Journal of Sustainable Forestry
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/wjsf20

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To cite this article: Thomas Walker, Peter Cardellichio, John S. Gunn, David S. Saah & John M. Hagan (2013) Carbon Accounting for Woody Biomass from Massachusetts (USA) Managed Forests: A Framework for Determining the Temporal Impacts of Wood Biomass Energy on Atmospheric Greenhouse Gas Levels, Journal of Sustainable Forestry, 32:1-2, 130-158, DOI: 10.1080/10549811.2011.652019

To link to this article: http://dx.doi.org/10.1080/10549811.2011.652019

Journal of Sustainable Forestry, 32:130–158, 2013

ISSN: 1054-9811 print/1540-756X online
DOI: 10.1080/10549811.2011.652019

Carbon Accounting for Woody Biomass from Massachusetts (USA) Managed Forests: A Framework for Determining the Temporal Impacts of Wood Biomass Energy on Atmospheric Greenhouse Gas Levels

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Policies based on assumed carbon neutrality fail to address the timing and magnitude of the net greenhouse gas (GHG) changes from using wood for energy. We present a "debt-then-dividend" framework for evaluating the temporal GHG impacts of burning wood for energy. We also present a case study conducted in Massachusetts, USA to demonstrate the framework. Four key inputs are required to calculate the specific shape of the debt-then-dividend curve for a given region or individual biomass facility. First, the biomass feedstock source: the GHG implications of feedstocks differ depending on what would have happened to the material in the absence of biomass energy generation. Second, the form of energy generated: energy technologies have different generation efficiencies and thus different life cycle GHG emissions profiles. Third, the fossil fuel displaced: coal, oil, and natural gas each have different emissions

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All authors were members of the Manomet Center for Conservation Sciences team contracted by the Commonwealth of Massachusetts Department of Energy Resources to study Biomass Sustainability and Carbon Policy in Massachusetts. The work presented here is based on that study and the public report released June 10, 2010.

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per unit of energy produced. Fourth, the management of the forest: forest management decisions affect recovery rates of carbon from the atmosphere. This framework has broad application for informing the development of renewable energy and climate policies. Most importantly, this debt-then-dividend framework explicitly recognizes that GHG benefits of wood biomass energy will be specific to the forest and technology context of the region or biomass energy projects.

KEYWORDS carbon emissions accounting, woody biomass energy, carbon debt, biogenic carbon emissions, Massachusetts Biomass Sustainability and Carbon Policy Study

INTRODUCTION

Greenhouse gas (GHG) emissions from bioenergy systems using forest biomass raise complex scientific and energy policy issues that require careful specification of an appropriate carbon accounting framework. This accounting framework should consider both the short- and long-term costs and benefits of using forest biomass instead of fossil fuels for energy generation. With conventional technologies, the carbon emissions produced when forest biomass is burned for energy are higher than the emissions from burning fossil fuels for an equivalent amount of energy. But over the long term, this carbon can be re-sequestered in growing forests. A key question for policymakers is the appropriate societal weighting of the short-term costs and the longer-term benefits of biomass combustion.

Government policies have reflected a widely held view that energy production from renewable biomass sources is beneficial from a GHG perspective. In its simplest form, the argument is that growing forests sequester carbon and as long as areas harvested for biomass remain forested, the carbon is reabsorbed in growing trees and consequently the net impact on GHG emissions is zero. In this context, biomass combustion for energy production has often been characterized as “carbon neutral” (Johnson, 2009).

The view that forest biomass combustion results in no net increase in atmospheric GHG levels has been challenged on the grounds that such a characterization ignores differences in the timing of carbon releases and subsequent re-sequestration in growing forests (e.g., McKechnie, Colombo, Chen, Mabee, & MacLean, 2011). Burning biomass for energy certainly releases carbon in the form of CO_2 to the atmosphere—in fact, as will be discussed below, per unit of useable energy biomass typically releases more CO_2 than natural gas, oil, or coal. For natural forests where stocks of carbon that would otherwise have been left to accumulate are harvested for biomass, forest regeneration and growth will not instantaneously recapture all the carbon released as a result of using the woody material for energy generation, although carbon neutrality—re-sequestering all the forest biomass carbon emitted—may occur at some point in the future if the harvested land is sustainably managed going forward. How long this will take for typical Massachusetts forest types and representative energy facilities, and under what conditions, was a focus of a recent study conducted for the Massachusetts Department of Energy Resources. Below we use the Massachusetts case study to present in depth the rationale and methodology for a model framework to evaluate the atmospheric GHG implications of switching from fossil fuel energy to forest-based biomass energy.

METHODS

Review of Previous Studies

The net GHG impacts of burning forest biomass for energy have been a topic of discussion since the early to mid-1990s. Beginning in 1995, Marland and Schlamadinger published a series of papers that addressed the issue, pointing out the importance of both site-specific factors and time in determining the net benefits of biomass energy (Marland & Schlamadinger, 1995; Schlamadinger & Marland, 1996a, 1996b, 1996c). This work initially was based on insights from a simple spreadsheet model, which evolved over time into the Joanneum Research GORCAM model (Marland, Schlamadinger, & Canella, 2011). A variety of other models are now available for performing similar types of bioenergy GHG analyses. These include CO2FIX (Schellhaas et al., 2004), CBM-CFS3 (Kurz et al., 2008), and RetScreen (Natural Resources Canada, 2009). Generally these models differ in their choice of algorithms for quantifying the various carbon pools, their use of regional forest ecosystems information, and the methods used to incorporate bioenergy scenarios. Other studies have addressed these issues for specific locations using modeling approaches developed for the conditions in the region (Morris, 2008). Work on the development of appropriate models of biomass combustion carbon impacts continues to be a focus of the Task 38 initiatives of the International Energy Agency (Bird et al., 2009).

In general, the scientific literature on the GHG impacts of forest biomass appears to be in agreement that these depend on the specific characteristics of the site being harvested, the energy technologies under consideration, and the time frame over which the impacts are viewed (IEA, 2009; Zanchi, Pena, & Bird, 2010). Site-specific factors that may have an important influence include ecosystem productivity, dynamics, and disturbance (e.g., dead wood production and decay rates, fire, etc.); the volume of material harvested from a site for biomass; the efficiency of converting biomass to energy; the characteristics of the fossil fuel system replaced; and the impact of biomass harvesting on forest product and land markets (Abt, Abt, & Galik, 2012).

Recent research has also raised several other site-specific issues. Bright, Cherubini, & Strømman (2009) cite research on albedo effects, which in some locations have the ability to offset some or potentially all the GHG effects of biomass combustion. The effect of climate change itself on carbon flows into and out of soil and aboveground live and dead carbon pools is another factor that has yet to be routinely incorporated into biomass energy analyses.

Developing a Carbon Accounting Framework

Energy generation, whether from fossil fuel or forest biomass feedstocks, releases GHGs to the atmosphere. The GHG efficiency—the amount of life cycle GHG emissions per unit of energy produced—varies based on both the characteristics of the fuel and the energy generation technology. However, combustion of forest biomass generally produces greater quantities of GHG emissions than coal, oil, or natural gas. If this were not the case, then substituting biomass for fossil fuels would immediately result in lower GHG emissions. The benefits of biomass energy accrue only over time as the "excess" GHG emissions from biomass are recovered from the atmosphere by growing forests. Researchers have recently argued that the carbon accounting framework for biomass must correctly represent both the short-term costs and the longer term benefits of substituting biomass for fossil fuel (Hamburg, 2010).

The carbon accounting framework developed for this study is constructed around comparisons of fossil fuel scenarios with biomass scenarios producing equivalent amounts of energy. The fossil fuel scenarios are based on life cycle emissions of GHGs and incorporate normalization factors for methane and nitrous oxides (Intergovernmental Panel on Climate Change [IPCC], 2000). Total GHG emissions for the fossil scenarios include releases occurring in the production and transport of natural gas, coal, or oil to the combustion facility as well as the direct stack emissions from burning these fuels for energy. Similarly, GHG emissions from biomass combustion include the stack emissions from the combustion facility and emissions from harvesting, processing, and transporting the woody material to the facility. Importantly, both the fossil fuel and biomass scenarios also include analyses of changes in carbon storage in forests through a comparison of net carbon accumulation over time on the harvested hectares with the carbon storage results for an equivalent stand that has not been cut for biomass but that has been harvested for timber under a business-as-usual (BAU) scenario. The approach includes the aboveground and belowground live and dead carbon pools that researchers have identified as important contributors to forest stand carbon dynamics. Typically wood products would also be included as an important carbon pool but because when these products are produced in the same quantities in both the BAU forest management and biomass scenarios, there will be no net change and thus there is no reason to track these explicitly.

The conceptual modeling framework for this study is intended to address the question of how atmospheric GHG levels will change if forest biomass displaces an equivalent amount of fossil fuel generation in the Massachusetts energy portfolio. As a proxy for atmospheric carbon impacts, the modeling quantifies the cumulative net annual change in forest carbon for the fossil and biomass scenarios, considering both energy generation emissions and forest carbon sequestration. In the fossil fuel scenarios, there is an initial CO_2 emissions spike associated with energy generation—assumed here to be equivalent to the energy that would be produced by the combustion of biomass harvested from one hectare—which is then followed by the sequestration of atmospheric CO_2 by hectare of forest from which no biomass is removed for energy generation. For the biomass scenario, there is a similar initial release of the carbon from burning wood harvested from an identical hectare of natural forest, followed by continued future growth and sequestration of carbon in the harvested stand.

A useful way to understand the relative carbon dynamics is to isolate the key drivers of atmospheric carbon flux due to forest biomass combustion. From this perspective, the incrementally greater amount of CO_2e associated with forest biomass energy is the relevant starting point. We define these incremental emissions as the biomass "carbon debt." This represents an investment, in the form of higher initial emissions that is paid down over time. The accounting approach introduces the concept of "carbon dividends" to represent these long-term benefits of investing in the development of forest biomass energy systems. The dividends can be thought of as the incremental reductions in future atmospheric carbon occurring after the carbon debt has been recovered. Note that our use of "debt" differs from the concept introduced by Fargione, Hill, Tilman, Polasky, and Hawthorne (2008) in that it represents the net increase in GHG emissions of biomass versus fossil energy generation technologies, rather than as an estimate of the initial removal of carbon from the forest inventory.

Graphically, the concepts of carbon debt and carbon dividend are illustrated in Figure 1. Figure 1a shows hypothetical carbon sequestration profiles for a stand harvested in a BAU timber scenario and the same stand with a harvest that augments the BAU harvest through a removal of an additional 20 tonnes of forest carbon. Figure 1b shows the net carbon recovery profile for the biomass versus BAU harvest. This represents the incremental growth of the stand following the biomass harvest (relative to the BAU harvest) and is calculated as the difference in growth between the biomass and BAU harvests. In this example, the carbon debt (9 tonnes) is shown as the difference between the total C harvested for biomass (20 tonnes) and the C released by fossil fuel burning (11 tonnes) that produces an equivalent amount of energy.

The carbon dividend is defined as the fraction of the equivalent fossil fuel emissions (11 tonnes) that is offset by forest growth at a particular point

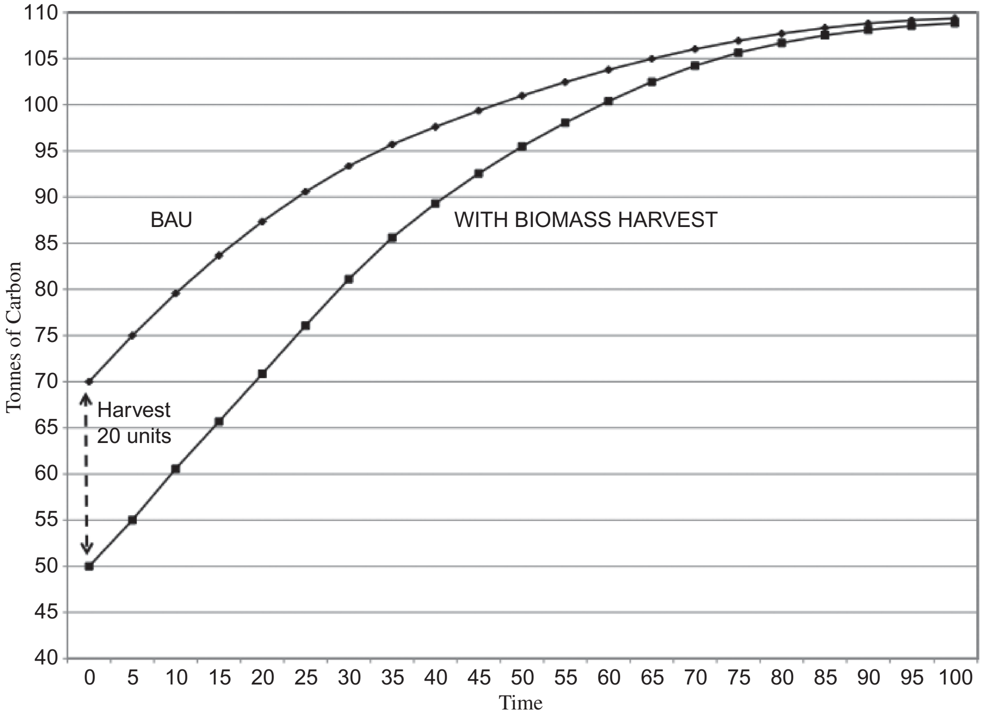


FIGURE 1a Hypothetical carbon sequestration profiles for a stand harvested in a "business as usual" (BAU) timber harvest scenario compared to the same stand with a harvest that augments the BAU harvest through a removal of an additional 20 tonnes of forest carbon.

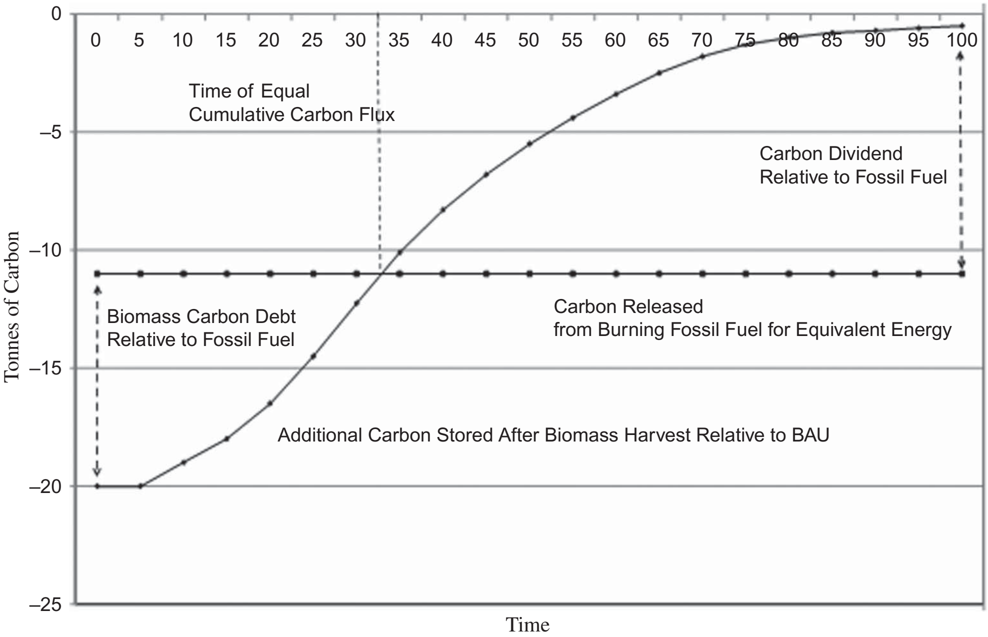


FIGURE 1b Hypothetical net carbon recovery profile for a biomass harvest versus BAU harvest.

in time. In the example, after the 9 tonne biomass carbon debt is recovered by forest growth (Yr 32), atmospheric GHG levels fall below what they would have been had an equivalent amount of energy been generated from fossil fuels. This is the point at which the benefits of burning biomass begin to accrue for the single stand, rising over time as the forest sequesters greater amounts of carbon relative to the BAU. Throughout this report the dividends are quantified as the percentage of the equivalent fossil fuel emissions that have been offset by forest growth. By approximately Yr 52, the regrowth of the stand has offset an additional 6 tonnes of emissions beyond what was needed to repay the carbon debt—representing an offset (or dividend) equal to 55% of the carbon that would have been emitted by burning fossil instead of biomass feedstocks. The carbon dividend, expressed as the percentage of the equivalent fossil fuel emissions offset by the growing forest, is calculated as the 6 tonnes of reduction (beyond the debt payoff point) divided by the 11 tonnes of fossil fuel equivalent that would have been needed to generate the energy produced by burning wood that released 20 tonnes of carbon. In this context, a 100% carbon dividend (almost achieved in year 100 in the hypothetical example) represents the time at which all 20 tonnes of emissions associated with burning biomass have been resequestered as new forest growth. In a benefit-cost analytical framework, decisionmakers would decide whether the trade-off of higher initial atmospheric carbon levels—occurring in the period before the carbon debt is fully recovered—is an acceptable cost given the longer term benefits represented by the carbon dividends.

To see why carbon debt is an important driver of impacts, consider the hypothetical case where a biomass fuel's CO_2e emissions from electricity production are one gram less per megawatt-hour (MWh) than that of coal (i.e., the carbon debt is negative). All else equal, one would prefer biomass from a GHG perspective since the emissions are initially lower per unit of energy, and this is the case even if one ignores that fact that cumulative net carbon flux to the atmosphere will fall further in the future as carbon is resequestered in regenerating forests. In the example, biomass would not be immediately carbon neutral, but would still have lower emissions than coal and would begin to accumulate carbon dividends immediately.

From an atmospheric GHG perspective, the policy question only becomes significant when CO_2e emissions from biomass are greater than that of the fossil fuel alternative. Because wood biomass emissions are typically higher than coal, oil and natural gas at large-scale electric, thermal, or CHP facilities, this is in fact the decision policymakers face. Framing the question this way shifts the focus away from total emissions, allowing the net carbon flux problem to be viewed in purely incremental terms. In our forest carbon accounting approach, the question then becomes how rapidly must the forest carbon sequestration rate increase after a biomass harvest in order to pay back the biomass carbon debt and how large are the carbon dividends that accumulate after the debt is recovered? The debt must be paid off before atmospheric GHG levels fall below what they would have been under a fossil fuel scenario. After that point, biomass energy is yielding net GHG benefits relative to the fossil fuel scenario.

In this framework, the net flux of GHGs over time depends critically on the extent to which the biomass harvest changes the rate of biomass accumulation on the post-harvest stand relative to the BAU. If the rate of total stand carbon accumulation, summed across all the relevant carbon pools increases very slowly, the biomass carbon debt may not be paid back for many years or even decades, delaying the time when carbon dividends begin to accumulate. Alternatively, for some stands, and especially for slow-growing older stands, harvesting would be expected to increase the carbon accumulation rate (at least after the site recovers from the initial effects of the harvest) and lead to relatively more rapid increases in carbon dividends. Determining the time path for paying off the carbon debts and accumulating carbon dividends is a principle focus of our modeling approach.

The above description pertains to a single stand or an aggregation of stands that are harvested in only 1 yr and thus would be relevant only in specific circumstances. For example, it may be the appropriate calculation for landowners who are interested in knowing how long it might take for their land to “recover” from a single-period harvest that will be used for biomass. This situation might also be informative if a landowner is interested in periodic harvesting of biomass for export markets. However, when the question is posed as to what will be the atmospheric carbon implications of building new bioenergy capacity, it is important to frame the debt-dividend model to consider the full range of landscape effects. The landscape includes a spatial component that requires aggregating across all stands that might be affected by bioenergy expansion. In addition, since a new bioenergy facility is likely to operate for many years, there is a temporal dimension that includes the effects of aggregating harvests over time.

There are two features of our analysis that make the spatial dimension of the problem computationally straightforward. As discussed later, our forestry model has been constructed to provide data for the behavior of an average stand in Massachusetts. Thus, although we use the data to represent a “single” hectare conceptually, it is more accurately described as an index of all forest types in the state and thus can be scaled up to any level of biomass harvest under consideration. The second feature results from our incremental approach to assessing biomass impacts. A large majority of the landscape in Massachusetts will remain “undisturbed” in a single year. The net effect of these areas on atmospheric carbon changes will be zero since net forest growth and inventory on this land will be the same in both the BAU and biomass scenarios; thus, in a given year, a comparison of harvested lands and all lands yields the same result.

The aggregation of biomass harvests over time is more complicated analytically: carbon recovery curves for each year need to be aggregated over the projection horizon and then compared with the cumulative level of fossil emissions. Figure 2 depicts the aggregation of carbon recovery curves associated with the biomass scenario over 120 yr. The top half of the figure uses the same data from the hypothetical case in Figure 1 to show the increase—and subsequent drawdown—of atmospheric carbon associated with the harvest in Yr 1. The lower half of the figure shows the stacking effect of summing these individual carbon recovery curves over time.

The curves in Figure 2b are plotted in 5-yr intervals. The envelope curve (the bold line) shows the amount of carbon in the atmosphere at any point

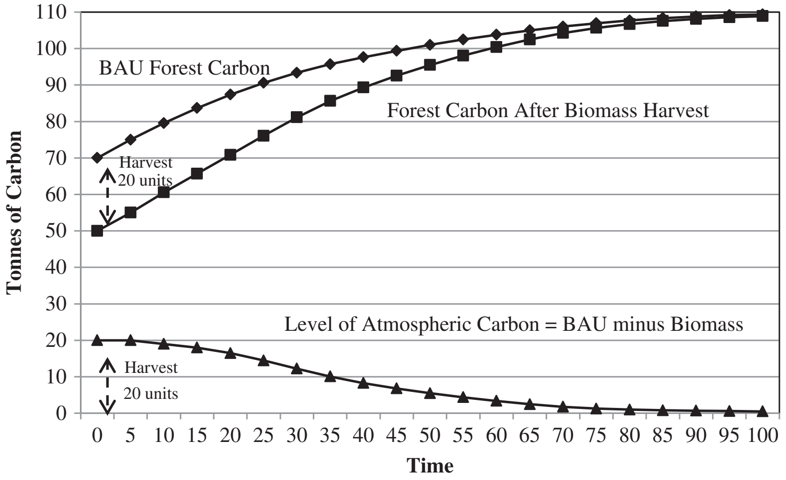


FIGURE 2a The hypothetical increase and subsequent drawdown of atmospheric carbon associated with a biomass harvest in Yr 1.

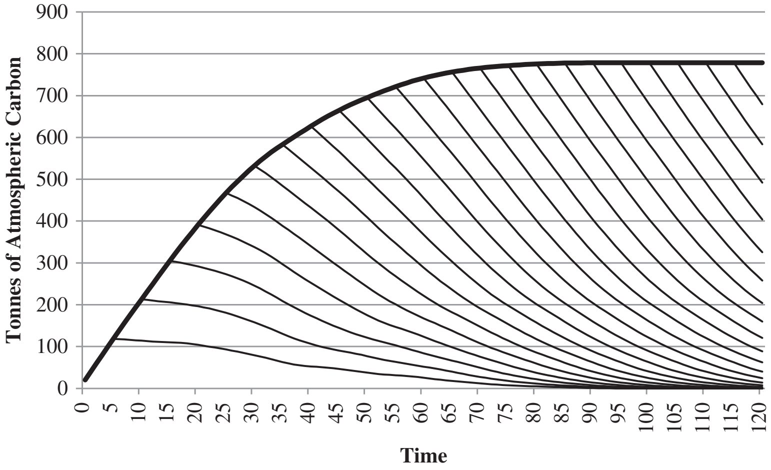


FIGURE 2b Aggregation of carbon recovery curves associated with a biomass harvest scenario over a 120-yr period.

in time as a result of the combined effects of biomass harvest/combustion and forest recovery. For example, in Yr 50, about 700 tonnes of carbon remain in the atmospheric due to biomass burning, and this is due to the resequestration of about 300 tonnes of the 1000 tonnes of carbon that were emitted over this period. Two assumptions are important in constructing this envelope curve: (a) the harvest continues every year for the entire period so that even if the bioenergy facility is mothballed, another will take its place, and (b) the same amount of biomass is harvested every year from an average stand with similar re-growth characteristics.

There are several parameters of the cumulative atmospheric carbon profile that can be derived from the profile of a single-period harvest. One of the more notable and obvious results is that cumulative curve will become horizontal in the same year that the atmospheric carbon level that can be attributed to harvesting the first stand has declined to zero. The cumulative atmospheric carbon profile associated with biomass harvesting is compared with the cumulative level of fossil fuel emissions that are displaced in Figure 3. Atmospheric carbon from fossil fuel burning over time is depicted as a straight line since emissions are assumed to be strictly additive to the atmosphere and the slope is simply the amount of the emissions in a single period. The point of equal cumulative flux is the time at which the level of carbon in the atmosphere is identical, regardless of whether energy is generated from fossil fuel or biomass (about 68 yr in this hypothetical example). Prior to that time, there would be more carbon resident in the atmosphere if biomass were used to displace fossil fuels. After that time, the atmosphere would have less carbon if biomass is used for energy; furthermore, cumulative dividends would rise rapidly because the slope of the cumulative fossil fuel curve remains unchanged while the slope of the biomass curve approaches zero.

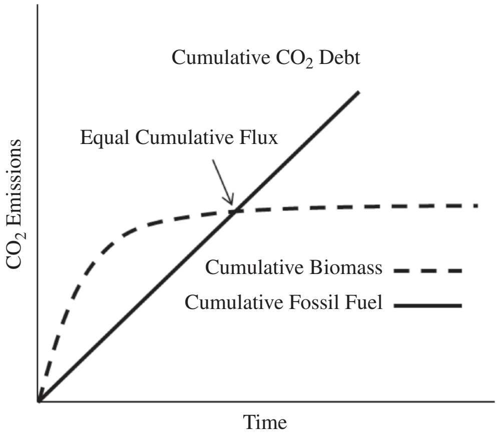


FIGURE 3 The cumulative atmospheric carbon profile associated with biomass harvesting is compared with the cumulative level of fossil fuel emissions that are displaced.

It is important to note that the point at which the cumulative carbon flux from biomass just equals the cumulative flux from fossil fuels (the point at which the biomass carbon debt is paid off) is not necessarily the point at which a policymaker is indifferent between the biomass and fossil fuel scenarios. For example, the policymaker might only be indifferent at the time when the discounted damages resulting from the excess biomass emissions just equals zero—this is the point in time at which early damages due to increased GHG levels from biomass are just offset by lower biomass damages in later years when net cumulative GHG flux from biomass is below that of the fossil fuel alternative. In this case, longer time periods are needed to reach the point defined as "fully-offset damages." The higher the discount rate—indicative of a greater preference for lower GHG levels in the near-term—the longer the time to reach the point of fully offset damages.

Forest Harvest and Growth Scenarios

Data used in the analyses were based upon Forest Inventory and Analysis (FIA) data from the U.S. Forest Service. We obtained inventory data from the FIA DB version 4.0 Data Mart from 1998–2008. FIA plot data (including tree lists) were imported into the Northeast (NE) Variant of the U.S. Forest Service Forest Vegetation Simulator (FVS) and are accepted as compatible with the model (Ray, Saunders, & Seymour, 2009). FVS is a widely accepted growth model within current forest carbon offset standards (e.g., Climate Action Reserve Forest Project Protocol 3.1 and the Chicago Climate Exchange Forest Offset Project Protocol) and as a tool to understand carbon implications of forest management within the scientific community (e.g., Keeton 2006; Ray, Saunders, & Seymour, 2009; Nunery & Keeton, 2010). The modeling package relies on NE-TWIGS (Hilt & Teck, 1989) as the growth and yield model to derive carbon biomass estimates in the Northeast. These growth and yield models are based on data collected by the U.S. Forest Service's Forest Inventory and Analysis unit from the 1950s through the 1980s. Developed by the U.S. Forest Service and widely used for more than 30 yr, the FVS is an individual tree, distance independent growth and yield model with linkable modules called extensions, which simulate various insect and pathogen impacts, fire effects, fuel loading, snag dynamics, and development of understory tree vegetation (Crookston & Dixon, 2005). FVS can simulate a wide variety of forest types, stand structures, pure or mixed species stands, and allows for the modeling of density dependent factors.

The FVS model modifies individual tree growth and mortality rates based upon density-dependent factors. As would be expected to be observed in nature, the model uses maximum stand density index and stand basal area as important variables in determining density related mortality. The NE Variant uses a crown competition factor as a predictor variable in some growth relationships. Potential annual basal area growth is computed using a species-specific coefficient applied to DBH (diameter at breast height) and a competition modifier value based on basal area in larger trees is computed. In the NE Variant there are two types of mortality. The first is background mortality which accounts for occasional tree deaths in stands when the stand density is below a specified level. The second is density related mortality which determines mortality rates for individual trees based on their relationship with the stand's maximum density. Regeneration in the NE Variant is user-defined (stump sprouting is built in) and we describe the regeneration inputs in more detail below.

The FVS Fire and Fuels Extension includes a carbon submodel that tracks carbon biomass volume based upon recognized allometric equations compiled by Jenkins, Chojnacky, Heath, and Birdsey (2003). The carbon submodel allows the user to track carbon as it is allocated to different "pools." Calculated carbon pools include: total aboveground live (trees); merchantable aboveground live; standing dead; forest shrub and herbs; forest floor (litter, duff); forest dead and down; belowground live (roots); belowground dead (roots). Soil carbon was not included explicitly in this analysis. Our FVS model simulations captured the carbon dynamics associated with the forest floor and belowground live and belowground dead root systems. Mineral soils were not included in our analyses, but appear generally not to be a long-term issue. A meta-analysis published in 2001 by Johnson and Curtis found that forest harvesting, on average, had little or no effect on soil carbon and nitrogen. However, a more recent review (Nave, Vance, Swanston, & Curtis, 2010) found consistent losses of forest floor carbon in temperate forest, but mineral soils showed no significant, overall change in carbon storage due to harvest, and variation among mineral soils was best explained by soil taxonomy. It is important to recognize the current scientific uncertainty around the role of timber harvesting in carbon dynamics but the evidence presented to date warrants attention but does not modify the conclusions derived from our modeling.

The study's debt-dividend carbon accounting framework takes the individual forest stand as the basic unit of analysis. For the fossil fuel baseline scenarios, a BAU forest management approach is assumed where the stand is harvested for timber but not for biomass. Thus, the modeling approach relies on a dynamic baseline for comparisons with the biomass alternative. The scenarios are summarized in Table 1 and include two alternative BAU specifications—one a relatively heavy cut that removes approximately 32% of the above-ground live biomass, and a lighter BAU that removes 20%. The heavier BAU is intended to represent the case where the landowners who decide to harvest biomass are the ones who cut more heavily in the BAU. The lighter harvest BAU represents a scenario where the distribution of landowners harvesting biomass is spread more evenly across the full range of landowners who currently harvest timber, as specified in the Massachusetts

TABLE 1 Forest Vegetation Simulator (FVS) Management Modeling Scenario Descriptions

Harvest category	Description	Carbon removed (tonnes)	Aboveground live carbon harvested (%)	Logging residues left on-site (%)
BAU 20%	Lighter BAU removal	6.3	20	100
BAU 32%	Heavier BAU removal	10.2	32	100
Biomass BA60	Moderate biomass removal: BAU & Biomass removal down to (13.38 m^2/ha (60 ft^2/acre) of stand basal area	19.3	60	35
Biomass 40%	Lighter biomass removal: BAU plus biomass removal equals 40% stand carbon	12.0	38	35
Biomass BA40	Heavier biomass removal: BAU & Biomass removal down to 8.92 m^2/ha (40 ft^2/acre) of stand basal area	24.3	76	35

Forest Cutting Plan data. For the BAU scenarios, all logging residues are left in the forest.

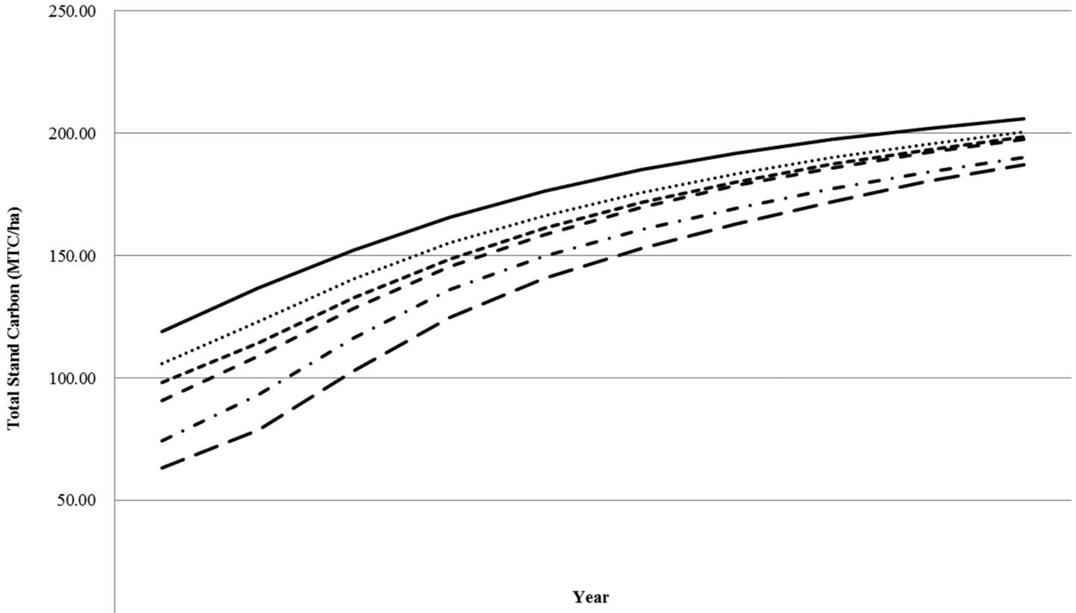
Changes in total stand carbon were quantified using the FVS model by decade through an evaluation of carbon in the aboveground and belowground live and dead carbon pools for each of the BAU and biomass harvest scenarios. The resulting carbon recovery profiles represent averages for a set of 88 plots in the Massachusetts FIA database with an initial volume of more than 10.1 tonnes of carbon per ha (25 MTC/ac) in the aboveground live pool. Figures 4a and 4b show the results of the FVS analysis as the accumulation of total stand carbon and aboveground live carbon over the next 90 yr. Table 2 presents the calculated carbon recovery profiles for six combinations of BAU and biomass forest management scenarios. These represent the incremental accumulation of total stand carbon for the biomass scenarios as compared to the BAU. These results are the starting point for the debt-dividend analyses discussed below.

Biomass and Fossil Fuel GHG Emissions

The life cycle emissions for typical biomass and fossil fuel energy technologies considered in this analysis are described in detail below and summarized in Table 3.

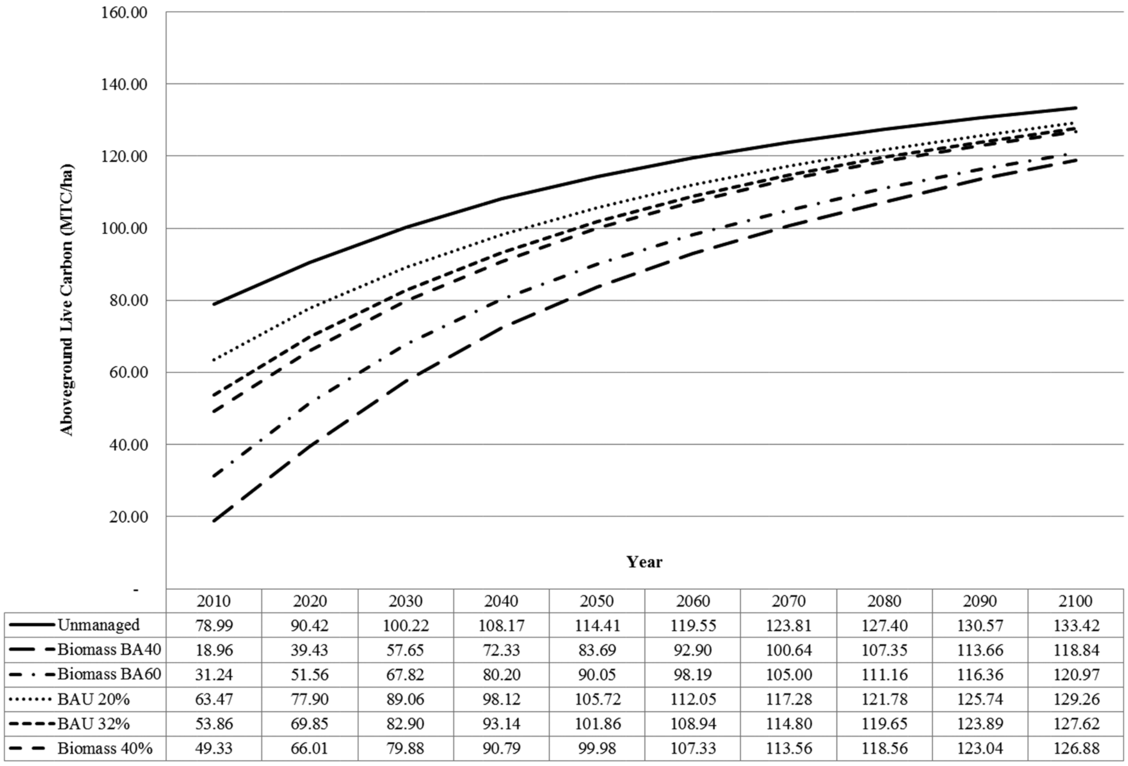
EMISSIONS FROM BIOMASS HARVESTING, PROCESSING, AND TRANSPORT

For green wood chips (delivered to a large-scale electric, thermal, or pellet facility), the estimates are based on releases of CO_2 associated with diesel fuel consumption in each of these processes. Harvest and chipping



	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Unmanaged	119.04	136.66	152.23	165.78	176.42	185.10	191.87	197.46	201.98	206.10
Biomass BA40	63.40	78.57	103.04	124.86	140.87	152.93	163.11	172.06	180.35	187.13
Biomass BA60	74.27	93.01	116.26	136.13	150.04	160.68	169.48	177.30	184.20	190.32
BAU 20%	105.97	122.93	140.64	155.18	166.45	175.86	183.61	190.12	195.66	200.65
BAU 32%	98.08	114.15	132.87	148.72	161.34	171.87	180.29	187.48	193.35	198.70
Biomass 40%	90.77	108.91	128.57	145.39	158.66	169.55	178.63	185.94	192.18	197.70

FIGURE 4a Forest Vegetation Simulator (FVS) accumulation of total stand carbon (MTC/ha) for harvest scenarios between 2010 and 2100.



	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Unmanaged	78.99	90.42	100.22	108.17	114.41	119.55	123.81	127.40	130.57	133.42
Biomass BA40	18.96	39.43	57.65	72.33	83.69	92.90	100.64	107.35	113.66	118.84
Biomass BA60	31.24	51.56	67.82	80.20	90.05	98.19	105.00	111.16	116.36	120.97
BAU 20%	63.47	77.90	89.06	98.12	105.72	112.05	117.28	121.78	125.74	129.26
BAU 32%	53.86	69.85	82.90	93.14	101.86	108.94	114.80	119.65	123.89	127.62
Biomass 40%	49.33	66.01	79.88	90.79	99.98	107.33	113.56	118.56	123.04	126.88

FIGURE 4b Forest Vegetation Simulator (FVS) accumulation of aboveground live carbon (MTC/ha) for harvest scenarios between 2010 and 2100.

TABLE 2 Carbon Sequestration Recovery Time by Harvest Scenario. Sequestration (Recovery) Is Expressed as the % Recovered by Each Time Period

Harvest scenario description	Carbon removed (tonnes/stand)	BAU vs. biomass total stand carbon % recovered by year								
		10	20	30	40	50	60	70	80	90
1. BAU 32% minus Biomass BA60	9.1	11.1	30.2	47.1	52.5	53.1	54.5	57.2	61.6	64.8
2. BAU 32% minus Biomass 40%	1.8	28.1	41.0	54.6	63.4	68.5	77.3	79.0	84.1	86.4
3. BAU 32% minus Biomass BA 40	14.1	−2.6	14.0	31.2	41.0	45.4	50.5	55.5	62.5	66.7
4. BAU 20% minus Biomass 40%	5.7	7.8	20.5	35.7	48.7	58.5	67.3	72.5	77.0	80.6
5. BAU 20% minus Biomass BA60	13.0	5.6	23.0	39.9	48.2	52.1	55.4	59.5	63.8	67.4
6. BAU 20% minus Biomass BA40	18.0	−4.2	11.7	28.8	39.9	46.1	51.9	57.6	64.0	68.3

TABLE 3 Life Cycle Carbon Emissions for Typical Biomass and Fossil Fuel Energy Technologies. Emissions Factors for Pellets Are Characterized Relative to the Thermal Technology Using Green Chips Which Are Shown in This Table. Sources and Calculations for These Data Are Described in the Text

Scenarios	Biomass	Coal	Oil (#6)	Oil (#2)	Natural Gas
Utility-scale electric	Kilograms/MWh				
Fuel prod & transport	7	14			34
Fuel combustion	399	270			102
Total	406	284			136
Thermal	Kilograms/MMBtu				
Fuel prod & transport	1		6	6	6
Fuel combustion	35		27	25	17
Total	36		33	31	23
CHP	Kilograms/MMBtu				
Fuel prod & transport	1		7	6	6
Fuel combustion	35		29	27	18
Total	36		35	33	24

costs were estimated using the U.S. Forest Service's Fuel Reduction Cost Simulator (Fight, Hartsough, & Noordijk, 2006). Chips were assumed to be transported 161–193 km (round-trip) to the combustion facility, using trucks carrying 25–30 green tonnes with an average fuel efficiency of 2.13 km/l. The results were verified for consistency with other relevant studies including: Consortium for Research on Renewable Industrial Materials CORRIM, 2004); University of Minnesota, Department of Forest Resources (2008); Finkral and Evans (2008); and Katers and Kaurich (2006).

LIFE CYCLE EMISSIONS FROM UTILITY-SCALE ELECTRIC

The biomass estimate is based on analysis of electricity generation and wood consumption from a set of power plants in this region with efficiencies in the 20 to 25% range. These data have been compiled from a combination of information from company websites and financial reports. The comparable data for natural gas and coal have been developed by the National Renewable Energy Laboratory (NREL; Spath & Mann, 2000; Spath, Mann, & Kerr, 1999) and include the full lifecycle CO_2e emissions.

LIFE CYCLE EMISSIONS FROM THERMAL FACILITIES

Biomass is based on a typical thermal plant with 50 MMBtu/hr of capacity and 75% efficiency, with a heat input of 120,000 MMBtu/yr Emissions data for heating oil and natural gas thermal plants were developed assuming that the typical capacity of the plants was also 50 MMBtu/hr. The oil facilities were assumed to run at 80% efficiency, while the natural gas plants were assumed to be more efficient at 85%. For natural gas, indirect emissions were calculated using the same percentages available in the NREL analysis of electric power plants. Indirect emissions from oil are based on estimates from the National Energy Technology Laboratory (Gerdes, 2009).

LIFE CYCLE EMISSIONS FROM CHP FACILITIES

Emissions for CHP facilities are also expressed on the basis of MMBtu of heat output, in which electrical energy is converted to a Btu equivalent. The analysis of these operations depends critically on the mix of thermal and electrical output in the plant design. In general, thermal-led facilities tend to relative emissions profiles that are similar to their thermal counterparts, while electric-led facilities more closely resemble the emissions profiles of electric power plants.

FOREST BIOMASS CARBON ACCOUNTING RESULTS

Energy Technology and Carbon Debt Recovery

An important insight from the study is the wide variability in the magnitude of carbon debts across different biomass technologies. This is a function of the way specific life cycle GHG characteristics of a bioenergy technology combine with the GHG characteristics of the fossil fuel energy plant it replaces to determine carbon debts. As shown in Table 4, carbon debts for situations where biomass thermal replaces oil-fired thermal capacity can be as low as 8%, whereas the debt when biomass replaces combined-cycle natural gas in large-scale electricity generation can range as high as 66%.

TABLE 4 Carbon Debt Summary. Excess Biomass Emissions Are Presented as a % of Total Biomass Emissions

Scenario	Coal	Oil (#6)	Oil (#2)	Natural gas
Electric	31%			66%
Thermal		8%	15%	37%
CHP		2%	9%	33%

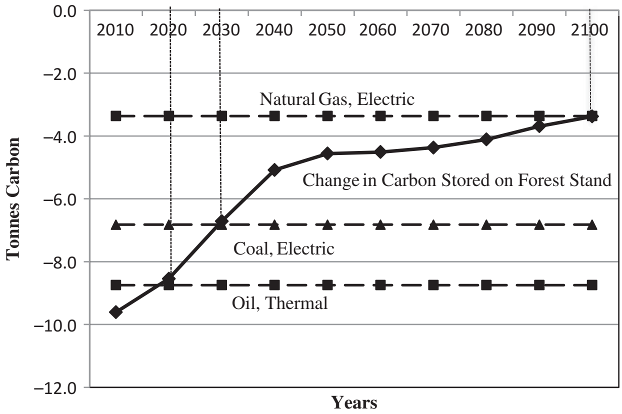


FIGURE 5 Illustration of the relationship between biomass energy technologies and the relevant fossil fuel energy equivalent and the timing of equal carbon flux.

Figure 5 provides an example of how the timing of GHG benefits is affected by technology considerations. The results make clear that biomass technology scenarios with higher percentage carbon debts will be slower to realize carbon dividends. Although the example is based on a single forest management scenario—32% removal of aboveground live carbon using a diameter limit partial harvest and a biomass harvest that extends the diameter limit approach to removal of all trees down to a residual basal area of 13.38 m^2 per ha (60 ft^2 per acre)—the results are indicative of the general principle that, holding forest management constant, the larger the percentage carbon debt, the longer the time required to begin accruing the benefits of biomass energy.

Carbon Recovery: Impacts of Harvesting Live Trees Versus Logging Residues

The stand modeling of forest carbon recovery indicates that removal of logging residues (tops and branches) will generally yield GHG benefits much more rapidly than harvests of live trees that would not have been harvested in the BAU scenario. Tops and limbs decay quickly if left in the forest and so their use comes with little carbon "cost" and this tends to shorten carbon

TABLE 5 Carbon Recovery Times (Expressed as % Recovered) Following the Removal of Tops and Limbs (T&L) in the BAU32 Harvest Scenario

	Number of years from initial harvest				
	10	20	30	40	50
Scenario 1					
Original (with T&L)	11%	30%	47%	53%	53%
No T&L	−9%	11%	31%	38%	38%
Scenario 2					
Original (with T&L)	28%	41%	54%	63%	68%
No T&L	−12%	−4%	16%	31%	39%
Scenario 3					
Original (with T&L)	−3%	14%	31%	41%	45%
No T&L	−22%	−6%	14%	25%	31%
Tops and limbs only	68%	87%	93%	96%	97%

recovery times. Conversely, if tops and limbs from a biomass harvest of cull trees were left in the woods to decay, this "unharvested" carbon would delay recovery times, effectively penalizing wood biomass relative to fossil fuels.

The carbon recovery times in the six scenarios presented in Table 2 are all based on the assumptions that 100% of tops and limbs are left in the forest in the BAU scenarios and 65% of all tops and limbs (from both the BAU and the incremental biomass harvest) are harvested in the biomass scenarios. The carbon recovery times for the three BAU32 scenarios are compared with the carbon recovery times when all tops and limbs are left in the forest in Table 5.

When tops and limbs are left on-site, all three scenarios show net carbon losses between the initial period and the 10-yr mark; in addition, carbon losses in Yr 10 are substantial relative to the recovery levels in the scenarios in which tops and limbs are taken and used for bioenergy. Scenario 2 (the lightest biomass harvest) shows the greatest impact from not utilizing tops and limbs, with carbon recovery times delayed by about three decades (about 50% of the original biomass harvest was comprised of tops and limbs). Thus, if BAU32 was followed by a light biomass harvest of only roundwood for use by a thermal facility, carbon debt recovery would require 20 to 30 yr (when compared to oil-based thermal), rather than occurring in less than 10 yr when tops and limbs are taken in whole-tree harvests.

In contrast, in the heavier biomass harvests, recovery times are extended only about 10 yr. In Scenario 1, the carbon debt incurred by replacing oil thermal by biomass thermal would be recovered in 20 yr instead of the 10 yr indicated when tops and limbs are utilized. In Scenario 3, carbon debt recovery times for replacement of oil thermal are extended from 20 to 30 yr.

Finally, it is interesting to consider the "harvest" and use of just tops and limbs. While this may not be directly applicable to forest management in Massachusetts (due to poor markets for pulpwood and limited opportunities for log merchandizing), it may be representative of situations involving non-forest biomass sources, such as tree trimming/landscaping or land clearing. The results in this case (also shown in Table 7) indicate rapid recovery, with nearly 70% of the carbon losses "recovered" in one decade. Thus, all bioenergy technologies—even biomass electric power compared to natural gas electric—look favorable when biomass "wastewood" is compared to fossil fuel alternatives.

Carbon Recovery: Impacts of Alternative Silvicultural Prescriptions

The impact of different silvicultural prescriptions was more difficult to evaluate using the FVS model. The six scenarios use a thin-from-above strategy linked to residual stand carbon targets for all harvests. These types of harvests tend to open the canopy and promote more rapid regeneration and growth of residual trees. While this silvicultural approach may provide a reasonable representation of how a landowner who harvests stands heavily in a BAU is likely to conduct a biomass harvest, it is less likely that someone who cuts their land less heavily would continue to remove canopy trees for biomass (unless they had an unusual number of canopy cull trees remaining after the timber quality trees are removed). More probable in this case is that the landowners would harvest the BAU timber trees and then selectively remove poor quality and suppressed trees across all diameter classes down to about 20 cm. We hypothesized that this type of harvest would result in a slower recovery compared to thinning from above.

Although study resources were not adequate to fully simulate this type of harvest for all 88 FIA stands, a sensitivity analysis was conducted for two stands with average volumes. For each of these stands, the analysis considered a BAU harvest removing 20% of the stand carbon, followed by removal of residual trees across all diameter classes above 8 inches down to basal areas similar to the target in Scenario 4. For these two stands, the results, shown in Table 6 indicate a slowing of carbon recovery profiles relative to Scenario 4, although two stands are not enough to draw any conclusions about average impacts of this silvicultural prescription. What can be said is that stands harvested in this manner will probably recover carbon more slowly than would be suggested by Scenario 4; how much more slowly on average was not determined; it is clear however that on a stand-by-stand basis the magnitude of the slowdown can vary considerably.

Cumulative Carbon Dividends

As discussed above, to model the cumulative debt-dividend profile for a biomass facility, it is necessary to aggregate the results of multiple harvests over the lifespan of the bioenergy facility. While the single year emissions results discussed in the examples above are useful for understanding the

TABLE 6 Timing of Carbon Recovery in Alternative Harvest Scenarios. Sequestration (Recovery) Is Expressed as the % Recovered by Each Time Period

Harvest scenario description	Carbon removed (tonnes/stand)	BAU vs. biomass total stand carbon % recovered by year								
		10	20	30	40	50	60	70	80	90
Stand 1, BAU20 minus Biomass40DBH	7.5	−9.6	15.1	63.5	84.6	94.8	113.9	126.4	133.6	137.8
Stand 1, BAU20 minus Biomass 40	5.9	−0.3	25.6	59.2	64.4	44.7	73.7	70.2	108.9	97.1
Stand 2, BAU20 minus Biomass40DBH	4.2	−2.7	−6.4	−3.1	22.6	68.6	62.5	90.4	84.4	100.9
Stand 2, BAU20 minus Biomass 40	6.4	6.1	20.4	34.8	44.6	69.5	69.1	99.4	92.3	93.5

relative impact of different factors on the magnitude and timing of the carbon recovery profile, a cumulative approach is critical to evaluating the impacts of an expansion of bioenergy capacity that will consume wood for many years. To provide these types of insights, the study assumes that biomass energy facilities will continue to operate and replace fossil fuel energy sources until 2100.

The cumulative analysis makes clear that the time required to begin realizing dividends from biomass energy is considerably longer than one might conclude if only a single year of emissions were evaluated. Unless biomass facilities burn only logging residues, best case results suggest it will take between 15 and 30 yr before forest biomass energy begins yielding lower GHG levels than fossil alternatives (Table 7). In the case of utility-scale electric plants, the modeling suggests a minimum of around 45 yr is required.

Considered from the dividends perspective, the results suggest that by 2050, only biomass thermal applications that replace oil are consistently yielding benefits relative to fossil fuels (Table 8). At that time, the carbon debts have generally not been paid off for either the natural gas thermal or coal and gas electricity facilities. However, extending this analysis through

TABLE 7 Years for Biomass Energy Emissions to Reach Equal Flux with Fossil Fuel Energy Emissions

Harvest scenario	Fossil fuel technology			
	Oil (#6), thermal	Coal, electric	Gas, thermal	Gas, electric
Mixed wood	15–30	45–75	60–90	>90
Logging residues only	<5	10	10	30

TABLE 8 Cumulative Carbon Dividends Between 2010 and 2050 (Harvest Scenarios Are from Table 2)

	Fossil fuel technology			
Harvest scenario	Oil (#6), thermal	Coal, electric	Gas, thermal	Gas, electric
1	22%	−3%	−13%	−110%
2	34%	11%	3%	−80%
3	8%	−22%	−34%	−148%
4	15%	−13%	−24%	−129%
5	16%	−11%	−22%	−126%
6	7%	−25%	−36%	−153%

TABLE 9 Cumulative Carbon Dividends Between 2010 and 2100 ((Harvest Scenarios Are from Table 2)

	Fossil fuel technology			
Harvest scenario	Oil (#6), thermal	Coal, electric	Gas, thermal	Gas, electric
1	40%	19%	12%	−63%
2	56%	42%	36%	−18%
3	31%	8%	0%	−86%
4	43%	24%	17%	−54%
5	37%	16%	9%	−69%
6	31%	8%	−1%	−86%

2100 does result in dividends in the form of lower GHG levels under all fossil replacement scenarios except where biomass replaces utility-scale natural gas electric plants (Table 9).

DISCUSSION

The analyses presented above make clear that technology choices for replacing fossil fuels, often independent of any forest management considerations, play an important role in determining the carbon cycle implications of burning biomass for energy. The choice of biomass technology, and the identification of the fossil capacity it replaces, will establish the initial carbon debt that must be recovered by forest growth above and beyond BAU growth. The carbon debts vary considerably across technologies. For typical existing configurations, replacement of oil-fired thermal systems with biomass systems leads to relatively low carbon debts. Carbon debts for large-scale electrical generation are higher. Because of its much lower GHG emissions per unit of useable energy, replacing natural gas for either thermal or electric applications results in significantly higher carbon debts than incurred in replacing other fossil fuels. CHP facilities, particularly those that optimized for thermal rather than electricity applications, also show very low initial carbon debts.

While the relative ranking of technologies by their carbon debt levels provides useful insights on relative carbon emissions per unit of useable energy, the specific time required in each case to pay off carbon debts and begin realizing the benefits of biomass energy, represented in this study by the carbon dividends, depends on what happens in the forests harvested for biomass fuel. The results of the study's analyses provide some broad insights into biomass carbon dynamics but are also subject a number of uncertainties that are difficult to resolve.

In general, the study found that the cumulative time required to begin realizing the benefits of biomass energy can be quite long, on the order of decades for most technologies, if biomass energy is assumed to be in the form of live trees harvested to replace fossil fuels continuously over the next century. However, the timing and magnitude of carbon dividends can be quite sensitive to the forest management practices adopted by landowners. Carbon recovery times can differ by decades depending upon assumptions about (a) the intensity of harvests; (b) the silvicultural prescriptions and cutting practices employed; (c) the fraction of the logging residues removed from the forest for biomass; and (d) the frequency at which landowners re-enter stands to conduct future harvests. However, more accurate predictions of the impacts of these factors on carbon dividends require a better understanding than of future landowner forest management practices. While detailed landowner surveys might improve society's understanding of this issue, the uncertainty cannot be completely resolved without actual observations of changes landowner behavior in response to increased biomass demand.

It is important to emphasize that after the point in time where GHG levels are equivalent for biomass and fossil fuels, biomass energy provides positive reductions in future GHG levels. Over time, under some scenarios these carbon dividends can become substantial, reducing GHGs by over 40% relative to continued fossil fuel use in some of our simulations through 2100. But the key question remains one of the appropriate weighting of near-term higher GHG levels with long-term lower ones. Policymakers will need to sort out these issues of societal time preferences and weight near term higher GHG emissions against longer term lower ones.

Applicability of Framework to Other Regions

The information provided by the debt-then-dividend framework offers policy makers greater ability to tailor wood biomass energy policies to achieve the most rapid and significant reductions in GHGs. The framework requires four key inputs to calculate the specific shape of the debt-then-dividend curve for a given state, region, country or even individual biomass facility:

1. Biomass feedstock source: The GHG implications of biomass feedstocks differ depending on what would have happened to the material in the absence of biomass energy generation. Energy generated from burning materials such as logging debris—material such as tops and branches that mostly would have decayed and entered the atmospheric carbon cycle relatively quickly absent collection for biomass energy generation—results in more rapid carbon recovery profiles than energy produced from harvests of live trees that would have continued sequestering carbon. The use of material derived from thinning activity that decreases the likelihood of catastrophic fire through a reduction in fuels loads also would have a different baseline emissions profile.
2. Form of energy generated: Wood biomass energy technologies have different generation efficiencies and thus different lifecycle GHG emissions profiles. For example, use of biomass for thermal applications generally yields lower initial carbon debts than biomass electricity generation.
3. Fossil fuel displaced: Coal, oil, and natural gas each have different GHG emission levels per unit of energy produced. Consequently, where biomass replaces a relatively GHG efficient fossil fuel like natural gas, the time needed to pay back carbon debts and realize the benefits of biomass can increase substantially.
4. Management of the forest: The land management decisions of forest owners can either slow or accelerate forest growth and therefore affect recovery rates of carbon from the atmosphere—see also Nunery and Keeton (2010). Important factors influencing the timing and magnitude of the carbon recovery include the intensity of harvests, their frequency, the optimization of harvest scheduling, and the specific silvicultural approach employed in the harvest.

Biomass Energy Policy Implications

The common assumption of wood biomass energy's carbon neutrality ignores complex forest carbon accounting dynamics and limits the ability of policymakers to optimize biomass energy strategies. A key policy insight from implementation of the debt-then-dividend framework is recognition of the sensitivity of the timing and magnitude of biomass GHG costs and benefits to the four factors discussed above. For example, in New England, using logging residues as feedstocks instead of coal at a utility-scale electricity plant can yield GHG benefits in 10 yr or less. But producing electricity from wood chips derived from poor quality whole trees (that would otherwise have continued to sequester carbon) to replace generation from high efficiency, natural gas-fired combined-cycle plants would not lower GHG levels for many decades. Similarly, use of wood to replace oil-fired thermal applications has the potential to yield GHG benefits more rapidly than use of the same wood to replace fossil-fired electric capacity. Where wood feedstock supplies are limited, these types of insights can allow policy makers to target renewable energy incentives more effectively.

A related advantage of the debt-then-dividend framework is that policy makers can calculate and then consider the tradeoff between higher short-term GHG costs and longer term GHG benefits. How policy makers view these trade-offs will have an important bearing on biomass energy policies. Categorical assumptions about carbon neutrality preclude an important social, scientific and political conversation about how soon GHG reductions should be achieved. Long-term GHG benefits might very well be worth the short-term costs, but that is a decision that should be made transparently by policy makers in consultation with the public.

The debt-then-dividend framework also highlights the importance of land management decisions for realizing biomass GHG benefits. Landowners face a wide array of possible wood biomass harvest strategies, both at the individual stand and landscape levels. For example, carbon recovery could be accelerated by increasing productivity of stands across intensively managed forest landscapes. However, these carbon objectives must be balanced with the societal need to maintain the flow of a wide range of ecosystem services from forests. The debt-then-dividend approach can help policy makers consider the role of new "best practices" guidelines for forest biomass harvesting and management.

Most importantly, the debt-then-dividend framework explicitly recognizes that GHG benefits of wood biomass energy development will be specific to the forest and technology context of specific regions and biomass energy projects. Broad generalizations based on carbon neutrality are unlikely to lead to optimal GHG policies. Instead, biomass GHG policies will be improved if governments implement the debt-then-dividend approach at appropriate scales, whether regional, state or even individual facility levels.

Limitations of Study

The study discusses a complex subject that is technically challenging and inevitably reflects a variety of critical uncertainties. Policymakers should carefully weigh these uncertainties, as well as other factors not addressed by our study, in shaping future energy policies for forest biomass. Below we summarize the key assumptions and limitations of the study.

- The study used average and/or typical values for GHG emissions from biomass and fossil fuel energy facilities. The carbon debt and dividend conclusions should be viewed as representative of typical or average conditions today, a state of affairs likely to change in the future given the evolution of technologies.

- The carbon analysis considers only biomass from natural forests. Tree care and landscaping sources, biomass from land clearing, and construction and debris waste materials have very different GHG profiles. The results for biomass from natural forests may understate the benefits of biomass energy development relative to facilities that would rely primarily on these other wood feedstocks that might otherwise enter the atmospheric carbon cycle more quickly.
- The analyses of recovery of carbon recovery by forests have focused primarily on average or typical forest conditions in Massachusetts. The responses of individual stands vary around these average responses, with some stands recovering carbon more rapidly and others less rapidly than the average. Due to the complexity of responses at the individual stand level, the study has not been able to isolate the characteristics of rapidly recovering stands using FVS. Should better data become available on this topic, it might be possible to design and implement forest biomass harvest policies that accelerate the average carbon recovery times reported here.
- Some landowners may face alternative BAU baselines that have not considered, and this suggests the need for caution in generalizing the study results. The study used the historical harvest trends in Massachusetts as the basis for our BAUs and we believe this is the most likely future for landowners in this state. However, we cannot rule out other BAU scenarios that could change the carbon recovery results in important ways. For example, if no biomass plants are sited in Massachusetts, will landowners actually face an alternative BAU where they can sell this material to out-of-state energy facilities? Under such a BAU assumption, expansion of in-state biomass energy generation will cause no increase in GHG impacts since the emissions would occur anyway.
- Views about how long it will take before truly low carbon energy sources are available to replace fossil fuels play a critical role in biomass policy decisions. If policymakers believe it will take a substantial amount of time to develop and broadly apply low or no carbon sources of energy, they may be more inclined to promote the development of biomass. Conversely, if they think that no or low carbon alternatives will be available relatively soon, say in a matter of one or two decades, they may be less inclined to promote development of biomass.
- Concerns about the relative importance of short- versus long-term consequences of higher carbon emissions may also play a role in how one interprets the results of this study. Those who believe that short-run increases in GHG levels need to be avoided at all costs will be less likely to favor biomass development than those focused on the potentially quite significant, but longer term, benefits of reduced GHG levels that could ultimately result from biomass development.

In light of all these factors, the study should be viewed as providing general indicators of the time frames for recovery of biomass carbon and the key factors that influence these estimates. Uncertainties remain and as such, the results suggest that new energy and environmental policies that rely on insights from this study should clearly take into account the impacts of the various uncertainties embedded in the report's analytic framework, assumptions, and methods.

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