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Life cycle assessment of lignocellulosic ethanol: a review of key factors and methods affecting calculated GHG emissions and energy use

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Lignocellulosic ethanol has potential for lower life cycle greenhouse gas emissions compared to gasoline and conventional grain-based ethanol. Ethanol production 'pathways' need to meet economic and environmental goals. Numerous life cycle assessments of lignocellulosic ethanol have been published over the last 15 years, but gaps remain in understanding life cycle performance due to insufficient data, and model and methodological issues. We highlight key aspects of these issues, drawing on literature and a case study of corn stover ethanol. Challenges include the complexity of feedstock/ecosystems and market-mediated aspects and the short history of commercial lignocellulosic ethanol facilities, which collectively have led to uncertainty in GHG emissions estimates, and to debates on LCA methods and the role of uncertainty in decision making.

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Introduction

Lignocellulosic ethanol offers the potential to diversify the transportation fuel pool with a renewable liquid fuel produced from a range of feedstocks, and can lower life cycle greenhouse gas (GHG) emissions intensity relative to conventional ethanol produced from grain and sugarcane. However, to ensure ethanol production 'pathways' meet environmental goals, improved understanding of the life cycle environmental impacts of lignocellulosic ethanol is critical before wider scale deployment.

Ethanol produced from corn grain and sugarcane are the dominant alternative light-duty vehicle transportation fuels replacing gasoline. Lignocellulosic ethanol has garnered significant attention over the past 15 years and consequently, numerous life cycle assessments (LCAs) have been completed, examining a wide range of feedstocks, and to a lesser extent, conversion processes. LCA, 'the compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle' [1], has been applied to a wide variety of products and incorporated into transportation fuel regulations [2–4]. While considerable developments in lignocellulosic feedstocks and ethanol conversion process technologies have been made alongside concomitant advances in LCA methods and applications, considerable gaps remain in our understanding of the impacts of lignocellulosic ethanol production.

The aim of this review is to highlight key aspects of the lignocellulosic ethanol 'pathway', particularly differences in feedstocks, processes, co-products, and in LCA methods that could materially impact calculated GHG emissions. A case study for the production of ethanol from corn stover is used to illustrate the diverse GHG outcomes that can result from differing data, assumptions and analysis methods. The study incorporates specific literature data (from 2000 to present).

Life cycle assessment methods and their application to lignocellulosic ethanol

LCA was initially designed to examine environmental impacts of historical or current production over short, defined time periods to identify the largest impact reduction potential and improvement strategies without 'burden shifting'. Traditional uses were to inform product development and policy. LCA is now also employed to enforce policy and to inform investors. LCA is the fundamental analysis tool to qualify fuels under a number of regulations (e.g., US Renewable Fuel Standard [2], European Union Renewable Energy Directive [3], California Low-Carbon Fuel Standard [4]). These initiatives mandate GHG emissions reductions for a regional fuel pool, or that an alternative fuel reduces GHG emissions by some prescribed level relative to an incumbent fuel.

While LCA approaches/methods have become more sophisticated since their inception, considerable methodological and application challenges remain [5,6]. There are two general types of LCA: attributional (aLCA) and consequential (cLCA). Both have a role in the analysis of lignocellulosic fuels, either via legislative initiatives or more broadly in the assessment of environmental performance. aLCA compares a candidate versus incumbent fuel based on physical relationships, while cLCA aims to determine overall impacts of the fuel's use within a dynamic economic system using various economic approaches [7]. An attributional study might include consequential components (e.g., indirect land use change (iLUC) — see 'Categories of lignocellulosic feedstocks' below for more information) or include system expansion (rather than allocation) [8]. The US EPA RFS2 Regulatory Impact Analysis used the Forestry and Agriculture Sector Optimization Model (FASOM) and Farm and Agricultural Policy Research Institute (FAPRI) model to predict GHGs associated with land use change (LUC) from corn and cellulosic ethanol production, which were then added to base aLCA GHG emissions [2]. Consequential studies use emissions factors derived from aLCA studies to quantify emissions related to changes in the economic models underlying the cLCA approach. This is illustrated by Rajagopal and Plevin [9••], who investigated how adoption of renewable fuels impacted oil and agriculture markets. Martin *et al.* [10••] recently reviewed aLCA and cLCA studies of biofuels, focusing on system boundaries and noting distinctions among the models/studies. There is an ongoing debate about the relevance of each type of LCA to decision making [11••,12••,13,14].

LCAs of lignocellulosic biofuels in the literature are prospective, as the first facilities have only recently entered production, which creates challenges in applying LCA [5,6,15]. Major life cycle phases (e.g., biomass/feedstock production, feedstock transportation, processing) and associated activities (e.g., on-farm fuel combustion) that have been included in many of the published LCAs of lignocellulosic ethanol from dedicated energy crops or agricultural residues are shown in Figure 1. LCAs have accounted for the emissions associated with these phases and associated cradle-to-gate (supply chain) activities (e.g., emissions associated with diesel fuel production for use in farm equipment). A key aspect of biofuels studies is the assumption that biogenic CO_2 emissions do not increase atmospheric CO_2 because the carbon released through lignin combustion, fermentation and ethanol combustion is exactly balanced with the carbon sequestered when the biomass regrows. Most lignocellulosic ethanol LCAs have focused on energy use and GHG emissions, and have compared ethanol use (in a low or high level blend with gasoline) in a light-duty vehicle to emissions of a reference gasoline vehicle. There are a few additional activities that are not shown in the figure that have been included in a small number of studies (e.g., transportation infrastructure).

Several reviews of lignocellulosic ethanol LCA studies have been completed [16–22]. Morales *et al.* reviewed over 100 LCA studies analyzing lignocellulosic ethanol, and concluded that the studies show a 'clear reduction in GHG emissions...' for ethanol compared to gasoline [23••]. The authors do caution that differences in methods chosen make comparing studies difficult. Borrion *et al.* [22] similarly concluded that results were dependent on system boundaries, functional units and allocation methods. Singh *et al.* [18] suggested that system boundaries, N_2O emissions, soil carbon dynamics and allocation methods for co-product credits are the greatest causes for uncertainty and variability.

Categories of lignocellulosic feedstocks

Lignocellulosic ethanol feedstocks are typically agricultural residues (e.g., stover, straw, bagasse), forestry products/residues (e.g., poplar, mill by-products), or dedicated energy crops (e.g., switchgrass, *Miscanthus*, energy cane). The production method and class of land for each category of feedstock affects overall GHG emissions [24]: some feedstocks are used directly, while others are residues of a primary crop (e.g., corn, wheat).

Agricultural and forestry residues are typically produced/removed during or after harvesting the primary 'crop'. Concerns over what constitute sustainable residue harvesting rates arise due to soil erosion, reduced primary crop productivity, and soil nutrient and carbon depletion, have resulted in limits being placed on the fraction of residues that can be removed from fields, typically 25–70% for agricultural residues [25•,26,27]. Nutrient removal due to residue harvest can be countered through the addition of exogenous fertilizers. Agricultural and forestry residues may be treated as by-products of the main crop/tree cultivated and, as a result, emissions associated with feedstock production may be allocated to the primary crop/tree harvested rather than to the residual cellulosic material. Upstream feedstock emissions, therefore, are normally restricted to those related to replacement nutrients and any additional energy required for residue harvesting (see Figure 1) [28]. Similarly, residues, which share cropland with the primary crop, are generally excluded from LUC impacts, with these impacts being allocated to the main marketable component of the material harvested. As a result, lignocellulosic ethanol produced from residues may have lower feedstock-related GHG emissions than that produced from dedicated energy feedstocks where the lignocellulosic material is the main marketable material.