ANL/ESD-13/9

Material and Energy Flows in the Production of Cellulosic Feedstocks for Biofuels for the GREET™ Model

Energy Systems Division

About Argonne National Laboratory
Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see www.anl.gov.

Availability of This Report
This report is available, at no cost, at http://www.osti.gov/bridge. It is also available on paper to the U.S. Department of Energy and its contractors, for a processing fee, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone (865) 576-8401
fax (865) 576-5728
reports@adonis.osti.gov

ANL/ESD-13/9

Material and Energy Flows in the Production of Cellulosic Feedstocks for Biofuels for the GREET™ Model

by
Zhichao Wang, Jennifer B. Dunn, Jeongwoo Han, and Michael Q. Wang
Energy Systems Division, Argonne National Laboratory

October 2013

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

ACKNOWLEDGEMENTS

This work was supported by the Biomass Program of the Office of Energy Efficiency and Renewable Energy of the United States Department of Energy, under contract DE-AC02-06CH11357. We acknowledge Thomas Voigt of the University of Illinois at Urbana-Champaign for helpful discussions on the development of miscanthus parameters. We also thank Timothy Volk of SUNY College of Environmental Science and Forestry and Martin Heller of University of Michigan for helpful discussions about willow biomass production. We thank Bill Stewart of the University of California at Berkeley for the discussion on the development of forest residue parameters. We also appreciate the very helpful review and comments from Timothy Volk of SUNY-ESF, Rich Pyter of Aloterra Energy, and Doug Karlen of USDA-ARS, NLAE. Any errors that remain are the responsibility of the authors.

ACRONYMS AND ABBREVIATIONS

BRDI	Biomass Research and Development Initiative
BTS2	U.S. Billion-Ton Study Update
Btu	British thermal unit
bu	bushel
C	Carbon
$CaCO_3$	calcium carbonate
CCLUB	Carbon Calculator for Land Use Change from Biofuels
CH_4	methane
Cl	chlorine
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CORRIM	Consortium for Research on Renewable Industrial Materials
DOE	Department of Energy
DOE-EERE	Department of Energy, Office of Energy Efficiency and Renewable Energy
ECN	Energy research Centre of the Netherlands
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EISA	Energy Independence and Security Act
FIA	Forest inventory and analysis
g/ha	gram per hectare
GHG	Greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
H	hydrogen
HHV	Higher heating value
IPCC	Intergovernmental Panel on Climate Change
K	potassium
K2O	potassium oxide
LCA	Life-cycle analysis
LHV	Lower heating value
LSB	Large square bales
LUC	Land-use change
LTSP	Long-term soil productivity

N	nitrogen
N_2O	nitrous oxide
NASS	National Agricultural Statistic Service
NRCS	Natural Resource Conservation Service
O	oxygen
P	phosphorus
PNNL	Pacific Northwest National Laboratory
RUSLE2	Revised Universal Soil Loss Equation
S	sulfur
SRWC	Short rotation woody crops
SOC	Soil organic carbon
SUNY-ESF	State University of New York, College of Environmental Science and Forestry
TPO	Timber Product Output
USDA	U. S. Department of Agriculture
USDA-OCE/WAOB	USDA/Office of the Chief Economist/World Agricultural Outlook Board
VOC	Volatile organic carbon
WEPS	Wind erosion prediction system

MATERIAL AND ENERGY FLOWS IN THE PRODUCTION OF CELLULOSIC FEEDSTOCKS FOR BIOFUELS FOR THE GREET^{TM} MODEL

Zhichao Wang, Jennifer B. Dunn, Jeongwoo Han, and Michael Q. Wang

ABSTRACT

Feedstock production is one of the key stages in the life cycle of biofuels. In this report, material and energy flows in the production of six cellulosic biofuel feedstocks are outlined: corn stover, miscanthus, switchgrass, willow, poplar, and forest residue. For each feedstock we develop estimates of the fertilizer intensity and energy intensity of production. We also provide composition and heating value data that are necessary in life cycle analysis of biofuels. Finally, we assess the energy intensity of transporting each feedstock to a biorefinery. In the final section of the report, we provide a summary table with feedstock production material and energy flows used in the GREET model.

1 INTRODUCTION

The United States imports and consumes more oil than any other country according to the Energy Information Administration (EIA, 2013). Petroleum consumption is dominated by the transportation sector, which consumes over 70% of petroleum in the U.S. (EIA, 2012). Additionally, the transportation sector contributes 28% to total U.S. greenhouse gas (GHG) emissions (EPA, 2013). Biofuels are receiving attention as an alternative to petroleum for the transportation sector because adopting these fuels could reduce its petroleum consumption and environmental impacts.

Cellulosic feedstocks are important to the advancement of biofuels in light of the Energy Independence and Security Act (EISA) of 2007 (U.S. Congress, 2007), which mandates 36 billion gallons of renewable fuel be in use by 2022. EISA breaks out the 36 billion gallons of biofuels into two categories based on feedstock type and life-cycle GHG emissions compared to petroleum fuels. (The base year for comparison to petroleum fuels is 2005.) 21 billion gallons of the total volume of renewable fuels in 2022 is mandated to be advanced biofuels, which ESIA defines as having 50% lower life-cycle GHG emissions than gasoline. This category excludes corn ethanol, but includes ethanol and other fuels from cellulosic feedstocks, sugars, or starch other than corn starch. Additionally, EISA mandates that 16 billion gallons of cellulosic biofuels be available for use in 2022. Fuels with this designation must achieve a 60% reduction in life-cycle GHG emissions compared to their petroleum-derived counterparts and can derive from any cellulose, hemicellulose, or lignin from renewable biomass.

To determine the life-cycle GHG emissions of a biofuel, it is important to characterize material and energy flows during feedstock production. In this report, we examine the production of six cellulosic feedstocks identified in the Billion-Ton Update (BTS2 (Department of Energy (DOE), 2011) report as contributing to the potential production of one billion dry tons (short ton) of biomass annually in a sustainable manner, including corn stover, miscanthus, switchgrass, willow, poplar, and forest residue. The aim of this document is to describe the development of parameters for the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model for key facets of the production (or, in the case of agricultural and forest residues, collection) of these cellulosic feedstocks, from the field to the conversion facility gate. These feedstocks may be used in the modeling of cellulosic ethanol pathways, pyrolysis fuel pathways, or other biofuel pathways. Additionally, they may be used in the calculation of life-cycle energy consumption and emissions of biopower.

The report is organized into nine sections with the first six sections following the introduction dedicated to individual feedstocks. The following variables are evaluated for each feedstock: availability and yield, energy consumption during field operations, agricultural chemical inputs, transportation of feedstock to the biorefinery gate, and feedstock elemental composition and lower heating value (LHV).Parameters related to transportation of these feedstocks are discussed in Section 8. In Section 9, we summarize GREET parameters, main conclusions, and outstanding issues for these feedstocks.

2 CORN STOVER

2.1 BACKGROUND

Corn stover, the in-field residue after corn grain harvest, is a potential cellulosic biomass feedstock for biofuels production. In the near term, it is possible that corn stover will be a primary biofuel feedstock because existing corn ethanol plants in the Corn Belt could be adapted to convert corn stover along with corn grain potentially yielding economies of scale (Schnepf and Yacobucci, 2013). Importantly, corn stover can be considered a surplus or waste product and its sustainable collection as a feedstock does not diminish food availability for humans or livestock.

2.2 YIELD AND AVAILABILITY

The BTS2 (DOE, 2011) assumes that the corn grain-to-stover mass ratio is 1:1 or 0.024 dry tons stover/bushel (bu) of corn grain. That study developed two scenarios for corn production: baseline and high-yield. In the baseline scenario, the corn grain yield is estimated based on a United States Department of Agriculture (USDA) report by the Office of the Chief Economist, World Agriculture Outlook Board (OCE-WAOB) that projects corn yields to 2019 (USDA-OCE/WAOB, 2010). The BTS2 then predicts yields to 2030 with a straight-line extension of the historic yield trend. In the high-yield scenario, the corn grain yield is assumed to increase by 2% annually. Corn grain and stover yields (calculated based on 0.024 dry tons/ bu corn grains) in these two scenarios are listed in Table 1. We show the projections through year 2022, the year through which EPA included a biofuel mandate in RFS2. In this study, we adopt the baseline, more conservative corn grain and stover yield.

Table 1. Corn grain and stover yield (DOE, 2011)

Year	Baseline [a]		High-yield [a]	
	Corn grain yield (bu/acre)	Total corn stover generated[b] (ton/acre)	Corn grain yield (bu/acre)	Total corn stover generated [b]
2012	163	3.8	163	3.8
2017	174	4.1	201	4.8
2022	183	4.3	228	5.4

[a] Based on projected national average corn yield.
[b] This amount is the total stover availability on a corn field assuming 0.024 dry tons stover/bu corn grain. Only a portion of this stover should be removed to avoid detrimental effects such as erosion and soil organic carbon (SOC) depletion (see Table 2 and discussion).

It is widely recognized that it is not sustainable to remove all corn stover from corn fields to avoid soil erosion and maintain soil nutrients and SOC levels (DOE, 2011; Muth et al., 2013). In fact, equipment efficiency prohibits complete removal of stover. In Muth et al. (2013), five levels (0, 22%, 35%, 52% and 83%) of residue removal rate are estimated based on currently available, double pass harvesting technologies and equipment.

In the BTS2 (DOE, 2011), the amount of agricultural residue that can be sustainably removed from agricultural cropland is subject to two modeled constraints. First, removals cannot exceed the tolerable soil loss limit as recommended by the USDA's Natural Resource Conservation Service (NRCS). Second, removal cannot result in long-term loss of soil organic matter as estimated by the Revised Universal Soil Loss Equation (RUSLE2) and the Wind Erosion Prediction System (WEPS). In general, both models provide estimates of soil erosion and other pertinent soil tilth parameters from agricultural systems with different crops, rotations, field topography and field management practices (e.g., tillage). Generally, farmers can either adopt conventional till, reduced till or no-till field management practices. Reduced till and no-till practices disturb the soil less and therefore may preserve more SOC than conventional till practices. The BTS2 (DOE, 2011) assumes corn stover can only be removed from fields managed with reduced or no-till practices. With these assumptions, taking into consideration the above constraints of maintaining baseline SOC and soil erosion levels, they estimated the sustainable corn stover availability between 2012 and 2030 at <$40, <$50 and <$60 per ton under both baseline and high-yield scenarios. The BTS2 adopted the total planted acres of corn from a USDA report (USDA-OCE/WAOB, 2010) in which the planted acreage of corn is approximately constant at 89.5 million acres between 2012 and 2019. We therefore assume that 89.5 million acres are planted with corn between 2012-2022. To calculate a national average removal rate of corn stover, we divide the total amount of sustainably available corn stover by this number of total planted acres (Table 2). In Table 2, the removal rates in different scenarios are no more than 31% of the available stover. However, the exact sustainable removal rate is highly dependent on local factors.

Table 2. Sustainably available corn stover at different farm gate prices (DOE, 2011)

Year	Sustainably available corn stover (Baseline scenario)						Collection ratio (collected/total generation)		
	National total (million dry tons)			Average (dry tons/acre)					
	<$40/ton	<$50/ton	<$60/ton	<$40/ton	<$50/ton	<$60/ton	<$40/ton	<$50/ton	<$60/ton
2012	19	72	86	0.21	0.80	0.96	0.06	0.21	0.25
2017	31	93	105	0.35	1.04	1.17	0.08	0.25	0.29
2022	42	108	120	0.47	1.21	1.34	0.11	0.28	0.31

One of the most recent and thorough studies on sustainable corn stover removal was conducted by Muth et al. (2013). These authors used county-level data to determine soil-rotation-tillage-yield scenarios and residue removal rates at a county level. Then the county-level data are summed to project the state and total national sustainably available residues. Muth et al. indicate that in some counties, it is not sustainable to remove any corn stover. In other counties, the sustainable stover removal rate could be as high as 4 dry tons/acre. Nationwide, they project that 136 and 192 million dry tons of corn stover could be sustainably removed in 2011 and 2030, respectively. These values convert to 1.5 and 2.1 dry tons/acre if the land used for corn agriculture is 89.5 million planted acres as described previously. This projection is higher than the BTS2 (DOE, 2011) because price constraints are not considered and conventionally-tilled fields are included as a source of stover. We adopt the BTS2 report values here because they are more conservative. However, it is possible that more corn stover than the BTS2 report predicts could be sustainably collected in the future.

2.3 COLLECTION, IN-FIELD TRANSPORTATION AND HANDLING

Steps needed for preparing corn stover as a cellulosic biofuel feedstock in a biorefinery are shown in Figure 1. Grinding at the conversion facility is accounted for in the conversion step in GREET.

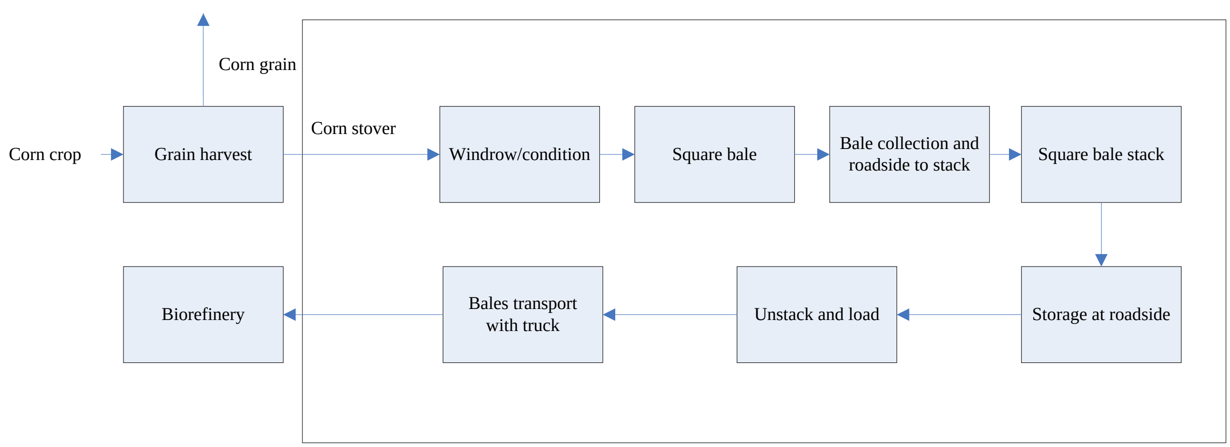

Figure 1. Scheme of preparing corn stover as feedstock for biofuels production.

Typically corn grain and stover are harvested in separate steps. Single pass harvesting of corn grain and stover is currently under development (Shinners et al., 2009). The in-field processes for corn stover collection generally consist of cutting the corn stalk, gathering and densifying the stover, and transporting it from the field to roadside storage (termed “roadsiding”) (Hess et al., 2009a). The combine harvester usually cuts the corn stalk during grain harvest. Following grain harvest, standing stubble, cobs, husks, and some leaves and tops pass through the harvester and are spread on the ground. This corn stover is conditioned and windrowed prior to baling. Conditioning is a process using rolls and/or flails to break the corn stalks for faster drying. For conventional baling, field drying is important as it could reduce dry matter loss, failed bales, and transportation costs. Although the magnitude of moisture reduction varies, in this design the moisture of the feedstock is assumed to be reduced from about 50% to 12% by field drying in the windrow (Hess et al., 2009a). Field drying can also occur after conditioning and before windrowing if a two-pass operation, commonly referred to as "mow and rake," is employed. This study adopts the scenario that Hess et al. (2009a) used, in which a single-pass conditioning and windrowing operation takes standing stubble directly to a windrow. Once the stover has been windrowed and is sufficiently dry, a large square baler stuffs and presses the biomass into 4 x 4 x 8 ft large square bales (LSB), and drops the bales in the field as they are made. Then, the bales are collected and transported to the side of the field. Round bales or square bales of different sizes could be made depending on the baler. Table 3 describes the energy consumption during corn stover collection. The latest study from Herron (2013) is also listed for comparison. Herron conducted field study on a 160-acre corn field in Iowa in 2011 and reports energy consumption for windrowing, baling and roadsiding and stacking. It is unclear whether conditioning was performed in his study. Herron reports very similar total energy consumption compared to that reported by Hess et al. (2009a) although there are some differences between the reported energy consumption for individual processes. One possible reason for this difference could be the use of different equipment. Additionally, Hess et al. estimate fuel consumption based on consumption estimates from either equipment specifications or manufacturer/dealer quotes whereas Herron used fuel consumption data from the field.

Table 3. Energy consumption during corn stover collection

Process	Equipment Hess et al. (2009a)	Energy Use (1000 Btu/ton of dry matter) Hess et al. (2009a)[a]	Herron (2013)
Condition/windrow	Tractor and shredder with windrow	91.2	101.6
Bale	Tractor and baler	77.3	46.7
Roadside and stack	Stacker	20	31[b]
Load to trucks	Loader	4	4[c]
Total		192.5	183.3

[a] Adpoted in the GREET model.
[b] For in-field bales transportation of 0.25-1 mile.
[c] Assumed the same as in Hess et al. (2009a).

Bales may be stored at the side of the field either uncovered or covered. Uncovered bales might undergo dry matter loss up to 16%. Covered bales, either within a building (4.8%) or in-field (8.4%), have much less dry matter loss (Emery, 2013). No energy consumption is assumed for bale storage. Parameters related to transportation from farm to biorefinery of corn stover, as well as of other feedstocks in this report, are discussed in Section 8.

2.4 ELEMENTAL COMPOSITION AND HEATING VALUE

Elemental composition, higher heating value (HHV) and lower heating value (LHV) of corn stover from several references are summarized in Table 4. The average values are used in GREET. The LHV is used in several calculations within GREET when corn stover is combusted or to account for total energy, which includes renewable energy. The carbon and sulfur contents of stover are used in calculating carbon dioxide (CO_2) and sulfur emissions during corn stover combustion, respectively.

Equation 1 (IPCC, 2006) is used to convert HHV into LHV. Note in Equation 2, the units of HHV and LHV are MJ/kg in Equation 1. They are converted to Btu/ton in Table 4.

$$LHV = HHV - 0.212 * H - 0.0245 * M - 0.0008 * O \quad (1)$$

Where

H = percentage hydrogen content as received
M= percentage moisture content as received
O = percentage oxygen content as received

Table 4. Elemental composition and heating value of corn stover

	Mullen et al. 2010	Wright et al. 2010	Agblevor et al. 1995			Hoskinson et al. 2007				Average
			Storage time after harvest			high cut top	high cut bottom	low cut	normal cut	
			0 week	26 weeks	52 weeks					
Ash (% dry)	4.9	6.0	5.0	5.4	5.8	4.6	5.7	4.7	5.7	5.3
C (% dry)	46.6	47.3	46.0	46.0	46.5	47.2	46.9	47.2	47.0	46.7
H (% dry)	5.0	5.1	5.9	5.4	6.1	5.7	5.6	5.7	5.8	5.6
N (% dry)	0.8	0.8	0.9	0.6	0.7	0.6	0.6	0.5	0.6	0.7
O (% dry)	40.1	40.6	41.4	39.2	40.1	42.0	41.2	41.8	40.9	40.8
S (% dry)	0.2	~0	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1
HHV (Btu/ dry ton)	16,154,000		16,026,000	15,690,000	15,406,000	15,750,000	15,750,000	15,664,000	15,750,000	15,774,000
LHV (Btu/ dry ton)	15,216,000		14,921,000	14,678,000	14,265,000	14,681,000	14,700,000	14,595,000	14,664,000	14,716,000

2.5 FERTILIZER REPLACEMENT RATES

The usage rate of fertilizer is an important parameter for assessing biofuels life-cycle energy use and GHG emissions. GREET calculates the energy associated with fertilizer production from its data for the production of the compounds that make up these fertilizers (Johnson et al., 2013).

Traditionally, the bulk of corn stover has been left on corn fields to replenish the soil with nitrogen (N), phosphorus (P), and potassium (K), which reintegrate into the soil and nourish the next season's crops. Stover collection as part of the biofuel supply chain will likely require farmers to supplement the nutrient content in collected stover with fertilizer. Recent studies provide new insight into the fertilizer replacement levels that are needed as a result of stover collection. Table 5 summarizes these studies' replacement rates, which assume the removed nutrients are replenished pound for pound. The fertilizer application rates exhibit great variability with geography and other factors. For example, there are major changes in plant composition between physiological maturity and harvest due to translocation of K, chlorine (Cl), and other mobile nutrients from the stalks and leaves. Thus, choosing a single value to represent replacement ratios for national corn stover production may not be representative. As a result, we chose conservative, round values for N, phosphate (P_2O_5), and potash (K_2O) replacement rates. The shares of different forms of N fertilizer are assumed to be the same as the GREET model default values (70.7%, 21.1%, and 8.2% for ammonia, urea, and ammonium nitrate, respectively), which were developed from national fertilizer consumption data from USDA National Agriculture Statistic Service (NASS, 2013). These shares of different forms of N fertilizer are also used for other feedstocks in this study where fertilizer application is needed. Although we convey the reported calcium carbonate ($CaCO_3$) value from Avila-Segura et al. (2011), we do not include a $CaCO_3$ replenishment rate in GREET at this time.

Table 5. Replacement rates for nitrogen, phosphorus, potassium, and calcium carbonate after corn stover collection (g fertilizer/dry ton stover collected)

Source	N	P	K	$CaCO_3$	Note
Avila-Segura et al. (2011)	5,912	755	10,190	29,158	
Karlen (2010)	9,179	1,093	9,835		
Hess et al. (2009b)	6,719	2,315	12,349		
Fixen (2007) [a]	8,626	2,588	14,528		
Lang (2002) [a]	6,810	2,679	11,350		
Petrolia (2006)		2,815	14,987		
Nielsen (1995) [a]	6,174	1,634	8,944		
O'Brien et al. (2010)	7,718	1,816	22,700		
Gallagher et al. (2003) [a]	5,751	1,194	12,113		Average of values from 10 different counties
Schechinger and Hettenhaus (2004) [a]	6,053	3,178	15,890		
Johnson et al. (2010)	4,994	1,040	6,784		Cobs
Johnson et al.(2010)	6,810	2,496	9,520		Above-ear stover
Johnson et al. (2010)	5,811	2,080	11,709		Below-ear stover
Sindelar et al. (2013)	5,256	894	10,395		Based on 3.3 ton/acre stover and 0.67 ton/acre cobs removal
This study	7,000	2,000	12,000		

[a] These studies were used to develop fertilization rates reported in the BTS2, which were 6,700 g nitrogen per dry ton, 2,300 g P_2O_5 per dry ton and 12,300 g K_2O per dry/ton corn stover, respectively. These rates are close to those used in GREET.

Note that Sindelar et al. (2013) observed corn stover's nitrogen content is positively correlated with the N fertilizer application rate during corn planting. This indicates that if in the future the fertilizer application rate decreases as corn agriculture technology develops, which historically has been the case, less nitrogen will need to be applied to corn fields that have had stover removed as a biofuel feedstock.

Nitrogen fertilizers go through nitrification and denitrification in fields, releasing N_2O. In GREET, this parameter is 1.525%, for all feedstocks based on a literature review (Wang et al., 2012).

2.6 SUMMARY

Key parameters developed in this analysis and used in GREET are listed in Table 6.

Table 6. Summary of parameters adopted in GREET

Parameter	Value
Corn stover removal rate (dry ton/acre)	0.96[a]
In-field energy consumption (1,000 btu/ dry ton)	192.5
Transportation	
Moisture content (%)	12
Payload (dry ton)	20[b]
Distance (mile)	50[c]
Elemental composition (% dry)	
C	46.7
H	5.6
N	0.7
O	40.8
S	0.1
Ash	5.3
LHV (Btu/ dry ton)	14,716,000
Supplement fertilizer usage rate (g fertilizer/ ton dry corn stover removed)	
N	7,000
P_2O_5	2,000
K_2O	12,000
N_2O emission from N-fertilizer (%)	1.525

[a] For year 2012, at cost <$60/ton, see Table 2 for other cases.
[b] Indoor LSB. See Table 34 for other cases.
[c] See Section 8 for calculations of this parameter

3 MISCANTHUS

3.1 BACKGROUND

Miscanthus is a genus comprising more than ten species of perennial C_4 grasses. They are native to eastern Asia, North India and Africa (Clayton et al., 2008; Hodkinson et al., 2002; Scally et al., 2001; Heaton et al., 2010). *Miscanthus* x *giganteus* (hereafter referred to as miscanthus) is one species of miscanthus of particular interest in recent decades. Generally, miscanthus has a higher total biomass yield than switchgrass and corn stover, two other cellulosic crops. It has high water use efficiency and the large and active root system is particularly effective at scavenging available nutrients and preventing them from leaching with draining water (Heaton et al., 2010). Previously, Miscanthus has been more intensively studied in European countries (Christian et al., 2008; Clifton-Brown et al., 2007; Lewandowski et al., 2000; 2003; Lewandowski and Schimidt, 2006). Interest in producing miscanthus domestically as a biofuel feedstock has recently increased.

Figure 2 diagrams the steps in miscanthus production.

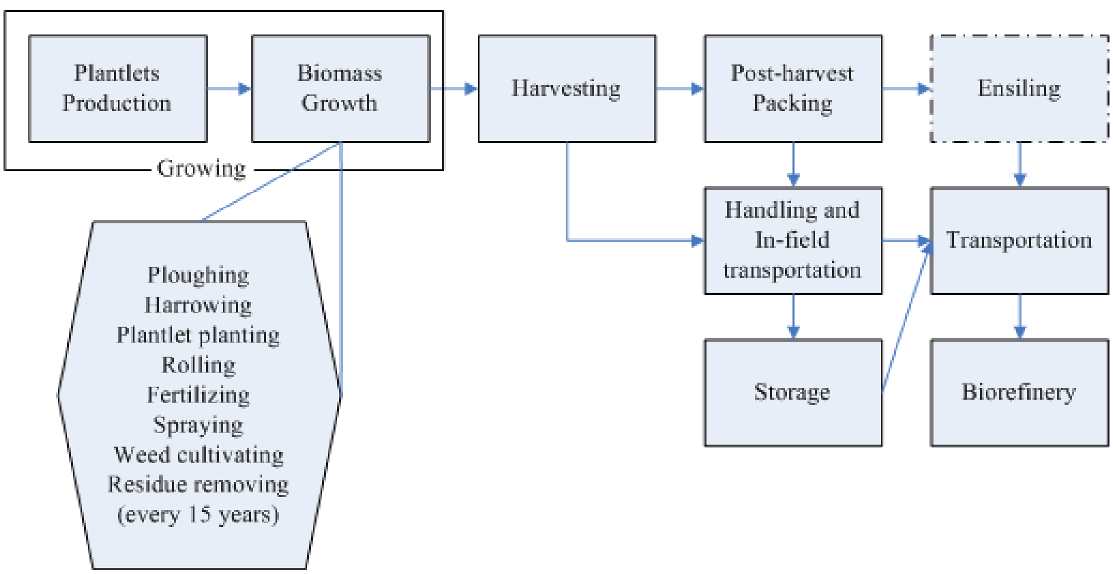

Figure 2. Processes for miscanthus biomass production from the field to the gate of biorefinery. Steps in solid boxes are considered in this report, while examples of other potential steps are indicated in dashed boxes.

Miscanthus does not form fertile seeds that are planted and grow to mature plants. Rather, plantlets (propagated from rhizome division) are grown either in greenhouses or in the field. Alternatively, commercial, rhizome-derived plugs can be purchased that have been grown in greenhouses or high-tunnels (Anderson et al., 2011). The plugs are more expensive than rhizomes but have well-established roots that enhance their chances for survival. This technique is relatively new, with little peer-reviewed information available (Anderson et al., 2011). In our analysis, we model a commercial miscanthus production facility that harvests rhizomes from mature miscanthus and plants these rhizomes directly in the field. In this document, however, we provide an estimate of the energy a greenhouse would consume. It is possible that rhizomes need to be stored in a temperature-controlled warehouse prior to planting as planting might not occur immediately after rhizome lifting. We assume, however, that the rhizomes are planted directly in the field after they are lifted. We will continue to monitor trends in miscanthus production and will include energy consumption for rhizome storage and in greenhouses used to produce miscanthus plantlets when possible. .

After harvest, the biomass can either be stored on-site (under a covering in the field or in a building) or packed for shipment. In the following sections, we describe and quantify inputs into the process in Figure 2 including energy, fertilizers, and agrochemicals. We begin with an estimate of miscanthus yield.

3.2 YIELD

Miscanthus has a growing cycle of 15 years or longer. Yield increases until the third year of growth after which it stays roughly constant until the 15th year. The biomass yield tends to decline after that— although some miscanthus stands produce acceptable yields beyond 15 years (Bullard and Metcalfe, 2001). Harvestable miscanthus yields range from 4.4-17.9 dry tons/acre/year throughout Europe (Lewandowski et al., 2000). In the United States, three-year average yields of 9.4-15.4 dry tons/acre/year were observed in North, Central and South Illinois after the third year of establishment (Heaton et al., 2008). Heaton et al. (2004) summarized studies that together contained 97 observations of miscanthus yield. The average yield after the third year of establishment was 9.8 dry tons/acre/year. Second year yields of 6.6, 6.9 and 7.8 dry tons/acre/year was observed at Adelphia, New Jersey, Mead, Nebraska, and Lexington, Kentucky, respectively (DOE, 2011). These yields will likely increase because full establishment of miscanthus usually takes three to five years (Lewandowski et al., 2000). Assuming no harvest for the first year, a second year yield of 6.6 dry tons/acre/year (1.3-12.5 dry tons/acre/year in the study of Heaton et al., 2008), and a yield of 9.8 dry tons/acre/year in the third to fifteenth year (Heaton et al., 2004), we adopted an average yield of 9.0 dry ton/acre/year for the whole life cycle of miscanthus. This value is reasonable because it is below the average value Heaton et al. (2004) report and it is on the low end of the range reported for miscanthus grown in different regions in Illinois (Heaton et al., 2008).

3.3 GROWING

The growing of miscanthus usually includes plantlets production, ploughing, harrowing, plantlets planting, irrigating (if necessary), fertilizing, spraying, weed cultivating and residue removing at the end of a life cycle. It is possible that in the future the development of herbicide might eliminate the need for weed cultivating. We will monitor this development and update GREET accordingly in the future.

Producing plantlets in a greenhouse can be energy intensive. Lewandowski and Schmidt (2006) report fuel oil consumption of 1.38 million Btu/acre/year during plantlet production in a greenhouse. Boehmel et al. (2008) provide a similar consumption rate, 1.12 million Btu/acre/year. The average of these two values converted to 139,689 Btu/dry ton based on a yield of 9.0 dry tons/acre/year is likely a good estimate of the energy intensity of greenhouse production of plantlets. We expect that in the United States, this energy would be provided by liquid propane or natural gas rather than fuel oil. We do not include this energy in GREET because we assume a miscanthus production facility would be located in a climate that did not require the use of greenhouses. Instead, as described above, rhizomes would be harvested from mature miscanthus and planted directly in the ground.

In the biomass growth stage, machinery operation consumes energy. These processes only happen at the first year of each cycle except for annual fertilizer application and, at the end of the cycle, residue removal. Table 7 summarizes equipment used in the biomass growth stage and how much diesel fuel each piece of equipment consumes. Both studies in Table 7 were conducted in Europe. It is possible that the equipment used in the U.S. and, subsequently, energy consumed during harvest, will be different. We will update these values once more data become available for production of miscanthus in the U.S. The diesel fuel consumption per unit time is calculated based on the power of each piece of equipment using D=0.22P (ASAE, 1997), where D is the diesel use (L/h) and P is the maximum power-take-off (PTO) power (kW). Then the total energy consumption per hectare is calculated by multiplying D by the duration of equipment operation per hectare. The final result is converted to gal/acre/year over the 15-year life cycle.

Table 7. Machinery used during miscanthus production and resulting diesel fuel consumption (Huisman et al. (1997) and Smeets et al. (2009))

	Fre-quency/yr	Years	Equip-ment	Tractor power (kW)	Diesel consump-tion (L/h)	Work time (h/ha)	Fuel use (L/ha/life cycle)	Fuel use (gal/acre/yr)[a]
Ploughing	1	1	Plough	88	19.4	1.3	25.2	0.18
Harrowing	2	1	Power harrower	75	16.5	0.4	13.2	0.09
Plantlet planting	1	1	Rhizome planter	100	22.0	1	22.0	0.16
Rolling	1	1	Roll	60	13.2	0.3	4.2	0.03
Fertilizing	1	15	Fertilizer spreader	60	13.2	0.5	99.0	0.71
Spraying	1	1	Sprayer	60	13.2	0.6	7.9	0.06
Weed cultivating	1	1	Weed cultivator	60	13.2	0.3	4.2	0.03
Residue removal (after 15 yr)	2	1	Rotary cultivator	100	22.0	0.8	35.2	0.25
Total								1.50

[a] Averaged value based on 15-year life cycle.

Fazio et al. (2011) report a diesel consumption rate of 13.0 gal/acre for the first year of establishment but do not specify the diesel consumption for fertilizing in the production years or for residue removal. Adding Table 7 values for fertilizing (0.71 gal/acre/year) and residue removal (0.25 gal/acre/yr) to this value, the total diesel consumption is then 1.78 gal/acre/year. Lewandowski and Schmidt (2006) convey an annual fuel consumption of 0.19 million Btu/acre/year, or 1.49 gal/acre/year. The average diesel fuel consumption from these two sources and Table 7, 1.59 gal/acre/year (22,816 Btu/dry ton), is adopted as the energy consumed during biomass growth.

3.4 HARVESTING, IN-FIELD HANDLING, AND STORAGE

In the literature, energy consumption during harvesting, packing and in-field handling is often lumped with harvest energy. This grouping complicates comparing harvest energies among studies and selecting a value for use in GREET. An additional challenge is the reporting of this energy in units of energy per acre per year from which energy consumption on a per dry mass basis is calculated using the miscanthus yield, which varies among studies. Generally, energy consumption per unit area for harvesting increases as the yield increases, but not necessarily linearly. Careful selection of the yield used in the calculation is therefore required. Harvesting of miscanthus can employ different kinds of equipment including choppers, forage harvesters, and mowers. Harvested biomass can be baled or chopped before being transported to storage or biorefinery. In Section 8, different scenarios for bale storage are developed (Table 34), and consequentially they impact the transportation fuel consumption. Table 8 summarizes energy consumption during miscanthus harvesting as contained in four different literature sources. Energy consumption is converted to Btu/ton based on a yield of 9.0 dry tons/acre/year since the yields in these studies are close to the yield we adopted here. We use the average of these values, 108,660 Btu/dry ton in GREET, which we assume includes loading bales onto trucks. The transportation of miscanthus from farm-to-biorefinery is discussed in Section 8.

Table 8. Energy inputs for miscanthus harvesting, packing and handling

References	Equipment	Yield (Dry ton/acre/year)	Energy consumption (Btu/ dry ton)
Venturi et al. (1999)	Mower, chopper	8.9	95,554
Venturi et al. (1999)	Mower, baler	8.9	189,223
Bullard and Metcalfe (2001)	Mower conditioner, baler, trailer, bale loader	3.5-17.0	93,155
Lewandowski and Schmidt (2006)	n/a	5.8-7.2	77,129
Boehmel et al. (2008)	Mower, conditioner, in-field transport	5.8-7.2	68,559
Smeets et al. (2009)	Self-propelled chopper, trailer	8.5	170,425
Fazio et al.(2011)	Chopper	7.6	66,578
Average			108,660

3.5 TOTAL ENERGY INPUT

In the technical literature, the total energy input for the production of a biomass feedstock is at times provided without an itemization of individual energy inputs or only itemization for certain categories (e.g., establishment energy input). Further, studies are not always transparent regarding whether their results reflect purchased or life-cycle energy consumption. Purchased energy is the amount of energy consumed on-site, for example at a factory or farm. Life-cycle energy includes the impact of producing that energy, encompassing steps such as crude oil recovery or coal mining. Table 9 lists energy input from several references. Our analysis results in a life-cycle energy consumption of 694,656 Btu/dry ton and 573,392 Btu/dry ton with and without transportation, respectively. These results exceed several of the literature values in Table 9 possibly because our analysis encompasses a larger system boundary, including upstream fuel production impacts. In GREET, the total farming purchased energy input (excluding fertilizers and transportation) is 271,165 Btu/ton, however, the total farming energy input when upstream impacts of fuel production are considered, is 314,887 Btu/ton. Because these numbers align well with the majority of studies in Table 9, we hypothesize that not all studies in Table 9 include life-cycle impacts and conclude that the values we have chosen for GREET are reasonable.

Table 9. Total energy input for the production of miscanthus biomass

References	Energy input (Btu/dry ton)
Venturi et al., 1999	758,435
Venturi and Venturi, 2003	342,795-942,688[a]
Lewandowski and Schmidt, 2006	342,795-557,043[b]
Boehmel et al.,2008	299,946-428,494[b]
Smeets et al., 2009	~495,323[c]

[a] Summarized from several sources.

[b] Transportation to biorefinery not included, purchased energy input for diesel, life-cycle energy input for fertilizer.

[c] Purchased energy input for purchased diesel, life-cycle energy input for fertilizer.

3.6 AGRICULTURAL MATERIALS INPUTS

Fertilizer and herbicide application rates for miscanthus production are presented in Table 10. Data were collected and adapted from several references in the technical literature. Consensus is lacking on the yield response of miscanthus to nitrogen fertilization. Most research on this topic includes significant amounts of nitrogen fertilizer to compensate for the uptake of nitrogen by miscanthus biomass. Some studies, however, observed no significant yield difference when nitrogen fertilizer was applied at rates of 0, 24.3 and 48.6 kg/acre/year (Christian et al., 2008). Cosentino et al. (2007), Danalatos et al. (2007), and Miguez et al. (2008) observed a similar lack of response to nitrogen fertilization increases. Davis et al. (2010) raised a hypothesis that biological N-fixation contributed to the N demand of miscanthus and therefore less or even no nitrogen fertilizer is needed for the production of miscanthus. This hypothesis could possibly explain the above phenomenon. Until research clearly shows no need for nitrogen fertilization in miscanthus cultivation, we assume nitrogen application is necessary. In the future, however, it is possible that nitrogen fertilizer application will decrease dramatically due to miscanthus' ability to fix nitrogen. A small number of studies included lime fertilization but data were insufficient to determine a lime application rate to use in GREET. We currently assume no fertilizer is applied to rhizomes during the plantlet production stage (Voigt, 2012).

Table 10. Application rates of fertilizers and herbicides for miscanthus production

References	Fertilizer (g/dry ton)			Herbicide
	N	P	K	(g/dry ton)
DEFRA (2001)	3,857	482	4,163	
Christian et al. (2008)	3,322	276	3,883	
Styles et al. (2008)	4,093	815	4,093	
Smeets et al. (2009)	2,630	526	5,697	110
Fazio et al. (2011)	3,681	581	2,939	131
Average	3,517	536	4,155	121
Range	2,630-4,093	276-815	2,939-5,697	110-131

3.7 ELEMENTAL COMPOSITION AND HEATING VALUE

Table 11 lists the elemental composition and heating value of miscanthus summarized from samples in Phyllis2 database from the Energy research Center of the Netherlands (ECN, 2012). The average values on dry basis are used in GREET.

Table 11. Elemental composition and heating value of miscanthus (ECN 2012)

	Mean	Min	Max	Std	# of samples
C (% daf)	49.47	43.88	51.97	1.22	62
H (% daf)	5.73	5	6.48	0.35	62
N (% daf)	0.53	0.1	1.83	0.28	62
O (% daf)	43.91	40.06	48.73	1.45	62
S (% daf)	0.08	0	0.57	0.07	59
Ash (% dry)	3.75	1.1	9.3	1.59	53
HHV (Btu/ daf ton)	17,015,000	14,631,000	19,107,000	508,000	61
LHV(Btu/ daf ton)	15,939,000	13,418,000	18,048,000	516,000	61
C (% dry)[a]	47.6				
H (% dry)[a]	5.5				
N (% dry)[a]	0.5				
O (% dry)[a]	42.3				
S (% dry)[a]	0.08				
LHV(Btu/dry ton)[a]	15,342,000				

[a] Converted from the daf (dry ash free) values based on the mean dry ash content of 3.75%.

3.8 SUMMARY

Development of miscanthus production parameters is summarized in Table 12, for inclusion in GREET.

Table 12. Miscanthus production parameters adopted in GREET

Parameter	Value
Yield	9.0
Energy consumption (1,000 Btu/ dry ton)	271.2
Diesel consumption	131.5
Liquid propane gas consumption [a]	139.7
Transportation	
Moisture content (%)	12
Payload (dry ton)	20[b]
Distance (mile)	35[c]
Elemental composition (% dry)	
C	49.5
H	5.7
N	0.5
O	43.9
S	0.08
Ash	3.8
LHV (Btu/dry ton)	15,342,000
Fertilizer usage rate (g fertilizer/ dry ton)	
N	3,517
P_2O_5	1,228
K_2O	5,008
Herbicide (glyphosate) (g/dry ton)	121
N_2O emission from N-fertilizer (%)	1.525

[a] For climate control of greenhouse. Not included in GREET.
[b] Indoor large square bales. See Table 34 for other cases.
[c] See Section 8 for calculations of this parameter

Figure 3 summarizes the year-to-year yield and fuel consumption for miscanthus production adopted in this study. As discussed above, yield levels off after year three. At the beginning and end of the miscanthus stand's life, fuel consumption is about 60% higher than during the main production years because additional agricultural activities occur.

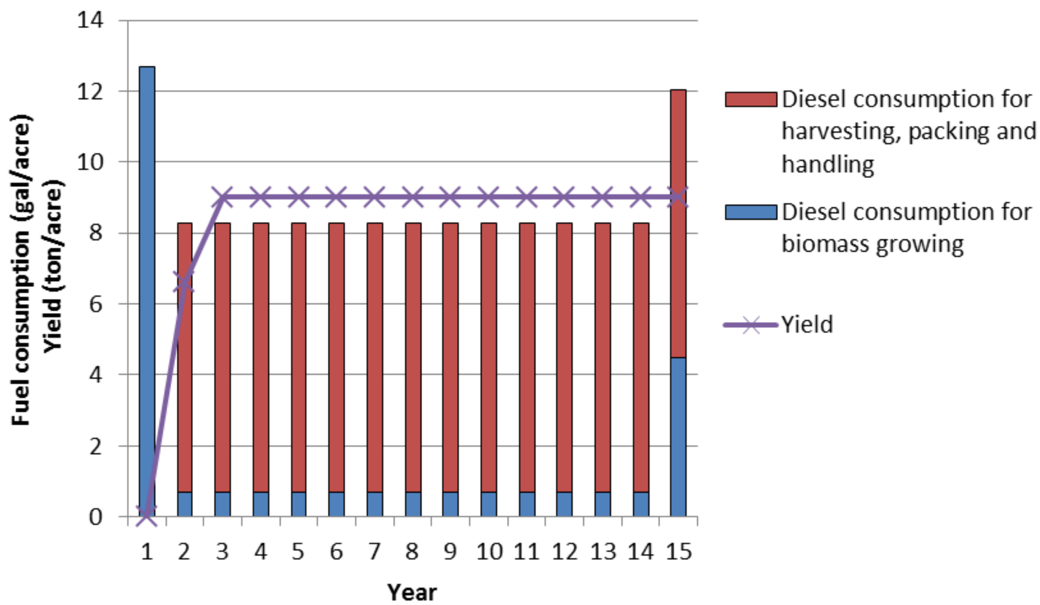

Figure 3. Year-to-year yield and fuel consumption for miscanthus production excluding fertilizer production and transportation.

4 SWITCHGRASS

4.1 BACKGROUND

Switchgrass is a tall perennial grass that has great potential as a biofuel feedstock in a wide variety of climates (Guretzky et al., 2011). The BTS2 report (DOE, 2011) summarized its advantages as a biofuel feedsock. Switchgrass is native to North America. It has consistently high yields with minimal inputs and is well-suited to marginal land. Additionally, it is relatively easy to establish from seed, and a seed industry already exists. Currently there are public and private breeding programs throughout the United States (DOE, 2011). The two main types of switchgrass are upland and lowland. Upland switchgrass grows in upland areas that are not subject to flooding, whereas lowland switchgrass grows well in flood plains and low-lying areas (Vogel, 2004). Generally, lowland plants have a later heading date and are taller with larger and thicker stems. The lowland switchgrass and the lowland x upland hybrids have the most potential for bioenergy production because of their high yields (DOE, 2011).

4.2 YIELD

Switchgrass has a two- or three-year establishment period after planting (Parrish and Fike, 2005). The stand life of switchgrass is expected to be at least 10 years (Sokhansanj et al., 2009; DOE, 2011). Good weed management and favorable precipitation will produce a crop equal to about half of potential production in the first year after the first frost. In the second year after planting, 75% to 100% of full production can be achieved (DOE, 2011).

Wullschleger et al. (2010) conducted a survey of publications that reported switchgrass biomass yield across the United States. They identified 18 publications, from which they compiled 1,190 observations of biomass yield from 38 sites in 17 states. The surveyed publications include 25 upland and 14 lowland cultivars. Annual switchgrass yield varied from less than 0.5 dry tons/acre to almost 18 dry tons/acre. But the most frequently observed yields were between 4.5 and 6.2 dry tons/acre. Wullschleger et al. report mean biomass yields of 3.9 and 5.8 dry tons/acre for upland and lowland switchgrass, respectively.

In this study, we assume a life-time of 10 years for switchgrass. After the two year establishment period ends, the annual yield is assumed to be 5.4 dry tons/acre, the midpoint of the above-mentioned yield range of 4.5-6.2 dry tons/acre. For the first and second year after planting, the yield is assumed to be 50% and 75% of full productivity, 2.7 and 4.0 dry tons/acre, respectively. Therefore the average annual yield over the 10-year life cycle is 4.9 dry tons/acre. As a comparison, in a study conducted by Idaho National Laboratory (Hess et al., 2009a), a switchgrass yield of 5 dry tons/acre is adopted. New cultivars of switchgrass are being bred for bioenergy-specific use and likely will obtain higher yields. For example, the Liberty cultivar yields 8.1 and 7.3 tons/acre/year over three productions years at Mead, NE and Dekalb, IL, respectively, much higher than the yield mentioned above (Cenusa Bioenergy 2013).

4.3 GROWING

The steps of switchgrass establishment include seed production, field preparation, seed planting, irrigating (if necessary), fertilizing and weed control (Sokhansanj et al., 2009; DOE, 2011). At the end of one life cycle, the residue needs to be removed. These procedures are similar to miscanthus establishment except that miscanthus is usually propagated from plantlets. In a study conducted by Schmer et al. (2008), the energy consumption of switchgrass establishment field operations and fertilization are estimated to be below 30,000 Btu/dry ton. This range falls below estimates of energy consumed during field establishment and fertilization for miscanthus (Section 3). One reason for this difference is that Schmer et al. did not include energy consumption for tilling because it may not be necessary to till switchgrass-producing field during establishment (Mitchell et al. 2012). Additionally, hours of operation for other field equipment is lower in Schmer et al. than for miscanthus (see Table 7). Finally, the literature reports we reviewed for the two feedstocks base these hours of operation on estimates from the literature rather than field measurements, which introduces a fair amount of uncertainty. In the absence of switchgrass-specific field establishment data, to be conservative, we assume that the energy consumption for switchgrass establishment, fertilizing in harvest years, and residue removal at the end of the life cycle is equivalent to that of miscanthus. The lifetime of the stand, however, is adjusted from 15 years to 10 years. The resulting diesel consumption is 1.9 gal/acre/year. With a yield of 4.9 dry tons/acre, this energy consumption converts to 50,030 Btu/dry ton. It is possible that this energy consumption will be less in the future as both switchgrass breeding and field operation technology develop. Additionally, when more switchgrass-specific data become available for the establishment phase of the switchgrass life cycle, we will revise GREET values accordingly.

4.4 HARVESTING, IN-FIELD TRANSPORTATION AND HANDLING

Switchgrass can be harvested and baled with commercially available haying equipment. A single harvest per growing year generally maximizes switchgrass yields, and harvesting after a killing frost ensures stand productivity and persistence. After harvest, poor switchgrass storage conditions can result in storage losses of 25% in a single year and can reduce biomass quality. Covered storage is necessary to protect the harvested biomass. (DOE, 2011)

Hess et al. (2009a) provide a detailed investigation of the techniques and energy consumption during switchgrass harvesting. Table 13 outlines each of the steps during switchgrass harvest and the corresponding energy consumption. The total of these steps, 127,700 Btu/dry ton is adopted for GREET. Further processing of the feedstock to a format appropriate for feeding to a conversion process by grinding, for example, is included in the conversion step energy consumption (e.g., Han et al., 2011).

Table 13. Energy use during switchgrass harvest

Process	Energy use (Btu/dry ton)	
	Hess et al., 2009	Womac et al. 2012
Condition and windrow	36,100	32,280[a]
Baling	69,600	51,650[b]
Roadside/Loading	18,000	
Loading to trucks	4,000	
Total	127,700	83,930[c]

[a] With a mower-conditioner powered with 86 PTO-kW tractor.

[b] With a round baler powered with 86 PTO-kW tractor.

[c] This total does not include roadside/loading energy.

For comparison, Table 13 also lists the results we generated based on one scenario in a recent study of Womac et al. (2012). This is a worst-case scenario in which the harvesting equipment's lowest ground speed and lowest throughput were considered. In this case, the turns and stops of the equipment cause productivity losses to be the highest of the scenarios they examined. The diesel fuel consumption per unit time is calculated based on the power of each piece of equipment using D=0.22P (ASAE, 1997), where D is the diesel use (L/h) and P is the maximum power-take-off (PTO) power (kW). Throughput (Mg/h) is adopted from Womac et al. (2012). Even though this is the most energy intensive scenario in the Womac et al. study, it is still lower compared to that in Hess et al. study. This scenario's total energy for conditioning, windrowing and baling is 21% lower than that which Hess et al. estimate. It is possible that different equipment was considered in the two studies. Additionally, the data sources used to calculate energy use during harvest was different for the two studies. Hess et al. used equipment specifications or manufacturer/dealer quotes to estimate fuel consumption. Womac et al., on the other hand, used fuel consumption data from the field. The transportation of switchgrass from farm-to-biorefinery is discussed in Section 8.

4.5 AGRICULTURAL MATERIALS INPUTS

Nutrient requirements for switchgrass agriculture are undoubtedly location-dependent. For example, Guretzky et al. (2011) report that switchgrass response to nitrogen fertilizer may be less pronounced in northern locations than in southern locations. Further, switchgrass management practices are still evolving. For these reasons, adopting a single value for fertilizer application rates is difficult.

Although switchgrass can survive on low-fertility soils, nitrogen fertilizer is required to optimize yield. The optimum nitrogen rate for switchgrass managed for biomass varies (Mitchell et al., 2008; 2010), and biomass declines with time if inadequate nitrogen is applied. Nitrogen fertilizer is not recommended during the planting year since nitrogen encourages weed growth, increases establishment cost, and increases economic risk associated with establishment if stands should fail (Mitchell et al., 2008; 2010). A general nitrogen fertilizer recommendation for the Great Plains and Midwest region is to apply 20 pounds (9,100 grams) of nitrogen per acre per year for each ton of anticipated biomass if harvesting during the growing season. Nitrogen application rates can drop to 12 to 14 pounds, or 5,400 to 6,400 gram, per acre per year for each ton of anticipated biomass if harvesting after a killing frost. In this case, less nitrogen is removed from the system and some nitrogen is recycled. Spraying herbicides to control broadleaf weeds is typically only needed once or twice every 10 years (DOE, 2011).

Table 14 outlines fertilizer and herbicide input rates that three recent studies report. Guretzky et al. (2011) examined the impacts of harvest system and N fertilizer rates on biomass yield and nutrient composition of switchgrass at sites in the southern Great Plains. These authors reported biomass yield as a function of N application rate. As Figure 4 illustrates, above 8,000 g N/dry ton, the switchgrass yield does not increase and may even decline. Bai et al. (2010) conducted a life- cycle analysis of switchgrass-derived ethanol and modified agricultural input data from Bullard and Metcalfe (2001) such that fertilizer is applied in every year, not just in the establishment year. Parrish and Fike (2005) published a comprehensive review of switchgrass agronomy for biofuel production and reported N application rates at six sites in the United States and Canada that had one harvest per year. These mass per area (g/ha) rates were converted to mass of nitrogen applied per mass switchgrass harvested assuming a yield of 6.7 dry tons/acre.

Table 14. Agricultural input rates for switchgrass production

Input (g/dry ton)	Guretzky et al. (2011)	Bai et al. (2010)	Parrish and Fike (2005)	Adopted for GREET
N	8,000[a]	7,700[a]	6,300	7,300
P	50[b]	150[c]		100
K	200[d]	300[e]		200
Lime		11,500		0
Herbicides		900		28

a. As ammonium nitrate
b. As CaH_2PO_4
c. As P_2O_5
d. As KCl
e. As K_2O

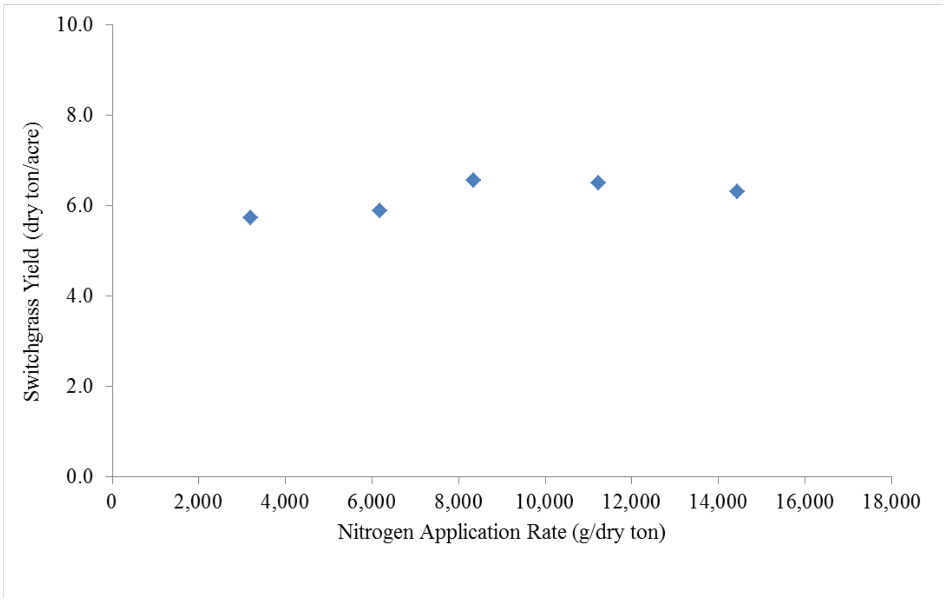

Figure 4. Switchgrass yield (Dry ton/acre) response to nitrogen application rate (g/dry ton) (Guretzky et al. 2011).

The nitrogen fertilizer application rate adopted for use in GREET is the average of the three studies' values for this parameter. It is slightly higher than the range of 5,400-6,400 g/dry ton for harvesting after a killing frost from the BTS2 report, but lower than the suggested 9,100 g/dry ton for harvesting during growing season. Both Guretzky et al. (2011) and Bai et al. (2010) indicated that the N fertilizer was ammonium nitrate. However, in this study we use the current GREET default values for the shares of different forms of N fertilizer. As more data becomes available on N fertilization of switchgrass, GREET may be revised to reflect different N fertilizer shares.

For phosphorus pentoxide (P_2O_5) and potassium oxide (K_2O), we average Bai et al. (2010) and Guretzky et al.'s (2011) data, which seem consistent with literature reports that switchgrass is P and K thrifty and would not require much of these fertilizers (Parrish and Fike, 2005; DOE, 2011). Insufficient data were available to alter the current values for herbicide application rate. Similarly, uncertainty surrounding benefits and application rates of lime applications (Parrish and Fike, 2005) preclude selection of a value for calcium carbonate ($CaCO_3$) application at this point. As no consensus has been reached concerning optimal fertilization rates for switchgrass (Parrish and Fike, 2005; Guretzky et al., 2011), we will continue to monitor the literature on this topic and update GREET in subsequent releases.

4.6 ELEMENTAL COMPOSITION AND HEATING VALUE

Table 15 lists the elemental composition and heating values obtained from Phyllis2 database (ECN, 2012). The average values on dry basis are used in GREET.

Table 15. Elemental composition and heating values of switchgrass (ECN 2012)

	Mean	Min	Max	Std	#of samples
Ash (% dry)	5.7	1.9	10.1	1.8	44
C (% daf)	49.4	45.2	53.2	2.3	15
H (% daf)	6.1	5.6	6.5	0.3	15
N (% daf)	0.64	0.37	1.30	0.19	32
O(% daf)	44.0	39.0	48.6	2.7	15
S (% daf)	0.12	0.00	0.21	0.06	15
HHV (Btu/daf ton)	16,525,000	15,750,000	17,385,000	602,000	14
LHV (Btu/ daf ton)	15,320,000	14,545,000	16,267,000	516,000	14
C (% dry) [a]	46.6				
H (% dry) [a]	5.8				
N (% dry) [a]	0.6				
O(% dry) [a]	41.5				
S (% dry) [a]	0.11				
LHV (Btu/dry ton) [a]	14,447,000				

[a] Converted from the daf (dry ash free) values based on the mean dry ash content of 5.7%.

4.7 SUMMARY

Key parameters developed in this analysis and used in GREET are listed in Table 16.

Table 16. Switchgrass production parameters adopted in GREET

Parameter	Value
Yield	4.9
Energy consumption (1,000 btu/ dry ton)	177.7
Growing	50.0
In-field harvesting and handling	127.7
Transportation	
Moisture content (%)	12
Payload (dry ton)	20[a]
Distance (mile)	50[b]
Elemental composition (% dry)	
C	49.4
H	6.1
N	0.64
O	44.0
S	0.12
Ash	5.7
LHV (Btu/dry ton)	14,447,000
Fertilizer usage rate (g fertilizer/ dry ton)	
N	7,000
P_2O_5	100
K_2O	200
Herbicide (glyphosate) (g/dry ton)	28
N_2O emission from N-fertilizer (%)	1.525

[a] Indoor LSB. See Table 34 for other cases.

[b] See Section 8 for calculations of this parameter

5 WILLOW

5.1 BACKGROUND

Short rotation woody crops (SRWC) have advantages including fast growth and high biomass yield in short rotation time. Two of the most studied SRWC species, willow and poplar, are investigated in this report with willow covered in this section and poplar in Section 6.

Generally, willow biomass is produced through the following steps. First, willow cuttings are produced in the nursery stage. After the field is prepared by removing existing vegetation, ploughing, disking, cultipacking and herbicide application (not all the operations are necessary depending on field conditions), the willow cuttings are planted using a planter at a density of 4,000-8,000 plants/acre (Heller et al., 2003; Labrecque and Teodorescu, 2005; Styles et al., 2008; Gonzalez-Garcia et al., 2010; DOE, 2011). Typically, willows are coppiced in the first year after planting, then harvested every 3-4 years (a rotation) after coppicing, and replanted after 6-7 rotations. Fertilizer, mainly nitrogen fertilizer, is usually applied after the first year coppice and also after each of the harvests, although some recent studies in the northeast United States indicate that there is no yield response in shrub willow to organic or inorganic fertilizer applications across a range of different sites (Quaye et al., 2011; Quaye and Volk, 2013). Other studies in southern Quebec have shown a yield response to fertilizer (Nissim et al., 2013). Willow could be harvested by different kinds of harvesting machinery. There are two major methods to collect willow biomass (and other long-stem fibrous crops): either as full length stems and then chipping or grinding them or by cutting and chipping the material in a single pass with either large forage harvester or smaller units attached to farm tractors (Eisenbies et al., 2012; Lechasseur and Savoie, 2005; Savoie et al., 2013). Full length stems may be handled in a bulk stack or may be tied, bundled, and transported. However, eventually, in most technologies for bioenergy production, the size of willow biomass needs to be reduced by chipping, shredding, or grinding. After harvest, the biomass can either be stored on-site or transported to the plant for storage before being used for bioenergy production. In the following sections, we describe and quantify inputs into the processes for SRWC production, including energy, fertilizers, and agrochemicals, beginning with a discussion of yield.

5.2 YIELD

As mentioned previously, willow is a perennial with multiple harvest rotations occurring between successive plantings. In this study, a 23-year lifetime is adopted for willow production, the willow is coppiced at the end of the first year and the first harvest occurs at the 4th year, and the 3-year rotation is repeated for the second through seventh harvest. At the 23rd year, the willow stools are removed and the land is prepared for next cycle. No useable biomass is harvested during the first or last year.

Volk et al. (2011) summarized a series of yield trials established across North America with older cultivars from the Ontario Ministry of Natural Resources and the University of Toronto and new genotypes from the State University of New York-College of Environmental Science and Forestry (SUNY-ESF) breeding program. For the older cultivars planted between 1993 and 2001, an average yield of 3.1 dry tons/acre/yr (bone dried short ton/acre/year) was obtained for the first rotation. For the new cultivars planted between 2005 and 2007, the average first rotation yield was 4.1dry tons/acre/yr. The average first rotation yield of top cultivars from each of the nine different locations was 5.2 dry tons/acre/yr and 5.5 dry tons/acre/yr for the older and new cultivars, respectively. These values provide a reasonable and relatively realistic upper limit for the first rotation yield for large scale production in North America with current technology; although higher yields of 7.7 and 7.0 dry tons/acre/yr were indeed observed for some certain species in trials at Boisbriand, QC, Canada and Arlington, WI, USA, respectively. Introduction of the new willow cultivars, as well as the effect of site conditions and improved management, had a positive impact on biomass yield. The yield in the second through seventh rotation usually increases compared to the first rotation. In the second rotation for 30 willow cultivars planted in Tully, NY, in 1997, production increased by 19.4% across all the cultivars and 23.0% for the commercial cultivars compared to the first rotation. In the fourth rotation, compared to the first rotation, a mean production increase of 13.6% across all the cultivars was observed, and the mean increase for the commercial cultivars was 30.8%.

Walsh et al. (2003) estimated the annual yield in different geographic regions in the United States (Table 17) and the average yields were close in these regions.

Table 17. Estimated willow yield in different regions in the United States (Walsh et al. 2003)

	Annual yield (dry ton/acre/yr)	
Region[a]	Average	Range
Lake States	4.6	4.1-5.3
Corn Belt	4.7	4.5-5.1
Appalachia	4.5	4.5-4.5
Northeast	4.9	3.2-5.8

[a] Lake States includes MI, MN, WI; Corn Belt includes IA, IL, IN, MO, OH; Appalachia includes DE, KY, MD, NC, TN, VA, WV; and Northeast includes CT, NH, NJ, NY, MA, ME, PA, RI, VT.

Labrecque and Teodorescu (2005) obtained first rotation yields ranging from 2.8-7.5 dry tons/acre/yr with 10 cultivars planted at Southern Quebec, Canada. The average yield is 5.2 dry tons/acre/yr. Over four rotations yields were 8.5 dry tons/acre/yr in fertilized plots and 6.1dry tons/acre/yr in unfertilized plots (Nissim et al., 2013). Outside of North America, Borzecka-Walker et al. (2008) obtained an average first rotation yield of 5.9 and 5.3 dry tons/acre/yr from four cultivars at two different locations in Poland, respectively.

Most currently available literature discussing willow agriculture only covers the yield of the first several rotations and not that of the whole life span. We will monitor the progress of studies on willow yield and update affected parameters in GREET accordingly.

In a life cycle analysis (LCA) study conducted by Heller et al. (2003), a yield of 4.5 dry tons/acre/yr was assumed for the first rotation as well as an increase of 36% for the second through seventh rotations. Based on this study and the yields mentioned above, herein we adopt a first rotation yield of 4.5 dry ton/acre/yr with an increase of 20% for the second through seventh rotations. The resulting total yield is 109.7 dry tons over 23 years or an annual yield of 4.8 dry tons/acre/yr. This is between the low (100.0 dry tons over 23 years) and high yields (131.1 dry tons over 23 years) used in a recent LCA study by Caputo et al. (2013).

5.3 FIELD OPERATION AND STORAGE

Table 18 summarizes field operation fuel consumption from Heller et al. (2003) and Caputo et al. (2013), which updated Heller et al. (2003). Comparison of these two studies reveals progress in willow production during the past decade. For example, Caputo et al. use a single pass cut-and-chip harvester based on a Case New Holland FR series forage harvester, in comparison with the Salix Maskiner Bender used in Heller et al. (2003). The forage harvester consumes more diesel per acre, but also has higher throughput than the Salix Maskiner Bender. Another major difference is the energy consumed during the production of willow cuttings. In Caputo et al.'s study, total energy consumed for willow cuttings production (including diesel, electricity and natural gas) is 524 Btu/dry ton willow chips whereas Heller et al. reported a value two orders of magnitude larger (21,161 Btu/ dry ton willow chips).

We summarize two other studies in addition to Heller et al. (2003) and Caputo et al. (2013), one in Spain (González-García et al., 2012) and the other in Italy (Goglio et al. 2009). Table 19 compares results from the four studies, which are in good agreement. We therefore adopted the values from Caputo et al. (2013) as being most representative and most recent for willow production in the United States. Overall, including the fuel consumption during willow cutting production, the energy consumption is 154,754 Btu/dry ton, of which 99% is diesel fuel.

Table 18. Fuel consumption for field operations during willow production

			Heller et al. (2003)				Caputo et al. (2013)	
Operation	Imple-ment used	Frequency (times/ life cycle)	P_{max}[a] (kW)	Operat-ing rate (h/ha)	Q_{diesel}[b] (gal/acre/ life cycle)	Q_{oil}[c] (10^{-3} gal/acre/ life cycle)	Q_{diesel} (gal/acre/ life cycle)	Q_{oil} (10^{-3} gal/acre/ life cycle)
Mow existing vegetation	Mower	1	54	1.5	2.6	8.6	2.1	3.8
Apply contact herbicide	Herbicide sprayer	1	37	0.5	0.5	2.3	0.7	1.3
Apply pre-emergent herbicide	Herbicide sprayer	1	37	0.5	0.5	2.1	0.7	1.3
Plow	Plow	1	60	1.7	3.1	10.3	2.4	4.3
Disk	Disk	1	54	1.4	2.3	8.0	2.0	3.6
Seed covercrop	Seeder	1	37	0.1	0.1	0.4	0.1	0.2
Mow covercrop	Mower	1					2.1	3.8
Disk	Disk	1	54	1.4	1.9	8.0	2.0	3.6
Cultipack	Culti-packer	2	54	0.7	2.0	8.1	2.0	3.6
Plant	Planter	1	78	2.5	6.1	18.0	3.6	6.5
Coppice	Mower	1	54	1.5	2.6	8.6	2.1	3.8
Weed control	Rototiller	1	54	1.6	3.4	9.1		
Fertilize	Fertilizer sprayer	7	75	0.2	3.2	10.3	2.1	3.8
Harvest[d]		7	78	3.0	74.2	151	105.6	190
Remove stools[e]		1			3.0		3.2	5.8
Apply herbicide	Herbicide sprayer						0.7	1.3
Total (life cycle)					105.3	245	131.4	237
Total (gal/ton)					1.0	0.026	1.2	0.022

[a] Maximum available power take off (PTO) power of the tractor

[b] Diesel fuel consumption. See Heller et al. (2003) for calculation methodology.

[c] Oil consumption. See Heller et al. (2003) for calculation methodology.

[d] Salix Maskiner Bender in Heller et al. (2003) and forage harvester in Caputo et al. (2013).

[e] In Heller et al. (2003), stool removal was assumed to consume 1 GJ/ha. The energy type was unspecified, although designated as non-diesel. We expect the energy was delivered by a liquid fuel. Here we converted the energy to an equivalent amount of diesel, which gives on an energy basis, 0.1 L diesel/ton. It is possible the fuel used was oil or gasoline. The contribution of this step to overall willow production is small and minimally affected by the uncertain identity of the liquid fuel consumed in the stool removal step.

Table 19. Fuel consumption for field operations during willow production in 4 different studies

Source	Heller et al. (2003)		Caputo et al. (2013)		Gonzalez-Garcia et al. (2012)		Goglio et al. (2009)	
Rotations	7		7		5		8	
Operation	frequency (times per life cycle)	Q_{diesel} (gal/acre/ life cycle)	frequency (times per life cycle)	Q_{diesel} (gal/acre/ life cycle)	frequency (times per life cycle)	Q_{diesel} (gal/arce/ life cycle)	frequency (times per life cycle)	Q_{diesel} (gall/acre/ life cycle)
Mow existing vegetation	1	2.6	1	2.1				
Apply contact herbicide	1	0.5	1	0.7				
Apply pre-emergent herbicide	1	0.5	1	0.7				
Plow	1	3.1	1	2.4	1	2.8	1	5.5
Disk	1	2.3	1	2.0	1	0.8	1	1.2
Seed covercrop	1	0.1	1	0.1				
Mow covercrop			1	2.1				
Disk	1	1.9	1	2.0			1	3.2
Cultipack	2	2.0	2	2.0				
Planting	1	6.1	1	3.6	1	4.8	1	5.9
Coppice	1	2.6	1	2.1	1	3.2	1	0.4
Weed control	1	3.4			1	3.2	1	1.3
Fertilize	7	3.2	7	2.1	5	4.6	8	1.5
Harvest	7	74.2	7	105.6	5	40.2	8	68.2
Remove stools	1	3.0	1	3.2	1	6.7		
collecting stools					1	1.6		
Spray herbicide				0.7			1	1.5
Total		105.3		131.4		67.9		88.7
Average (gal/dry ton)		1.0		1.2		1.1		0.9

Figure 5 summarizes yield and fuel consumption data used to develop GREET parameters for willow production. Yield levels off after year seven. The year of planting is more fuel intensive, compared to the years in which the willow is harvested.

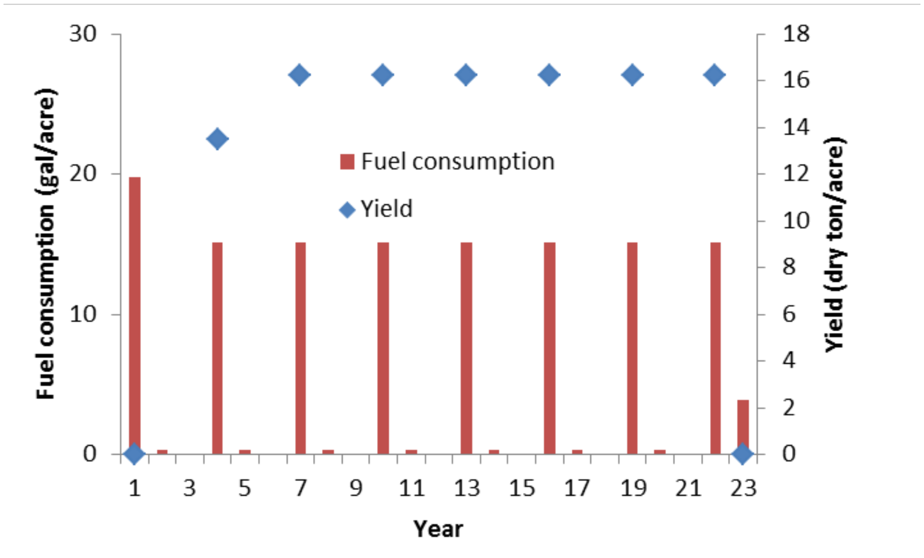

Figure 5. Yield and fuel consumption for willow production excluding fertilizer production and transportation. Note: The yield represents the total harvested dry biomass at the end of each rotation. Useable biomass is not produced during years 1 and 23.

Willow biomass can be stored in the forms of either stems or chips. The conservation of willow stems in full length is very simple and risks of degradation are practically non-existent (Lechasseur and Savoie, 2005). According to Culshaw and Stokes (1995), no infrastructure is necessary for storage and losses are minimal. Storage of full-length stems provides an additional benefit of natural air drying. The storage of fresh wood chips usually requires an infrastructure to dry mechanically (ventilation, heating, mixing machinery) and to avoid biomass decomposition (Culshaw and Stokes, 1995). However, in this study, as previously mentioned in Table 18, we assume using a forage harvester to harvest willow biomass which directly chops it into chips. The fresh willow has a moisture content of around 50%, and well-aerated wood chips can dry from 50% to 20% (Savoie, 2013). We assume the willow chips are dried to 30% moisture content before transported to the biorefinery. This value is also suggested by Sue Jones through personal communication (Jones, 2011). Jones is the lead author of a Pacific Northwest National Laboratory (PNNL) case study which uses hybrid poplar chips as feedstock for pyrolysis biofuel production (Jones et al., 2009). We do not include volatile organic carbon (VOC) or GHG emissions such as methane, nitrous oxide (CH_4, N_2O) that may stem from dry matter loss during storage or the effective yield decrease caused by dry matter loss. This effective yield decrease impacts all stages upstream of harvesting. The transportation of willow from farm-to-biorefinery is discussed in Section 8.

5.4 AGRICULTURAL MATERIAL INPUTS

Agricultural material inputs for willow production consist of two parts: inputs for willow cuttings production and inputs for willow growth.

Willow cuttings are assumed to be produced onsite and the energy usage for transporting the willow cuttings from the nursery to the field is small and omitted. Material inputs for the production of 26,120,250 cuttings (on 1 ha over 24 harvests) are adopted from the study of Caputo et al. (2013) and shown in Table 20.

Table 20. Agricultural material inputs for willow cuttings production

Inputs	Total usage[a]	Unit	Unit/ dry ton[b]	Btu/dry ton
Diesel	640	gal	0.001	178
Electricity	46,890	Kwh	0.1	346
Natural gas	4.95	m^3	0.00001	0.4
Herbicide (Glyphosate, 3times)	7.5	Kg	0[c]	
Ammonium sulfate fertilizer	600	Kg N	0.001	
Urea fertilizer	449	Kg N	0.001	

[a] For the production of 26,120,250 cuttings (Caputo et al. 2003).

[b] Total consumption per 26,120,250 cuttings converted to consumption per unit mass of harvested dry willow biomass, assuming a plantation density of 6,200 cuttings/acre and a willow biomass yield of 4.8 tons/acre/yr.

[c] Value is too insignificant to show.

Use of fertilizer and herbicides depends on factors including soil properties, climate conditions, field conditions and operations, economics, and farmers' preferences. Choosing a representative fertilizer application rate is challenging. Labrecque and Teodorescu (2005) did not fertilize or irrigate, but still obtained an acceptable yield of 2.8-7.5 dry ton/acre/yr for the first rotation. Similarly, Quaye and Volk (2011) also reported comparable biomass production among several fertilization treatments and controls. These studies indicated that an acceptable biomass yield might be reached with little or no fertilizer addition under some conditions, especially when nutrient-containing leaves remain on site and contribute to nutrient recycling. However, in most other studies, at least nitrogen fertilizer is used periodically for compensation for the uptake by harvested biomass. Compared to the usage of nitrogen fertilizer, less application rate data for phosphorous and potassium fertilizers exists. In a recent study (DOE, 2011) and the study of Caputo et al. (2013), no phosphorous or potassium fertilizers input were applied during willow production. Likewise in GREET, no phosphorous or potassium fertilizers are used (Table 20).

Fertilizer and herbicide application rates for willow production adopted in GREET are presented in Table 21. The last column of Table 21 shows the total fertilization application rate taking the inputs in Table 20 into consideration. We will continue to monitor the literature for new information on fertilizer application rates in willow production.

Table 21. Application rates of fertilizers and herbicides for willow production

	Application Rate (kg/acre/lifetime)	Application Rate (g/dry ton)	Total application rate including cuttings production (g/dry ton)
N (in the form of $(NH_4)_2SO_4$)	283	2,581	2,583
N in other forms	0	0	1
P_2O_5	0	0	0
K_2O	0	0	0
Herbicide (Glyphosate)	3.0	27	27

5.5 ELEMENTAL COMPOSITION AND HEATING VALUE

Typical composition and lower heating value (LHV) of willow biomass from Phyllis2 database (ECN, 2012) is listed in Table 22. The average values are used in GREET.

Table 22. Elemental composition and LHV of willow biomass (ECN 2012)

Sample No.	% (dry weight)						LHV (Btu/dry ton)
	C	H	N	O	S	Ash	
345	50.2	5.9	0.1	42.2	-	1.59	14,832,000
719	49.1	5.89	0.36	43.7	0.03	0.95	15,555,000
947	49.3	6.6	1.1	40.8	0.1	2.10	16,096,000
2249	50	5.9	0.7	41.8	0.05	1.60	15,142,000
2715	44.7	5.7	0.2	46.2	0.03	1.30	15,357,000
Average	48.7	6.0	0.5	42.9	0.05	1.51	15,396,000

5.6 SUMMARY

A summary of the parameters developed for willow are presented together with poplar results in Section 6.

6 POPLAR

6.1 BACKGROUND

Literature reports for poplar (*Populus ssp.*) production encompass more species than do literature accounts of willow production. Different *Populus* species could exhibit different lifetimes and harvest performance. Usually, poplar production requires intensive management and large amounts of agricultural material inputs. Poplar is not drought tolerant. However, it has potential for high growth rates under the right conditions. Also, extensive genetic research has been conducted and improvements in yield and traits like insect resistance are likely in the medium term (Kline and Coleman, 2010). These factors make poplar attractive despite of its disadvantages.

The density of plantation of poplar varies in the literature: 302-680 plants/ acre (U.S. Department of Energy 2011); 435 plants/acre (Zalesny et al. 2009); and 1100 plants/acre (James et al. 2010). Under the right conditions, *Populus spp.* plantings can be harvested three to four years after cutback. More than eight rotations are possible during one plantation. However, longer rotation times are usually mentioned or assumed in literature. The BTS2 report (DOE, 2011) set the poplar rotation time at eight years. Gasol et al. (2009) assumed a 16 lifetime of years and a 5-year rotation. Alder et al. (2007) assumed a 10-year lifetime. In this study, a 25-year lifetime is adopted for poplar production. Poplar is harvested in years 9, 17 and 25. At the 25th year, the poplar stools are removed and the land is prepared for next cycle.

6.2 YIELD

The BTS2 report (DOE, 2011) estimated the productivity of poplar at 3.5-6.0 dry tons/acre/yr. In a survey conducted by Kline and Coleman (2010), hybrid poplars achieved yields of 2.25 dry tons/ acre/yr on plantations in the southeastern United States, but 6.75 dry tons/acre/yr on trial plots. Riemenschneider et al. (2001) reported a yield of 7 dry tons/acre/yr in the North Central United States. Biomass yield ranges of the best six cultivars in the study of Zalesny et al. (2009) conducted in the Midwestern United States are summarized in Table 23.

Table 23. Poplar biomass yield in Midwestern United States (Zalesny et al., 2009)

Location	Age (year)	Yield (dry ton/acre/yr)
Westport, MN	5	1.0-1.7
	8	3.6-4.5
	10	4.0-5.0
Waseca, MN	7	4.6-6.0
Arlington, WI	3	2.3-3.2
	6	6.6-9.3
	8	7.2-9.4
Ames, IA	4	1.9-2.4
	7	5.0-9.3
	9	6.0-10.9

Walsh et al. (2003) estimated the annual yield of poplar in different regions in the United States (Table 24). The average yield ranges from 3.6-5.8 dry tons/acre/year in these regions.

Table 24. Poplar yield in different geographic regions in the United States (Walsh et al., 2003)

	Annual yield (dry tons/acre/yr)	
Region[a]	Average	Range
Lake States	4.4	3.5-5.3
Corn Belt	4.6	3.7-5.2
Southeast	4.5	3.8-5.2
Appalachia	3.6	4.0-5.2
North Plains	3.8	3.3-4.3
South Plains	3.7	3.3-4.0
Northeast	4.0	3.4-4.5
Pacific Northwest	5.8	5.5-6.0

[a] Lake States includes MI, MN, WI; Corn Belt includes IA, IL, IN, MO, OH; Southeast includes AL, AR, FL, GA, LA, MS, SC; Appalachia includes DE, KY, MD, NC, TN, VA, WV; North Plains includes MT, ND, SD, WY; South Plains includes CO, KS, NE, OK, TX; Northeast includes CT, NH, NJ, NY, MA, ME, PA, RI, VT; and Pacific Northwest includes OR, WA.

In Quebec, a yield of 8.1 dry ton/acre/yr was observed without fertilizers or irrigation (Labrecque and Teodorescu, 2005). Gasol et al. (2009) used 6.0 dry ton/acre/yr in their LCA study in Spain.

Based on the yields obtained above, we adopt an annual yield of 4.5 dry ton/acre/yr. The resulting total yield per plantation is 112.5 dry ton/acre. We will monitor literature reports of poplar production and update GREET parameters accordingly.

6.3 FIELD OPERATION AND STORAGE

Currently no detailed, itemized energy consumption information is available for poplar cuttings production. Vande Walle et al. (2007) estimated the energy use for cuttings production to be 115,093 Btu/acre. We then calculate an energy intensity for cuttings production of 1,032 Btu/ dry ton by dividing the energy consumed during cuttings production by the total yield of 112 dry tons/acre. We assume this energy comes from diesel. Fuel consumption for different field operations is summarized in Table 25 according to Alder et al. (2007) and DOE (2011).

Table 25. Fuel consumption for field operations during poplar production

Operation	Frequency (times/ life cycle)	Q_{diesel} (gal/acre)	Q_{diesel} (gal/acre/life cycle)
Plow	1	2.1	2.1
Disk	2	1.6	1.2
Cultivate	6	0.5	33.
Planting	1	6.1	6.1
Fertilize	9	0.2	1.5
Apply pesticide	9	0.3	2.5
Apply lime	1	0.2	0.2
Fell	3	10.3	31.0
Skid	3	9.9	29.7
Chip	3	37.0	110.9
Apply post-harvest herbicide	3	0.3	0.8
Total			189.5
Average (gal/ton)			1.7

As a comparison, Mann and Spath (1997) estimated the diesel consumption for field operations to be 8.9 gal/acre/yr, which gives 2.0 gal/ dry ton. Overall, adding in the fuel consumption during poplar cutting production, the diesel fuel consumption is 219,150 Btu/dry ton.

Figure 6 summarizes the yield and fuel consumption data used to develop GREET parameters for poplar production. In contrast to fuel consumption patterns over the cycle of a willow crop, in the case of poplar, more fuel is consumed in the years of harvest than in the planting year. This is because poplar has a longer rotation than willow (8 years vs. 3 years). Additionally, willow needs to be coppiced in the first year after planting whereas poplar does not.

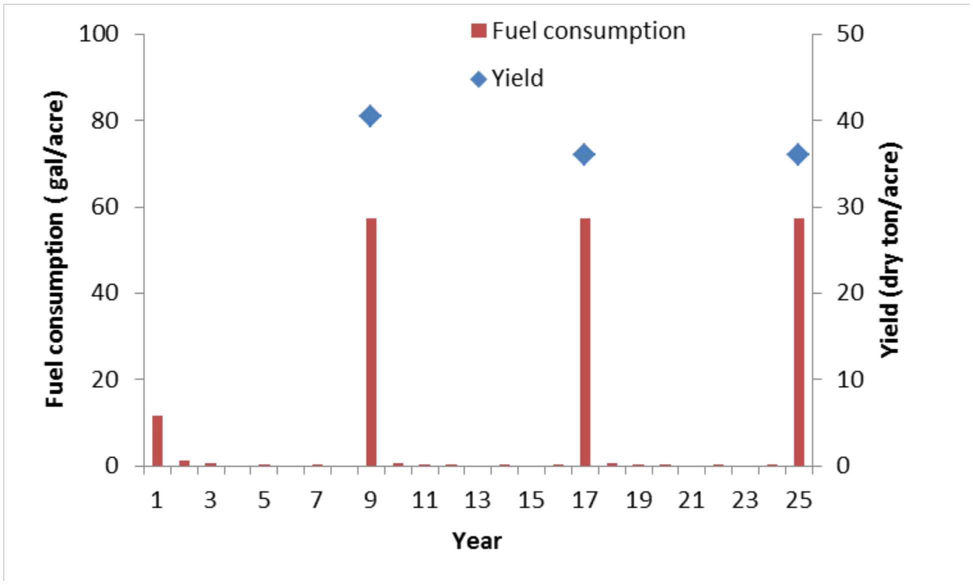

Figure 6. Yield and fuel consumption for poplar production excluding fertilizer production and transportation. Note: The yield represents the total harvested dry biomass at the end of each rotation based on a lifetime average annual yield of 4.5 ton/acre.

Similar to willow, in this study, we assume all the poplar biomass is chipped in the field and transported to the biorefinery for storage. We do not include VOC or GHG emissions (CH_4, N_2O) that may stem from dry matter loss during storage or the effective yield decrease caused by dry matter loss. This effective yield decrease impacts all stages upstream of harvesting. GREET may include poplar dry matter loss effects in the future. The transportation of poplar from farm-to-biorefinery is discussed in Section 8.

6.4 AGRICULTURAL MATERIAL INPUTS

Fertilizer and herbicide usage rates are summarized in Table 26 according to Alder et al. (2007). Fertilizer is applied in years 3, 5, and 7 during each rotation. For each application, application rates of N, P_2O_5 and K_2O are 34, 11, and 23 kg/acre, respectively. 972 kg/acre of limestone is applied to the field before plantation. Herbicide is applied three times during each rotation; pesticide is applied once.

Table 26. Application rates of fertilizers and herbicides for poplar production

	Rate (kg/acre/lifetime)	Rate (g/dry ton)
N	238	2,743
P_2O_5	79	914
K_2O	159	1,828
Limestone	972	8,640
Herbicide (Glyphosate)	9	82
Pesticide (Other)	6	54

6.5 ELEMENTAL COMPOSITON AND HEATING VALUE

Composition data for poplar biomass is listed in Table 27. The average values are used in GREET.

Table 27. Elemental composition and LHV of poplar biomass

Source	% (dry weight)						LHV (Btu/dry ton)
	C	H	N	O	S	Ash	
Brown, 2003	48.5	5.9	0.5	43.7	0.01	1.43	
Huang et al., 2009	50.0	6.3	0.2	42.2	0.02	1.32	
Miles et al., 1995	50.2	6.1	0.6	40.4	0.02	2.7	
USDOE-EERE, 2006	51.7	4.5	0.2	35.1	0.03		
Gasol et al., 2009	50.3	6.1	0.4	41.5	0.03	2.62	
Average	50.1	5.8	0.4	40.6	0.02	2.02	15,929,000[a]

[a] Average value of Poplar samples 287, 289, 290, 291, 293, 700, 1340, 1828, 1930 in Phyllis2 database (ECN, 2012).

6.6 SUMMARY

The production parameters for SRWC willow and poplar are summarized in Table 28, for inclusion in GREET. Poplar harvest is estimated to be more energy intensive than willow harvest. One possible reason is that poplar has a stem with a larger diameter than willow and therefore requires different harvesting equipment that consumes more energy to cut and chip it. Nitrogen fertilization rates, however, are similar for the two SRWC. Differences between these two SRWC may be a result of this small sample set of studies describing their production in the U.S.

Table 28. Willow and poplar production parameters adopted in GREET

Parameter	Values	
	Willow	Poplar
Yield (dry tons/acre)	4.8	4.5
Farming energy (Btu/ dry ton)	154,754	219,150
Diesel consumption	154,407	219,150
Electricity	346	
Nature gas	0.4	
Transportation		
Payload (wet tons)	25 [a]	25 [a]
Average transport distance (mile)	50 [a]	50 [a]
Moisture content (%)	30 [a]	30 [a]
Fertilizer usage rate (g/dry ton)		
N	2,584	2,743
P_2O_5	0	914
K_2O	0	1,828
Herbicide (g/dry ton)	27	136
Limestone (g/dry ton)		8,640
Elemental composition		
C	48.7	50.1
H	6.0	5.8
N	0.5	0.4
O	42.9	40.6
S	0.05	0.02
Ash	1.51	2.02
LHV (Btu/dry ton)	15,396,000	15,929,000
N_2O emission from N-fertilizer (%)	1.525	1.525

[a] See Section 8 for this parameter

7 FOREST RESIDUE

7.1 BACKGROUND

Every year, the forest industry generates residues that are potential feedstocks for biofuels production. There are two major sources of residues from forest stands. The first is logging residues, which include the limbs and tops of large trees, cull trees and cull tree components, and downed trees from harvesting operations. The second source is forest thinnings, which are the non-merchantable components of forest stands that are thinned as part of fire risk reduction efforts and restoration harvests (DOE, 2011). We start with the estimate of yield and availability of forest residue.

7.2 YIELD AND AVAILABILITY

Table 29 presents the available amount of the major forest residues in the U.S. estimated by the BTS2 report (DOE, 2011). The BTS2 report estimates this availability with two separate methods and then combines them to estimate composite operations. The first method is recovering the logging residue left at the landing area after conventional harvesting, using the Timber Product Output (TPO) database (USDA Forest Service, 2007a). The second method is to simulate uneven age thinning operations on all non-reserved timberland in the Unites States using USDA Forest Service forest inventory and analysis (FIA) plots (Smith et al., 2009). The separate estimates of county-level supply curves from these two methods are combined into a single, composite estimate for a county. They predict there will be a transition from the first method to the second as the utilization of forest residue evolves and assumes a 50:50 ratio over the next 30 years.

Notably, the amount of forest residues available through sustainable harvesting is significantly lower than the total amount of residues available. With the application of best management practices or through formal forest certification programs, sustainable harvesting can be achieved (BRDI, 2008). It avoids adverse environmental effects like soil erosion, fertilizer deficit and ecological habitat damage. Availability is also a function of price, with total residue availability increasing when the price of forest residue increases.

Table 29. Availability of Forest Residue in Million dry tons (DOE, 2011)

	Logging Residues	Forest Thinnings	Composite operations
Total available	68	78	73
Residues available through sustainable harvesting methods	47	28	38
Residues available based on a price of <$40/dry ton	47	20	34
Residues available based on a price of <$30/dry ton	20	19	20

The average annual timberland harvested area from 2001-2005 was 10.8 million acres (Smith et al., 2009). We use this average harvested area and the sustainably available forest residue, 38 million dry tons, in Table 29, to get the national average. The resulting national average yield of sustainably available forest residue is about 3.5 dry tons/acre. Local yields could vary considerably from this number.

7.3 COLLECTION, PREPROCESSING, AND TRANSPORTATION

In the United States, three main methods are used for timber harvesting: whole-tree, tree-length and cut-to-length harvesting. In whole-tree harvesting, feller bunchers cut down and gather the whole trees. Next, skidders haul them to the landing area for delimbing and stocking. In tree-length harvesting, trees are felled and delimbed at the stump, and the stems are transported to the landing area. In cut-to-length harvesting, trees are also felled and delimbed at the stump, but the harvested wood is further processed into defined log lengths and then transported to the landing area. In the U.S., 80% of the total harvest is accomplished with the whole-tree method. Cut-to-length and tree-length methods account for 15% and 5%, respectively (Leinonen, 2004).

In whole-tree harvesting, forest residues are hauled together with the major timber products to the landing area where they are either left/disposed, or chipped and transported to power plants or to other points-of-use. This method is used for the generation of both forest thinnings and logging residues (Leinonen, 2004). In the tree-length and cut-to-length harvesting methods, the residues are left at the stump. Currently, there is insufficient economic motivation to haul these residues to the landing area (Daystar et al., 2012). As a result, we do not consider trees harvested in this manner to be a viable feedstock for biofuel production and limit our analysis to whole-tree harvesting only.

A meta-analysis conducted by Johnson and Curtis (2011) found no overall effects of harvesting on SOC levels and a slightly reduced SOC following whole tree harvesting. However, responses for individual studies vary in a wide range. A study evaluating the North American Long-Term Soil Productivity (LTSP) program found no overall effects of biomass removal on subsequent forest growth over 10 years. And it is the removal of forest floor (fallen leaves, bark, stems above the soil surface), not removal of the harvested trees and residue that would serve as a biofuel feedstock, that reduced soil carbon (C) concentrations (Powers et al., 2005). We assume no SOC changes are caused by forest residue removal based on these reports. Furthermore, in the whole-tree harvesting case, forest residue is removed from the landing area, not from the forest interior. Therefore, its removal for biofuels production does not induce additional soil carbon change or supplement fertilizer issues for the forest land compared to other disposal method.

Figure 7 (a) and (b) diagram the processes for producing wood chips from logging residues and forest thinnings, respectively. Equipment used and energy consumed for production of forest thinnings and logging residues are based on Johnson et al. (2012) and listed in Table 30.

It is necessary to choose a co-product allocation method in developing life-cycle data for forest residues. For forest thinnings, no allocation is needed. The residues are assigned the full energy consumed in felling, skidding, and chipping. However, logging residues, could be considered either a waste product or a co-product. For this type of forest residue, an allocation method must be chosen. If logging residues are treated as a waste product, only the energy used to chip the collected residues would be attributed to the biofuel feedstock. Alternatively if it is treated as a co-product, the energy consumption and environmental burdens can be allocated between the primary wood product and residues by mass fraction. An economic allocation approach could also be taken. Daystar et al. (2012) investigate the influence of co-product allocation methodology on LCA results for biofuels. They assume the forest residue accounts for 11% of the total mass of forest residue plus primary product. They found results were similar (23.4 g CO_2e/ MJ) when logging residues were treated as a co-product with mass allocation and 22.8 g CO_2e/ MJ when they were treated as a waste product. Nevertheless, two options are built in GREET to address this issue, as shown in Table 30.

(a)

(b)

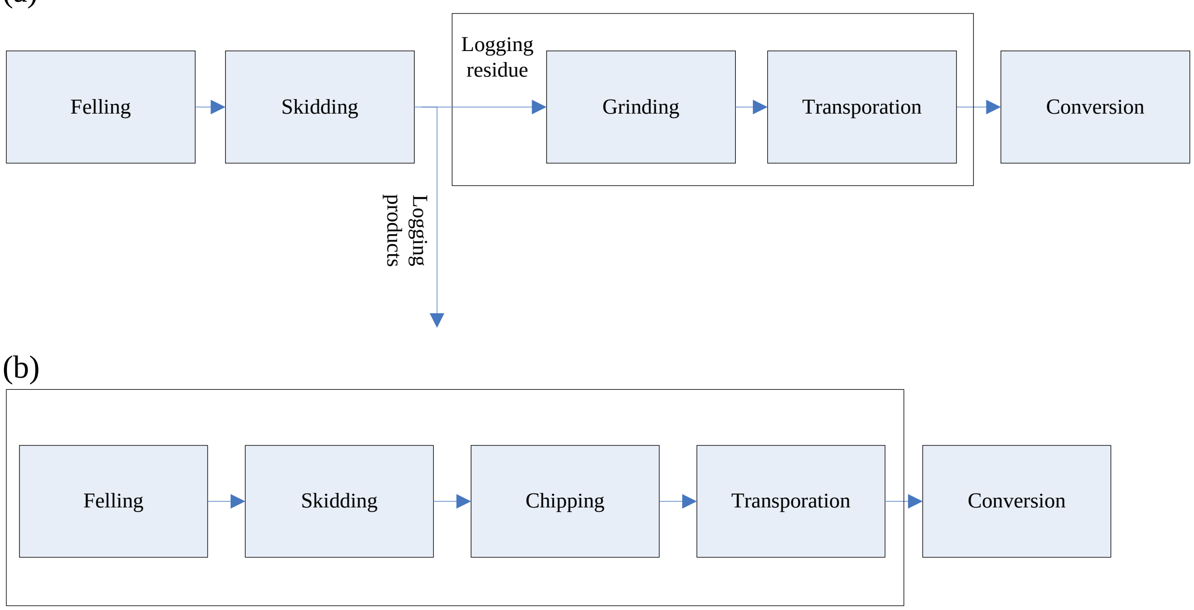

Figure 7. Production of wood chips from (a) logging residues, and (b) forest thinnings.

Table 30. Equipment used and energy consumed in the production of forest thinnings and logging residues (Johnson et al. 2012)

Operation	Logging residues		Forest thinnings	
	Equipment	Diesel consumption[a] (L/dry ton)	Equipment	Diesel consumption (L/dry ton)
Felling	Large biomass feller buncher	0 (0.20)	Large biomass feller buncher	0.20
Skidding	Large biomass skidder	0 (0.63)	Large biomass skidder	0.63
Loading	Hydraulic loader	0.20		
Preprocessing	On-site horizontal grinder	0.72	Medium whole tree chipper	0.31
Total		0.92 (1.75)		1.14
Total (Btu/ dry ton)		118,006 (225,000)		146,353

a Values in parentheses reflect mass allocation between residue and main product.

In the GREET model, the user has the option of choosing among logging residues, forest thinnings, and a weighted average of these two types of forest residue as a biofuel feedstock. The weighted average diesel fuel consumption for collecting and preprocessing one ton of forest residue into chips could be calculated based on Table 30 assuming a ratio of 50:50 for forest thinnings to logging residues (Table 31).

Table 31. Diesel consumption for collecting and preprocessing 1 ton forest residue with different mass ratios of logging residues: forest thinnings

Logging residues: Forest thinnings	Total diesel consumption (Btu/ dry ton)	
	Logging residue treated as waste	Logging residue treated as co-product with mass allocation
100:0	118,006	225,000
50:50	132,180	185,677
0:100	146,353	146,353

As a comparison, Whittaker et al. (2011) estimate diesel fuel consumption at 0.32, 0.24 and 0.49 gal/m^3 biomass for felling, skidding and chipping, respectively, in a study on recovery of UK forest residue. In sum, the diesel fuel consumption is 1.05 gal/m^3. If we assume the density of forest residue is 0.53 dry ton/m^3 (DOE , 2011) the total fuel consumption on a mass basis is 2.0 gal/dry ton (253,577 btu/dry ton). Whittaker et al. treat the forest residues as a co-product of timber production and allocated energy consumed between the main timber product and the residue. If the residue is treated as a waste, only the 0.49 gal/m^3 for chipping would be assigned to it. In that scenario, energy consumed to provide the residue as a biofuel feedstock would be 118,764 Btu/dry ton, which is close to the values derived in Table 31. In addition, Daystar et al. (2012) estimate the energy consumption of forest residues collection as 187,000 btu/ dry ton. It is unclear, however, whether this value includes upstream energy consumption (e.g., for the production of diesel fuel).

The transportation distance of forest residues would vary substantially with yield and biofuel facility capacity. With the same approach used for other feedstocks, the average transportation distance is 54 miles (see parameters and calculations in Section 8). In the study of Johnson et al. (2012), the overall one-way hauling distance for the base case was set at 90 miles, slightly longer than the surveyed distance to sawmills of 80 miles found in a survey conducted by the Consortium for Research on Renewable Industrial Materials (CORRIM) Phase II forest resource project (Oneil et al.,2009). Johnson et al. (2012) also considered scenarios of 30 and 60 miles. Transportation distances are assumed to be 50 miles from forest to a biofuel plant which converts 771,300 dry tons/year by Daystar et al. (2012). In this document, we choose the most conservative value of 90 miles (one-way) from the literature.

7.4 ELEMENTAL COMPOSITON AND HEATING VALUE

Key characteristics of forest residue developed in this study that may influence the life-cycle analysis of biofuel production include moisture content, density, heating value and elemental composition.

The moisture content of fresh forest residue is usually between 40% and 60% (Leinonen, 2004). If it is stored and naturally dried, the moisture content could drop to 30% (Whittaker et al., 2011). We assume the forest residue is dried to 30% moisture content before it is transported.

Table 32 summarizes the elemental composition and LHV from Daystar et al. (2012) and seven forest residue data sets from the Phyllis2 database (ECN, 2012). The average values are adopted in GREET.

Table 32. Elemental composition and LHV of forest residue[a]

	Daystar et al. (2012)	Phyllis 846	Phyllis 1664	Phyllis 3121	Phyllis 1907	Phyllis 3186	Phyllis 3187	Phyllis 3190	Average	Unit
C	52.0	50.3	49.8	53.1	51.0	49.0	49.0	48.1	50.3	% dry weight
H	6.5	4.6	6.2	6.2	6.2	6.0	6.0	6.0	6.0	% dry weight
N	0	1.0	0.9	1.1	0.4	0.1	0.1	0.5	0.5	% dry weight
O	41	40	41	37	39	44	44	43	41	% dry weight
S	0	0.11		0.07	0.05	0.01	0.01	0.05	0.04	% dry weight
Ash	0.4	4.0	2.2	2.9	3.2	0.8	0.6	4.9	2.4	% dry weight
LHV		16,490,000		17,291,000		17,712,000	17,730,000	17,222,000	17,289,000	Btu/ dry ton

[a] The numbers associated with table entries from the Phyllis2 database are the database's numerical identifiers for these data.

7.5 SUMMARY

In this document, we develop new production parameters for forest residue, summarized in Table 33, for inclusion in GREET. Previously in GREET, the energy consumption associated with forest residue collection as a biofuel feedstock was 230,000 Btu/dry ton. All energy consumption was allocated to the production of forest residue from the total production of forest products (including saw logs and round wood) based on mass fractions. The previous GREET value is very close to the 225,000 Btu/dry ton value developed in this report when mass allocation is also used. Furthermore, GREET now allows the user to select whether forest residue is handled as a co-product or a waste.

Table 33. Forest residue parameters adopted in GREET

Parameter	Value
Yield (Dry tons/acre/year)	3.5
Diesel consumption for collection and preprocessing[a] (Btu/dry ton)	
Logging residues only	118,006
Forest thinnings only	146,353
Logging residues and forest thinnings 50:50	132,180
Transportation	
Average transport distance (one-way) (mile)	90
Payload (wet tons)	25
Moisture content (%)	30
Elemental composition (% dry)	
C	50.3
H	6.0
N	0.5
O	41
S	0.04
Ash	2.4
LHV (Btu/dry ton)	17,289,000

[a]See Table 31 for values when logging residue is treated as a co-product.

8 TRANSPORTATION

Energy consumption during transportation depends on the form of feedstock in which it is transported, the transportation distance, mode of transportation, moisture content of feedstock, payload, and fuel economy of the transportation vehicle.

Currently, the major form in which corn stover, miscanthus and switchgrass are or are expected to be transported is bale. Willow, poplar and forest residue, are more likely be transported as chips. All feedstocks are assumed to be transported by heavy duty trucks.

Hess et al. (2009a) provide a detailed analysis of corn stover bales transportation. Standard 8-ft-wide by 53-ft-long semi-tractor trailers transport the large square bales, which have dimensions of 4 × 4 × 8 ft. Key parameters for bales transportation used in GREET are provided in Table 34. These parameters are also applied to switchgrass and miscanthus bales in this study.

Table 34. Road transport factors used in GREET for corn stover, switchgrass, and miscanthus

Parameter	Indoor LSB[a]	Covered LSB	Uncovered LSB
Biomass volume (ft^3/bale)	128	128	128
Biomass density (dry lb/ft^3)[b]	11	10.6	9.7
Moisture content (wt%)	12%	12%	12%
Number bales/truck	26	26	26
Actual payload (wet tons/truck)	23	22	20
Dry biomass/truck (tons/truck)	20	19	17
Dry matter loss	2%	2%	2%

[a] Large square bale has dimensions of 4 x 4 x 8 ft.
[b] Shinners et al. (2010).

For chips of willow, poplar, and forest residue, we assume the truck payload is 25 wet tons in GREET. The moisture content of the wood chips during transport is 30%.

Transportation distances depend on the size of the biorefinery, the land area surrounding the biorefinery which provides feedstock to the biorefinery, and the feedstock removal rate per unit area. In this study, a conceptual biorefinery that consumes 800,000 dry tons of feedstock annually is assumed for all feedstocks studied (Hess et al., 2009a).

To determine the transportation distance, the supply radius for corn stover and other feedstocks included in this report is first calculated with Equation 2 (Hess et al., 2009a). The supply radius is a function of the biofuel plant's annual demand for feedstock, the feedstock removal rate, the percent of the supply area under cultivation, the percent of cultivated land planted for the target crop, and the percent of growers participating in growing the targeted crop.

$$SR = \sqrt{\frac{FS}{Y} * \frac{c}{\pi*(\%CA)*(\%TC)*(\%GP)}} \qquad (2)$$

Where

SR=supply radius (miles)
FS = demanded annual feedstock supply (dry tons)
Y = feedstock removed per acre (dry tons/acre)
*c = conversion constant between acre and square mile (1.5625*10^{-3} square mile/acre)*
%CA = percent of cultivated acres
%TC = percent of cultivated acres planted for target feedstock
%GP = percent of growers participating in supplying biomass

The average transportation distance is then calculated by assuming an equal distance distribution of acres throughout the supply radius. Finally, a road winding factor of 1.2 is applied to the average transportation distance.

Values for above parameters are listed in Table 35. Rounded numbers are used in GREET.

Table 35. Calculation of transportation distance for different feedstocks

	Corn stover	Miscanthus	Switch-grass	Willow	Poplar	Forest residue	Unit
Y	0.96	9.0	4.9	4.8	4.5	3.5	dry ton/acre/year
FS	800,000	800,000	800,000	800,000	800,000	800,000	dry ton/year
% CA	50	50	50	50	50	50	%
% TC	50	5	5	5	5	5	%
% GP	50	100	100	100	100	100	%
SR	58	42	57	58	59	67	mile
Calculated transfer distance	46	34	46	46	48	54	mile
Transfer distance adopted	50	35	50	50	50	90[a]	mile

[a] See discussion in Section 7.

In GREET, the back-haul distance is equivalent to the distance from the farm to the biorefinery. The fuel economy of a heavy-duty truck is 5.0 miles/diesel gallon.

9 CONCLUSION AND OUTSTANDING ISSUES

9.1 CONCLUSIONS

Table 36 summarizes the values for key parameters developed for all six cellulosic biomass feedstocks. For some feedstocks different scenarios were considered for this report (e.g., for forest residue) but include only one scenario in this summary table. Farming energy intensity is relatively similar for all six feedstocks, ranging from 132-193 thousand Btu/dry ton. Variation in the use of nitrogen fertilizer is greater. This parameter ranges from 2,600 to 7,300 g N/dry ton. Given the energy intensity of nitrogen fertilizer production and the on-field N_2O emissions that stem from its application, this parameter is very important and can be a key driver for biofuel LCA results (Wang et al. 2012). Overall fertilizer requirements are highest for corn stover.

Table 36. Key parameters adopted in GREET

	Corn stover	Miscanthus	Switchgrass	Willow	Poplar	Forest residue	Unit
Yield	0.96	9.0	4.9	4.8	4.5	3.5	dry tons/acre/year
Farming energy	192.5	131.5	177.7	154.8	219.2	132.2	1000 Btu/dry ton
Transportation							
Moisture content	12	12	12	30	30	30	%
Average transport distance	50	35	50	50	50	90	mile
Payload	20	20	20	17.5	17.5	17.5	dry tons
Fertilizer usage rate							
N	7,000	3,517	7,300	2,584	2,743	-	g/dry ton
P_2O_5	2,000	1,228	100	0	914	-	g/dry ton
K_2O	12,000	5,008	200	0	1,828	-	g/dry ton
Herbicide	-	-	28	27	136	-	g/dry ton
Limestone	-	-	-	-	8,640	-	g/dry ton
Elemental composition							
C	46.7	47.6	46.6	48.7	50.1	50.3	% (dry weight)
H	5.6	5.5	5.8	6.0	5.8	6.0	% (dry weight)
N	0.7	0.5	0.6	0.5	0.4	0.5	% (dry weight)
O	40.8	42.3	41.5	42.9	40.6	41	% (dry weight)
S	0.10	0.08	0.11	0.05	0.02	0.04	% (dry weight)
Ash	5.3	3.75	5.7	1.51	2.02	2.4	% (dry weight)
LHV	14,716,000	15,342,000	14,447,000	15,396,000	15,929,000	17,289,000	Btu/ dry ton
N_2O emission from N-fertilizer	1.525	1.525	1.525	1.525	1.525	-	%

9.2 OUTSTANDING ISSUES

Generally, Argonne will track advances and changes in production and conversion technologies for cellulosic biomass feedstocks. A discussion of specific elements that may merit further investigation follows.

Farming Energy and Energy Aallocation

Research on cellulosic bioenergy feedstocks is in its early stages. More information will become available as experience grows with optimal field operation, appropriate fertilization rates and harvesting techniques. In comparison, corn farming is much more mature. Argonne will update the parameters in GREET that reflect field conditions as new data becomes available. One likely source of data that will soon be available is the results of the Regional Feedstock Partnership, a DOE funded effort seeking to advance feedstock production technologies.

Currently in GREET, corn stover is considered a waste, and therefore energy consumption of a certain number of field operations is not assigned to it. However, it is possible in the future as the bioenergy industry evolves, the value of corn stover will increase such that they it might not be considered to be a waste. In that case, an allocation method is needed to allocate the energy consumption between the cellulosic biomass and the main products (e.g., corn grain).

Land-use Change

GREET estimates land-use change (LUC) GHG emissions for corn, corn stover, switchgrass, and miscanthus ethanol pathways in its Carbon Calculator for Land Use Change from Biofuels Production (CCLUB) module. The CCLUB users' manual (Dunn et al. 2013a) and several publications (Kwon et al. 2013, Dunn et al. 2013b) document the data and methodology used in CCLUB. LUC GHG emissions for additional feedstocks and biofuel pathways may be included in future GREET releases.

Spatial Factors

Many aspects of cellulosic biomass production are dependent on local factors such as weather and soil type. Although GREET is not currently configured to specifically consider location-dependent factors, users can enter user-defined values for farming quantities such as fertilizer application rates and harvesting energy consumption to develop location-specific results.

Time series

Corn agriculture teaches that over time, technology to grow crops can improve resulting in increased yields with less energy and fertilizer input (Wang et al. 2011). We developed a time series for the yield of the feedstocks considered in this report (Table 37). Yield data for corn stover is extracted from Table 2. For miscanthus, switchgrass, willow and poplar, the BTS2 report (DOE, 2011) assumed a baseline increase rate of 1% and a high increase rate of 2-4% annually. We adopt the more conservative baseline of 1% annual increase in yield. Forest residue yield does not change because it is an average value over 30 years based on the BTS2 report (DOE, 2011). It is unclear whether these yield increases will be accompanied by decreases in fertilizer and harvest energy intensity.

Table 37. Time series for the yield of six cellulosic feedstocks

Year	Yield (dry tons/acre/year)					
	Corn stover	Miscanthus	Switchgrass	Willow	Poplar	Forest residue
2012	0.96	9.0	4.9	4.8	4.5	3.5
2017	1.17	9.5	5.1	5.0	4.7	3.5
2022	1.34	9.9	5.4	5.3	5.0	3.5

REFERENCES

Agblevor, F.A., Besler, S., and Wiselogel A.E., 1995. *Fast pyrolysis of stored biomass feedstocks*. Energy Fuels 9(4): 635-640.

Alder, P.R., Del Grosso, S.J., and Parton, W.J., 2007. *Life cycle assessment of net greenhouse-gas flux for bioenergy cropping systems.* Ecological Applications 17: 675-691.

Anderson, E., Arundale, R., Maughan, M., Oladeinde, A., Wycislo, A., and Voigt, T., 2011. *Growth and agronomy of miscanthus x giganteus for biomass production*. Biofuels 2(2): 167-183.

ASAE (American Society of Agricultural Engineers) D497.3, 1997. *Agricultural machinery management data.* In: Hahn, R.H., Purschwitz, M.A., and Rosentreter, E.E. (eds.), ASAE Standards (1997), 44th edition, ASAE, St. Joseph, MI, pp. 363-37.

Avila-Segura, M., Barak P., Hedtcke J.L., and Posner J.L., 2011. *Nutrient and Alkalinity Removal by Corn Grain, Stover, and Cob Harvest in Upper Midwest USA.* Biomass and Bioenergy 35:1190–1195.

Bai, Y., Luo, L., and Van der Voet, E., 2010, *Life-cycle assessment of switchgrass-derived ethanol as transport fuel*. International Journal of Life-Cycle Assessment, DOI: 10.1007/s11367-010-0177-2.

BRDI (Biomass Research and Development Initiative), 2008. *Increasing feedstock production for biofuels: economic drivers, environmental implications, and the role of research*. Washington, DC. 146 pp.

Boehmel, C., Lewandowski, I., and Claupein, W., 2008. *Comparing annual and perennial energy cropping systems with different management intensities.* Agricultural System 96: 224-236.

Borzecka-Walker, M., Faber, A., and Borek, R., 2008. *Evaluation of carbon sequestration in energetic crops (Miscanthus and coppice willow).* International Agrophysics 22: 185-190.

Brown, R.C., 2003. *Biorenewable resources: Engineering new products from agriculture*. Iowa State press, Ames, IA.

Bullard, M., and Metcalfe P., 2001. *Estimating the energy requirements and CO_2 emissions from production of the perennial grasses miscanthus, switchgrass, and red canary grass.* Prepared for the government of the United Kingdom, report number ETSU B/U1/00645/REP.

Cenusa Bioenergy., 2013. *Agro-ecosystem approach to sustainable biofuels production via the pyrolysis-biochar platform.* Prepared for the USDA for Grant Number 2011-68005-30411. (Available at https://www.cenusa.iastate.edu/PublicFile/_GetPublicFile?publicFileId=68, last accessed October 25, 2013.)

Christian, D.G., Riche, A.B., and Yates, N.E., 2008. *Growth, yield and mineral content of Miscanthus x giganteus grown as a biofuel for 14 successive harvests*. Industrial crops and products 28:320-327.

Clayton, W.D., Harman, K.T. and Williamson, H., 2008. *GrassBase—The Online World Grass Flora Royal Botanic Gardens*, Kew. (Available at http://www.kew.org/data/grasses-db.html. last accessed October 25, 2013.)

Clifton-Brown, J.C., Breuer, J., and Jones, M.B., 2007. *Carbon mitigation by the energy crop, Miscanthus*. Global Change Biology 13, 2296–2307.

Cosentino, S.L., Patane, C., Sanzone, E., Copani, V., and Foti, S., 2007. *Effects of soil water content and nitrogen supply on the productivity of Miscanthus x giganteus Greef et Deu in a Mediterranean environment*. Industrial crop and products 25: 75-88.

Culshaw, D., and Stokes, B., 1995. *Mechanisation of short rotation forestry, Biomass and Bioenergy*. 9: 127-140.

Danalatos, N.G., Archontoulis, S.V., and Mitsios I., 2007. *Potential growth and biomass productivity of Miscanthus x giganteus as affected by plant density and N-fertilization in central Greece*. Biomass and Bioenergy 31: 145-152.

Davis, S.C., Parton, W.J., Doleman, F.G., Smith, C.M., Del Grosso, S., and Angela, K., et al., 2010. *Comparative biogeochemical cycles of bioenergy crops reveal nitrogen-fixation and low greenhouse gas emissions in a miscanthus x giganteus agro-ecosystem.* Ecosystems 13: 144-156.

Daystar, J., Reeb, C., Venditti, R., Gonzalez, R., and Puettmann, M.E., 2012. *Life-Cycle Assessment of Bioethanol from Pine Residues via Indirect Biomass Gasification to Mixed Alcohols*. Forest Prod. J. 62(4):314-325.

DOE (U.S. Department of Energy), 2011. *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry.* Perlack, R.D., and Stokes, B.J. (lead authors), ORNL/TM-2011/224, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Dunn, J. B., Mueller, S., Kwon, H.Y., Wander, M., Wang, M. 2013a, *Carbon Calculator for Land Use Change from Biofuels Production (CCLUB) Users' Manual and Technical Documentation*. ANL/ESD/13-8. Argonne National Laboratory.

Dunn, J.B., Mueller, S., Kwon, H.Y., and Wang, M.Q., 2013b. *Land-use change and greenhouse gas emissions from corn and cellulosic ethanol*. Biotechnology for Biofuels, 6:51.

ECN (Energy research Centre of the Netherlands), 2012. *Phyllis2, database for biomass and waste.* (Available at http://www.ecn.nl/phyllis2, last accessed September 18, 2013).

EIA (U.S. Energy Information Administration), 2012. Annual Energy Review 2011.

EIA (U.S. Energy Information Administration), 2013. *International Energy Statistics.* Available at http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm, last accessed October 25, 2013.)

Eisenbies, M.H., Abrahamson, L.P., Castellano, P., Foster, C., McArdle, M., Posselius, J., Shuren, R., Stanton, B., Summers, B., Volk, T.A., and Zerpa, J., 2012. *Development and Deployment of a Short Rotation Woody Crops Harvesting System Based on a New Holland Forage Harvester and SRC Woody Crop Header Proceedings from Sun Grant National Conference: Science for Biomass Feedstock Production and Utilization*, New Orleans, LA. Retrieved from www.sungrant.tennessee.edu/NatConference/

EPA (U.S. Enviornment Protect Agency) 2013. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2011*. EPA 430-R-13-001.

Emery, I., 2013. *Direct and indirect greenhouse gas emissions from biomass storage: Implications for life cycle assessment of biofuels.* Dissertation. Purdue University, West Lafayette, IN.

Fazio, S., and Monti, A., 2011. *Life- cycle assessment of different bioenergy production systems including perennial and annual crops.* Biomass and Bioenergy 35: 4868-4878.

Fixen, P.E., 2007, *Potential Biofuels Influence on Nutrient Use and Removal in the U.S.*, Better Crops 91:12–14.

Gallagher, P., Dikeman, M., Fritz, J., Wailes, E., Gauther, W., and Shapouri, H., 2003. *Biomass from Crop Residues: Cost and Supply Estimates.* USDA-OCE/WAOB (U.S. Department of Agriculture, Office of the Chief Economist, World Agriculture Outlook Board), Agricultural Economic Report No. 819.

Gasol C.M., Gabarrell X., Anton A., Rigola M., Carrasco J., Ciria P., and Rieradevall J., 2009. *Life-Cycle Analysis of poplar bioenergy system compared with Brassica carinata energy crop and natural gas in regional scenario*. Biomass and Bioenergy 33: 119-129.

Goglio P., and Owende P.M.O., 2009. *A screening LCA of short rotation coppice willow (Salix sp.) feedstock production system for small-scale electricity generation*. Biosystems Engineering 103: 389-394.

González-García S., Mola-Yudego B., Dimitriou I., Aronsson A., and Murphy R., 2012. *Environmental assessment of energy production based on long term commercial willow plantations in Sweden.* Science of the Total Environment 421-422: 210-219.

Guretzky, J.A., Biermacher, J.T., Cook, B.J., Kering, M.K., and Mosali, J., 2011. *Switchgrass for forage and bioenergy: harvest and nitrogen rate effects on biomass yields and nutrient composition*, Plant Soil, DOI: 10.1007/s11104-010-0376-4.

Han, J., Elgowainy, A., Palou-Rivera, I., Dunn, J.B., and Wang, M.Q., 2011, *Well-to-Wheels Analysis of Fast Pyrolysis Pathways with GREET*, Center for Transportation Research, Argonne National Laboratory.

Heaton E.A., Dhleman F.G., and Long S.P., 2008. *Meeting U.S. biofuel goals with less land: the potential of Miscanthus*. Global Change Biology 14: 2000-2014.

Heaton E., Voigt, T., and Long, S.P., 2004. *A quantitative review comparing the yields of two candidate C4 perennial biomass crops in relation to nitrogen, temperature and water*. Biomass and Bioenergy 27:21-30.

Heaton E.A., Dohleman F.G., Fernando Miguez A., Juvik J.A., Lozovaya V., Widholm J. et al. 2010. *Miscanthus: A Promising Biomass Crop.* Advances in Botanical Research, Vol. 56.

Heller, M.C., Keoleian, G.A. and Volk, T.A., 2003. *Life-cycle assessment of a willow bioenergy cropping system*. Biomass and Bioenergy 25: 147-165.

Herron, M., 2013. *Integration of Advanced Logistical Systems and Focused Bioenergy Harvesting Technologies to Supply Crop Residues and Energy Crops in a Densified Large Square Bale Format*. 2013 DOE BETO Project Peer Review.

Hess, J.R., Kenney, K.L., Ovard, L.P., Searcy, E.M., and Wright, C.T, 2009a, *Commodity-Scale Production of an Infrastructure-Compatible Bulk Solid from Herbaceous Lignocellulosic Biomass*, Idaho National Laboratory, INL/EXT-09-17527.

Hess, J.R., Kenny K.L., Wright C.T., Perlack R., and Turhollow A., 2009b. *Corn Stover Availability for Biomass Conversion: Situation Analysis*, Cellulose 16:599–619.

Hodkinson, T.R., Chase, M.W., Lledo, M.D., Salamin, N., and Renvoize, S.A., 2002. *Phylogenetics of Miscanthus, Saccharum and related genera (Saccharinae, Andropogoneae, Poaceae) based on DNA sequences from ITS nuclear ribosomal DNA and plastid trnL intron and trnL-F intergenic spacers*. Journal of Plant Research 115, 381–392.

Hoskinson, R.L., Karlen D.L., Birrell S.J., Radtke C.W., and Wilhelm W., 2007, *Engineering, Nutrient Removal, and Feedstock Conversion Evaluations of Four Corn Stover Harvest Scenarios*, Biomass and Bioenergy 31:126–136.

Huang, H.J., Ramaswamy S., Al-Dajani, W., Tschirner, U., and Cairncross, R.A., 2009. *Effect of biomass species and plant size on cellulosic ethanol: A comparative process and economic analysis.* Biomass and Bioenergy 33: 234-246.

Huisman, W., Venturi, P., and Molenaar, J., 1997. *Costs of supply chains of miscanthus giganteus.* Industrial Crops and Products 6: 353-366.

IPCC (Intergovernment Panel on Climate Change), 2006. *Guidelines for National Greenhouse Gas Inventories*. Volume 2: Energy.

James, L.K., Swinto, S.M., and Thelen, K.D., 2010. *Profitability analysis of cellulosic energy crops compared with corn.* Agronomy Journal 102: 675-687.

Johnson, D.W., and Curtis, P.S., 2001. *Effects of forest management on soil C and N storage: meta analysis.* For. Ecol. Manag. 140:227-238.

Johnson, J.M.F., Wilhelm, W.W., Karlen, D.L., Archer, D.W., Wienhold, B., Lightle, D.T. et al., 2010. *Nutrient Removal as a Function of Corn Stover Cutting Height and Cob Harvest Bioenerg*. Res. (2010) 3:342–352, DOI 10.1007/s12155-010-9093-3

Johnson, L., Lippke, B., and Oneil, E., 2012. *Modeling Biomass Collection and Woods Processing Life-Cycle Analysis*. Forest Prod. J. 62(4):258‒272.

Johnson, M., Palou-Rivera, I., and Frank, E.D., 2013. *Energy consumption during the manufacture of nutrients for algae cultivation*. Algal Research. Accepted.

Jones, S.B., 2011. Personal communication.

Jones, S.B., Holladay, J.E., Valkenburg, C., Stevens, D.J., Walton, C., Kinchin, C., et al., 2009, *Production of Gasoline and Diesel from Biomass via Fast Pyrolysis, Hydrotreating and Hydrocracking: A Design Case*, PNNL-18284, Pacific Northwest National Laboratory, Richland, Wash., Feb., http://ww.pnl.gov/main/publications/external/technical_ reports/PNNL-18284.pdf. Accessed Sept. 2011

Karlen, D.L., 2010, *Corn Stover Feedstock Trials to Support Predictive Modeling.* GCB Bioenergy 2:235–247.

Kline, K.L., and Coleman, M.D., 2010. *Woody energy crops in the southeastern United States: Two centuries of practitioner experience.* Biomass and Bioenergy 34: 1655-1666.

Kwon, H.Y., Mueller, S., Dunn, J.B., and Wander, M.M., 2013. *Modeling state-level soil carbon emission factors under various scenarios for direct land use change associated with United States biofuel feedstock production*. Biomass Bioenerg 55:299–310.

Labrecque, M., and Teodorescu, T.I., 2005. *Field performance and biomass production of 12 willow and poplar clones in short-rotation coppice in southern Quebec (Canada).* Biomass and Bioenergy 39: 1-9.

Lang, B., 2002, *Estimating the Nutrient Value in Corn and Soybean Stover,* Fact Sheet BL-112, Iowa State University Extension, Ames, Iowa.

Lechasseur, G.G., and Savoie, P., 2005. *Cutting, bundling and chipping short-rotation willow.* CSAE/SCGR, Paper no. 05-080.

Leinonen, A., 2004. *Harvesting Technology of Forest residues for fuel in the USA and Finland*. Espoo 2004. VTT Tiedotteita. Research Notes 2229. 132 p. + app. 10 p.

Lewandowski, I., and Schmidt, U., 2006. *Nitrogen, energy and land use efficiencies of miscanthus, reed canary grass and triticale as determined by the boundary line approach.* Agriculture, Ecosystems & Environment 112: 335-346.

Lewandowski, I., Clifton-Brown, J.C., Scurlock, J.M.O., and Huisman, W., 2000. *Miscanthus: European experience with a novel energy crop.* Biomass and Bioenergy 19: 209-227.

Lewandowski, I., and Heinz, A., 2003. *Delayed harvest of Miscanthus—Influences on biomass quantity and quality and environmental impacts of energy production*. European Journal of Agronomy 19, 45–63.

Mann, M.K., and Spath, P.L., 1997. *Life- cycle assessment of a biomass gasification combined-cycle system*, NREL/TP-430-23076, National Renewable Energy Laboratory, Golden, CO.

Miguez, F.E., Villamil, M.B., Long, S.P., and Bollero, G.A., 2008. *Meta-analysis of the effects of management factors on Miscanthus x giganteus growth and biomass production*. Agriculture and Forest Meteorology 148: 1280-1292.

Miles, T.R., Baxter, L., Bryers, R.W., Jenkins, B.M., and Oden, L.L., 1995. *Alkali deposits found in biomass power plants.* A preliminary investigation of their extent and nature: Natioanl Renewable Energy Laboratory Report NREL/TP-433-8142.

Mitchell, R.B., Vogel, K.P., and Sarath, G., 2008. *Managing and enhancing switchgrass as a bioenergy feedstock*. Biofuels, Bioproducts & Biorefining 2(6):530–539.

Mitchell, R.B., Vogel, K.P., Schmer, M.R., and Pennington, D., 2010. Switchgrass for biofuel production. (Accessed at http://www. extension.org/pages/26635/switchgrass-for-biofuel-production on March 25, 2010.)

Mitchell, R., Vogel, K. P., and Uden, D. R., 2012. *The feasibility of switchgrass for biofuel production*. Biofuels 3(1): 47-59.

Mullen, C.A., Boateng, A.A., Goldberg, N.M., Lima, I.M., Laird, D.A., and Hicks, K.B., 2010. Bio-oil and bio-char production from corn cobs and stover by fast pyrolysis. Biomass Bioenergy 34(1): 67-74.

Muth, D.J., Jr., Bryden, K.M., and Nelson, R.G., 2013. *Sustainable agricultural residue removal for bioenergy: A spatially comprehensive U.S. national assessment*. Applied Energy 102: 403–417

NASS (National Agricultural Statistics Services), 2013. Quick Stats 2.0 http://quickstats.nass.usda.gov/

Nielsen, R.L., 1995, *Questions Relative to Harvesting and Storing Corn Stover*, AGRY-95-09, Purdue University, Agronomy Extension, West Lafayette, Ind.

Nissim, W.G., Pitre, F.E., Teodorescu, T.I, and Labrecque, M., 2013. *Long-term biomass productivity of willow bioenergy plantations maintained in southern Quebec, Canada.* Biomass and Bioenergy 56:361-369

O'Brien, D.M., Dumler, T.J., and Jones, R.D.,, 2010, *The Economics of Selling Crop Residue Biomass for Cellulosic Ethanol Production at the Farm Level*, presented at Agricultural and Applied Economics Association, Canadian Agricultural Economics Society, and Western Agricultural Economic Association, Inc., 2010 Joint Annual Meeting, Denver, Colo., July 25–27, (Available at http://econpapers.repec.org/paper/agsaaea10/61649.htm. Last accessed October 25, 2013).

Oneil, E.E., Johnson, L.R., Lippke, B.R., McCarter, J.B., McDill, M.E., Roth, P.A., and Finley, J.C., 2009. *Life-cycle impacts of Inland Northwest and Northeast/North Central forest resources.* Module A. CORRIM Phase II Report. CORRIM, University of Washington, Seattle. 26 pp.

Parrish, D.J., Fike, J.H., 2005, *The Biology and Agronomy of Switchgrass for Biofuels*, Critical Reviews in Plant Sciences, DOI: 10.1080/07352680500316433.

Petrolia, D.R., 2006, *Ethanol from Biomass: Economic and Environmental Potential of Converting Corn Stover and Hardwood Forest Residue in Minnesota*, presented at American Agricultural Economics Association Annual Meeting, Long Beach, Calif.

Powers, R.F., Scott, D.A., et al., 2005. *The North American long-term soil productivity experiment: findings from the first decade of research*. For Ecol Manag. 220:31-50

Quaye, A.K., and Volk, T.A., 2011. *Soil nutrient dynamics and biomass production in an organic and inorganic fertilized short rotation willow coppice system.* Aspects of Applied Biology 112: 1-8.

Quaye, A.K., and Volk, T.A., In Press. *Biomass production and soil nutrients in organic and inorganic fertilized willow biomass production systems.* Biomass and Bioenergy (2013), http://dx.doi.org/10.1016/j.biombioe.2013.08.002

Riemenschneider, D.E., Berguson, W.E., Dickmann, D.I., Hall, R.B., Isebrands, J.G., Mohn, C.A., Stanosz, G.R., and Tuskan, G.A., 2001. *Poplar breeding and testing strategies in the north-central U.S.: Demonstration of potential yield and consideration of future research needs.* The Forestry Chronicle 77: 245-253.

Savoie, P., 2013. *Harvesting, Drying and Storage of Short-Rotation Willow*. Charlottentown workshop on *Exploring the potential growing and burning willow on-farm*, February 2013.

Savoie, P., Hebert, P.L., Robert. F., 2013. *Harvest of short rotation woody crops with small to medium size forage harvesters*. ASABE Paper No. 131620174, Kansas City, MO, July 21-24, 2013.

Scally, L., Hodkinson, T.R., and Jones, M.B., 2001. *Origins and taxonomy of Miscanthus*. In Miscanthus for Energy and Fibre, (M. B. Jones and M. Walsh, eds.). James & James, London.

Schmer, M.R., Vogel, K.P., Mitchell, R.B., and Perrin, R.K., 2008. *Net energy of cellulosic ethanol from switchgrass.* PNAS 105(2):464-469.

Schnepf R., and Yacobucci, B.D., 2013. *Renewable Fuel Standard (RFS): Overview and Issues.* Congressional Research Service. Report for Congress, Prepared for Members and Committees of Congress. http://www.fas.org/sgp/crs/misc/R40155.pdf .

Schechinger, T.M., and Hettenhaus, J., 2004. *Corn stover harvesting: experiences in Iowa and Wisconsin for the 1997–1998 and 1998–1999 crop years.* ORNL/SUB-04-4500008274-01. Oak Ridge National Laboratory, Oak Ridge, TN.

Shinners, K.J., Boettcher G.C., Hoffman D.S., Munk J.T., Muck R.E., and Weimer P.J., 2009. *Single-pass harvest of corn grain and stover: performance of three harvester configurations.* Transactions of the ASABE. Vol. 52(1): 51-60

Shinners, K.J., Boettcher, G.C., Muck, R.E., Weimer, P.J., and Casler, M.D., 2010. *Harvest and Storage of Two Perennial Grasses as Biomass Feedstocks.* Transactions of the ASABE 53:2, p 359-370.

Sindelar, A.J., Lamb, J.A., Sheaffer, C.C., Rosen, C.J., and Jung, H.G., 2013. *Fertilizer Nitrogen Rate Effects on Nutrient Removal by Corn Stover and Cobs.* Agronomy Journal 105 (2):437-445.

Smeets, E.M.W., Lewandowski, I.M., and Faaij, A.P.C., 2009. *The economical and environmental performance of miscanthus and switchgrass production and supply chains in a European setting.* Renewable and Sustainable Energy Reviews 13: 1230-1245.

Smith, W.B., Miles, P.D., Perry, C.H., and Pugh, S.A., 2009. *Forest Resources of the United States*, 2007. Gen. Tech. Rep. WO-78. U.S. Department of Agriculture, Forest Service, Washington, DC. 336 pp.

Sokhansanj, S., Mani, S., Turhollow, A. et al., 2009. *Large-scale production, harvest and logistics of switchgrass (Panicum virgatum L.)- current technology and envisioning a mature technology.* Biofuels, Bioproducts and Biorefining 3: 124-141.

Styles, D., Thore, F., and Jones, B., 2008. *Energy crops in Ireland: an economic comparison of willow and Miscanthus production with conventional farming systems. Biomass and Bioenergy* 32:407-421.

U.S. Congress, 2007. *Energy Independence and Security Act of 2007*, Washington, D.C.

USDA-OCE/WAOB (U.S. Department of Agriculture, Office of the Chief Economist, World Agriculture Outlook Board). 2010. USDA agricultural projections to 2019. OCE-2010-1. Washington, DC. 100 pp. (Accessed at http://www.ers. usda.gov/ Publications/OCE101/OCE101.pdf on March 23, 2011).

USDOE-EERE (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy), *Biomass feedstock and composition database* (2006). Available at: http://www1.eere.energy.gov/biomass/printable_versions/feedstock_databases.html (Aug. 2012).

Vande Walle, I., Van Camp, N., Van de Casteele, L., Verheyen, K., and Lemeur, R., 2007. *Short-rotation forestry of birch, maple, poplar and willow iin Flanders (Belgium) II. Energy production and CO_2 emission reduction potentiall. Biomass and Bioenergy* 31: 276-283.

Venturi, P., and Venturi, G., 2003. *Analysis of energy comparison for crops in European agricultural systems.* Biomass and Bioenergy 25:235-255.

Vogel, K.P., 2004. *Switchgrass. In Warm-season (C4) grasses*. L.E., Moser et al. (eds.). ASA-CSSA-SSSA, Madison, WI. pp. 561–588.

Voigt, T., *Personal communication.* March 28, 2012.

Volk, T.A., Abrahamson, L.P., Cameron, K.D., Castellano, P., Corbin, T., Fabio, E. et al., 2011.*Yields of willow biomass crops across a range of sites in North America. Aspects of Applied Biology,* 112: 67-74 (2011).

Walsh, M.E., De la Torre Ugarte, D.G., Shapouri, H., and Slinsky, S., 2003. *Bioenergy crop production in the United States- Potential quantities, land use change, and economic impacts on the agricultural sector.* Environmental and Resource Economics 24: 313–333.

Wang, M.Q., Han, J., Dunn, J.B., Cai, H., and Elgowainy, A., 2012. *Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for U.S. use.* Environ Res Lett 7, 045905, DOI:10.1088/1748-9326/7/4/045905.

Wang, M.Q., Han, J., Haq, Z., Tyner, W.E., Wu, M., and Elgowainy, A., 2011. *Energy and greenhouse gas emission effect of corn and cellulosic ethanol with technology improvements and land use changes.* Biomass and Bioenergy 35: 1885-1896.

Whittaker, C., Mortimer, N., Murphy, R., and Matthews, R., 2011. *Energy and greenhouse gas balance of the use of forest residues for bioenergy production in the UK. Biomass and Bioenergy,* 35 (11). pp. 29-45. ISSN 0961-9534.

Womac, A.R., Hart, W.E., Bitra V.S., and Kraus, T., 2012. *Biomass harvesting of high-yield low-moisture switchgrass: equipment performance and moisture relations. Applied Engineering in Agriculture,* 28(6): 775-786.

Wright, M.M., Satrio, J.A., Brown, R.C., Daugaard, D.E., and Hsu, D.D., 2010. *Techno-economic analysis of biomass fast pyrolysis to transportation fuels*, (No. NREL/TP-6A20-46586). National Renewable Energy Laboratory, Golden, CO.

Wullschleger, S.D., Davis, E.B., Borsuk, M.E., and Gunderson, C.A., Lynd LR, 2010. *Biomass production in switchgrass across the United States: database description and determinants of yield*. Agronomy Journal 102:1158–1168.

Zalesny, R.S. Jr., Hall, R.B., Zalesny, J.A., McMahon, B.G., Berguson, W.E., and Stanosz, G.R., 2009. *Biomass and Genotype × Environment interactions of Populus energy crops in the midwestern United States*. Bioenergy Research 2: 106-122.

Energy Systems Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 362
Argonne, IL 60439-4815

www.anl.gov

Argonne National Laboratory is a U.S. Department of Energy
laboratory managed by UChicago Argonne, LLC