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Carbon debt and carbon sequestration parity in forest bioenergy production

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Abstract

The capacity for forests to aid in climate change mitigation efforts is substantial but will ultimately depend on their management. If forests remain unharvested, they can further mitigate the increases in atmospheric CO_2 that result from fossil fuel combustion and deforestation. Alternatively, they can be harvested for bioenergy production and serve as a substitute for fossil fuels, though such a practice could reduce terrestrial C storage and thereby increase atmospheric CO_2 concentrations in the near-term. Here, we used an ecosystem simulation model to ascertain the effectiveness of using forest bioenergy as a substitute for fossil fuels, drawing from a broad range of land-use histories, harvesting regimes, ecosystem characteristics, and bioenergy conversion efficiencies. Results demonstrate that the times required for bioenergy substitutions to repay the C Debt incurred from biomass harvest are usually much shorter (< 100 years) than the time required for bioenergy production to substitute the amount of C that would be stored if the forest were left unharvested entirely, a point we refer to as C Sequestration Parity. The effectiveness of substituting woody bioenergy for fossil fuels is highly dependent on the factors that determine bioenergy conversion efficiency, such as the C emissions released during the harvest, transport, and firing of woody biomass. Consideration of the frequency and intensity of biomass harvests should also be given; performing total harvests (clear-cutting) at high-frequency may produce more bioenergy than less intensive harvesting regimes but may decrease C storage and thereby prolong the time required to achieve C Sequestration Parity.

Keywords: bioenergy, biofuel, C cycle, C sequestration, forest management

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Introduction

The search for alternatives to fossil fuel energy has yielded several possibilities, many of which are derived from biomass. Bioenergy has been viewed as a promising alternative to fossil fuels because of its capacity to increase the energy security in regions that lack petroleum reserves and because their production and combustion does not require a net transfer of C from Earth's lithosphere to its atmosphere. While bioenergy is understandably among the most heavily promoted and generously subsidized sources of renewable energy, recent research has brought greater attention to the environmental costs of broad-scale bioenergy production (Fargione *et al*., 2008; Searchinger *et al*., 2008, 2009) as well as the limits of how much energy it can actually produce (Field *et al*., 2008).

One alternative to crop-based biofuels is woody biomass harvested directly from forests, an avenue thought to be more promising than harvesting non-woody species for a variety of reasons. First, woody biomass stores more potential energy per unit mass than non-woody biomass (Boundy *et al*., 2011). Second, many forms of non-woody biomass are often utilized following a lengthy conversion process to ethanol or biodiesel, a process which results in a significant loss of potential energy of the harvested biomass (Field *et al*., 2008) as well as additional energy that may be expended in the conversion process itself (Walker *et al*., 2010). By contrast, woody biomass is more readily utilized for energy production without any further modifications (Richter *et al*., 2009). Third, landscapes managed for bioenergy production using woody biomass are able to store more C per unit of land area than crop-based biofuels.

Woody biomass is already a primary source of energy for 2 billion people; the FAO estimates that over half of the world's total round wood removals from forests and trees outside forests are intended for bioenergy production (FAO; Parikka, 2004). Many of these harvests are specifically intended to provide a C-neutral energy source to substitute for fossil fuels (Parikka, 2004; Richter *et al*., 2009; Buford & Neary, 2010), yet such harvests can arrest the C sequestration of many forests far short of their full potential (Harmon *et al*., 1990; Canadell & Raupach, 2008; Pan *et al*., 2011). Much of the world's

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forested land area stores far less C than it potentially could (House *et al.*, 2002; Canadell & Raupach, 2008), and foregoing future harvest/s could provide a more rapid amelioration of atmospheric CO_2 then bioenergy production. A recent study conducted in US West Coast forests examined the C storage/bioenergy production trade-offs of many ecosystems and found that the current C sink for most ecosystems is so strong that it cannot be matched or exceeded through substitution of fossil fuels by forest bioenergy over the next 20 years. However, due to its reliance on existing field data instead of simulation models, it could not extrapolate these results beyond the 20-year period (Hudiburg *et al.*, 2011). Another recent study that addressed these trade-offs is the so-called 'Manomet' study, which modeled bioenergy production systems for different forest types in Massachusetts and found that utilizing forests for bioenergy production reduces C storage without providing an equitable substitution in the near-term (Walker *et al.*, 2010). However, the approach taken by the 'Manomet' study dealt short-term repayment in C Debts at the stand level, while our approach focuses on the C Debt that is incurred as a result harvesting forests for bioenergy production over the long-term at the landscape level. We provide further description of our concept of C Debt *sensu* Fargione *et al.* (2008) by contrasting it with what we refer to as the C Sequestration Parity, which we outline in the discussion below.

Carbon debt

Compared to fossil fuels, woody biomass yields a lower amount of energy per unit mass of C emitted. Since biomass harvesting reduces C storage but does not produce the same amount of energy that would be obtained from an equal amount of C emissions from fossil fuel combustion, recouping losses in C storage through bioenergy production may require many years. We refer to this recoupment as the *C Debt Repayment*, calculated as the change in C storage resulting from bioenergy harvests and associated C substitution, demonstrated in Fig. 1. A mathematical representation is given below in Eqn (1), where $C^{m}_{storage(t)}$ is the amount of C stored in a managed forest at time t, $C^{m}_{storage(0)}$ is the amount of C stored in a managed forest at $t = 0$ (before bioenergy harvests have begun), and $C^{m}_{harvest(t)}$ is the amount of C biomass harvested from a managed forest at time t, which is multiplied by the bioenergy conversion factor $\eta_{biomass}$:

$$C^{m}_{debt(t)} = C^{m}_{storage(t)} - C^{m}_{storage(0)} - \sum_{t=1}^{n} C^{m}_{harvest(t)} \times \eta_{biomass} \quad (1)$$

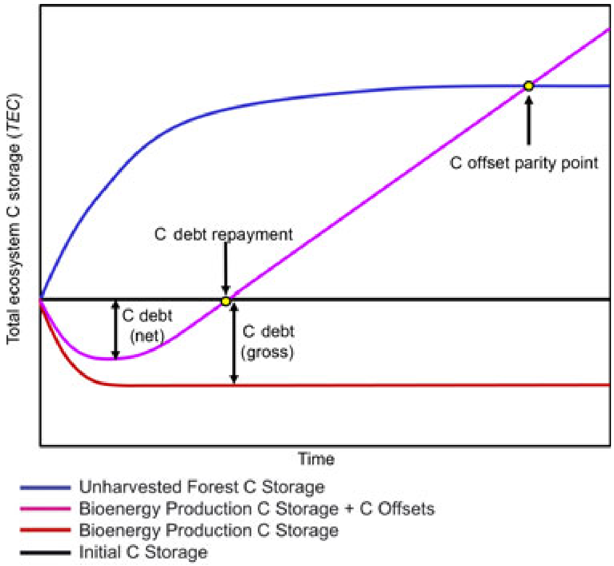

Fig. 1 Conceptual representation of C Debt Repayment vs. the C Sequestration Parity Point. C Debt (Gross) is the difference between the initial C Storage and the C storage of a stand (or landscape) managed for bioenergy production. C Debt (Net) is C Debt (Gross) + C substitutions resulting from bioenergy production.

Carbon sequestration parity

A repayment of the C Debt does not necessarily imply that the forest has been managed for maximal amelioration of atmospheric CO_2. If a forest is managed for the production of bioenergy to substitute for traditional fossil fuel energy as part of an effort to ameliorate atmospheric CO_2 concentrations, such a strategy should be gauged by the climate change mitigation benefits that would accrue by simply leaving the forest unharvested. Ascertaining the point at which a given strategy provides the maximal amount of climate change mitigation benefits requires accounting for the amount of biomass harvested from a forest under a given management regime, the amount of C stored under a given management regime, and the amount of C that would be stored if the forest were to remain unharvested (Schlamadinger & Marland, 1996a,b,c; Marland & Schlamadinger, 1997; Marland *et al.*, 2007). It is expected that a forest that is continuously managed for bioenergy production will eventually produce enough bioenergy to 'recoup' the associated loss in C storage (the so-called carbon debt) through the substitution of bioenergy for fossil fuel energy. However, the ultimate effectiveness of this strategy should be determined by the amount of time required for the sum of the total ecosystem C storage and bioenergy C substitution to exceed the amount of C that would be stored if that same forest were to remain unharvested (Fig. 1). We refer to this difference as the C sequestration differential ($C^{m}_{differential(t)}$), illustrated in Eqn (2) below:

$$C^{m}_{differential(t)} = C^{u}_{storage(t)} - C^{m}_{storage(t)} - \sum_{t=1}^{n} C^{m}_{harvest(t)} \times \eta_{biomass} \quad (2)$$

where $C^{u}_{storage(t)}$ is the amount of C stored in an *unmanaged* forest at time *t*. We refer to the crossing of this threshold as the point of *C Sequestration Parity*. Thus, we make a distinction between the amount of time required for the bioenergy production system to recoup any reductions in C storage resulting from bioenergy production (C Debt repayment) and the amount of time required for the bioenergy production system to equal the C than would be stored if the forest were to remain unharvested (C Sequestration Parity Point), as the latter represents a more ambitious climate change mitigation strategy (Fig. 1).

Materials and methods

We simulated the growth and harvest of woody biomass using a significantly updated version of the ecosystem simulation model LANDCARB (Harmon, 2012). LANDCARB is a landscape-level ecosystem process model that can simulate a full spectrum of potential harvesting regimes while tracking the amount of material harvested, allowing one to simulate ecosystem C storage while tracking the amount of fossil fuel C that could be substituted by using harvested materials as biomass fuels. LANDCARB integrates climate-driven growth and decomposition processes with species-specific rates of senescence and mortality while incorporating the dynamics of inter- and intra-specific competition that characterize forest gap dynamics. Inter- and intra-specific competition dynamics are accounted for by modeling species-specific responses to solar radiation as a function of each species' light compensation point and assuming light is delineated through foliage following a Beer-Lambert function. By incorporating these dynamics the model simulates successional changes as one life-form replaces another, thereby representing the associated changes in ecosystem processes that result from species-specific rates of growth, senescence, mortality, and decomposition.

LANDCARB represents stands on a cell-by-cell basis, with the aggregated matrix of stand cells representing an entire landscape. Each cell in LANDCARB simulates a number of cohorts that represent different episodes of disturbance and colonization within a stand. Each cohort contains up to four layers of vegetation (upper tree layer, lower tree layer, shrub, and herb) that each have up to seven live pools, eight dead pools, and three stable pools. For example, the upper and lower tree layers are comprised of seven live pools: foliage, fine-roots, branches, sapwood, heartwood, coarse-roots, and heart-rot, all of which are transferred to the appropriate dead pool following mortality. Dead sapwood and dead heartwood can be either standing or downed to account for the different microclimates of these positions. Dead pools in a cell can potentially contribute material to three, relatively decay-resistant, stable C pools: stable foliage, stable wood, and stable soil. There are also two pools representing charcoal (surface and buried).

Our modeling approach with LANDCARB was designed to account for a broad range of ecosystem characteristics and initial landscape conditions of a forest, both of which are influential in determining rate of C debt repayment and the time required for C sequestration parity. Forests with high productivity can generate fossil fuel substitutions more rapidly than forests with low productivity. Conversely, forests with high-longevity biomass raise the C storage of the ecosystem (Olson, 1963), which has implications for C debt and C sequestration parity. Furthermore, forests can contain a wide range of C stores even within a fixed range of productivity and C longevity (i.e., lower rates of mortality and decomposition; Smithwick *et al*., 2007), yet we know of no study to date that has examined the impact of forest productivity and biomass longevity on C Debt repayment or C Sequestration Parity. Furthermore, we know of no previous study that examines a sufficiently large range of forest management strategies and land-use histories to ascertain exactly what sort of situation/s might provide for an efficient utilization of forest biomass for bioenergy production.

To provide a more comprehensive evaluation of the effectiveness of utilizing forest bioenergy as a substitute for fossil fuels, we performed our analysis across a wide range of ecosystem properties by simulating three levels of forest growth and three levels of biomass longevity, resulting in nine distinct ecosystems (Table 1). Levels of longevity were drawn from published rates of bole growth efficiency, mortality, and decomposition (growth and biomass Harmon *et al*., 2005). The upper and lower bounds of these parameters were intended to cover the range of these processes for most of the world's temperate forests. Our parameters are largely drawn from forests of the US Pacific Northwest, but the extreme values of bole growth efficiency, mortality, and decomposition could be considered extreme values of other forests as well, thereby giving our results maximal applicability.

We ran each of our nine simulated ecosystems under four sets of initial landscape conditions: afforesting post-agricultural land (age = 0), forest recovering from a severe disturbance (age = 0), old-growth forest (age > 200 years), and a forest harvested on a 50-year rotation (mean age ~25 years). Each combination of ecosystem characteristics and land-use history was simulated with seven different management strategies (Table 2), which included one unharvested control group as well as three biomass harvest frequencies (25, 50, 100 years) applied at two different harvest intensities (50% harvest of live stems, 100% harvest of live stems). We assumed that our post-agricultural landscape did not have any legacy C storage apart from a small amount of soil C, thus our post-agricultural simulation did not have any spin-up simulation. However, simulations of the other land-use histories all had a 500-year spin-up simulation were run to establish initial live, dead, and soil C stores. Additionally, for the two simulations that were recovering from harvests and prior disturbance (recently disturbed and rotation forest) we tracked the respective C stores from these events. To simulate a landscape that had previously been harvested on a 50-year rotation, we simulated an annual clearcut on 2% of the landscape throughout the 50 years prior to the

Table 1 Table of selected growth, mortality, and decomposition characterstics for each of our nine ecosystems. Classifications G1, G2, and G3 represent increasing growth rates, represented by the Site Index. L1, L2, and L3 represent increasing biomass longevities. The group with the lowest potential C storage had the lowest growth rate (G1) combined with the highest rates of mortality and decomposition that yielded the lowest rates of biomass longevity (L1). The upper and lower bounds of our rates of growth and longevity were intended to cover the range of these processes for most of the world's forests, thereby giving our results maximal applicability. Thus, the group referred to as G1-L1 is the group with the lowest potential C storage, while the group referred to as G3-L3 has the highest potential C storage. Also note that L1 and L3 values represent extreme values of mortality and decomposition, whereas L2 represents a median value, rather than a midpoint between L1 and L3. $\text{Mortality}_{\text{MAX}}$ is the maximum rate of mortality, while k_{Foliage} and $k_{\text{Heartwood}}$ are decomposition constants for foliage and heartwood. Potential C Storage is the mean amount of C storage of an old-growth stand under these characteristics, as measured over a 500 year interval

Group	Bole growth efficiency +ΔMg Stem C/+ΔMg Leaf C)	$\text{Mortality}_{\text{MAX}}$ (yr^{-1})	k_{Foliage} (yr^{-1})	$k_{\text{Heartwood}}$ (yr^{-1})	Potential C storage (Mg C ha^{-1})
G1-L1	0.35	0.03	0.25	0.1	212
G1-L2	0.35	0.02	0.2	0.02	230
G1-L3	0.35	0.01	0.15	0.01	296
G2-L1	0.54	0.03	0.25	0.1	359
G2-L2	0.54	0.02	0.2	0.02	492
G2-L3	0.54	0.01	0.15	0.01	621
G3-L1	0.84	0.03	0.25	0.1	645
G3-L2	0.84	0.02	0.2	0.02	757
G3-L3	0.84	0.01	0.15	0.01	954

Table 2 List of all bioenergy production system characteristics simulated. We incorporated four land-use histories, three levels of biomass accumulation, three levels of biomass longevity, three different harvest frequencies and two levels of harvest intensity

Land-use histories	Growth rates	Biomass longevities	Harvest frequencies	Harvest intensities
Post-agricultural (age = 0)	G1*	L1*	100 (100Y)	50% (050H)
Recently disturbed (age = 0)	G2*	L2*	50 (50Y)	100% (100H)
Rotation forest (age ~25)	G3*	L3*	25 (25Y)	
Old-growth (age > 200)				

*See Table 1 for details.

completion of the spin-up. In accordance with a prior framework for harvested C decomposition, we assumed that 60% of the harvested C would go directly into long-term C storage mediums (i.e., houses, buildings) that decayed at the rate of 1% per year (Harmon & Marks, 2002). The remaining 40% of the harvested C was assumed to be lost to the atmosphere during manufacturing (Harmon & Marks, 2002). Landscapes were first harvested for bioenergy production in the year following the completion of the spin-up.

Initial conditions of our disturbed forest were analogous to those of a severe pine beetle outbreak. To simulate this condition, we initiated a total mortality of all trees at the end of the spin-up, prior to the biomass harvests. We then simulated an annual salvage logging on 5% of the landscape for each of the 5 years following the simulated pine-beetle disturbance (25% of the landscape was salvage logged). We assumed that 75% of all salvageable biomass was removed in each salvage logging. Salvageable materials harvested in the first 5 years following disturbance were assumed to be stored in wood products and subject to the same decomposition scheme outlined above for the 50-year Rotation Harvest. Such conditions are fairly similar to those in a landscape subject to a high-severity, stand-replacing wildfire, though a landscape subject to a pine beetle infestation will initially have more C storage than one experiencing a high-severity wildfire. However, this difference is temporary and would have a minimal effect on the long-term effects of biomass harvesting, thus this set of initial conditions could also be considered as a proxy for the initial conditions that would follow a high-severity wildfire.

Wildfire

Our analysis also incorporates wildfires in all simulations, not only because they are naturally occurring phenomena in many forest ecosystems, but also because amount of harvestable biomass in an ecosystem can be altered by the event of wildfire, which needs to be accounted for. In the LANDCARB model, fire severity controls the amount of live vegetation killed and the amount of combustion from the various C pools, and is influenced by the amount and type of fuel present. Fires can increase (or decrease) in severity depending on how much the weighted fuel index a given cell exceeds (or falls short of) the fuel level thresholds for each fire severity class (T_{light}, T_{medium}, T_{high}, and T_{max}) and the probability values for the increase or decrease in fire severity (P_i and P_d). For example, a low-severity fire may increase to a medium-severity fire if the fuel index

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sufficiently exceeds the threshold for a medium-severity fire. Fuel level thresholds were set by monitoring fuel levels in a large series of simulation runs where fires were set at very short intervals to see how low fuel levels needed to be to create a significant decrease in expected fire severity.

The fire regime for low-growth forests (G1) is characterized by a low-severity, high frequency fire regime, with a mean fire return interval (MFRI) of 16 years (Bork, 1985), similar to the fire regime in a Ponderosa pine forest, also a low-growth rate forest. Fire regimes for the medium and high-growth forests (G2, G3) consisted of high-severity, low frequency (MFRI = 250 years) fire regimes, similar to that of a Douglas-fir or Sitka spruce forest (Cissel *et al.*, 1999). We generated exponential random variables to assign the years of fire occurrence (Van Wagner, 1978) based on literature estimates (Bork, 1985) for mean fire return intervals (MFRI) for each ecosystem. The cumulative distribution for our negative exponential function is given in Eqn (1) where X is a continuous random variable defined for all possible numbers x in the probability function P and λ represents the inverse of the expected time for a fire return interval given in Eqn (2).

$$P\{X \le x\} = \int_0^x \lambda e^{-\lambda x} \mathrm{d}x \qquad (1)$$

where

$$E[X] = \frac{1}{\lambda} \qquad (2)$$

Fire severities in each year generated by this function are cell-specific, as each cell is assigned a weighted fuel index calculated from fuel accumulation within that cell and the respective flammability of each fuel component, the latter of which is derived from estimates of wildfire-caused biomass consumption.

Bioenergy conversion factors

Previous studies on the mitigation potential of bioenergy have yielded conflicting conclusions about the potential for bioenergy production from woody biomass (Schlamadinger & Marland, 1996a,b,c; Marland & Schlamadinger, 1997; Marland *et al.*, 2007; Walker *et al.*, 2010). Differences in these conclusions are due, in part, to the different assumptions regarding the efficiency of bioenergy utilization. Energy is required for transporting biomass and powering bioenergy conversion facilities, and some is lost due to inefficiencies in the conversion process (Hamelinck *et al.*, 2005; Walker *et al.*, 2010). Thus, it is difficult to provide a one-size-fits-all estimate of bioenergy conversion efficiency. Rather than using one value, we will evaluate a range of bioenergy conversion efficiencies, ranging from 0.2 to 0.8, to ascertain the sensitivity of C offsetting schemes to the range in variability in the energy conversion process. We estimate the *average* bioenergy conversion factor for woody biomass ($\eta_{biomass}$) to be 0.51, meaning that harvesting 1 Mg of biomass C for bioenergy production will substitute for 0.51 Mg fossil fuel C since less energy per unit C emissions is obtainable from biomass compared to fossil fuel. Calculations for this conversion factor ($\eta_{biomass}$) are in the Supporting Information. A conversion factor of 0.8 represents a highly efficient utilization of bioenergy, though such a conversion efficiency is likely not realistic. Conversely, a conversion factor of 0.2 represents a highly inefficient method of energy utilization, though some bioenergy facilities and conversion processes do operate at this low level of efficiency (Walker *et al.*, 2010).

We ran our analysis across 252 distinct scenarios, as we had nine distinct ecosystems (based on three levels of forest growth for three levels of biomass longevity), four initial types of initial landscape conditions, and seven treatment groups (one control, plus three treatment frequencies applied at two levels of intensity). Output from the 252 distinct modeling scenarios was analyzed using seven different bioenergy conversion factors, meaning that our analysis had 1764 combinations of ecosystem properties, initial landscape conditions, harvest frequencies, and bioenergy conversion factors. Our analysis quantifies the degree to which the harvesting and utilization of forest-derived bioenergy alters the landscape-level C storage and bioenergy production in order to calculate (1) the time required for the C mitigation benefits accrued by forests managed for bioenergy production to repay the C Debt incurred from the harvest, and (2) the time required for the C mitigation benefits accrued by forests managed for bioenergy production to achieve C Sequestration Parity, the point at which the sum of forest C storage and bioenergy C substitution equals or exceeds the C mitigation benefits of a comparable forest that remained unharvested.

Results

Times required for repayment of the carbon debts

Most Post-Agricultural landscapes repaid their C debts within 1 year because their initial live C storages were low to begin with and did not require any waiting period for the repayment of their C Debt (Fig. 2). Thus, by undergoing a conversion from a Post-Agricultural landscape to a bioenergy production landscape, there was a repayment of the C Debt as well as an increase in landscape C storage. Similarly, Rotation Harvest landscapes harvested for bioenergy production every 100 years increased their C storage, as they were previously harvested at a frequency of 50 years. Most of the Rotation Harvest landscapes repaid their C Debt in a year due to their initially low live C storage, as their average stand age is ~25 years. However, some of these landscapes that were clear-cut every 50 or 25 years required much longer to repay their C Debt. Harvesting with greater frequency and intensity lowers C storage and prolongs the time needed for repayment of the C Debt; clear-cut harvests performed on Rotation Harvest landscapes every 25 years required 100 to over 1000 years to repay their C Debt. Once a landscape requires several years to repay its C Debt, it may then exhibit sensitivity to the bioenergy conversion efficiencies used to calculate rate at which it can substitute for C emissions from fossil

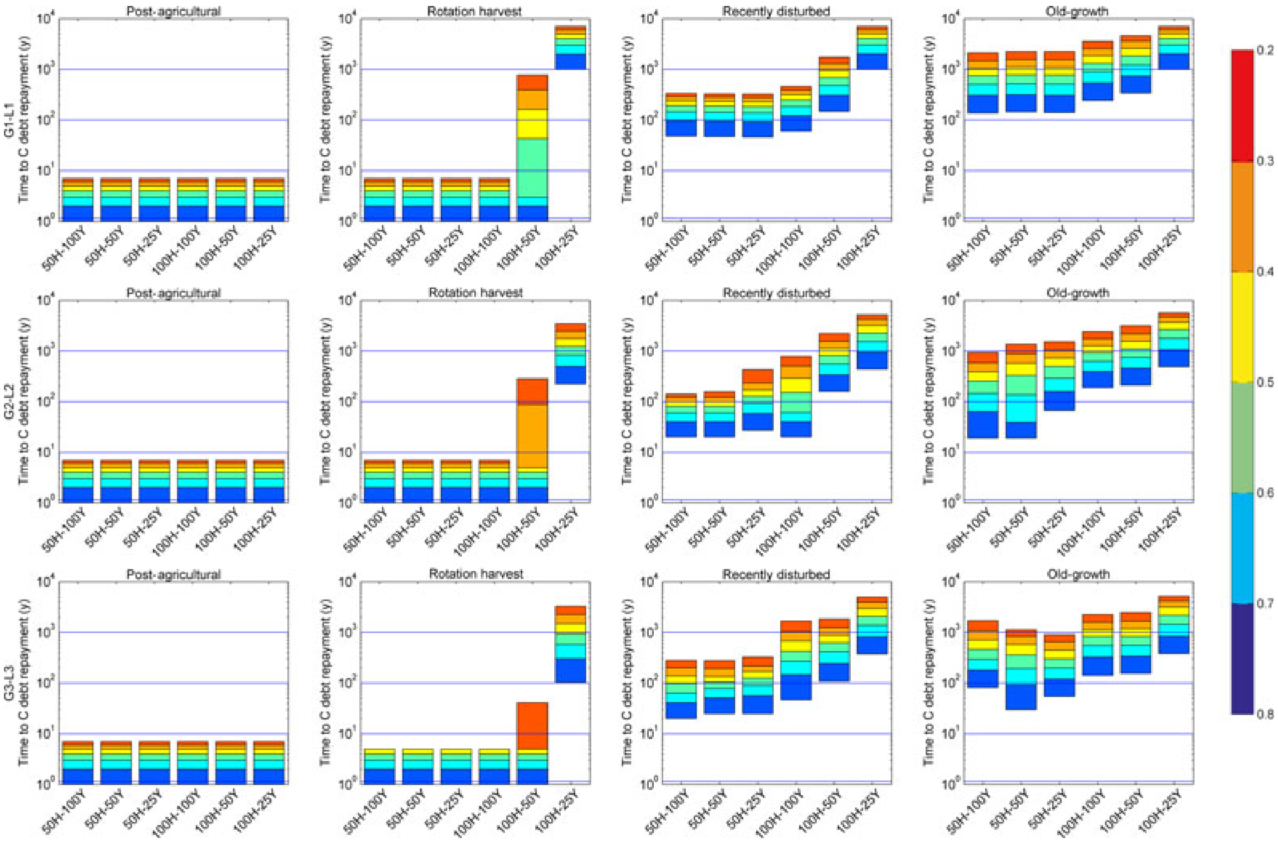

Fig. 2 Comparisons of the time required for a repayment of the C Debt Repayment among three of our nine ecosystem types, each with six biomass harvesting regimes and four land-use histories. Note that times are represented on a log scale. Different harvesting regimes are indicated on the *x*-axis, with 50% and 100% harvesting intensity represented as 50H and 100H, respectively. Harvest frequencies of 25, 50, and 100 years are represented as 25Y, 50Y, and 100Y.

fuels. Recently Disturbed landscapes required more time for a repayment of the C Debt and were much more sensitive to harvest frequency, harvest intensity, and bioenergy conversion efficiencies (Fig. 2). Following disturbance, these landscapes can store high amounts of dead C that can persist for decades. Due to low net primary production following disturbance, recovery to pre-disturbance levels of C storage can take many years, ranging from 20 to over 1000 years. Old-growth landscapes usually took the longest amount of time to repay their C debts because their initial C storages were so high, ranging from 19 to over 1000 years.

Times required to reach carbon sequestration parity

The amounts of time required for C Sequestration Parity were usually longer than the amounts of time required for a repayment of the C debt. In general, Old-Growth landscapes achieved C Sequestration Parity at a faster rate than other categories of land-use history since they have more initial biomass available for bioenergy production (Fig. 3). Recently Disturbed landscapes were the second fastest, followed by Rotation Harvest landscapes, though differences between these two categories of land-use history are relatively minor. Post-Agricultural landscapes took longer than the other categories of land-use history, due to of a lack of initial biomass available to harvest for bioenergy production.

Times required to reach C Sequestration Parity were longest for the low-productivity ecosystems and shortest for the high-productivity ecosystems (Fig. 3), indicating that high productivity ecosystems were able to more quickly recoup their substantial reductions in C storage compared to the rates at which low-productivity ecosystems were able to recoup their considerably smaller reductions in C storage. Within each respective grouping of ecosystem productivity (G1, G2, G3), there were significant effects of different biomass longevities (L1, L2, L3) on the amount of time required for C Sequestration Parity. Increased biomass longevity (i.e., lower rates of mortality and decomposition) increased

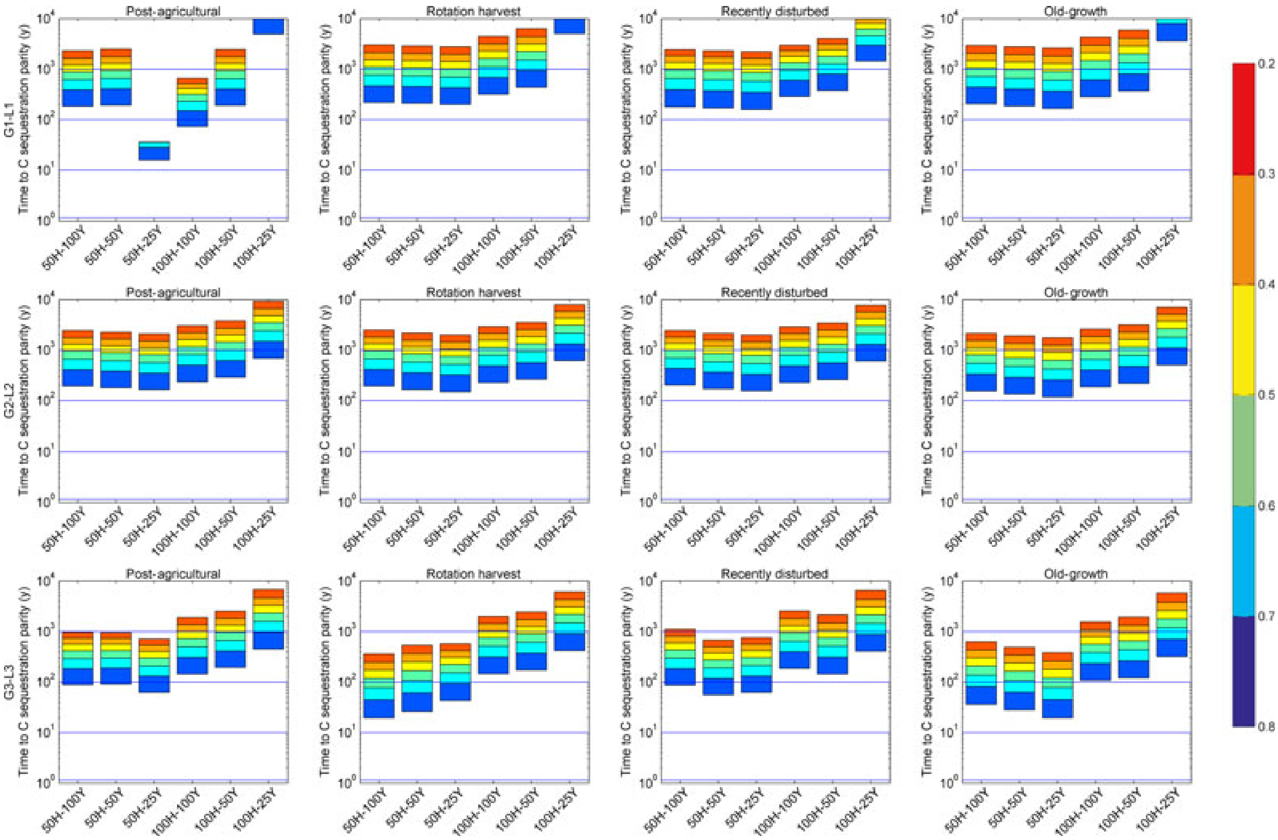

Fig. 3 Comparisons of the time required for a repayment of the C Sequestration Parity among three of our nine ecosystem types, each with six biomass harvesting regimes and four land-use histories. Note that times are represented on a log scale. Different harvesting regimes are indicated on the *x*-axis, with 50% and 100% harvesting intensity represented as 50H and 100H, respectively. Harvest frequencies of 25, 50, and 100 years are represented as 25Y, 50Y, and 100Y.

the times required to reach C Sequestration Parity, a trend which was consistent across all three rates of ecosystem productivity.

Regardless of land-use history and ecosystem characteristics, most scenarios required well over 100 years to reach C Sequestration Parity. Simulations with total harvests performed every 25 years often required more than 1000 years for C Sequestration Parity. Some scenarios achieved C Sequestration Parity in < 50 years, but most of these were scenarios with relatively high bioenergy conversion efficiencies. Harvests performed at lower frequency (50, 100 years) and intensity (50% harvest) required less time; partial harvests (50% harvest) performed every 25 years appeared to reach C Sequestration Parity more rapidly than any other management regime. Harvesting frequency and intensity appeared to affect all ecosystems similarly. Without exception, performing a clear-cut every 25 years resulted in the greatest reduction in C storage and required the longest periods to achieve C Sequestration Parity, suggesting that attempts to generate bioenergy from forests would be most effective in substituting for fossil fuels when managed for moderate amounts of production over a long time scale.

Discussion

Delays in the time required for a net benefit of a substitution of bioenergy for fossil fuels are caused by two factors. First, harvesting materials for bioenergy increases the C losses from the forest over the losses caused by mortality and decomposition, thus, increasing the amount of biomass harvest for bioenergy production will increase the C Debt. Second, since there is less potential energy per unit of C emissions in biomass energy compared to fossil fuels, substituting biomass for fossil fuels does not result in a 1 : 1 substitution of energy per unit of C emission. Consequently, ecosystems that are capable of quickly repaying their C Debts were those that had little C storage to begin with.

Our simulations demonstrated that initial landscape conditions and land-use history were fundamental in determining the amount of time required for forests to repay the C Debt incurred from bioenergy production.

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While Recently Disturbed and Old-Growth landscapes required considerable time to repay their C Debts, Post-Agricultural and Rotation Harvest landscapes were capable of repaying their C Debt in relatively short time periods, often within 1 year. However, a quick repayment of the C Debt and an increase in C storage does not imply a high degree of bioenergy production; it merely indicates that more C is being stored in a bioenergy production system. Post-Agricultural landscapes undergoing afforestation have minimal initial C storage, and managing them for an appreciable yield of bioenergy production would require a considerable waiting period. Furthermore, the conversion of an agricultural field to a forest could have short-term climatic warming effects while the afforesting landscape is in the early stages of succession, since a decrease in landscape albedo resulting from afforestation could yield climatic warming effects that would overshadow any climatic cooling effects associated with an uptake of atmospheric CO_2 (Jackson *et al.*, 2008; Anderson *et al.*, 2011), as the latter would be relatively small during the early stages of forest succession. By contrast, a Rotation Harvest system would not undergo a significant change in albedo during a transition to a landscape managed for bioenergy production. However, Rotation Harvests have a much different legacy than a Post-Agricultural landscape, since a history of harvesting on the landscape implies that there is additional wood being stored in wood products which are slowly decomposing (see Methods). Consequently, the ongoing decomposition of previously harvested materials lowers terrestrial C storage.

The times required for Old-Growth landscapes to repay C Debt were similar to the times required for them to achieve C Sequestration Parity, since the initial C storage of an old-growth landscape is at or near the level of C that could be stored in the landscape if it were to remain unharvested. Consequently, Old-Growth landscapes required long periods of bioenergy production to achieve C Debt Repayment and C Sequestration Parity. For the three other land-use histories, reaching the point of C Sequestration Parity requires much more time than a repayment of C Debt. Trends were quite consistent among the Recently Disturbed, Rotation Harvest, and Old-Growth landscapes and most simulations required at least 100 years to reach C Sequestration Parity (Fig. 3).

Times required for C Sequestration Parity were longest for the low-productivity ecosystems and shortest for the high-productivity ecosystems. Similarly, the effects of biomass longevity were quite consistent among the Recently Disturbed, Rotation Harvest, and Old-Growth landscapes (Fig. 3). Within each respective grouping of ecosystem productivity (G1, G2, G3), there were significant effects of different biomass longevity rates (L1, L2, L3) on the amount of time required to reach a point of C Sequestration Parity. Higher rates of biomass longevity (i.e., lower rates of mortality and decomposition) resulted in longer times required for C Sequestration Parity, a trend which was consistent across all three rates of ecosystem productivity (Fig. 3). Such a result may seem counterintuitive at first, but the net effect of lowering mortality and decomposition rates is that potential C storage is increased. Since ecosystems with lower mortality and slower decomposition have higher potential C storage, more bioenergy substitutions must be produced to exceed the amount of C stored in a forest that is allowed to grow without harvest. Annual biomass harvest varied little among our different levels of longevity. Therefore, higher rates of biomass longevity raised the target for C Sequestration Parity without resulting in a comparable increase of bioenergy production. We note that biomass longevity is largely a function of the environmental factors that control rates of biomass decomposition, such as temperature and moisture, and is governed by catastrophic disturbances to a lesser degree. Our simulations reiterate previous findings (Mitchell *et al.*, 2009; Campbell *et al.*, 2012) about the limited impact that wildfires have on biomass longevity; wildfires may temporarily lower the C storage of the landscape but most of the losses that occur are among unharvestable components of the forest, such as leaf litter and fine woody debris. Most of the harvestable biomass remains unconsumed even by high-severity wildfires and can either be salvage harvested shortly thereafter or persist on the landscape for decades (Mitchell *et al.*, 2009; Campbell *et al.*, 2012).

However, C storage is not the only way that vegetation affects climate, as different levels of surface reflectance (albedo) and evapotranspiration result in different levels of heat absorbance in the terrestrial biosphere (Jackson *et al.*, 2008; Anderson *et al.*, 2011). Utilizing degraded agricultural lands for the production of bioenergy via non-woody plant species (i.e., switchcane, switchgrass, etc.) could both reduce heat absorbance in the terrestrial biosphere and produce bioenergy to serve as a substitute for fossil fuels. A recent study by Beringer *et al.* (2011) estimated that, by 2050, the cultivation of bioenergy crops on degraded agricultural land could produce 26–116 EJ yr^{-1}, 3–12% of projected global energy demand. Additional energy may be obtained from secondary sources, such as residues from agriculture and forestry, municipal solid waste, and animal manures, and the combined production potential could potentially be around 100 EJ yr^{-1} by then (Ifeu, 2007; Iea, 2009; Wbgu, 2009; Haberl *et al.*, 2010), thereby generating an additional 10% of projected global energy demand (13–22% total). However, it is unclear what proportion of degraded agricultural lands would be better utilized for climate change mitigation via reforestation, rather than by non-woody bioenergy production. Non-woody bioenergy crops would need a sufficiently high surface reflectance if their climate change mitigation benefits were to exceed the mitigation benefits of afforestation, but the studies conducted on this topic have yielded conflicting results. Some studies have suggested that land cover types with high albedos could yield a greater cooling to the atmosphere than temperate forests (Diffenbaugh & Sloan, 2002; Oleson *et al*., 2004; Bala *et al*., 2007) while other studies have shown the opposite (DeFries *et al*., 2002; Jackson *et al*., 2005; Juang *et al*., 2007), indicating that further research on these tradeoffs is needed.

Further research is also needed to ascertain the potential conversion efficiencies of woody biomass. Our findings indicate that an accounting of the C emissions that are necessary for the harvest, transport, and firing of woody biomass must be performed if forest bioenergy is to be utilized without adding to atmospheric CO_2 concentrations in the near-term. Many of our combinations of forest productivity, biomass longevity and harvesting regimes required more than 100 years to achieve C Sequestration Parity, even when the bioenergy conversion factor was set at near maximal level. A consideration of stand characteristics and land-use history may also prove to be imperative for any bioenergy production system to be effective. Competing land-use objectives make it highly unlikely that forests will be managed purely for C mitigation efforts, and many of the current management objectives within existing forests will undoubtedly prevent them from reaching their full C storage potential. Achieving the maximal C mitigation potential of what remains becomes all the more imperative, as mean global temperatures, sea-level rise, or the melting of ice sheets may continue long after any future stabilization of atmospheric CO_2 and other greenhouse gases (Jones *et al*., 2009). Managing forests for maximal C storage can yield appreciable, and highly predictable, C mitigation benefits within the coming century, while managing forests for bioenergy production will require careful consideration if they are to provide a C neutral source of energy without yielding a net release of C to the atmosphere in the process.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Times for Carbon Debt Repayment for all Post-Agricultural landscapes.

Figure S2. Times for Carbon Sequestration Parity for all Post-Agricultural landscapes.

Figure S3. Times for Carbon Debt Repayment for all Rotation Harvest landscapes.

Figure S4. Times for Carbon Sequestration Parity for all Rotation Harvest landscapes.

Figure S5. Times for Carbon Debt Repayment for all Recently Disturbed landscapes.

Figure S6. Times for Carbon Sequestration Parity for all Recently Disturbed landscapes.

Figure S7. Times for Carbon Debt Repayment for all Old-Growth landscapes.

Figure S8. Times for Carbon Sequestration Parity for all Old-Growth landscapes.

Appendix S1. Energy Conversion Calculations.

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