CRADLE-TO-GATE LIFE CYCLE ASSESSMENT OF SWITCHGRASS FUEL PELLETS MANUFACTURED IN THE SOUTHEASTERN UNITED STATES[1]

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Abstract. Developing renewable energy sources with low environmental impacts is becoming increasingly important as concerns about consuming fossil fuel sources grow. Cultivating, harvesting, drying, and densifying raw biomass feedstocks into pellets for easy handling and transport is one step forward in this endeavor. However, the corresponding environmental performances must be quantified. This study presents cradle-to-gate life cycle inventory and impact assessment data for switchgrass fuel pellets potentially manufactured in the US Southeast. Because there are no current manufacturers of switchgrass pellets, inventory data were based on field trials of cultivation and harvest of switchgrass combined with a separate study of wood pelletization. Energy inputs for cultivation and harvest of switchgrass were collected by survey from farmers in Tennessee and represent the years 2008, 2009, and 2010. Data for pelletization were taken from a report on wood pellet manufacturing in the US Southeast. To produce 1.0 Mg of pellets

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that contain 18.0 GJ of potential bioenergy, 4.1 GJ of fossil energy inputs were required. Switchgrass crops require relatively little energy and inputs for the cultivation and harvest processes. The majority of the environmental burdens are associated with drying and pelletizing the raw material.

Keywords: Switchgrass, LCA, biomass, pellets, environmental impacts, life cycle inventory, Tennessee.

INTRODUCTION

Many factors are motivating the development of biofuels and bioproducts: high petroleum prices, a desire for energy independence, the need for rural economic diversification, and concern about the environmental impacts of using fossil carbon sources (Kojima and Johnson 2006; Lee et al 2008; Peters and Thielmann 2008). Regarding the last point, products and fuels made from plants inherently have environmental advantages: they are renewable and solar-powered, and when sustainably harvested, their use is carbon-neutral to greenhouse gas (GHG) concentrations and global climate change. There is growing debate about these potential environmental benefits, however, and more attention is being paid to the amount of fossil carbon resources consumed in the production and processing of bioenergy and the potential tradeoffs involved (eg between food and fuel). Although the environmental advantages of biobased resources remain important, they can no longer be assumed. They must be demonstrated using generally accepted methods. Life cycle assessment (LCA) is an internationally accepted standard method for evaluating the environmental impacts of processes and products (ISO 2006a). This LCA study focuses on switchgrass (*Panicum virgatum* L.).

Switchgrass is indigenous to Central and North America. In the southeastern United States (SE), this perennial crop has a growing season from May through September and can reach up to 2.4 m tall. Switchgrass along with other perennial grasses and crops are being considered as new sources for bioenergy and bioproducts. In addition, switchgrass is attractive because it requires little fertilization for high productivity, possesses a high gross calorific value, is noninvasive, and can be cultivated on marginal lands, thus limiting competition with food production (Wilson et al 2012; Brassard et al 2014; Daystar et al 2014; Quinn et al 2014). Also, several studies have reported that switchgrass production can be fully sustainable (McLaughlin and Walsh 1998; McLaughlin et al 2002). Still, under intensive management practices for the biofuel industry, sustainable production as well as maximum productivity of switchgrass will probably require nitrogen if not phosphorous fertilization (Muir et al 2001; Karp and Shield 2008; Mooney et al 2009). Therefore, it is expected that through selective breeding, highly productive switchgrass species with high nitrogen-use efficiency will be created, thus lowering the need for nitrogen fertilization and increasing both yield and soil carbon sequestration and perhaps improving site fertility (McLaughlin and Walsh 1998; McLaughlin et al 2002; Blanco-Canqil 2010; Wright and Turhollow 2010). Because these crops are harvested seasonally and are bulky to handle and transport, densification processes such as pelletization may be necessary as a primary processing step (Wilson et al 2012). Pellets are designed to be dry, dense, easily handled, and stable in long-term storage.

Pellets are burned directly for fuel or can be an initial processing step in a biorefinery or biofuel conversion process. Wood pellets are an established fuel product that is growing in importance in the United States and abroad, driven by rising fuel prices and demands for green energy sources. Switchgrass pellets have the potential to join wood pellets in this growing market. A study by Sultana and Kumar (2012) evaluated and ranked biomass feedstock-based pellets with a multicriteria assessment model based on environmental, economical, and technical factors. Wood pellets were named the best among the five alternatives evaluated, closely followed by switchgrass pellets. Particularly in the Southeast, interest in switchgrass has been established and the crop is currently being cultivated and harvested for energy and research purposes (Qualls et al 2012; Daystar et al 2014).

Some LCA data on switchgrass or similar crop pellet production have been published for Canadian and European contexts (Jannasch et al 2001; Tilman et al 2006; Smeets et al 2009; Cherubini and Jungmeier 2010; Kalita 2012; Li and Mupondwa 2012). This study focuses on the US Southeast. The data are intended for analyses of pelletized biofuels and for related products (eg when switchgrass or pellets are a component of a biorefinery).

METHODS

Goal

The goal was to develop an inventory of the inputs and outputs associated with the production of switchgrass pellets in the US Southeast for 2010. Results were used in life cycle inventory assessment (LCIA) and interpretation phases to identify major sources of environmental impacts and to compare the environmental impacts of switchgrass pellets with other energy sources (eg natural gas). The output of this study is intended for use by researchers and practitioners as an input to the life cycle analysis of biomass materials.

Scope

The scope of this study was a cradle-to-gate LCA of switchgrass pellets and includes data from cultivation and harvest of switchgrass plantations established in east Tennessee as part of the University of Tennessee Biofuels Initiative (UTBI) (2008). Funded by a $70.5 million state investment, this initiative has been charged with developing a cellulosic biofuels industry in Tennessee. Part of this approach was to hire farmers to grow switchgrass as well as to create a pilot biorefinery located in Vonore, TN. Raw material transportation values to a pelletization plant were assumed. Because no commercial switchgrass pellet mill data were available, data from a survey of wood pelletization mills in the US Southeast were used (Reed et al 2012). Primary data for the cultivation and harvest of switchgrass were collected by a survey of participating farmers (UTOBP 2010). In this study, growth and cultivation are used interchangeably.

Data

Cultivation and harvest data were collected by a survey sent to switchgrass farmers. The crop stands ranged from first year to mature, third year. Because inputs (primarily fertilizer treatments) decrease after stand establishment and yields increase, the data were averaged and weighted across a 10-yr period (the assumed stand rotation).

From September to December 2010, 61 switchgrass farmers contracted with the UTBI were contacted and sent a production data survey. The surveyed farmers operated switchgrass farms primarily in the southeastern region of Tennessee (Vonore, TN). Another gate-to-gate life cycle inventory (LCI) was conducted on the hardwood flooring residues pelletization process using a similar survey method sent to operating pellet mills in Alabama, Kentucky, Tennessee, Virginia, and West Virginia (Reed et al 2012). SimaPro LCA modeling software (Pré Consultants 2012) calculated the overall cradle-to-gate emissions of switchgrass pelletization using a network of related inventories associated with inputs for both the cultivation and harvest of switchgrass (resource harvesting) and the pelletization process (gate-to-gate). The US LCI Database (NREL 2012) was the main secondary LCI data source.

Wood pellet value was chosen because it is based on regional commercial production of a similar material. The procedures and report of this study follow the standards in ISO (2006a, 2006b). The procedures and report also follow the research guidelines for LCI used by other researchers in the Consortium for Research on Renewable Industrial Materials (CORRIM) group (CORRIM 2010).

The cradle-to-gate manufacture of switchgrass pellets comprises the following processes: cultivation and harvesting of switchgrass, transportation (switchgrass feedstock), storage, drying, size reduction by hammer-milling, pelletizing, cooling, and storing (bagged or in bulk). This study did not include bagging in the system boundary and evaluated the system as if the pellets were to be prepared for bulk storage.

Unit Process and System Boundary

The processes described in Fig 1 are the basic flows within the system boundary for the cradle-to-gate LCI of the switchgrass pellet manufacturing model. The functional unit was 1 Mg (1 tonne = 1000 kg) of switchgrass pellets (5% MC). The following describes each of the manufacturing processes:

Cultivation and harvest. Switchgrass is grown as a perennial crop, with each stand lasting for 10 yr before reestablishment. In the Southeast, cultivation and harvesting usually occurs during mid to late fall. Initially, fields are plowed, fertilized, seeded, and treated with herbicides for weeds. No irrigation is used. During harvesting, the switchgrass is cut, field-dried, baled, and loaded on tractor-trailer trucks for transport. Farmers in our study used switchgrass farming recommendations from the UTBI (Garland 2007).

Transportation. After baling, the switchgrass is loaded on diesel tractor-trailer trucks and transported to the pellet mill for storage and processing.

Storage. In a projected model of a switchgrass pelleting facility, raw material would be transported by truck to the pellet mill. The raw material would then be stored in a dry facility on site. Inputs for raw material collection include diesel fuel and/or liquid propane gas for transportation and/or handling. No storage losses were assumed.

Drying. Raw materials for pelletizing usually require drying to about 10% MC. According to Sanderson et al (2006) and Shinners et al (2010), initial moisture content of switchgrass at the time of cutting ranges from 43 to 66%. Volatile organic compounds emitted during drying were estimated at 0.04 kg/Mg switchgrass (Eller et al 2011).

Pelletization. Because of the inability to collect data for the pelletization process, this study treated pelletization as a single process from Reed et al (2012). Pelletization includes size reduction, pelletizing, and cooling processes. After the material is collected, it is broken down into small, uniform particles (≈2 mm) using a hammer mill. The hammer mill is operated by electric motors. Next, pellets (≈6 mm in diameter and 25 mm long) are extruded using machinery that is similar to the equipment used to form feed pellets for the agriculture industry. Pelletizers use large electric motors to extrude the pellets through steel dies. High pressure (≈300 MPa)

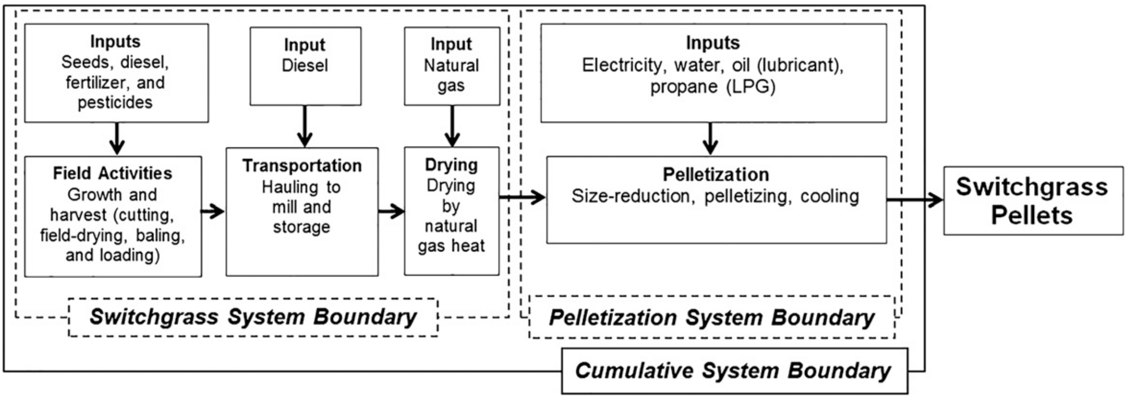

Figure 1. System description for the cradle-to-gate production of switchgrass pellets.

and temperatures (≈90°C) soften lignin and bind the switchgrass particles together to make uniform and consistent pellets. Although no adhesives are required for this process, small amounts of lubricants and water are sometimes added to improve processing. Finally, the pellets are hot when they emerge from the pelletizer. They are stored in a hopper and allowed to cool under ambient conditions before further handling, transportation, and consumption.

Assumptions

Assumptions and data collection and analysis followed the protocol defined in CORRIM (2010). Additional conditions included the following:

- All data from the switchgrass farmer survey were weight-averaged across a period of 10 yr to account for input and yield variations during the 10-yr life of the stands (Smeets et al 2009; Daystar et al 2014). The input and yield values reported for year 3 were assumed to be the same for the subsequent 7 yr.
- The seeding rate (only for the first year) was assumed to be 7.8 kg/ha (USDA NRCS PMP 2009). The impacts associated with seeds come from the seed inputs used.
- Given that the machinery and storage facilities (from the farmers we surveyed) are one-time constructions and are used in various other capacities, storage facilities, pellet facilities, and farm machinery construction were not considered in this study. Not including capital goods and infrastructure is consistent with LCI data from other energy sources including natural gas found in the US LCI Database (NREL 2012). Natural gas was used in this study as a comparison with switchgrass pellets for energy use, enabling a direct comparison.
- Transportation of switchgrass at 20% MC from field to mill was based on an assumption of a 73.9-km average haul distance.
- Switchgrass typically dries on the field from between 43 and 66 to 20% MC or less before being baled and shipped to the plant for drying (Rinehart 2006; Sanderson et al 2006). Also, as the growing season progresses, the moisture content decreases. Drying input (natural gas) of the switchgrass prior to pelletization was estimated by an expert in the area of biomass processing (Follmer 2012) at 872 MJ/Mg to dry switchgrass to 10% MC, thus requiring 27.09 m^3 of natural gas combusted at 80% efficiency (FPL 2004).
- The pelletization process for dry switchgrass was assumed to be the same as for pelletization of wood processing residues, as reported by Reed et al (2012) except no wood residues were burned for drying the incoming switchgrass. The process of pelletizing switchgrass will change the density of the biomass raw material and will evaporate some moisture. Therefore, it was assumed that 0.95 Mg of oven-dry switchgrass is required to produce 1 Mg of pellets with a final product moisture content of 5%. From previous literature, we assumed density for switchgrass pellets would be 600 kg/m^3 (Jannasch et al 2001).
- This study assumed 100% yield of pellets from the raw material and that no raw material was lost as dust and that all poorly formed pellets or fine particles were recycled in the system. However, Jannasch et al (2001) speculated that 95% yield might be more realistic, because of the loss of raw material during processing.

Life Cycle Impact Assessment Method

LCI assessment was performed using the tool for the decrease and assessment of chemical and other environmental impacts (TRACI 2) (Bare 2011). TRACI is a midpoint-oriented methodology developed by the US Environmental Protection Agency specifically for the US. Nine impact categories were examined, including global warming potential (GWP [kg CO_2-eq]), acidification potential (H^+ moles-eq), carcinogenics (kg benzene-eq), noncarcinogenics (kg toluene-eq), respiratory effects (PM 2.5-eq), eutrophication potential (kg N-eq), ozone depletion (kg chlorofluorocarbons-11-eq), ecotoxicity (2,4-D-eq), and smog potential (kg NO_x-eq). Carcinogenics and noncarcinogenics effects are human health impacts (Huijbregts et al 2005).

Life Cycle Inventory

Of the 61 farmers surveyed, 12 (19%) responded with complete data in terms of switchgrass production, seed rate, fuel use, and herbicide and pesticide inputs. The survey was sent out in 2010 and represents cultivation and harvest data for 2008, 2009, and 2010. Usable responses were collected from 12 farmers with data on 152 ha, or about 7% of the 2090 ha in switchgrass production. The survey responses for wood pellet manufacturers represented 2009 production data from approximately 25% of the total number of operating mills in the Southeast. The only available wood pellet production data estimated total production in the Southeast region in 2008 at 591.8 kt (Spelter and Toth 2009). Total production of the responding wood pellet mills was 303.9 kt of pellets per year or about 51%.

The switchgrass yield data collected in our survey (13.9 Mg/ha) were consistent with published data (Jannasch et al 2001; Mooney et al 2009), but reported inputs (eg electricity) were less. However, the reported data on the pelletization process were consistent with energy consumptions reported in other studies (Thek and Obernberger 2004; Mani et al 2006; Hagberg et al 2009; Sokhansanj et al 2009; Zhang et al 2010; Sjolie and Solberg 2011; Uasuf and Becker 2011; Katers et al 2012; Pa et al 2012). The weight-averaged electrical usage of 145.5 kWh/Mg reported per functional unit of wood pellets used in this study (Reed et al 2012) was significantly more than values estimated in some publications for switchgrass pelletization (Smeets et al 2009). The inputs per functional unit (1.0 Mg) were calculated based on an average switchgrass yield of 13.9 Mg/ha per year (oven-dry, 0% MC). Variation in the reported inputs was great, in part, because of differences in the ages of the switchgrass stands (see coefficient of variation, Table 1). Of the material inputs for the cultivation and harvest of switchgrass, the most significant was nitrogen fertilizer. Other inputs included diesel, phosphorous fertilizer, pesticides, herbicides, and surfactant. The most significant input for pellet-making operations in the Southeast was electricity. Other fuels used for equipment (ie tractors, trucks, forklifts) included diesel fuel and liquid petroleum gas. Other raw material inputs used in the manufacture of wood pellets are water, oil, and grease. Water is used to adjust the moisture content, and oil and grease are used for lubrication during the pelletizing process.

Pelletization primarily has energy and switchgrass inputs and only one output—switchgrass pellets. Finished pellets contain about 5% MC. Therefore, the switchgrass input is only 0.95 Mg of oven-dry switchgrass to produce 1.0 Mg of switchgrass pellets (Table 2). Feedstock is dried before arriving at the pellet mill.

Pelletization does not create a solid waste stream. All residues are recycled in the pelletization process, and airborne particulate emissions (dust) are assumed to be insignificant and thus were not included in the analysis. On-site pelletizing air emissions, water effluents, and solid waste generation were insignificant. The emission data in this study (Tables 3 and 4) were

Table 1. Cradle-to-farm-gate inputs for 1.0 Mg of switchgrass (oven-dry basis) in the US Southeast.

Inputs	Units	Average value[a]	Coefficient of variation (%)[b]
Diesel (tractor use)	L	3.98	46
Nitrogen (fertilizer)	kg	4.77	84
Phosphorous (fertilizer)	kg	0.49	224
2,4-Dichlorophenoxyacetic acid (pesticide)	L	0.05	219
Glyphosate (herbicide)	L	0.05	213
Surfactant	L	0.03	332
Seed[c]	kg	0.56	n/a

[a] Average value is the weighted average across a 10-yr switchgrass stand rotation, where inputs and yields are assumed to be constant in years 3–10.

[b] Coefficient of variation is standard deviation/average of the reported data, without any weighting for stand age.

[c] Seed input values were not reported by the farmers. The value listed here is from the literature (USDA NRCS PPM (2009).

Table 2. Farm-gate-to-mill-gate inputs for 1.0 Mg of switchgrass pellets (5% MC) in the US Southeast.

Input	Units	Value
Switchgrass (growth and harvest [oven-dry basis])	Mg	0.95
Diesel-powered truck (switchgrass transportation to pellet mill)	tkm	84.28
Natural gas (swichgrass drying)	m^3	27.09
Pellet manufacturing[a]		
Corn oil (lubricant)	L	1.38
Ground water	L	23.91
Electricity	kWh	145.67
Liquid petroleum gas	L	0.09

[a] Based on the inventory for the pelletization of wood processing residues (Reed et al 2012).

those associated with field activities, transport, and drying of the switchgrass, as well as those associated with the production of the other pelletization inputs (electricity and corn oil). Because electricity is the primary energy for pelletization, the source of the fuel used for electricity generation is important in determining the environmental impacts of pellet making. In the eastern United States and for the study years 2008–2010, the primary fuel sources for electricity were coal, nuclear energy, and natural gas (EIA 2012). The cumulative life cycle emissions associated with pelletization (including particulates; Table 3) were pregate (ie those associated with switchgrass and electricity production). No emission control measures were used during pelletization, and there were no emissions to soil in this inventory.

Life Cycle Assessment

Pelletization converts a potential fuel or raw material for products into a more convenient form. Thus, it is interesting to analyze the additional environmental impacts that are associated with this convenience.

For the pelletization process alone, electricity production contributes the most to the total impact for five of the nine TRACI-defined impact categories evaluated (global warming, acidification, carcinogenics, respiratory effects, and smog) (Reed et al 2012). Impacts associated with switchgrass cultivation and harvesting are most important for four impact categories (noncarcinogenics, eutrophication, ozone depletion, and ecotoxicity). Impacts associated with drying the feedstock (natural gas) are notable in every impact category except eutrophication and ozone depletion (Fig 2). Switchgrass cultivation and harvest contributes nearly all of the impact toward eutrophication and ozone depletion, which is caused by runoff and emissions associated with the production and use of fertilizers.

The primary input for cultivation and harvesting of switchgrass is nitrogen fertilizer. However, impact assessment shows that other fuels and chemicals add to the environmental burden of

Table 3. Cradle-to-mill-gate emissions to air[a] for 1.0 Mg of switchgrass pellets (5% MC) in the US Southeast.

Substance	Switchgrass growth and harvest (kg)	Switchgrass transport (kg)	Switchgrass drying (kg)	Switchgrass pelletization (kg)	Cumulative (switchgrass growth, harvest, transport, drying and pelletization) (kg)
CO_2 (fossil)	4.01	7.53	58.75	114.08	184.37
CO_2 (biomass)	0.06	0.01	0.18	2.22	2.47
NO_x	0.02	0.05	0.06	0.32	0.45
SO_2	0.10	0.00	0.52	0.75	1.37
SO_x	0.01	0.01	0.00	0.03	0.05
Methane	0.07	0.01	0.31	0.26	0.65
Particulates (unspecified)	0.00	0.00	0.00	0.08	0.08
Volatile organic compounds (VOC)	0.00	0.00	0.06	0.01	0.07

[a] US Southeast–cumulative, mass-allocated SimaPro life cycle inventory values.

Table 4. Cradle-to-mill-gate emissions[a] to water for 1.0 Mg of switchgrass pellets (5% MC) in the US Southeast.

Substance	Switchgrass growth and harvest (kg)	Switchgrass transport (kg)	Switchgrass drying (kg)	Switchgrass pelletization (kg)	Cumulative (switchgrass growth, harvest, transport, drying, and pelletization) (kg)
Biological oxygen demand (BOD)	0.01	0.00	0.03	0.01	0.04
Suspended solids	1.38	0.38	4.25	1.23	7.24
Chemical oxygen demand (COD)	0.01	0.00	0.07	0.01	0.10
Chloride	1.10	0.29	3.40	0.95	5.74

[a] US Southeast—cumulative, mass-allocated SimaPro life cycle inventory values.

this process. The primary input for manufacturing pellets is electricity, and because electricity is mostly generated from nonrenewable and fossil fuels, this input significantly impacts several environmental impact categories including GWP, acidification, carcinogenics, and smog.

Biomass energy sources are sometimes considered to be carbon-neutral (Tilman et al 2006; USEPA 2009; Daystar et al 2014) for accounting purposes because the carbon dioxide (CO_2) released during energy production is offset by CO_2 absorption during photosynthesis (Bare 2011). However, some fossil energy inputs are required for the production of most biofuels. The fossil energy required for the production of switchgrass pellets was calculated from the inventory data tabulated by SimaPro and weighted for their energy content (higher heat value). This analysis revealed that switchgrass pellets are very fossil fuel efficient; ie the amount of fossil fuel used to generate the pellets is small compared with the potential bioenergy in the pellets (Fig 3). To produce 1.0 Mg of pellets that contained 18.0 GJ of potential bioenergy, 4.1 GJ of fossil energy inputs were required. In this study, embodied energy is defined as the energy used or consumed to make the product from cradle-to-gate pellet mill output.

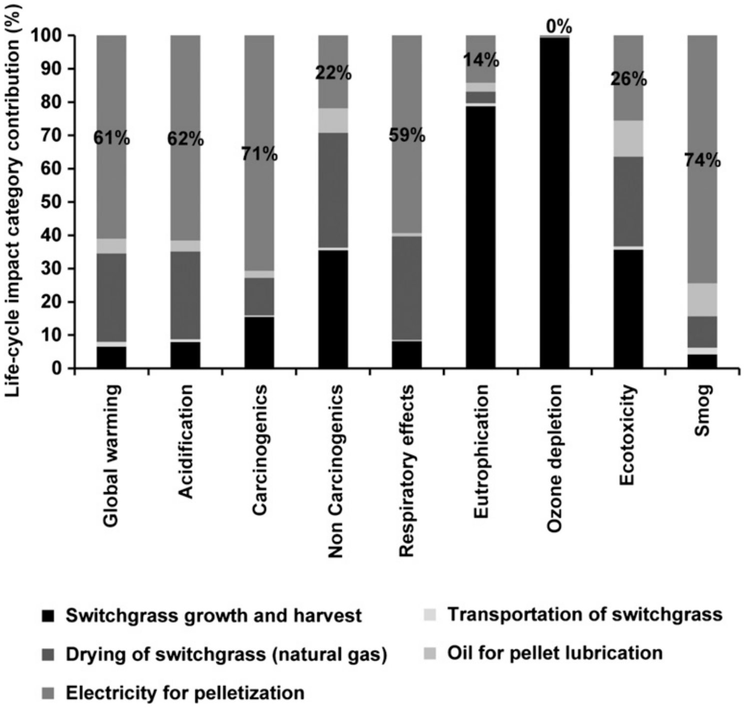

Figure 2. Impact categories showing relative contribution of the cradle-to-gate inputs in pelletizing switchgrass.

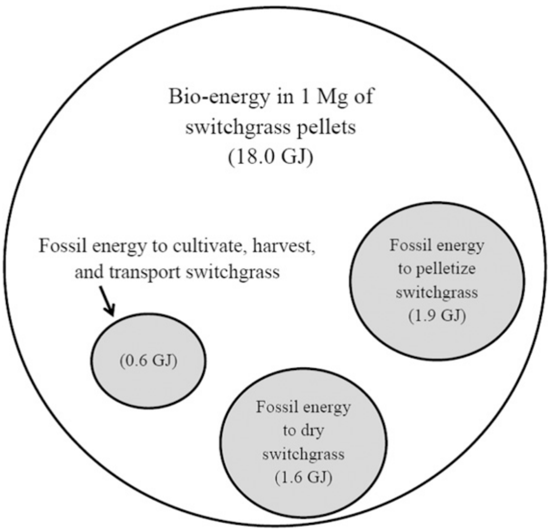

Figure 3. Potential bioenergy and embodied fossil energy in 1 Mg of switchgrass pellets. Bioenergy content value from FPL (2004).

Because of the high net bioenergy content of switchgrass pellets, use of switchgrass for fuel would offer a significant GWP advantage compared with fossil fuels including natural gas (Fig 4). This LCA scenario assumes equivalent combustion efficiencies (80%) (FPL 2004) and includes biogenic CO_2 emissions and absorption. The results suggest a decrease in global warming impact of more than 80% for switchgrass pellets compared with a natural gas alternative. The Energy Independence and Security Act of 2007 requires a cellulosic biofuel to provide a 60% decrease in GHG emissions compared with fossil fuel alternatives (USEPA 2009); however, these GHG emission reduction calculations involve consideration of land-use change (LUC) impacts. This study did not consider impacts associated with LUC. Also, for LUC impacts, Daystar et al (2014) reported no change in net GHG emissions when converting from cropland or grassland, which would be the primary source for new switchgrass cultivation instead of forestland. Thus, if the conversion to switchgrass from cropland or grassland occurred, LUC impacts on the impact assessment would be minimal.

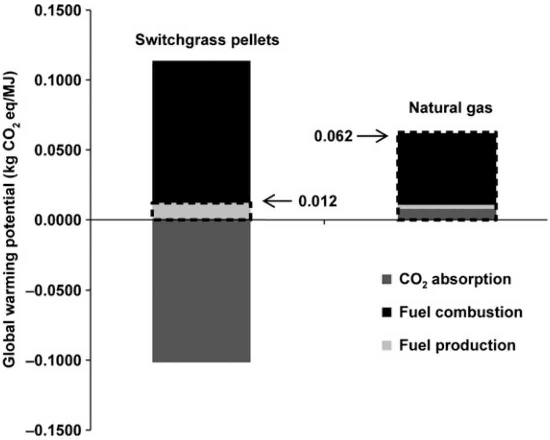

Figure 4. Global warming potential of switchgrass pellets and natural gas fuels, by life stage. Transportation of the fuels to the combustion facility was not considered.

As with all LCI and impact assessments, the conclusions that can be drawn are influenced by the underlying assumptions. This study focused on a particular method of growing and harvesting switchgrass (for the use of a pilot switchgrass bioenergy refinery and research) in a particular location (southeast Tennessee). The pellet operations surveyed used results from mills attached to hardwood flooring facilities. Results for mills that use other resources—particularly those that require additional drying as part of the pellet-making process—would be different (Hagberg et al 2009). Therefore, a sensitivity analysis was conducted to evaluate the environmental impacts of forced drying using natural gas. Additionally, the study that established the inventory for the pelletization process was heavily influenced by the local electrical generation source (mostly coal). Mills in other areas (eg areas that rely on mainly hydropower for electrical generation) will produce different GWP results from those calculated in this study. Therefore, a second sensitivity analysis explored effects of electricity from two other grids using different electricity sources.

This study involved a cradle-to-gate LCA of switchgrass pellets; therefore, environmental impacts beyond the mill gate could be important but were not included, eg when biomass transportation to markets in Europe were considered (Magelli et al 2009; Dwivedi et al 2014). However, this study provides an initial scenario that can be added to or altered for future studies.

Sensitivity Analysis

This study conducted two sensitivity analyses. The two analyses evaluated the changes in environmental impacts from changing the amount of natural gas consumed during forced drying of switchgrass before pelletization and from altering the electricity grid mix used in the pelletization process.

In the first analysis, natural gas was burned to force-dry switchgrass to 10% MC to produce a feedstock dry enough for pelletization. The initial switchgrass moisture content varied substantially, and thus, the MC of the switchgrass before being force-dried varied too. Therefore, to evaluate forced-drying stage impacts within the cradle-to-gate analysis, a sensitivity analysis was performed by increasing (high) and decreasing (low) natural gas consumption by 20% from the study (baseline) value of 27.09 m^3/Mg switchgrass pellets and then comparing all three. All other inputs remained the same. The low and high values were 21.67 and 32.51 m^3/Mg, respectively. Figure 5 shows the differences in environmental impacts, and as expected, increasing natural gas consumption increased all impacts and vice versa for decreasing natural gas consumption. Also, the changes were linear with some impacts changing more than others. Noncarcinogenics and ozone depletion had the greatest changes at ±18%, whereas smog had the lowest change at ±2%. On the basis of the results, switchgrass should be field-dried as much as practically possible to lower moisture content and thus lower natural gas consumption during forced drying.

For the second sensitivity analysis, electricity input to the pelletization process contributed substantially to the environmental impacts of producing switchgrass pellets. Thus, it was interesting to explore the impact of different potential electricity sources at the time of data collection. In this study, the electricity input used was based on an eastern US grid mix that was primarily coal-based. When a different US source was selected, impact categories showed varying results. Figure 6 presents a comparison between an eastern US grid mix, a western US grid mix, and a Texas grid mix. From Fig 6, it is evident that producing switchgrass pellets in a western US grid mix would have less impact in all categories. Comparatively, producing in the Texas grid mix would produce the greatest impacts in five of the nine categories (global warming, acidification,

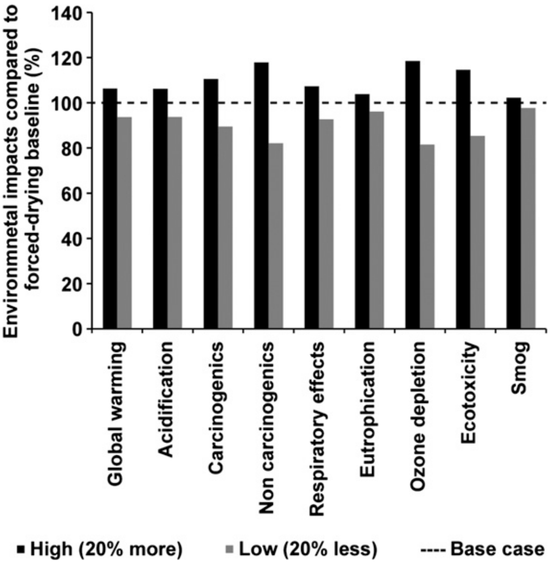

Figure 5. Sensitivity analysis of changing natural gas consumption for force-drying switchgrass.

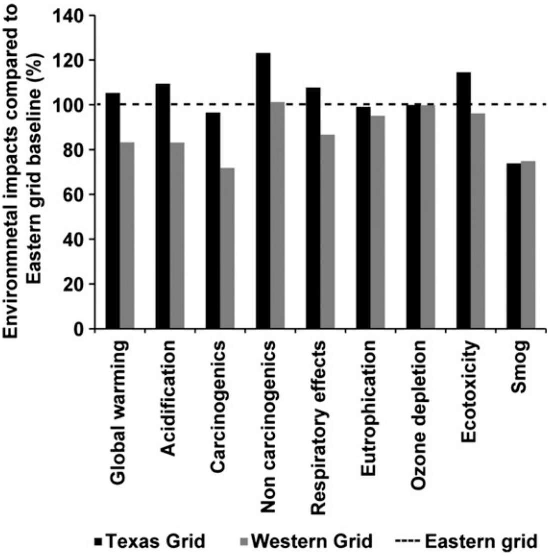

Figure 6. Sensitivity analysis of US Eastern grid mix, US Western grid mix, and US Texas grid mix for pelletization.

noncarcinogenics, respiratory effects, and ecotoxicity). The eastern US grid mix had a higher smog impact than the others, and all three grid mixes had relatively the same ozone depletion impact.

The differences in generation sources among these three grids help explain why the western US grid mix has less impact. For the Texas grid mix, the primary source for electricity generation is natural gas (50%) followed by coal (≈35%), nuclear (≈12%), and renewable and miscellaneous sources (≈3%) (EIA 2012). For the eastern US grid mix, the primary source for electricity is coal (≈58%) followed by nuclear (≈22%), natural gas (≈10%), and renewable and miscellaneous sources (10%) (EIA 2012). Although the western US grid mix does heavily rely on coal (≈32%) and natural gas (≈23%) for electricity generation, this grid also uses a significantly higher proportion of hydropower (≈27%) along with other renewables (≈18%) (EIA 2012).

Interpretation

Fertilizing had the greatest impact associated with the prepelletization processes of cultivation and harvesting. These LCIA results are consistent with Kalita (2012). This occurred because fertilizer requires large quantities of fossil fuels for its production along with run-off and emissions. Additionally, impacts from fertilizing are substantially higher for eutrophication and ozone depletion even when from cradle-to-gate mill pellet output. However, switchgrass has an advantage that it typically consumes less fertilizer while being highly productive compared with other biomass resources (Wilson et al 2012; Brassard et al 2014; Daystar et al 2014). This environmental advantage was not explored further because it was beyond the goal and scope of this study. It is expected, as more nitrogen-use-efficient switchgrass becomes available, that these fertilization impacts will decrease.

The impact categories of noncarcinogenics, ozone depletion, ecotoxicity, and carcinogenics tended to follow natural gas consumption used for forced drying of switchgrass. Therefore, special attention should be paid when cutting and then field-drying switchgrass. A possible way to aid this endeavor to lower these impacts is to pay farmers based on the moisture content as well as mass of the incoming switchgrass feedstock. This would provide an incentive for the farmer to field-dry the switchgrass as much as possible before having the material transported to the pellet mill for processing. Of course, to ensure a quality pellet, the incoming switchgrass feedstock quality would have to be monitored as well.

Data from a survey of switchgrass farmers were combined with an estimate for drying energy and inventory data from the pelletization of wood residues. LCI analysis of switchgrass pellets indicated that the potential bioenergy in the pellets was more than four times the total fossil energy used to create them. Therefore, switchgrass pellets, if used as a fuel in place of natural gas, would result in a >80% decrease in GWP, a considerable GHG savings. A sensitivity analysis using different US grid mixes shows that switchgrass pellets produced using the western electricity grid would have fewer environmental impacts in all nine impact categories. Conversely, switchgrass pellets produced using Texas grid electricity would have the greatest impacts in five of the nine impact categories.

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