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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

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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

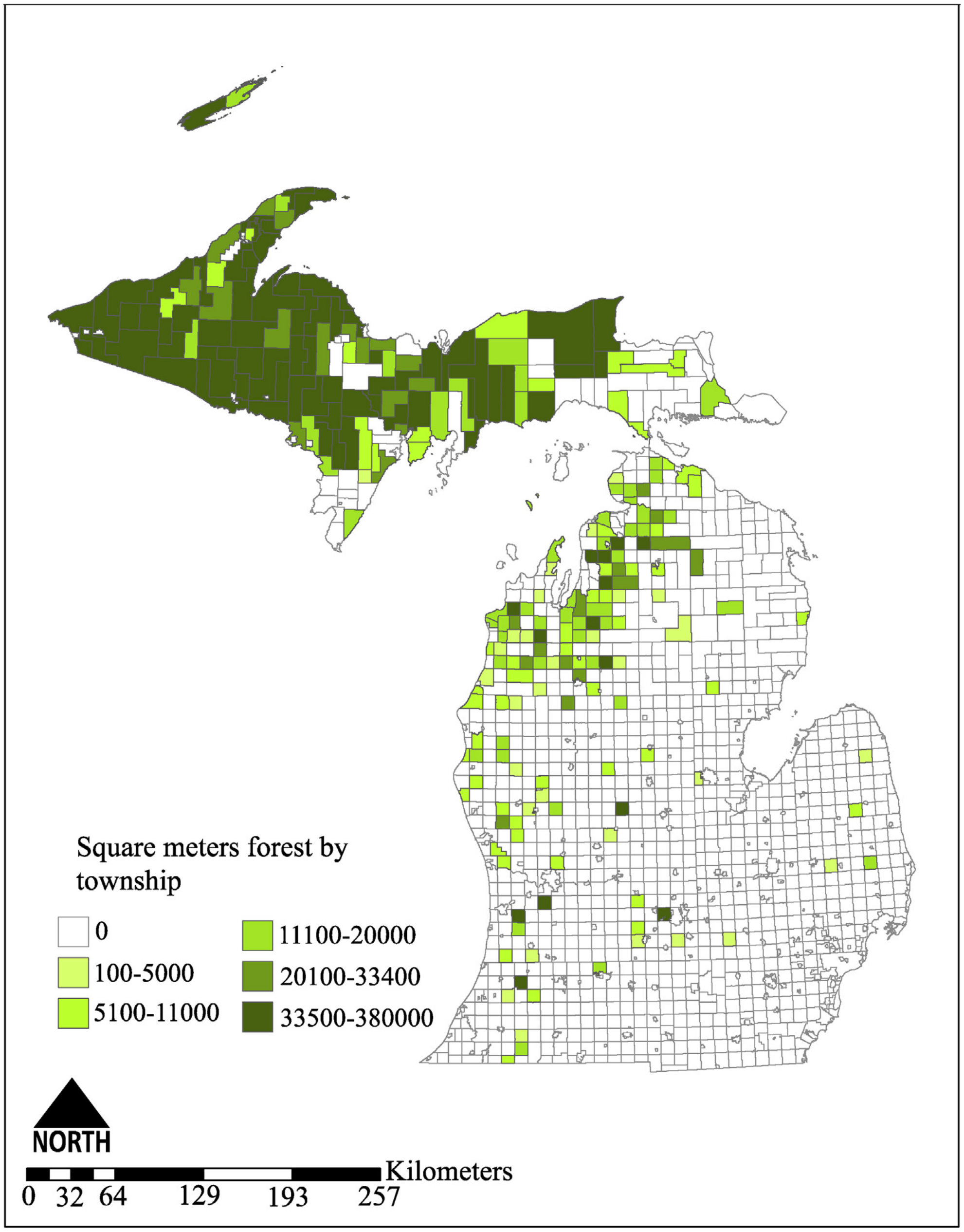

Fig. 1. The forest acreage owned per NIPF landowner, expressed as a landowner average by township, as self reported by forest landowner respondents in the Private Landowner Forest Decisions Survey 2011 as part of the present study.

system boundaries do not include the downstream delivery of ethanol beyond the biorefinery gate. However, we do include avoided C emissions from the displacement of fossil fuel by the ethanol produced. CEBRAM calculates the system NCB of a cellulosic ethanol production system as the biomass transportation distance varies, caused by differences in simulated rates of participation in forest harvest and feedstock sale by NIPF owners (hereafter ‘participation’). The model approximates C used in forest harvest, transport, and complete pretreatment and processing for cellulosic ethanol. The second goal of CEBRAM was to simulate C accounting frameworks that either included or excluded (see below, Section 2.5) the ecosystem C balance of all aggraded and harvested NIPF stands in the landscape over time, under a range of participation rates. CEBRAM was written in Microsoft Excel, and is available as Supporting online material, together with all parameter values.

To include the C balance of forest ecosystems, CEBRAM used output from a previously developed model of forest management, harvest, and C dynamics in northern Michigan, MITRIX [6]. MITRIX simulates the effects of management practices on forest tree species composition, growth and succession, and dynamics in tree size classes by species. It is calibrated to produce empirically observed rates of tree growth in Michigan in response to thinning and other “methods of cut” commonly used [6]. Also important for the present analysis, MITRIX includes a complete C balance for managed forest ecosystems, including C in living trees above and belowground, C in downed woody debris, C in forest soils, and the accumulation of C over time that results from inputs of foliar, root, and woody litter from growing trees [4,6,30,31]. We used MITRIX results for both the woody biomass production and ecosystem C stocks under simulations of forest harvest or aggradation (Fig. 2). The full code for MITRIX can be accessed through an open source

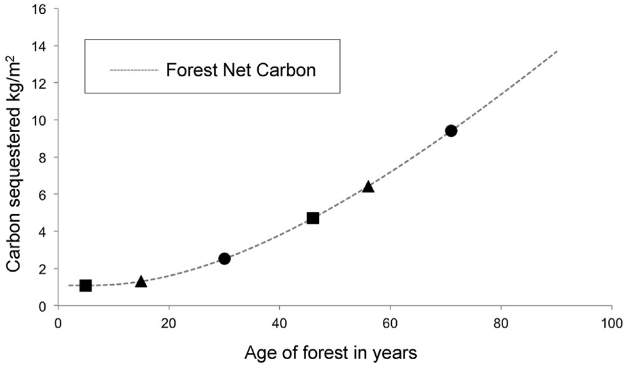

Fig. 2. Storage of C accelerates over time in a total forest ecosystem calculation that includes trees, downed woody debris, foliar and root litter, and soil organic matter. Shown here is total ecosystem C in a typical second growth aspen stand after a 30 year rotation harvest in northern Michigan (23). Following clear-cutting, the lag time before acceleration of ecosystem net C storage is caused by logistic growth in living tree biomass together with growth in the forest floor and downed woody debris as the early-successional forest enters a self-thinning stage after a few decades. To illustrate how this enters into CEBRAM model calculations, time periods between each pair of symbols of the same type (from square to square, from triangle to triangle, and from circle to circle) are all 40 years. Forests stands starting at 5 (square), 15 (triangle), and 30 (circle) years of age at the start of a simulation accumulate increasing amounts of C storage over a 40 year simulation, if unharvested.

database run by the University of Michigan [6].

2.4. CEBRAM model assumptions

A hypothetical biorefinery was assumed to be located in northern Michigan, a region where one small biorefinery exists and a proposed second biorefinery may be built [32–35]. Northern Michigan is well represented by our landowner survey respondents (Fig. 1). Here we provide a brief overview of model assumptions and calculations; greater detail is provided by Brunner [36] and the full model can be found in the Supplementary material associated with this paper. Feedstock for the biorefinery was assumed to come from the merchantable biomass in a 30 year old aspen forest [6]. The feedstock was assumed to be harvested by first thinning unwanted biomass followed by the use of feller and forwarder equipment to cut and transport remaining biomass to the road [37]. Transport distances for vehicles to and from the harvest sites were calculated using the straight line distance multiplied by a regional scale average coefficient for road tortuosity of 1.3 [36]. Energy used to load and unload the vehicles transporting the biomass, along with the energy needed to chip the biomass into uniform 1.60 mm pieces was included as biomass processing [37,38]. Our hypothetical biorefinery used the dilute acid/simultaneous saccharification and cofermentation process for ethanol conversion; the C emissions from enzyme production, building upkeep, and waste processing were all calculated and included [20,24,39]. The energy to run the biorefinery was assumed to be supplied by burning the waste lignin from the biomass [39]. The biorefinery was assumed to operate at maximum capacity, processing 700 000 dry kilograms of biomass per day for 365 days per year [40,41]. The gasoline offset due to available ethanol was calculated on an energy basis from cradle to gate using the GREET life cycle model (version 1.0.0.7837) [42]. Wet biomass was assumed to be 40% moisture, which then would air dry to an assumed 7% moisture [25,43]. Loss of wood mass due to drying was also calculated [43].

Michigan forests are highly productive and have a long history of industrial forest management and harvest, but currently 43% of timberland in Michigan is owned and managed in relatively small parcels (e.g. between 0.162 km^2 and 0.324 km^2) by NIPF landowners [28,44,45]. Because of the importance of NIPF landowners in Michigan and our interest in focusing on this group, we assumed that all biomass feedstock came from NIPF land. NIPF owners were considered *participants* if they harvested their biomass for sale to the biorefinery on a 30 year rotation [46,47]. Nonparticipating NIPF owners were assumed to allow their forests to aggrade, unharvested, throughout the length of the simulation period [19]. Whereas NIPF owners in reality have a broader range of land management options, including forest harvest for other forest products, we used only these two options to highlight the C sequestration tradeoff between producing a renewable fuel that displaces gasoline and allowing the trees to sequester C through growth [29].

CEBRAM was constructed to calculate, as a dependent variable, the landscape area needed under different scenarios to supply biomass to the biorefinery. This landscape area depended on the NIPF landowner participation rate, the percentage of NIPF land in the landscape, the annual feedstock demand of the biorefinery, the rate of forest biomass growth given initial age distributions and growth curve, and the rotation period of forest harvest. Here we report a range of NIPF landowner participation rates across scenarios, or simulations. The participation rate in a particular simulation determined the landscape area from which biomass was harvested (hereafter, *simulation area*). A lower participation rate meant that harvests would need to come from a greater distance, producing a larger simulation area, because the biorefinery was assumed to operate at full capacity. Biomass sources located near the biorefinery were assumed to be harvested before biomass located further away. We normalized our results across the simulation area (which varied based on NIPF landowner participation) and report our results for system NCB on a unit area basis, kg/m^2, calculated over a 40 year simulation period.

Because forest C storage depends strongly on forest history [30,48,49], but because this history can vary enormously, we used a simplifying assumption in our simulations: land use history of NIPF land was assumed to include regular forest harvest on a 30 year rotation, having occurred over a long enough period of time and averaged over enough forest patches that the landscape was in a steady state mosaic [7]. The actual forested landscape is much more heterogeneous. This simplification was useful and informative because it allowed us to scale up the effects of decisions made in a single patch type as if the forest patches in the landscape were populated entirely with that type. We also assumed an even distribution of the initial ages of forest stands from ages 1–30 years and even spatial distributions of stands in each age class throughout the landscape. Although hypothetical, this provides a convenient and plausible baseline of an actively harvested landscape with constant landscape C capital (or zero net C balance) against which alternative scenarios can be compared. The landscape was also assumed to have an even distribution of NIPF owner land over the simulation area. For a given NIPF owner participation rate, we assumed an even spatial distribution of participation and nonparticipation.

Our analysis further assumed that any ethanol produced was used to displace gasoline use on an energy equivalent basis. We used C emissions values for conventional gasoline from cradle to gate from the GREET model, as well as the C emissions from combustion [42,50–52]. We assumed that consumer driving habits did not change as a result of ethanol availability and that all ethanol produced would be consumed.

2.5. Boundary definitions for calculations of system NCB

We used two contrasting accounting frameworks to calculate values of system NCB: EB, for *Energy Balance*; and EB + LU, for

Energy Balance and Land Use. Both used the same hypothetical biorefinery, partially forested landscape, and homogeneous initial distribution of forest ages in the landscape mosaic. The only difference between these two accounting frameworks was the system boundary definition regarding how C values in growing forests were incorporated into the calculation. The EB framework used Equation (1) and the EB + LU framework used Equation (2):

$$T = (c_g \cdot \tau) - [\tau \cdot (c_h + c_d + c_l + c_i + c_e)] \tag{1}$$

$$T_b = [F + (c_g \cdot \tau)] - [\tau \cdot (c_h + c_d + c_l + c_i + c_e)] \tag{2}$$

where T is the total net C balance from the cellulosic ethanol biorefinery and gasoline displacement per year (c_g) over the 40 year time horizon, and T_b includes T together with F, the net C sequestered per year by all NIPF land in the simulation area over the 40 year time horizon. Other terms represent C emissions per year from harvest (c_h), from biomass transport (c_d), from the loading and unloading process (c_l), from running the chipper (c_i), and from the process of making the ethanol (c_e). The multiplier τ represents the length of the simulation, 40 years.

In the EB accounting framework for system NCB (Equation 1), only the energy balance of the ethanol production system was considered. This is a typical framework used for life cycle accounting of a fuel system. In the EB + LU accounting framework for system NCB (Equation 2), the net ecosystem C balance was included from all NIPF owned forest land in the simulation area, including both participating and nonparticipating NIPF landowners. To assess the effect of NIPF owner participation, both accounting frameworks were used to calculate system NCB over a range of NIPF owner participation.

3. Results

3.1. Survey of nonindustrial private forest owners

Of the 1203 copies of the survey instrument mailed, 106 were returned undelivered and 505 were returned with responses, yielding an effective response rate of 46%. The land area managed by the NIPF owner respondents was concentrated in Michigan's Upper Peninsula (Fig. 1). When asked about the purposes for which they used their forest land, 82% responded that they used the land for hunting, fishing or trapping; 70% used the land for conservation purposes; 69% used the land for timber or firewood harvest; 68% used their land for "just being around nature" (as worded in the survey) and 52% used it for camping, hiking, or birding. The vast majority of respondents (98%) did not rely on income from their forest land as their primary source of income.

When asked whether they would harvest and sell trees at the market value for timber, as feedstock for cellulosic ethanol production, one third of respondents reported that they would be willing, while 41% were not sure. Only 10% of respondents said they would not harvest their trees for use in cellulosic ethanol or not harvest trees at all. Only 8% of respondents indicated that the market price for timber or biomass would be the only factor in their decision making; 37% indicated that they would consider market price along with other factors, while others responded that they would take into account non-market factors such as recreation and conservation (37%) or "other worthwhile goals" (40%). Overall, 47% of respondents had a positive view of selling, at the market value for timber, some or all of their trees for cellulosic ethanol feedstock. A small proportion (4%) responded that they already harvested their forest biomass for production of alternative fuels, including cellulosic ethanol, although no industrial scale cellulosic ethanol biorefinery existed in Michigan at time of the survey.

Our landowner survey also asked about potential compensation to NIPF landowners for managing their forests to sequester C. While this did not enter into CEBRAM calculations, we present brief results here because it is relevant to the broader consideration of landowner decision making and landscape C sequestration. The full text of the survey, together with its complete analysis, was provided by Brunner [36]. Just over half of the respondents (55%) indicated they would either consider maintaining or would definitely maintain their forest to sequester C in exchange for "appropriate" (as worded in the survey) financial compensation. Of those positive responses, 36% said they would definitely sequester C for compensation, while 64% said they would consider doing so. There were 15% of respondents overall who said that compensation for C storage would not affect their decision making related to forest harvest. A portion of respondents (22%) said they needed more information before they would decide whether to manage forests for C storage in exchange for compensation. Finally, 5% said they would not consider maintaining their forest stand to sequester C for compensation. Interestingly, survey responses were significantly and positively correlated among individuals who supported using their forest biomass for cellulosic ethanol production and those that supported using their forest to sequester C [36].

3.2. CEBRAM model

At the 47% participation rate, the EB accounting framework had a system NCB of 0.024 kg/m^2 over 40 years (Table 1). The EB + LU accounting framework at the 47% participation rate had a system NCB of 1.09 kg/m^2 over 40 years (Table 2). This positive value of system NCB in both accounting frameworks indicates that more C was offset or sequestered than was emitted by the biofuel harvest, transport, and conversion system. The much greater positive value (greater by a factor of 45) in the EB + LU framework relative to the EB framework indicates that land management in NIPF owned land contributed a strong positive effect on system NCB when the ecosystem C balance in the simulation area was included in the accounting.

To assess the effect of NIPF owner participation rates on system NCB, we examined CEBRAM simulation results for participation rates ranging from 28% to 88% (Tables 1 and 2; Fig. 3). The high end of the range was based on our survey results, combining the 47% who would be willing to sell some or all of their biomass to the biorefinery with the 41% who responded that they needed more information. The low end of the range was based on the economically feasible transport radius, 161 km (100 miles) [53], which translated into a 28% participation rate in CEBRAM simulations. At the most likely participation rate of 47%, with the mixed land cover in northern Michigan and a realistic growth curve for aspen forest, the simulation area calculated by CEBRAM had a radius of 123 km.

In the EB framework, NIPF owner participation across the full scope considered here contributed to a tripling of the system NCB per unit land area, ranging between 0.014 kg/m^2 for 28% participation to 0.045 kg/m^2 for 88% participation, over 40 years (Table 1). This resulted from two factors that occurred when participation was greater. First, biomass was transported over shorter distances on average, because the biorefinery feedstock demand was met by more NIPF owners located closer to the facility. Second, with the shorter transport distances, the biorefinery feedstock demand was met over a smaller simulation area; it decreased from a radius of 123 km at 47% participation to 90 km at 88% participation. Because we defined and express system NCB on an area normalized basis over the simulation area in each case, the "fixed" emissions such as those associated with chipping and processing the feedstock are divided over a smaller landscape area when NIPF participation is

Table 1
C emissions (negative values) and C gains (positive values) for the biorefinery in the **EB** accounting framework. In this framework, only the hypothetical biorefinery and harvesting, transport, and ethanol processing are included in the system boundary. Ethanol yields total 222 254 m^3/y and gasoline CO_2 emissions from production and combustion total 2.95 Mg/m^3. Values in the table are C measured in kg/m^2 over the entire 40 year time horizon. Landowner participation rates from 0.28 to 0.88 are shown; bold numbers indicate the most likely NIPF owner participation rate, 0.47, as determined by the Private Landowner Forest Decisions Survey 2011.

Landowner participation rate	Forest harvest	Transport and processing	Ethanol production	Displaced gasoline production and combustion	System NCB over 40 years
0.880	−0.011	−0.013	−0.117	+0.187	0.046
0.850	−0.011	−0.013	−0.113	+0.180	0.043
0.800	−0.010	−0.012	−0.106	+0.170	0.042
0.750	−0.010	−0.012	−0.100	+0.159	0.037
0.700	−0.009	−0.011	−0.093	+0.148	0.035
0.650	−0.008	−0.010	−0.086	+0.138	0.034
0.600	−0.008	−0.009	−0.080	+0.127	0.030
0.550	−0.007	−0.009	−0.073	+0.117	0.028
0.500	−0.006	−0.008	−0.066	+0.106	0.026
0.470	**−0.006**	**−0.008**	**−0.062**	**+0.100**	**0.024**
0.450	−0.006	−0.007	−0.060	+0.095	0.022
0.400	−0.005	−0.007	−0.053	+0.085	0.020
0.350	−0.005	−0.006	−0.046	+0.074	0.017
0.300	−0.004	−0.005	−0.040	+0.064	0.015
0.280	−0.004	−0.005	−0.037	+0.059	0.013

Table 2
C emissions (negative values) and C gains (positive values) for the landscape biorefinery system in the **EB + LU** accounting framework. In this framework, the system boundary includes all of the elements of the EB system together with the ecosystem C balance of NIPF owned land in the simulation area. Ethanol yields total 222 254 m^3/y and gasoline CO_2 emissions from production and combustion total 2.95 Mg/m^3. Values in the table are C measured in kg/m^2 over the entire 40 year time horizon. Landowner participation rates from 0.28 to 0.88 are shown; bold numbers are for 0.47 participation rate as in Table 1.

Landowner participation rate	Forest harvest	Transport and processing	Ethanol production	Displaced gasoline production and combustion	Forest C storage	System NCB over 40 years
0.880	−0.011	−0.013	−0.117	+0.187	+0.242	0.288
0.850	−0.011	−0.013	−0.113	+0.180	+0.303	0.346
0.800	−0.010	−0.012	−0.106	+0.170	+0.404	0.446
0.750	−0.010	−0.012	−0.100	+0.159	+0.505	0.542
0.700	−0.009	−0.011	−0.093	+0.148	+0.606	0.641
0.650	−0.008	−0.010	−0.086	+0.138	+0.707	0.741
0.600	−0.008	−0.009	−0.080	+0.127	+0.808	0.838
0.550	−0.007	−0.009	−0.073	+0.117	+0.909	0.937
0.500	−0.006	−0.008	−0.066	+0.106	+1.01	1.04
0.470	**−0.006**	**−0.008**	**−0.062**	**+0.100**	**+1.07**	**1.09**
0.450	−0.006	−0.007	−0.060	+0.095	+1.11	1.13
0.400	−0.005	−0.007	−0.053	+0.085	+1.21	1.23
0.350	−0.005	−0.006	−0.046	+0.074	+1.31	1.33
0.300	−0.004	−0.005	−0.040	+0.064	+1.41	1.43
0.280	−0.004	−0.005	−0.037	+0.059	+1.46	1.47

higher. In this accounting framework in which feedstock source area is considered but not the ecosystem C storage in the source area, greater NIPF participation produces a greater positive system NCB per unit area.

In the EB + LU framework, when C storage in NIPF owned land was included, the relationship between NIPF owner participation and system NCB reversed and became much more pronounced. Higher rates of participation led to significantly *lower* values of system NCB in the integrated biorefinery and landscape system (Table 2). The reason for this was that in our simulations, the magnitude of C sequestration by aggraded forests was much greater than the avoided net C emissions from displaced gasoline combustion (Table 2). Values of system NCB ranged from 1.468 kg/m^2 for 28% participation to 0.287 kg/m^2 for 88% participation over the 40 year period.

A sensitivity analysis was run on the model using one at a time variable adjustment by ±10%, keeping the participation rate steady at 47%. The only independent variable that impacted the NCB of EB + LU was the length of simulation, which yielded an NCB of 1.25 kg/m^2 when increased or 0.940 kg/m^2 when decreased, a change of 15% (Table 3). Several variables caused a change in the NCB for EB, including a variable for: the biomass lost as wood dries, the ethanol produced for every kilogram biomass processed, the C emissions from the biorefinery, the energy in gas relative to the energy in ethanol, and the C emissions from gasoline (Table 4). These last two variables changed the NCB of EB by 42%. By shifting the variable for C emissions from the biorefinery by 10%, the NCB for EB would change inversely by 26%.

4. Discussion

4.1. Cellulosic ethanol

Several previous studies have emphasized the importance of considering land use or land use change and its effects on C accounting when assessing net C emissions related to biofuel production. Melillo et al. [54] used a combination of economic and terrestrial bioscience models to predict the impact of future potential expansion of biofuel production. As anticipated demand for biofuels increased it was predicted that unused, forested land would be converted for biofuel production. Searchinger et al. [11] calculated that gasoline production would emit more C per MJ over 30 years than biomass based ethanol over the same period of time. However, when indirect land use change was included, the

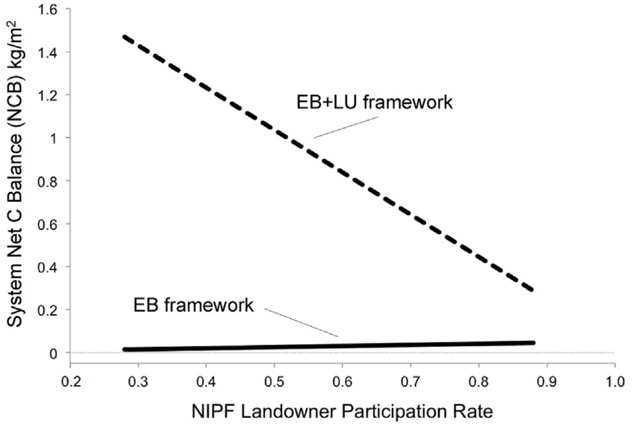

Fig. 3. System NCB (Net Carbon Balance) for a hypothetical biorefinery in northern Michigan under different rates of nonindustrial private forest (NIPF) owner participation in sales of biomass to the biorefinery. A higher positive value for system NCB indicates more C is offset or sequestered. Two accounting methods were contrasted: Energy Balance (EB) and Energy Balance and Land Use (EB + LU). The EB accounting framework shows a small positive value of net C independent of NIPF owner participation. The EB + LU accounting framework shows higher system NCB, which is greater when fewer NIPF owners participate. When C associated with land use is included (EB + LU), lower NIPF owner participation in forest harvest allows forest land to be taken out of the harvest rotation, sequestering C at a greater rate.

Table 3

Changes to net C balance (NCB) under the **EB + LU** accounting framework when individual model variables are increased or decreased by 0.1. In this framework, the system boundary includes all of the elements of the EB system together with the ecosystem C balance of NIPF owned land in the simulation area. Values in the table for NCB are C measured in kg/m^2 over the entire 40 year time horizon. Change indicates the percent change between the original NCB of 1.09 kg/m^2 and the NCB of the one at a time variable adjustment sensitivity analysis; values in the change column are unitless. All NCB values were calculated using a 0.47 participation rate, the most likely NIPF owner participation rate as determined by the Private Landowner Forest Decisions Survey 2011. Bold information indicates where sensitivity analysis NCB changed by more than 0.1. Negative change values indicate an inverse relationship between the direction of variable change and the change in NCB value.

Variable changed	Increased 10%		Decreased 10%	
	NCB	Change	NCB	Change
Biorefinery biomass limit	1.09	0.00	1.09	0.00
Wet to dry biomass converter	1.10	0.00	1.09	0.00
Wet biomass to forest area converter	1.10	0.00	1.09	0.00
Percent merchantable biomass	1.10	0.00	1.09	0.00
Length of forest rotation period	1.13	0.03	1.06	−0.03
Percent of forest owned by NIPF	1.20	0.10	0.98	−0.10
Energy used to process wet biomass	1.09	0.00	1.09	0.00
CO2 emissions from diesel by energy	1.09	0.00	1.10	0.00
Road tortuosity	1.09	0.00	1.09	0.00
Truck weight limit	1.09	0.00	1.09	0.00
Truck fuel efficiency, empty	1.09	0.00	1.09	0.00
Truck fuel efficiency, full	1.09	0.00	1.09	0.00
CO2 from diesel by cubic meter	1.09	0.00	1.09	0.00
Energy to load trucks	1.09	0.00	1.09	0.00
Energy to unload trucks	1.09	0.00	1.09	0.00
Energy to run biomass chipper	1.09	0.00	1.09	0.00
Ethanol production rate	1.10	0.00	1.09	0.00
CO2 from ethanol production	1.09	−0.01	1.10	0.01
MJ gas compared to MJ ethanol	1.10	0.01	1.08	−0.01
CO2 from gasoline	1.10	0.01	1.08	−0.01
C sequestered by area forest	1.20	0.10	0.99	−0.10
Length of simulation	**1.26**	**0.15**	**0.94**	**−0.14**
CO2 to C converter	1.10	0.00	1.09	0.00

Table 4

Changes to net C balance (NCB) under the **EB** accounting framework when individual model variables are increased or decreased by 0.1. In this framework, only the hypothetical biorefinery and harvesting, transport, and ethanol processing are included in the system boundary. Values in the table for NCB are C measured in kg/m^2 over the entire 40 year time horizon. Change indicates the percent change between the original NCB of 0.024 kg/m^2 and the NCB of the one at a time variable adjustment sensitivity analysis; values in the change column are unitless. All NCB values were calculated using a 0.47 participation rate, the most likely NIPF owner participation rate as determined by the Private Landowner Forest Decisions Survey 2011. Bold information indicates where sensitivity analysis NCB changed by more than 0.1. Negative change values indicate an inverse relationship between the direction of variable change and the change in NCB value.

Variable changed	Increased 10%		Decreased 10%	
	NCB	Change	NCB	Change
Biorefinery biomass limit	0.023	0.00	0.024	0.00
Wet to dry biomass converter	**0.027**	**0.14**	**0.020**	**−0.14**
Wet biomass to forest area converter	0.026	0.10	0.021	−0.10
Percent merchantable biomass	0.026	0.10	0.021	−0.10
Length of forest rotation period	0.021	−0.09	**0.026**	**0.12**
Percent of forest owned by NIPF	0.026	0.10	0.021	−0.10
Energy used to process wet biomass	0.023	−0.03	0.024	0.03
CO2 emissions from diesel by energy	0.022	−0.05	0.025	0.05
Road tortuosity	0.023	−0.01	0.024	0.01
Truck weight limit	0.024	0.01	0.023	−0.01
Truck fuel efficiency, empty	0.023	0.00	0.024	0.00
Truck fuel efficiency, full	0.023	0.00	0.024	0.00
CO2 from diesel by cubic meter	0.023	−0.01	0.024	0.01
Energy to load trucks	0.024	0.00	0.024	0.00
Energy to unload trucks	0.024	0.00	0.024	0.00
Energy to run biomass chipper	0.023	−0.02	0.024	0.02
Ethanol production rate	**0.027**	**0.16**	**0.020**	**−0.16**
CO2 from ethanol production	**0.017**	**−0.26**	**0.030**	**0.26**
MJ gas compared to MJ ethanol	**0.034**	**0.42**	**0.014**	**−0.42**
CO2 from gasoline	**0.034**	**0.42**	**0.014**	**−0.42**
C sequestered by area forest	0.024	0.00	0.024	0.00
Length of simulation	0.026	0.10	0.021	−0.10
CO2 to C converter	0.026	0.10	0.021	−0.10

calculated net C emissions were increased by as much as 50% relative to gasoline combustion [11]. Similarly, Liu et al. [14] concluded that C emissions from biofuel production and associated land use change were greater than the C offset from displacing fossil fuels. Numerous additional studies have concluded that the direct or indirect effects of land use change on C balance was significant and merited inclusion in analyses of the C balance of systems proposed for the production of cellulosic ethanol [10,53–57].

Our EB + LU framework shows that at lower rates of participation greater values of system NCB were realized. This calculation included the impact cellulosic ethanol production had on C at the biorefinery level as well as the C impact from aggraded forest on NIPF owned land. The EB + LU framework revealed that NIPF owner decisions do not just impact the net C balance of the biorefinery by determining the distance of biomass transport. Decisions by forest owners have a much larger impact on system NCB by choosing whether to harvest their trees. Our results indicate that such alternative options should be included and examined as opportunity costs for C sequestration in more bioenergy systems studies. DeCicco [58] concludes that replacing fossil fuels with biofuels is not nearly as immediate or effective at reducing NCB than terrestrial carbon management would be. Our model results agree, showing that much more C could be sequestered in aggrading forests than could be offset by the combined production of ethanol fuel and its use to displace gasoline. We recognize that other goals are sometimes given for the growth of the renewable fuel industry in the USA, including energy security and supporting local economies through forestry and agriculture, whereas our analysis only considers system C balance. We also recognize that our analysis presents a highly simplified case that examines only one contrasting pair of management options in one type of forest in the region.

The results from the sensitivity analysis indicate that the calculated NCB for EB + LU is only sensitive to changes to the length of the simulation (Table 3). This impact from changing the length of the simulation is due to the direct connection between the age of aggraded trees and the amount of C sequestered in the landscape. Changing the time horizon over which the simulation is run could have an impact on a landscape level analysis, increasing positive NCB as more time passes, or decreasing it as less time passes. The EB accounting framework is not sensitive to changes in the length of the simulation.

The two variables that had the most impact on the NCB calculation for EB were energy in gas relative to the energy in ethanol and the C emissions from gasoline (Table 4). Both of these variables come from reliable sources, suggesting a 10% change to either value in either direction is unlikely. The relative energy in gasoline when compared to ethanol comes from comparing two fuels on an energy basis [51], while the calculation for C emissions in gasoline comes from the GREET model, put out by the Argonne National Laboratory [42].

The NCB under the EB account framework is sensitive to the variable concerning the C emissions from biorefinery production (Table 4). These emissions would arguably shift depending on the kind of technology used to process cellulose, so a change in NCB is quite possible. The numbers used for this variable come from peer-reviewed sources [20,23,39], but a change in technology or an error in the number could alter the NCB in the EB accounting framework in either direction. The NCB under the EB account framework is also sensitive to the dry/wet biomass converter, a variable that relies on the assumption that wet biomass contains 40% moisture and dry biomass contains 7%. Controlling the moisture in biomass through air drying is not precise, so this variable could have an impact on the certainty of the NCB outcome under the EB accounting framework. Biomass moisture content can easily be controlled with the use of a kiln to dry out the wood, but this was kept out of the current analysis to simplify the parameters of the model. Using a kiln would assure the biomass moisture content, but it would use a form of energy, so the NCB would likely decrease [59]. A change to any one of these sensitive variables does not change the trends observed in either EB or EB + LU, but could impact the value for NCB.

4.2. *Nonindustrial private forest owner opinions*

Our survey indicates that interest in using biomass to make cellulosic ethanol is around 47% among NIPF owners enrolled in Michigan's Commercial Forest Program. Those surveyed are likely to have a more favorable view towards harvest than overall NIPF owners, and in conjunction may feel more comfortable with harvest for cellulosic ethanol [36,60]. Given the differences in attitudes towards timber management between NIPF owners at large and those who completed the landowner survey, overall NIPF owner interest in cellulosic ethanol timber harvest may be lower [45,53,61,62]. On the other hand, 41% of our survey respondents wanted more information before deciding whether they would harvest their biomass for feedstock, suggesting that actual participation could be also higher.

Many of our survey respondents indicated support both for harvesting their forest biomass to supply biofuel feedstock and for using their forest land for C sequestration [36]. By showing that these goals can be contradictory in the case study we analyzed here, our analysis is directly relevant to the decision-making by these households as well as decision-making by public land managers who may be considering the dual goals of providing feedstock and managing landscape net C balance. In reality these landowners and decision makers have a greater variety of management options that we did not consider here, but that it would be worthwhile to explore using carbon accounting frameworks. All models are simplifications, but a question to ask is whether a model embodies a useful set of simplifications for analysis of a particular issue. This study produced the useful result that, in assessing system NCB where the landscape is considered part of the system, in intensively managed early-successional forests in this region, forest aggradation should be considered as a baseline against which to compare C sequestration options. Landowner and manager decisions to harvest also affect the amount of feedstock supplied per unit radius of land, impacting the efficiency and scale of biorefineries, information that is also useful to utilities and energy planning. Finally, the mandates under the Energy Independence and Security Act of 2007 [1] have increased interest in cellulosic ethanol production, further increasing the importance of understanding the carbon-balance implications of choices and activities of landowners and forest managers.

5. Conclusions

In Michigan, the willing participation rate of NIPF owners to harvest trees as a feedstock for cellulosic ethanol was quantified to be 47%. At this rate, over a 40 year period, the cellulosic ethanol biorefinery has a positive system NCB of 0.024 kg/m^2, when averaged over the feedstock source area but not including ecosystem C balance in the source area landscape (Table 1). Our sensitivity analysis revealed that changes to biorefinery technology and the energy needed to control moisture content could impact the calculated NCB. When C accounting included the biorefinery and source area landscape as an integrated system, including ecosystem processes that determine C storage, there was a much greater system NCB at 47% participation, with 1.09 kg/m^2 gained over a 40 year period (Table 2). This higher rate of C sequestration resulted primarily from the aggradation of C stocks in short-rotation aspen forests of NIPF owners who chose *not* to participate in the harvest of forest biomass.

Many of the assumptions made in the CEBRAM model were used to simplify the complexity of the analysis of a combined biorefinery land use system at the landscape scale. This analysis should be viewed as providing insight into a particular, typical forest stand type and set of silvicultural and management practices in the region. In reality, the forested landscapes of northern Michigan are more heterogeneous and there is a much greater range of management practices. Even among NIPF owners, there is a range of forest types and ages, as well as management practices and harvest regimes. Future work could involve increasing the complexity of land use choices represented in CEBRAM, specifying and diversifying the types of forestry products used to make cellulosic ethanol, or focusing on which silvicultural management techniques produce the greatest NCB. Of further benefit to this body of research would be a place-based model that accounted for a broader heterogeneity in forest types and management practices when assessing the NCB of an industrial biorefinery. An analysis with such a level of landscape realism and specificity is outside the scope of this study.

Our results show that partial participation in the heterogeneous population of NIPF owners produces a compromise: a biorefinery can meet its feedstock needs within a realistic landscape radius while the decisions not to participate, made by many forest landowners in our model (informed by a stakeholder survey), significantly raise the landscape C storage. If NIPF owners care more about limiting net C emissions than about how that is accomplished, then using their forest land to sequester C would be more effective than harvesting their forests for conversion to cellulosic ethanol. While biorefineries in Michigan are likely to have a positive net C balance, much greater rates of C sequestration can be realized in short-rotation aspen forests by taking NIPF owned forests out of rotation harvesting and allowing them to build higher ecosystem C stocks over time through forest growth.

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Appendix A. Supplementary material

Supplementary material related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2015.08.002.

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