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Exploring impacts of process technology development and regional factors on life cycle greenhouse gas emissions of corn stover ethanol

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ABSTRACT

This paper examines impacts of regional factors affecting biomass and process input supply chains and ongoing technology development on the life cycle greenhouse gas (GHG) emissions of ethanol production from corn stover in the U.S. Corn stover supply results in GHG emissions from −6 gCO_2eq./MJ ethanol (Macon County, Missouri) to 13 gCO_2eq./MJ ethanol (Hardin County, Iowa), reflecting location-specific soil carbon and N_2O emissions responses to stover removal. Biorefinery emissions based on the 2011 National Renewable Energy Laboratory (NREL) process model are the single greatest emissions source (18 gCO_2eq./MJ ethanol) and are approximately double those assessed for the 2002 NREL design model, due primarily to the inclusion of GHG-intensive inputs (caustic, ammonia, glucose). Energy demands of on-site enzyme production included in the 2011 design contribute to reducing the electricity co-product and associated emissions credit, which is also dependent on the GHG-intensity of regional electricity supply. Life cycle emissions vary between 1.5 and 22 gCO_2eq./MJ ethanol (2011 design) depending on production location (98%–77% reduction vs. gasoline). Using system expansion for co-product allocation, ethanol production in studied locations meet the Energy Independence and Security Act emissions requirements for cellulosic biofuels; however, regional factors and on-going technology developments significantly influence these results.

1. Introduction

Sustainability-related concerns surrounding fossil fuel use, and improvements in biomass conversion technologies have increased interest in producing fuels from lignocellulosic feedstock. Considerable focus has been placed on the development of second generation biofuels from non-food biomass (e.g., [6,20,21]). With improvements in biomass pre-treatment, reductions in enzyme loading and prices, and the production of valuable co-products such as pellets and electricity, the financial metrics of lignocellulosic biofuel production have improved [13]. Lignocellulosic biomass feedstock options include energy crops, forest and agricultural residues, and the organic fraction of municipal solid waste. These feedstocks do not directly compete with agricultural crops, and in the case of crop residues, are produced from biomass already grown on the same parcel of land.

Corn stover, an agricultural residue, is gaining interest as a feedstock because it is an abundant and inevitable co-product of corn grain production [4]. Corn stover and grain are produced in approximately equal amounts. [9,23] discuss that corn stover could be used for ethanol production in the U.S., provided it is removed from the field in a sustainable manner, e.g., with minimal soil erosion and preservation of soil carbon. In the U.S. most of the corn stover is left in the fields; [19] reported that only 5% of the total corn stover is removed, and that it is used as animal feed and bedding. The amount of stover which could be removed without soil organic carbon loss is dependent upon geography and local/regional soil conditions [19,20] suggest that the stover removal rate ranges from 25% to 50% in the U.S.

Life cycle assessment (LCA) provides a transparent methodology that can be used to examine biofuel production. Life cycle studies have evaluated lignocellulosic ethanol production from a variety of feedstocks including: corn stover, switchgrass, hybrid poplar, alfalfa and reed canary grass (e.g., [2,8,18,25–27]). The studies examined the production and use in road transportation vehicles of ethanol/gasoline blends in the forms of E10 (10 vol% ethanol), E85 (85 vol%

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ethanol), and E100 (100% ethanol). Each of these studies reported a reduction in GHG emissions for the ethanol compared with the reference fossil fuel(s). LCA studies are particularly relevant in jurisdictions that use GHG metrics to accompany biofuel mandates, such as the Low Carbon Fuel Standard in California [5], and the GHG reductions stipulated under the US Energy Independence and Security Act [7].

There are a number of LCAs of the corn stover to ethanol process (e.g., [12,16,21,24,25]). These studies all reported that replacing gasoline with ethanol produced from corn stover would reduce GHG emissions; however, the percentage reductions (compared to gasoline) reported in the studies vary between 58% and 106%. Key factors impacting the study results include: agricultural activities associated with corn stover production; the design of the conversion process, which impacts electricity and thermal energy demands; the source of electricity; and assumptions regarding enzyme and process chemical inputs to the conversion process. According to [7]; to meet the requirements for categorization as a cellulosic biofuel, ethanol should reduce GHG emissions by 60% compared to gasoline. [24] studied both National Renewable Energy Laboratory (NREL) [1] and Michigan State University conversion process design models, but most other studies relied only on technical process information for conversion of stover to ethanol reported by NREL [1]. Hsu et al. [12,16,24] used US-average data for corn yield, fertilizer application rate and electricity grid intensity. Sheehan et al. [25] determined the aforelisted data based on a specific location in Iowa. These studies did not include the impact of geographical variation on their LCA results, and did not distinguish between different stover harvesting requirements and biorefinery locations. Furthermore, there have been significant changes in the NREL conversion process design since 2002, including a major update published in 2011 [13]. Changes in the NREL design model include a process for enzyme production, the introduction of new chemicals (ammonia and caustic) to the process, and significant changes in ethanol yield and electricity generation capacity.

The objective of this paper is to evaluate impacts of process technology development and regional aspects on life cycle GHG emissions associated with ethanol produced from corn stover in the U.S. In particular, we develop our life cycle models based on the updated process model published by NREL [13]. We additionally provide a comparison of NREL [13] and [1] process designs, and compare our life cycle results with those of [12]; a study based on NREL [1] design. To our knowledge this is the first life cycle study comparing the 2002 and 2011 NREL designs. The impacts on life cycle GHG emissions of site-dependent variations in agricultural practices and outcomes, regional variations in the electricity grid and different emissions allocation methods are examined. Resulting life cycle GHG emissions are compared with EISA's thresholds to assess the implications of ethanol conversion technology development and regional parameters on GHG emissions of corn stover ethanol.

2. Methodology

2.1. Life cycle assessment

Life cycle inventory analysis models are developed to quantify GHG emissions associated with ethanol production from corn stover. The life cycle system boundary includes activities associated with the corn stover-ethanol production process from field to ethanol use in a light duty vehicle as a blended fuel with gasoline. These include corn farming and stover harvesting, pre-processing of stover, transportation of stover and ethanol production in a biorefinery (Fig. 1), transportation of ethanol and final combustion of ethanol. The functional unit is 1 MJ of ethanol (E100) produced. Spreadsheet-based models are developed to quantify life cycle emissions of selected GHGs (CO_2, CH_4, and N_2O) which are reported as carbon dioxide equivalents (CO_2eq.) based on 100-year global warming potentials [15].

2.2. Corn stover production

Corn stover produced in eight counties located in the U.S. corn belt is examined. These counties are: Hardin (IA), Fulton (IL), Tuscola (MI), Morrison (MN), Freeborn (MN), Macon (MO), Hamilton (NE), and Codington (SD). These counties are selected to correspond with counties evaluated previously by Ref. [19] as there is now a body of relevant data for corn and corn stover production in these counties. It is assumed that a bioethanol plant (biorefinery) located in each county obtains and processes stover harvested in the same county. If the stover supply from one county is not sufficient for the NREL [13] design (700,000 t/year), additional stover is assumed to be provided from neighboring counties. Corn stover is assumed to be harvested in a second pass through the field [25]. The corn stover is harvested, collected, preserved and stored in square and round bales. The dry matter content of stover and ratio of stover to grain are 79% and 1:1, respectively [17].

2.3. Allocation of GHG emissions to stover production

Corn stover is a co-product of corn grain production; therefore, it is necessary to allocate emissions between these two products. There are different co-product treatment approaches utilized in LCA, including allocation and system expansion [14]. Two approaches, system expansion and mass allocation, are used in this study to distribute emissions from corn production and harvesting to stover and grain.

System expansion is the most common approach used in previous studies (e.g., [12,19,24,25]). In the system expansion approach, only emissions related to the additional activities required to harvest stover are assigned to the stover. The environmental effects of harvesting stover include changes in nitrogen related emissions and soil organic carbon levels, phosphorous loss, additional nutrient requirements in the subsequent growing

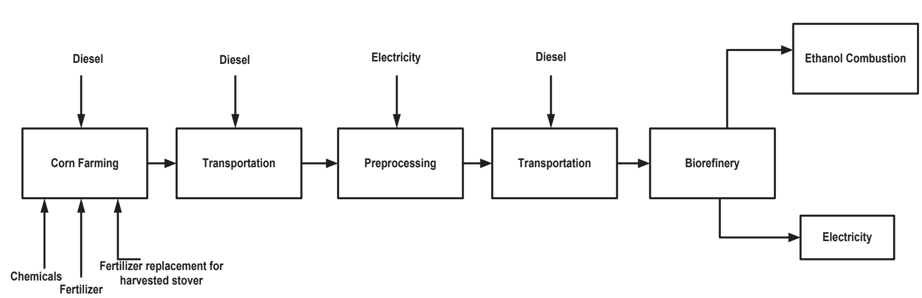

Fig. 1. System boundaries for life cycle assessment of E100 from corn stover.