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Research paper

Cellulosic ethanol production: Landscape scale net carbon strongly affected by forest decision making

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ABSTRACT

In producing cellulosic ethanol as a renewable biofuel from forest biomass, a tradeoff exists between the displacement of fossil fuel carbon (C) emissions by biofuels and the high rates of C storage in aggrading forest stands. To assess this tradeoff, the landscape area affected by feedstock harvest must be considered, which depends on numerous factors including forest productivity, the amount of forest in a fragmented landscape, and the willingness of forest landowners to sell timber as a bioenergy feedstock. We studied landscape scale net C balance by combining these considerations in a new, basic simulation model, CEBRAM, and applying it to a hypothetical landscape of short-rotation aspen forests in northern Michigan, USA. The model was parameterized for forest species, growth and ecosystem C storage, as well as landscape spatial patterns of forest cover in this region. To understand and parameterize forest owner decision making we surveyed 505 nonindustrial private forest (NIPF) owners in Michigan. Survey results indicated that 47% of these NIPF owners would willingly harvest forest biomass for bioenergy. Model results showed that at this rate the net C balance was 0.024 kg/m^2 for a cellulosic ethanol system without considering land use over a 40 year time horizon. When C storage in aggrading, nonparticipating NIPF land was included, net C balance was 1.09 kg/m^2 over 40 years. In this region, greater overall C gains can be realized through aspen forest aggradation than through the displacement of gasoline by cellulosic ethanol produced from forest biomass.

1. Introduction

The future development of industrial scale production systems for cellulosic ethanol could help meet the renewable energy goals of the Energy Independence and Security Act (EISA) of 2007. This legislation mandated that in the USA 49.0 million m^3 of renewable fuel would be blended with gasoline by 2010 and 136 million m^3 of renewable fuel would be blended into gasoline by 2022. These renewable fuels were mandated to include 60.6 million m^3 of advanced biofuel production, including cellulosic ethanol [1]. Biofuels are included in the Act because grasses and woody crops fix carbon (C) as they grow, and the displacement of fossil fuels with ethanol from biomass has the potential to lower net C emissions over the cycle of plant growth, fuel conversion, and combustion.

However, woody biomass sources like forests also play a large role in the global scale exchanges of C between the land and the atmosphere and have the potential to mitigate the effects of rising atmospheric CO_2 by removing atmospheric CO_2 and storing C as forests aggrade [2,3]. If forests are left to aggrade, C accumulates not only in the wood growth but also in the annual production of foliar and fine root litter. Through ecosystem processes that limit decomposition or stabilize C in soil, forest floor and soil C pools continue to increase at high rates for decades after initiation of a new forest stand [4–6]. Many strategies are being assessed to manage forest C balance at scales from individual forest stands to large regions. These include reforestation, avoided degradation and deforestation, forest aggradation (unharvested growth), and silvicultural management to promote forest C storage [7].

In this context, if a biomass fuel system relying on forest biomass is considered as a strategy for mitigating rising atmospheric CO_2, it is worthwhile to compare the proposed biomass fuel system against the aforementioned other potential uses of forests to mitigate rising atmospheric CO_2 [8,9]. However, to rigorously

Abbreviations: CEBRAM, Cellulosic Ethanol BioRefinery Accounting Model; EB, Energy Balance; EB + LU, Energy Balance and Land Use; GREET, Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation; MITRIX, Michigan matrix; NCB, Net Carbon Balance; NIPF, Non Industrial Private Forest.

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assess such life cycle net C gain of a biomass fuel system, careful definition of system boundaries is needed, including conceptual, spatial, and temporal boundaries. One such choice of boundary is to include the C balance associated with the land use for land on which the feedstock is produced. This has been a controversial topic in the assessment of net C emissions from biofuel systems [10–14].

Other considerations, such as the constraints on ethanol biorefineries must be taken into account when judging the effectiveness of cellulosic ethanol as a C mitigating option. For an industrial scale biorefinery to obtain forest biomass much of the feedstock would need to come reliably from landowners over a series of harvest rotations. This need for supply puts small forest landowners in an important position. The more feedstock they are willing to harvest and sell, the lower the distances over which biomass must be transported to fuel the biorefinery. The larger the size of a biorefinery, the greater flow of biomass needed, thus the area over which biomass needs to be transported scales directly with biorefinery size [15,16]. In economic terms, this is a negative return to scale because average transport costs increase with distance. It is also likely to be a negative return to scale for C emissions because this transportation requires energy (and thus C emissions). Small forest landowners with a history of selling their wood to pulp mills or to other wood industries in decline would be in a good position to benefit from and support the success of the cellulosic ethanol industry, and, in conjunction, the EISA mandate [1,15–17]. If these landowners are concentrated in sufficient numbers near the biorefinery, they could also help to minimize economic costs for a biorefinery [18]. Yet, a growing number of private forest landowners in the north central USA are choosing to make management decisions geared toward aesthetics and recreation, maintaining their growing forests, rather than harvesting for timber sales [19].

A novel aspect of our analysis is that we address forest management decision making by forest landowners, specifically nonindustrial private forest (NIPF) owners in northern Michigan, in relation to cellulosic ethanol production. In our analysis, willingness to harvest trees for feedstock affects both the distance over which biomass is transported and the amount of aggrading forest that remains within the transport radius. We addressed the following research question: To what extent are NIPF owners in northern Michigan willing to harvest their forests for bioenergy feedstock, and how do different levels of such private biomass sales impact the system net C balance of an industrial scale biorefinery?

Here we also address an important aspect of the land use and renewable fuels debate by comparing the net C balance of a cellulosic ethanol system from forest biomass at the landscape scale versus forest aggradation as an alternative in the identical landscape. Many analyses in the current literature address the question of how effective, from either a C or an economic perspective, is a given biofuel or C sequestration policy [20–27]. A second question we indirectly address here is stated differently: How does overall net C balance compare in the uses of forest land for either aggradation or rotation harvests for biofuel feedstock, when both the biofuel production system and feedstock source area are considered at the appropriately large spatial scale and relevant time horizon? Such place based analyses have been done before as a way to assess the land use impact of a particular biofuel production chain [13].

2. Methods

2.1. Scope of the project

We focus on forested landscapes and ecosystems of northern Michigan, USA, which includes the Upper Peninsula and the northern areas of the Lower Peninsula. We consider a hypothetical, industrial scale, cellulosic ethanol biorefinery that would use forest tree biomass from short-rotation aspen forests in this region as its feedstock. The model does not intend to capture the full diversity of forest stands over northern Michigan, nor does it try to capture all silvicultural methods available or used. Rather, our modeling analysis considers a simplified hypothetical landscape composed of aspen stands harvested on a 30 year rotation, a silvicultural practice common in the region. We define the concept of a system Net C Balance (hereafter *system NCB*) as the net C balance determined by an accounting framework over a particular choice of conceptual system boundary. We compare two such accounting frameworks, or two such choices of system boundary for the production of cellulosic ethanol from forest biomass in Michigan: both include the biorefinery and C emissions related to harvest, transport, and conversion to ethanol, but one system boundary also includes the C gain forest aggradation in the surrounding landscape. Both analyses include a simplified, uniform spatial distribution of forest patches in the mixed land cover of this region (which affects transport distance). While the actual forested landscapes of this region are heterogeneous in composition, ownership, and management, this simplification allowed us to conduct a straightforward analysis of two frameworks for calculating scaled-up, hypothetical NCB if a landscape were homogeneous in forest composition and management in all respects except for decisions whether to harvest individual stands. We included realistic rates of forest growth and rates of ecosystem processes controlling forest C balance [6; see Methods]. The system NCB is expressed in kg/m^2 over the entire forested area within the radius of feedstock harvest and transport and summed over the 40 year time horizon. A positive value for system NCB indicates that more C was sequestered in the forests of the landscape or displaced from fossil fuel combustion than was emitted to the atmosphere through biomass harvest, transport, and conversion to ethanol. Further details are provided below (Section 2.5).

2.2. Survey of nonindustrial private forest owners

To assess the willingness of NIPF landowners to harvest and sell their forest biomass as bioenergy feedstock and to gain insight into their decision making criteria, we conducted a mail survey of NIPF owners in Michigan. The survey was titled the “Private Forest Landowner Decisions Survey 2011,” hereafter the *landowner survey*. It was four pages in length, asking a variety of questions about criteria and information that landowners would use in making decisions about forest management, harvest, and biomass supply for biorefineries. It also probed how such decisions by NIPF owners relate to their understanding and preferences regarding biofuels, C sequestration, and related issues such as climate change. The sampled population was NIPF owners who were enrolled in the state of Michigan's Commercial Forest Program whose addresses were posted for public access online in 2010 [28]. The landowner survey was mailed to 1203 such addresses in February 2011 and responses were accepted until the end of May 2011. The Commercial Forest Program had 8903 square kilometers enrolled, representing 11% of Michigan's forest area [28]. Survey respondents owned land representing about 0.5% of Michigan's forest area (Fig. 1).

2.3. CEBRAM model structure

We developed and applied a new model, CEBRAM (Cellulosic Ethanol BioRefinery Accounting Model) to calculate system NCB. The goal of the model was twofold. First, it was created to calculate the C impact of a cellulosic ethanol biorefinery from cradle to gate—from tree growth through ethanol production [29]. Our