilian Sugarcane refers to conversion of whole plant (extractable sugars and subsequently bagasse).

For the purposes of determining financial viability of biorefining, the transport distance, and therefore the growth yield and maximum geographical growth density, may significantly impact the financial viability of the biochemical biosugar platform for certain biomass types. For example, assume that the biosugar platform is employed to produce succinic acid, with a conversion yield from biosugar of 0.25 g/g sugar (Geraili *et al.* 2013; Wang *et al.* 2013), the market price of succinic acid is $4.00 kg^{-1} (Taylor 2010 RSC), the capital and overhead cost is $0.46 per kg and conversion cost is $0.62 per kg (Luo *et al.* 2010; Claypool 2013; Efe *et al.* 2013), for a 15-year project term assuming 3% interest on capital, straight-line depreciation, a 15% tax rate, and US$ in 2015. In this scenario only corn grain, forest residues, switchgrass, and Genera switchgrass will be financially viable feedstocks for a biosugar-to-succinic acid biorefinery, though with internal rates of return ranging from 1% to 6% (Appendix Tables A5 and A6).

Although this discussion has focused on the biochemical conversion route to this point, one alternative is a thermochemical conversion route, for which yield is not strictly correlated to polysaccharide content, but instead correlates well with carbon content, moisture content, and ash content (Daystar *et al.* 2013).

Table 7. Major Inputs and Outputs Allocated to the Feedstock Production, Harvest, Storage, and Transportation Life Cycle for Delivery of a BDMT Biomass to the Biorefinery, Assuming a 500,000 BDMT yr^{-1} Scale

Life Cycle Stage	Flow	Units	Corn Grain	Corn Syrup	Corn Stover	Genera Corn Stover	Softwood	Eucalyptus	Unmanaged Hardwood	Forest Residues	Switchgrass	Genera Switchgrass	Sweet Sorghum	Genera Biomass Sorghum	Palm EFB	Rice Hulls	Thai Sugarcane Bagasse	Brazilian Sugarcane	Brazilian Sugarcane Bagasse	Brazilian Eucalyptus
Establish	Urea	kg BDMT^{-1}					1.6	2.2		0.10					0.47		5.3			0.72
Establish	Phosphorus	kg BDMT^{-1}	3.7	1.4	2.1	0.77					1.2	1.05	2.6	1.8	3.2	5.4	5.4	0.30	0.10	4.8
Establish	Potassium	kg BDMT^{-1}	1.8	0.68	1.0	0.39					12	11.6	1.3	0.9	13	3.7	7.2	1.2	0.41	1.4
Establish	Lime	kg BDMT^{-1}	2.0	0.75	1.1	0.42					47	16.8						3.7	1.2	37
Establish	Nitrogen	kg BDMT^{-1}	13	5.1	7.6	2.84					6.4	6.10	6.4	4.5	4.0	13		0.92	0.30	0.89
Establish	Diesel	L BDMT^{-1}					0.65	1.9		0.45		2.65								0.54
Establish	Motor oil	L BDMT^{-1}													3.1E-4					
Establish	Irrigation	L BDMT^{-1}													13	3.5E4				9.2
Mainten.	Glyphosate	kg BDMT^{-1}	0.17	0.07	0.10	0.04				1.0E-3					0.39	11	5.9E-4	0.07	0.02	0.04
Mainten.	Pursuit	kg BDMT^{-1}									1.8	1.59								
Mainten.	MSO	kg BDMT^{-1}									2.5	2.17								
Mainten.	2,4-D	kg BDMT^{-1}									0.85	0.78			0.40					
Mainten.	Alzarine 90	kg BDMT^{-1}											0.14	0.10						
Mainten.	Dipel ES	kg BDMT^{-1}											0.15	0.10						
Mainten.	Paraquat	kg BDMT^{-1}													0.11					
Mainten.	Bipyridylium	kg BDMT^{-1}													0.12		1.5E-3			
Mainten.	Pyrethroid	kg BDMT^{-1}													0.02					
Mainten.	Organophosphate	kg BDMT^{-1}													0.07					
Mainten.	Generic pesticide	kg BDMT^{-1}	8.7E-3	3.3E-3	4.9E-3	2E-2									2.4		3.8E-3			
Harvest	Diesel	L BDMT^{-1}	11	4.2	6.3	2.38	7.6	7.6	7.6		4.5	4.06	3.1	2.2	3.8		48	1.6	0.51	11
Harvest	Gasoline	L BDMT^{-1}	1.7	0.65	1.0	0.37	3E-2	0.09		6	3.0									
Harvest	Land Burning	kg CO_2 BDMT^{-1}																16	5.4	
Storage	Diesel	L BDMT^{-1}									0.6	0.6	0.84	0.54						
Storage	Electricity	kWh BDMT^{-1}	33	12	19	6.94									0.13					
Transport	Transport	t*km	81	81	81	130	138	134	380	566	107	77	366	61	160	34	75	34	66	92

Note, mass allocation methods used for feedstocks with coproducts are described in Appendix Table A3.

While forest residues, switchgrass, softwood and rice hulls are less feasible than other studied feedstocks for the biochemical conversion route, these feedstocks may be more appropriate for a thermochemical conversion pathway, as outlined by various researchers from the National Renewable Energy Laboratory (NREL; Dutta *et al*. 2011).

Life Cycle Assessment

The feedstock production and supply chain material and energy flow data related to chemical, energy and fuel use, transport distance, and degradation during storage were modeled using SimaPro 7.3 (PRé 2013) to generate the life cycle inventory (LCI). Upstream and downstream emission and resource use data were calculated using ecoinvent v2.2 (Frischknecht *et al*. 2005). Process data generated using the supply chain models and from literature for each cradle-to-gate feedstock production system are shown in Table 7.

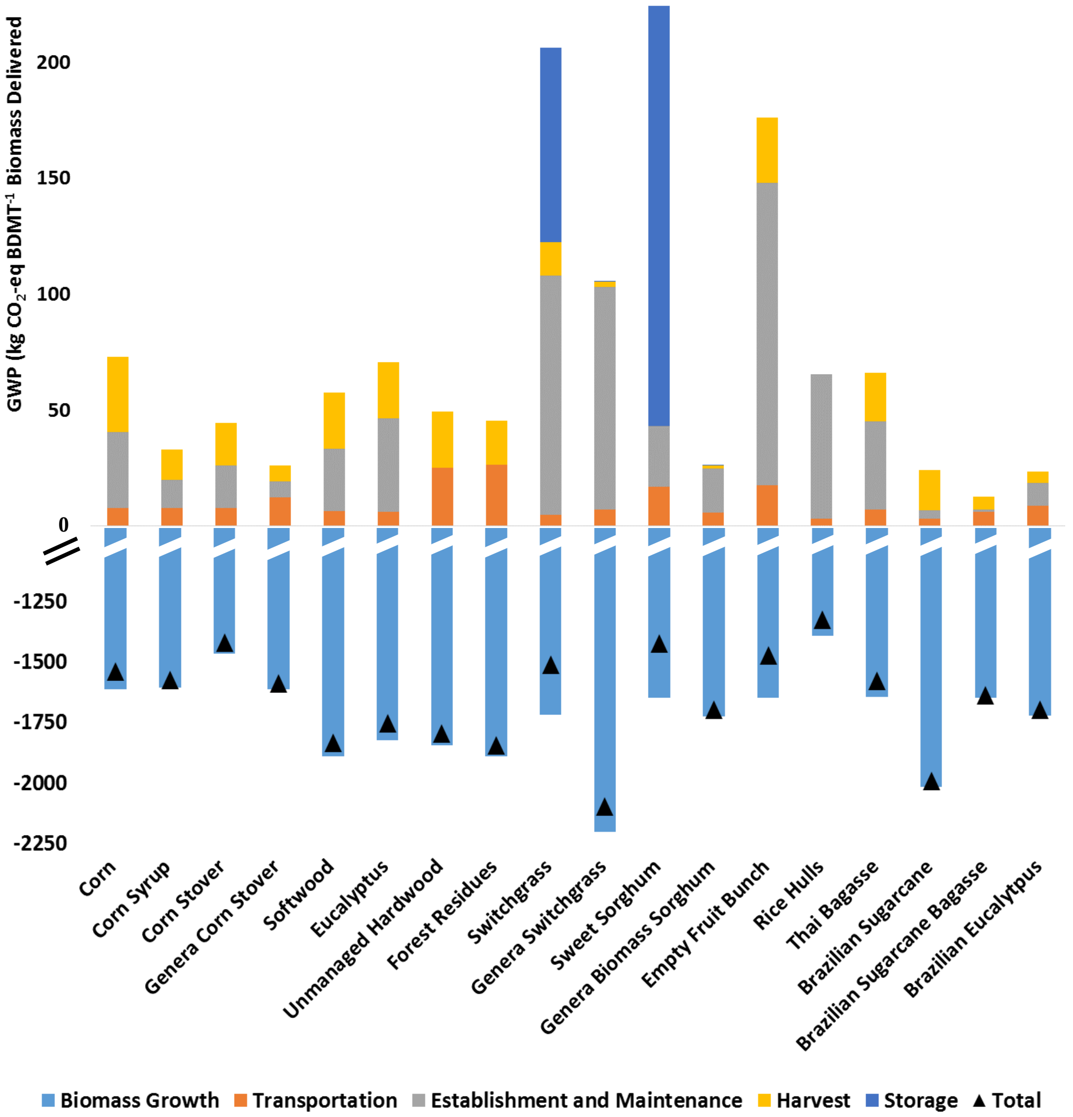

Fig. 4. Global warming potential (GWP) per BDMT biomass delivered and the life cycle stage-wise contributions. Please note the y-axis has an axis break at approximately -1000 kg CO$_2$-eq and two scales, for above and below the origin. The positive bars indicate the actual non-biogenic emissions based GWP impact without the biomass growth contribution.

To conduct the life cycle impact assessment (LCIA) the TRACI 2 impact assessment method was used to calculate mid-point impacts based upon the LCI developed in SimaPro. The typical output of such analysis is raw LCIA values in table form (Table A2 of Appendix) and normalized to the scenario with the highest impact for each impact category (Fig. A2 of Appendix). Herein, the global warming potential and other values were given as raw values (Fig. 4) and all TRACI impacts were presented using a heat map method (Fig. 5), developed using Tableau software (2014).

It is important to note that while the transportation distances vary greatly and in some cases contributed substantially to the delivered cost value for each feedstock, the transport emissions contribute only minimally to the net environmental burden for each feedstock supply system. Other important factors include the use of pre-harvest burning for sugarcane in Brazil and Thailand, which can directly impact the global warming potential (GWP) for each feedstock. Land use change (LUC) impacts were not included in the main TRACI impact assessment, but other studies by the authors have determined that LUC impacts can greatly impact the net GWP impact cradle-to-gate (Daystar 2014; Daystar *et al.* 2014; Reeb *et al.* 2014). Global warming potential values for feedstock production and supply are also provided per kg of bio-based sugar produced (Appendix Fig. A2 and A3).

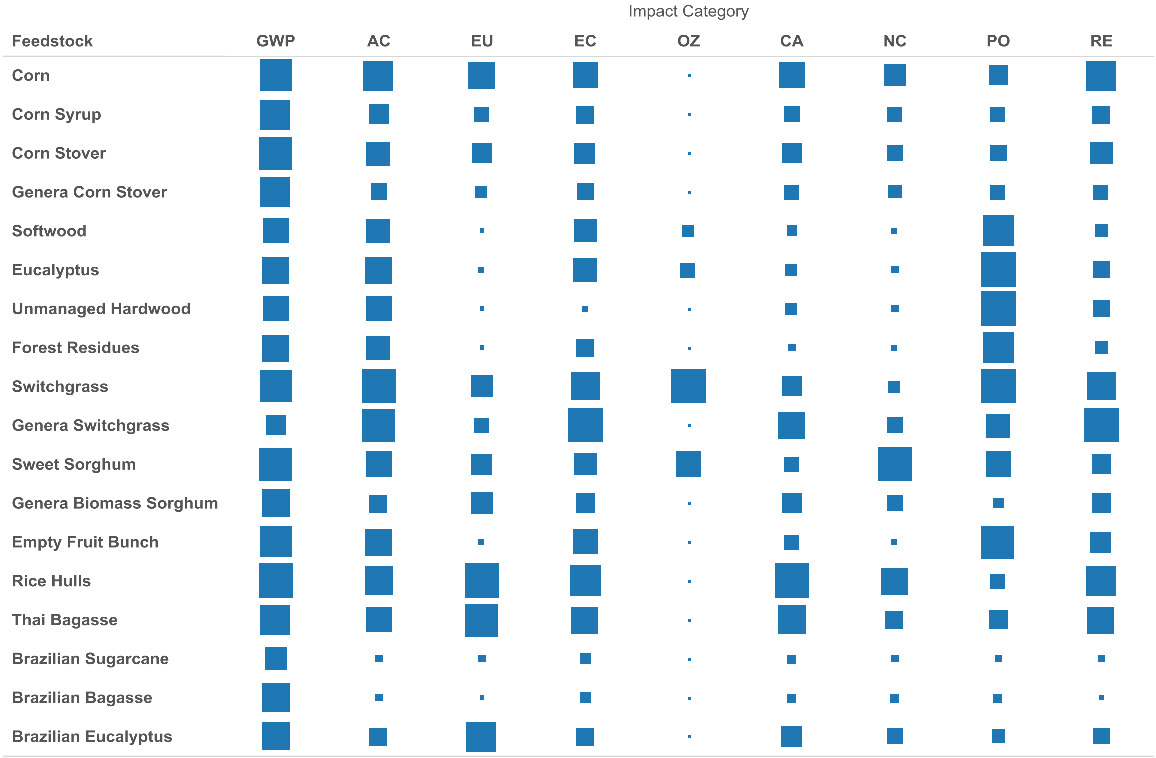

Fig. 5. TRACI impact assessment results for all feedstocks cradle-to-gate. Larger squares indicate higher environmental impact within a category per BDMT. Raw TRACI impact values in table form can be found in Appendix Table A2. For the GWP impact category all of the scenario values were negative; in this plot the size of the square is larger for those scenarios with larger net GWP impacts.

From the TRACI results, and for the scenario assumptions used here, it is clear that simply because a feedstock is a residue co-product within a system does not mean that it inherently results in lower environmental and human health impacts. For example, the agricultural by-product rice hulls result in the highest environmental impacts for GWP. The second-highest GWP impact was attributed to sweet sorghum, an energy crop. Rice hulls were most impactful for global warming potential, eutrophication, ecotoxicity, and carcinogenics, while switchgrass was most impactful for acidification, ozone depletion, and photochemical oxidation. It should be noted that the environmental impacts of rice hull were mass allocated between rice grain and the rice hull; it is acknowledged that the rice grain is the driver that motivates the rice plant growth. For some feedstocks economic allocation may be more appropriate, however mass allocation was used throughout this study so that results would be comparable. Sweet sorghum resulted in the highest non-carcinogenics impact, and corn resulted in the largest respiratory effect.

This analysis is a cradle-to-gate comparison between feedstocks for a bio-refinery model. When combined with sugar yield, energy of conversion, cost of biorefining, and other factors, an educated determination of which feedstock and bio-refinery conversion pathway is least costly and least environmentally burdensome is possible. Where competing feasibility criteria exist, trade-offs must be taken into account during decision making. Part 2 of this manuscript explores methods for comparing competing criteria.

CONCLUSIONS

1. Several biomass types have been identified that have sufficient availability to satisfy the ongoing demand of an operating bio-based sugar refinery at 500,000 BDMT yr^{-1}.
2. From among biomass feedstock types studied, those produced in Southeast Asia and South America generally resulted in a lower delivered cost than those produced in North America.
3. The major cost drivers for most biomass types were transportation and biomass purchase price.
4. Optimizing biomass supply systems for transport improves the cost position, but does not appreciably reduce global warming potential impacts.
5. Calculating sugar yield enables the calculation of a yield-adjusted feedstock cost per metric tonne of biosugar produced, a more meaningful measure of feedstock cost to produce sugars than delivered mass cost or delivered carbohydrate cost.
6. Rice hull biomass has the lowest delivered cost but a low carbohydrate content, a potential issue for storage, transportation and processing feasibility.
7. Rice hulls, empty fruit bunch, sweet sorghum, and corn stover resulted in the highest global warming potential, followed closely by Genera corn stover, corn, corn syrup, switchgrass, and Thai sugarcane bagasse. Contribution analysis shows that chemical inputs such as fertilizer use contribute substantially to an increase in the net global warming impacts for these feedstocks.
8. Biorefining for chemicals such as bio-succinic acid production may be financially feasible, depending upon the biomass type chosen, feedstock purchase or production cost, conversion yield, and the implications of throughput capacity on scale-related capital costs.

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APPENDIX

Table A1. Chemical Composition of Studied Feedstock Biomass Species

		Corn Grain	Corn Syrup	Corn Stover	Genera Corn Stover	Softwood	Eucalyptus	Unmanaged Hardwood	Forest Residues	Switchgrass	Genera Switchgrass	Sweet Sorghum	Genera Biomass Sorghum	Empty Fruit Bunch	Rice Hulls	Thai Bagasse	Brazilian Sugarcane	Brazilian Bagasse	Brazilian Eucalyptus
Glucan	%	54	100	36	36	44	45	49	39	33	33	68	68	44	33	41	69	39	47
Total Hemi-celluloses	%	18	0	26	26	19	21	19	26	28	28	12	12	28	26	23	8	24	20
Arabinan	%	3	0	3	3	0	0.3	0	2	3	3	0	0	0	0	2	0	2	5
Xylan	%	15	0	19	19	7	13	17	12	22	22	12	12	0	0	20	8	22	12
Mannan	%	0	0	0.3	0.3	10	1	2	10	0	0	0	0	0	0	0.2	0	0	2
Galactan	%	0	0	2	2	2	1	0	3	1	1	0	0	0	0	1	0	1	2
Uronic acids	%	0	0	2	2	0	6	0	0	2	2	0	0	0	0	0	0	0	0
Extractives	%	3	0	4	4	0	4	2	5	13	13	8	8	4	4	8	0	5	4
Ash	%	3	0	4	4	0.4	0.3	1	1	5	5	1	1	1	19	4	1	2	3
Lignin	%	12	0	13	13	27	30	27	29	18	18	10	10	23	19	26	22	25	26
Closure	%	89	100	82	82	90	100	98	100	97	97	99	99	100	100	100	100	95	100

Table A2. Environmental and Human Health Impacts, per Bone-Dry Metric Tonne of Biomass Delivered, for Each Feedstock by TRACI Impact Category.

	GWP	AC	EU	EC	OZ	PO	CA	NC	RE
Corn Grain	-1540	37	6.4E-1	18	5.6E-6	2.1E-1	1.9E-1	3735	1.4E-1
Corn Syrup	-1575	15	2.4E-1	8.5	3.6E-6	1.2E-1	8.1E-2	1708	5.3E-2
Corn Stover	-1422	22	3.6E-1	12	3.1E-6	1.4E-1	1.1E-1	2325	8.3E-2
Genera Corn Stover	-1589	11	1.4E-1	7.7	1.3E-6	1.2E-1	6.3E-2	1490	3.5E-2
Softwoods	-1833	24	3.0E-2	13	1.3E-3	5.4E-1	3.0E-2	359	3.0E-2
Eucalyptus	-1753	28	4.0E-2	16	1.9E-3	6.1E-1	4.0E-2	432	4.0E-2
Unmanaged Hardwood	-1797	27	3.0E-2	1.0	4.3E-7	6.1E-1	4.0E-2	432	4.0E-2
Forest Residues	-1793	24	2.0E-2	9.0	1.8E-7	5.3E-1	2.0E-2	323	3.0E-2
Switchgrass	-1517	45	4.8E-1	21	9.6E-3	6.2E-1	1.1E-1	1105	1.2E-1
Genera Switchgrass	-2096	43	2.4E-1	31	1.1E-5	3.2E-1	2.0E-1	2300	1.8E-1
Sweet Sorghum	-1423	25	4.3E-1	13	5.4E-3	3.6E-1	6.0E-2	8700	6.0E-2
Genera Biomass Sorghum	-1699	14	4.5E-1	10.2	2.3E-6	7.2E-2	1.0E-1	1960	5.6E-2
Empty Fruit Bunch	-1474	28	4.6E-2	18	2.8E-5	5.7E-1	7.0E-2	354	7.3E-2
Rice Hulls	-1328	30	1.1	27	4.1E-6	1.3E-1	3.2E-1	5646	1.4E-1
Thai Bagasse	-1580	26	1.0	20	2.2E-5	2.0E-1	2.3E-1	2597	1.1E-1
Brazilian Sugarcane	-2008	3.0	6.2E-2	2.9	1.5E-6	3.2E-2	2.4E-2	460	1.0E-2
Brazilian Bagasse	-1642	2.7	2.0E-2	3.3	1.5E-7	4.6E-2	2.2E-2	596	4.8E-3
Brazilian Eucalyptus	-1700	13	8.1E-1	9.1	5.0E-6	1.0E-1	1.2E-1	1993	4.7E-2

Units for impact categories are: GWP (kg CO_2-eq.), AC (moles of H+-eq), EU (kg N-eq.), EC (kg 2,4-D-Eq), OZ (kg CFC-11-Eq), PO (kg NOx-Eq), CA (kg benzene-Eq), NC (kg toluene-Eq), and RE (kg PM2.5-Eq).

Table A3. Primary and Coproducts for Feedstock Supply Systems and Mass Allocation Ratios Used

Feedstock	Primary Product	Mass Percentage	Co-products	Mass Percentage	Mass Allocation Ratio
Corn Grain	Corn Grain	44%	Syrup & Stover	56%	44%
Corn Syrup	Corn Syrup	4.3%	Grain & Stover	95.7%	4.3%
Corn Stover	Corn Stover	52%	Grain & Syrup	48%	52%
Genera Corn Stover	Genera Corn Stover	52%	Grain & Syrup	48%	52%
Softwood	Softwood	100%	n/a	n/a	100%
Eucalyptus	Eucalyptus	100%	n/a	n/a	100%
Unmanaged Hardwood	Unmanaged Hardwood	100%	n/a	n/a	100%
Forest Residues	Softwood	60%	Forest Residues	40%	40%
Switchgrass	Switchgrass	100%	n/a	n/a	100%
Genera Switchgrass	Switchgrass	100%	n/a	n/a	100%
Sweet Sorghum	Sorghum	100%	n/a	n/a	100%
Genera Biomass Sorghum	Sorghum	100%	n/a	n/a	100%
Palm EFB	Palm Oil	91%	Palm EFB	9.2%	9.2%
Rice Hulls	Rice Grain	80%	Rice Hulls	20%	20%
Thai Bagasse	Cane Sugar	67%	Bagasse	33%	33%
Brazilian Sugarcane	Cane Sugar	100%	n/a	n/a	100%
Brazilian Bagasse	Cane Sugar	67%	Bagasse	33%	33%
Brazilian Eucalyptus	Eucalyptus	100%	n/a	n/a	100%

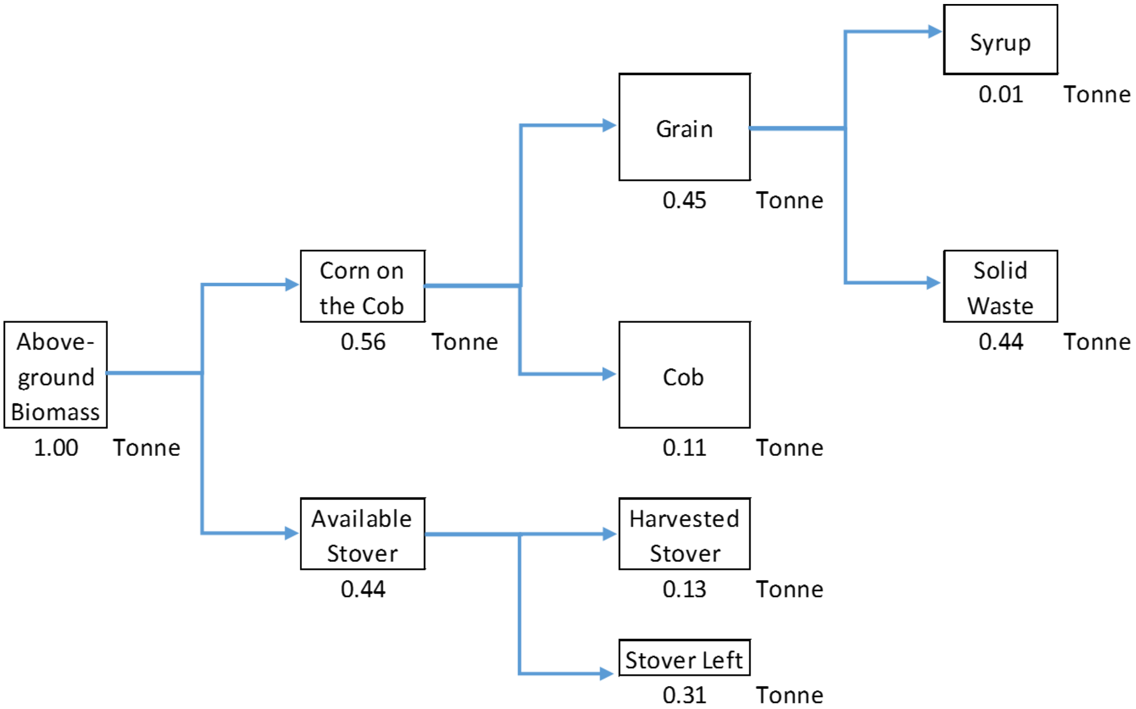

Fig. A1. Mass balance of the corn grain, corn syrup, and corn stover co-production system

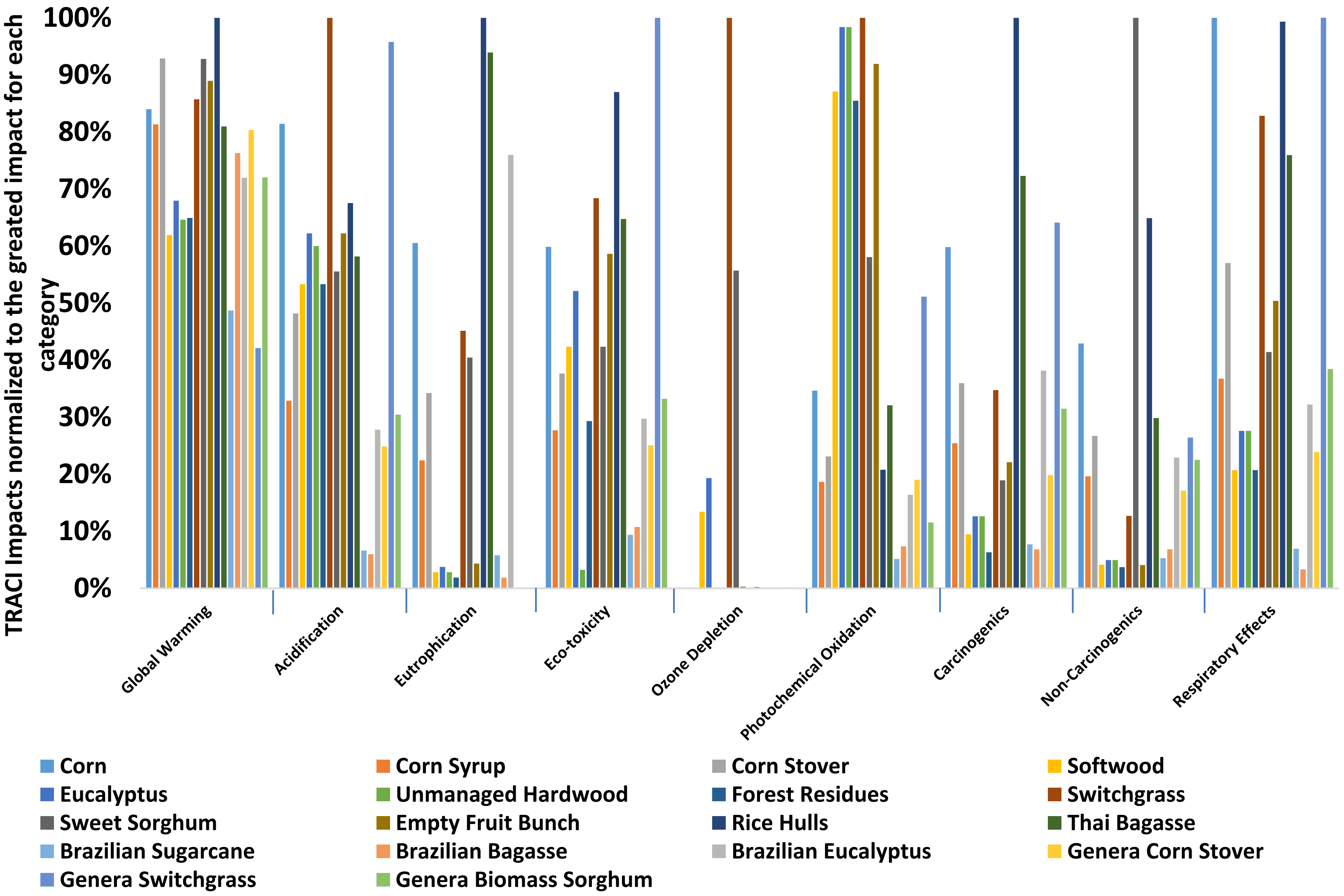

Fig. A2. TRACI impacts normalized to 100% of the greatest impact for each category

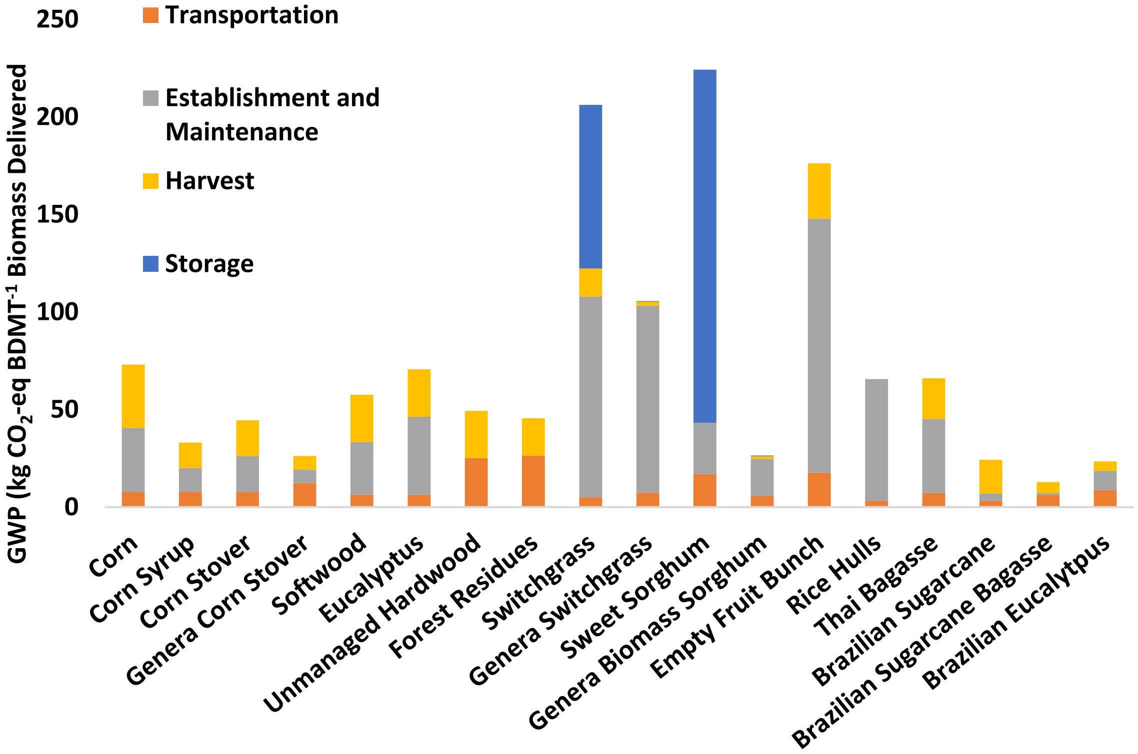

Fig. A3. Global warming contribution analysis for feedstock production and delivery per bone-dry metric tonne of biomass delivered; biomass growth is not included

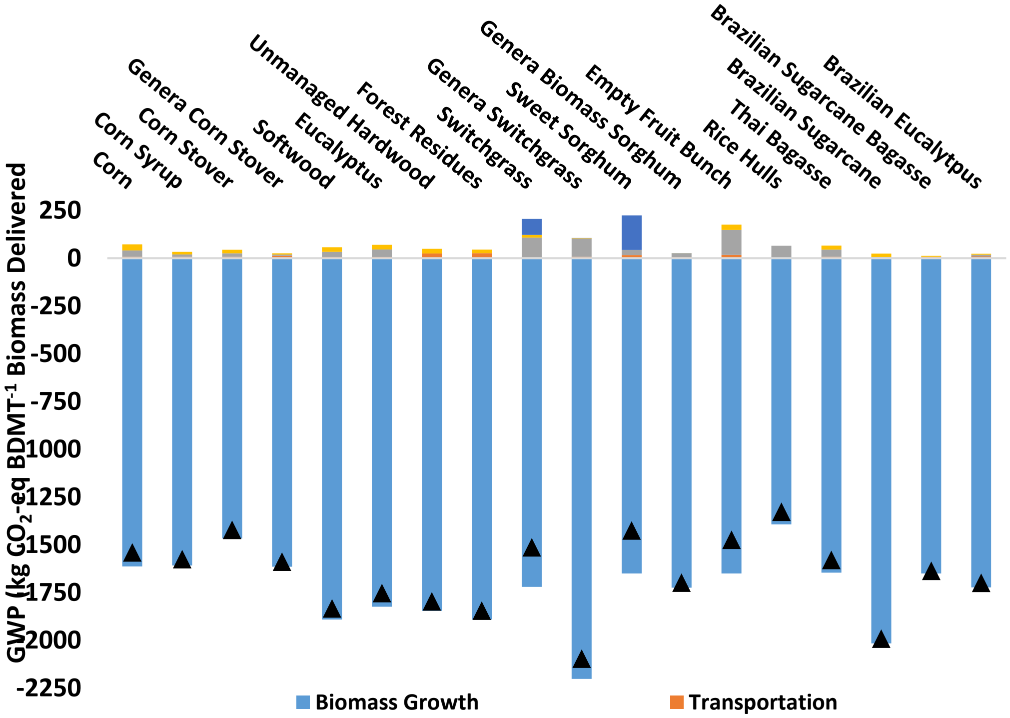

Fig. A4. Global warming contribution analysis for feedstock production and delivery per metric tonne of biosugar produced; biomass growth is included here

Table A4. Global Warming Potential, in kg CO_2-Eq. per Bone-Dry Metric Tonne of Biomass Delivered, and Contribution by Chemical and Life Cycle Stage for Each Biomass Feedstock

	Corn	Corn Syrup	Corn Stover	Genera Corn Stover	Softwood	Eucalyptus	Unmanaged Hardwood	Forest Residues	Switchgrass	Genera Switchgrass	Sweet Sorghum	Genera Biomass Sorghum	Empty Fruit Bunch	Rice Hulls	Thai Bagasse	Brazilian Sugarcane	Brazilian Sugarcane Bagasse	Brazilian Eucalyptus
Biomass Growth	-1613	-1608	-1466	-1615	-1891	-1824	-1846	-1891	-1720	-2202	-1650	-1725	-1650	-1393	-1646	-2016	-1650	-1723
Transportation	7.67	7.67	7.67	12.30	6.41	6.27	25.06	26.41	4.99	7.31	17.00	5.79	17.75	3.22	7.11	3.22	6.25	8.72
Urea															31.99			4.33
Phosphorus	1.49	0.56	0.84	0.32						0.43		1.05		2.19	2.21	0.12	0.04	1.97
Potassium	0.98	0.36	0.55	0.21						6.20		0.68		1.96	3.82	0.66	0.22	0.74
Lime	0.02	0.01	0.01	0.01						0.21						0.05	0.02	0.46
Nitrogen	27.97	10.48	15.75	5.93						12.70		13.30		27.82		1.91	0.62	1.85
Glyphosate	2.33	0.87	1.31	0.50										14	0.01	0.97	0.03	0.49
Pursuit										30.60								
MSO										41.80								
2,4-D										2.58								
Atrazine												0.74						
Dipel												3.11						
Bipyridylium															0.02			
Unspecified pesticide	0.10	0.04	0.06	0.02											0.05			
Irrigation														16.08				0.00
Diesel										1.37								
Establishment and Maintenance	32.9	12.3	18.5	6.98	26.9	40.1	0.0	0.0	103	95.9	26.2	18.9	130	62.4	38.1	3.71	0.930	9.84
Diesel	5.01	2.72	2.73	1.04						2.10		1.39			20.80	0.97	0.26	4.80
Gasoline	0.78	0.30	0.45	0.17														
Electricity	26.73	10.03	15.04	5.66														
Land Burning emissions																16.28	5.37	
Harvest	32.5	13.0	18.2	6.87	24.2	24.2	24.2	19.1	14.3	2.10	0.00	1.39	28.3	0.00	20.8	17.3	5.64	4.80
Storage									83.9	0.31	181	0.34						
Total	-1540	-1575	-1422	-1589	-1833	-1753	-1797	-1845	-1514	-2096	-1426	-1699	-1474	-1328	-1580	-1992	-1637	-1700

Table A5. Parameters for Preliminary Financial Analysis of Bio-Succinic Acid Production Based on Literature Values and Feedstock Costs Described Herein

Feedstock	Feedstock Capacity tonne/year	Biosugar Yield kg/BDMT	Feedstock Cost/tonne biosugar	Biosugar Production tonnes/year	Project Years	Capacity tonne /year	Succinic Yield t/t biosugar	Succinic Production tonnes/year	Cost of Production $/tonne	Succinic Market Price $/tonne	Annual Rate of Depreciation
Corn	500,000	626	$225	313,000	15	13,608	0.25	78,250	$620	$4,000	0.0667
Corn Grain	500,000	700	$263	350,000	15	13,608	0.25	87,500	$620	$4,000	0.0667
Corn Stover	500,000	551	$129	275,500	15	13,608	0.25	68,875	$620	$4,000	0.0667
Genera Corn Stover	500,000	551	$147	275,500	15	13,608	0.25	68,875	$620	$4,000	0.0667
Softwood	500,000	570	$179	285,000	15	13,608	0.25	71,250	$620	$4,000	0.0667
Eucalyptus	500,000	611	$154	305,500	15	13,608	0.25	76,375	$620	$4,000	0.0667
Unmanaged Hardwood	500,000	615	$171	307,500	15	13,608	0.25	76,875	$620	$4,000	0.0667
Forest Residues	500,000	358	$250	179,000	15	13,608	0.25	44,750	$620	$4,000	0.0667
Switchgrass	500,000	493	$266	246,500	15	13,608	0.25	61,625	$620	$4,000	0.0667
Genera Switchgrass	500,000	49	$258	24,500	15	13,608	0.25	6,125	$620	$4,000	0.0667
Sweet Sorghum	500,000	654	$102	327,000	15	13,608	0.25	81,750	$620	$4,000	0.0667
Genera Biomass Sorghum	500,000	350	$158	175,000	15	13,608	0.25	43,750	$620	$4,000	0.0667
Palm EFB	500,000	649	$97	324,500	15	13,608	0.25	81,125	$620	$4,000	0.0667
Rice Hulls	500,000	460	$54	230,000	15	13,608	0.25	57,500	$620	$4,000	0.0667
Thai Bagasse	500,000	550	$166	275,000	15	13,608	0.25	68,750	$620	$4,000	0.0667
Brazilian Sugarcane	500,000	753	$96	376,500	15	13,608	0.25	94,125	$620	$4,000	0.0667
Brazilian Bagasse	500,000	504	$175	252,000	15	13,608	0.25	63,000	$620	$4,000	0.0667
Brazilian Eucalyptus	500,000	626	$116	313,000	15	13,608	0.25	78,250	$620	$4,000	0.0667

Table A6. Results of Preliminary Financial Analysis of Bio-Succinic Acid Production Based on the Parameters in Table A5 and Literature Values.

Feedstock	Feedstock Cost $/tonne biosugar	Feedstock Cost $/year	Infrastructure Investment	Cost of Capex	Depreciation	Revenue $/year	Tax @ 15%	Production Costs	Margin	IRR	Margin per tonne
Corn	$900	$281,700,000	$48,515,000	$3,331,363	$3,234,333	$309,765,667	$46,464,850	$48,515,000	-$26,784,453	-8%	-$342.29
Corn Grain	$1,052	$368,200,000	$54,250,000	$3,725,167	$3,616,667	$346,383,333	$51,957,500	$54,250,000	$23,249,333	5%	$266
Corn Stover	$516	$142,158,000	$42,702,500	$2,932,238	$2,846,833	$272,653,167	$40,897,975	$42,702,500	-$129,367,453	-70%	-$1,878
Genera Corn Stover	$588	$161,994,000	$42,702,500	$2,932,238	$2,846,833	$272,653,167	$40,897,975	$42,702,500	-$109,531,453	-53%	-$1,590
Softwood	$716	$204,060,000	$44,175,000	$3,033,350	$2,945,000	$282,055,000	$42,308,250	$44,175,000	-$76,828,400	-31%	-$1,078
Eucalyptus	$616	$188,188,000	$47,352,500	$3,251,538	$3,156,833	$302,343,167	$45,351,475	$47,352,500	-$112,904,653	-48%	-$1,478
Unmanaged Hardwood	$684	$210,330,000	$47,662,500	$3,272,825	$3,177,500	$304,322,500	$45,648,375	$47,662,500	-$92,733,800	-36%	-$1,206
Forest Residues	$1,000	$179,000,000	$27,745,000	$1,905,157	$1,849,667	$177,150,333	$26,572,550	$27,745,000	$2,582,373	1%	$58
Switchgrass	$1,064	$262,276,000	$38,207,500	$2,623,582	$2,547,167	$243,952,833	$36,592,925	$38,207,500	$19,332,173	6%	$314
Genera Switchgrass	$1,032	$25,284,000	$3,797,500	$260,762	$253,167	$24,246,833	$3,637,025	$3,797,500	$1,137,453	4%	$186
Sweet Sorghum	$408	$133,416,000	$50,685,000	$3,480,370	$3,379,000	$323,621,000	$48,543,150	$50,685,000	-$188,866,480	-102%	-$2,310
Genera Biomass Sorghum	$632	$110,600,000	$27,125,000	$1,862,583	$1,808,333	$173,191,667	$25,978,750	$27,125,000	-$61,875,333	-45%	-$1,414
Palm EFB	$388	$125,906,000	$50,297,500	$3,453,762	$3,353,167	$321,146,833	$48,172,025	$50,297,500	-$193,912,547	-109%	-$2,390
Rice Hulls	$216	$49,680,000	$35,650,000	$2,447,967	$2,376,667	$227,623,333	$34,143,500	$35,650,000	-$177,001,867	-205%	-$3,078
Thai Bagasse	$664	$182,600,000	$42,625,000	$2,926,917	$2,841,667	$272,158,333	$40,823,750	$42,625,000	-$88,432,667	-39%	-$1,286
Brazilian Sugarcane	$384	$144,576,000	$58,357,500	$4,007,215	$3,890,500	$372,609,500	$55,891,425	$58,357,500	-$226,492,360	-111%	-$2,406
Brazilian Bagasse	$700	$176,400,000	$39,060,000	$2,682,120	$2,604,000	$249,396,000	$37,409,400	$39,060,000	-$71,964,480	-33%	-$1,142
Brazilian Eucalyptus	$464	$145,232,000	$48,515,000	$3,331,363	$3,234,333	$309,765,667	$46,464,850	$48,515,000	-$163,252,453	-84%	-$2,086

Margin values in red indicate negative net earnings per tonne succinic acid produced for that feedstock conversion scenario. Production level assumed to vary based upon sugar yield from 500,000 bone-dry metric tonnes of biomass converted per year. Tax rate is assumed to be 15%, debt/equity ratio assumed to be 40%/60%. Infrastructure cost assumed to vary linearly with feedstock processing capacity.