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Forest biomass energy: assessing atmospheric carbon impacts by discounting future carbon flows

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Abstract

Although forest biomass energy was long assumed to be carbon neutral, many studies show delays between forest biomass carbon emissions and sequestration, with biomass carbon causing climate change damage in the interim. While some models suggest that these primary biomass carbon effects may be mitigated by induced market effects, for example, from landowner decisions to increase afforestation due to higher biomass prices, the delayed carbon sequestration of biomass energy systems still creates considerable scientific debate (i.e., how to assess effects) and policy debate (i.e., how to act given these effects). Forests can be carbon sinks, but their carbon absorption capacity is finite. Filling the sink with fossil fuel carbon thus has a cost, and conversely, harvesting a forest for biomass energy – which depletes the carbon sink – creates potential benefits from carbon sequestration. These values of forest carbon sinks have not generally been considered. Using data from the 2010 Manomet Center for Conservation Sciences 'Biomass sustainability and carbon policy study' and a model of forest biomass carbon system dynamics, we investigate how discounting future carbon flows affects the comparison of biomass energy to fossil fuels in Massachusetts, USA. Drawing from established financial valuation metrics, we calculate internal rates of return (IRR) as explicit estimates of the temporal values of forest biomass carbon emissions. Comparing these IRR to typical private discount rates, we find forest biomass energy to be preferred to fossil fuel energy in some applications. We discuss possible rationales for zero and near-zero social discount rates with respect to carbon emissions, showing that social discount rates depend in part on expectations about how climate change affects future economic growth. With near-zero discount rates, forest biomass energy is preferred to fossil fuels in all applications studied. Higher IRR biomass energy uses (e.g., thermal applications) are preferred to lower IRR uses (e.g., electricity generation without heat recovery).

Keywords: biomass energy, carbon neutrality, carbon sequestration, forest carbon dynamics, social discount rate

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Introduction

The problem of climate change represents the most serious environmental problem of our time. Anthropogenic climate change is caused by the increase of atmospheric greenhouse gases, especially carbon dioxide, which comes largely from extracting and burning fossils fuels. Any solution to climate change must include eliminating most carbon emissions from fossil fuel combustion.

Biomass energy is one alternative. Biomass, or plant matter, is currently the world's largest source of renewable energy, in part because a large segment of the world's low-income population uses biomass fuels such as wood, charcoal, and animal dung for cooking (IEA 2012). Some forms of biomass energy are inexpensive compared to other energy sources, at least in some regions of the world. Industrialized countries use biomass to a limited extent for residential and industrial heating, electricity generation, and vehicle fuel. Based on such modern uses, bioenergy already contributes around half of the renewable energy portfolio in both the EU and the United States, with wood constituting around half of the bioenergy shares (European Commission 2014; EIA 2015).

Biomass carbon neutrality

In the past, all biomass energy was considered to be carbon neutral as long as it was based on sustainable yields: Burning biomass releases carbon, but assuming land use and productivity do not change, plants later reabsorb this carbon in new growth. In the case of short-rotation biomass crops such as switchgrass, this reabsorption of emitted carbon dioxide can take place in less than a year. But for woody biomass, carbon dioxide

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released in combustion may not be completely reabsorbed by new tree growth for decades or even centuries (depending on region and forest type). Many studies have now demonstrated that this time interval between carbon release and reabsorption can be a source of temporary greenhouse gas increases and thus that biomass is not necessarily carbon neutral or may only be carbon neutral over longer timeframes (Marland & Schlamadinger, 1997; Johnson, 2009; Cherubini *et al*., 2011; Hudiburg *et al*., 2011; McKechnie *et al*., 2011; Holtsmark, 2012; Schulze *et al*., 2012; Lamers & Junginger, 2013; Mika & Keeton, 2015).

The state of Massachusetts, USA, commissioned the Manomet Center for Conservation Sciences to do a study of forest biomass energy carbon dynamics (Walker *et al*., 2010, 2013; hereafter referred to as the Manomet report). The Manomet report quantified carbon emissions from forest biomass energy used in different applications and estimated carbon reabsorption times for Massachusetts forests. For most uses of biomass energy, more carbon is released initially than when using fossil fuels to produce the same quantity of energy, so an initial 'carbon debt' is incurred (Fargione *et al*., 2008). Growing forests gradually reabsorb or payback this carbon debt. The number of years until forests absorb more carbon than would have been released by fossil fuel use is called the 'carbon payback'. After payback, continued forest carbon sequestration generates a 'carbon dividend' (Walker *et al*., 2010). Depending on the energy application, reference fossil fuel, and assumed forest management strategy, forest biomass carbon payback periods can range from less than a decade to many decades.

The Manomet report compared net emissions of a bioenergy scenario and a fossil fuel scenario over time, considering the amount of biomass harvested within the actively managed forest landscape. In the Massachusetts context, biomass energy demand was not expected to increase the annual total acreage harvested. As the unmanaged forest landscape was assumed to remain constant, the Manomet results did not reflect any afforestation across the landscape, which might be induced by greater use of biomass energy and higher biomass prices (as discussed below). The prolonged carbon payback for Massachusetts forest biomass energy was mainly driven by the greater GHG emissions per unit of energy for biomass vs. fossil energy. The Manomet report was criticized for being a stand-level study (Lucier, 2010), that is, for not including possible carbon benefits of market-induced afforestation, although using a landscape-level framework can also reduce carbon benefits as measured by carbon debts and dividends (see Cardellichio & Walker, 2010).

While the Manomet report and similar studies have not necessarily prescribed continued use of fossil fuels instead of biomass energy, policymakers might conclude this. By itself, the carbon debt approach suggests ambiguity about replacing fossil fuels with biomass energy – higher atmospheric carbon levels now and lower levels later. But carbon debt and payback alone do not adequately describe the temporal values of atmospheric carbon, because it is not clear what a reasonable payback period might be: 5 years, 50 years, and 500 years might all be considered reasonable payback periods in different contexts. Carbon payback alone does not reveal whether forest biomass energy is superior to fossil energy for reducing climate change.

Cherubini *et al*. (2011) use a different approach in modeling carbon emissions from fossil fuels and forest biomass energy. They find that atmospheric carbon emissions from forest biomass combustion are always less than those from fossil fuel combustion, because there is an additional sink for the biomass carbon from replacement plant growth, assuming sustainable forest management. Cherubini *et al*. use this difference to calculate the global warming potential from biomass energy as a fraction of the global warming potential for fossil fuels, which they call $\mathrm{GWP}_{\mathrm{bio}}$. While this approach is consistent with treatment of other greenhouse gases and conceptually useful, from a policy perspective it has limitations similar to carbon debt, in that $\mathrm{GWP}_{\mathrm{bio}}$ varies with the time horizon considered. For example, in one scenario, biomass carbon has 96% of the global warming potential of fossil fuel carbon for a 20-year time horizon, 43% for a 100-year horizon, and only 8% of fossil fuel warming potential for a 500-year horizon (Cherubini *et al*., 2011). Policymakers do not necessarily know the relevant time horizon, which greatly affects conclusions about the desirability of biomass energy. The temporal value of carbon emitted or avoided is not explicitly considered.

Another thread of the biomass carbon literature looks at induced market effects of biomass energy policy, for example, the possibility that promoting biomass energy use will increase biomass prices and lead to afforestation or to changes in forest management practices. When these effects are considered, forest biomass energy use can lead to reduced atmospheric carbon levels even in the short run. Galik & Abt (2012) consider differences by forest type and scale in Virginia, USA, based on increased co-firing of biomass with coal in electric power plants. While estimated carbon effects in unmanaged forest stands are similar to those found by the Manomet Report, already-managed plots show lower carbon debts with faster carbon paybacks. At larger scales, changes in forest management and forest land cover create or enlarge carbon sinks, mainly due to anticipated future bioenergy markets, resulting in no net carbon debt at the largest scales. Other studies find similar results at the US level (White *et al.*, 2013) and world level (Daigneault *et al.*, 2012), with induced market feedbacks mitigating emissions from biomass harvests. In some scenarios, the initial plot-level biomass carbon debt is reduced or eliminated through changes elsewhere in the landscape.

While induced market effects are appropriate policy considerations, they are highly uncertain and do not negate the need to consider the primary carbon effects of forest biomass carbon emissions and sequestration. The total effect of biomass energy use is governed by a forest ecosystem's limited capacity to absorb atmospheric carbon. Modeling the ecology of forest carbon pools and fluxes is already fraught with scientific uncertainties, and modeling induced market effects – for example, land-use change driven by biomass prices – adds additional levels of uncertainty to the analysis. Our approach provides an alternative framework for evaluating the primary carbon effects of forest biomass energy use at all scales. Any induced market effects that may occur would be in addition the primary effects modeled here.

Forests as carbon sinks

A key to understanding biomass carbon temporal values is the finite capacity of the forest as a carbon sink. Young forests sequester carbon rapidly, but sequestration slows dramatically as forests age, and new growth is balanced by decay (Schlamadinger & Marland, 1996; Ryan *et al.*, 1997; Eriksson *et al.*, 2007). Over centuries, net forest carbon sequestration asymptotically approaches zero, although there is some debate about whether a minimal level of carbon sequestration continues even in old-growth forests (Luyssaert *et al.*, 2008). Because forest carbon sequestration is effectively finite and has a value (in avoided climate change costs), there is a benefit to reducing the current carbon stock and allowing for rapid carbon sequestration in the future, that is, being able to sequester future carbon emissions has an option value. The cost in current carbon emissions of burning trees and wood residuals for energy is at least partially offset by the increased value of the enlarged forest carbon sink. Most forest biomass models to date have not explicitly accounted for this option value created by harvesting forests and thus have underestimated the value of using forest biomass energy as compared to fossil fuels.

As noted by Cherubini *et al.* (2013), biomass energy carbon emissions are fundamentally different from fossil fuel emissions, because biomass emissions are temporary and reversible. In this study, we build on that idea and describe circumstances under which forest biomass energy is carbon preferable to fossil fuel energy.

Social discount rates

Utilizing forest biomass energy has carbon benefits as compared to using fossil fuels, but as shown by the Manomet report and others, society must wait to receive these benefits. In economics, a discount rate is used to reflect the cost of waiting. In this study, we utilize this economic tool for analyzing carbon emissions and sequestration occurring at different points in time. While the approach described here is economic, the results are broadly applicable to biomass energy use and provide a stronger theoretical foundation for biomass energy policy than carbon debt and payback metrics used in the past.

A private discount rate for an individual or business is normally thought to be the opportunity cost of capital, perhaps equal to a bank interest rate or a return to equity expected by shareholders. The appropriate discount rate for society as a whole is a more difficult question, and appropriate social discount rates for climate change and other long-term sustainability issues are much debated in the literature. A recent report by the US Environmental Protection Agency discusses this issue in some detail and notes that 'there is no consensus about what [discount] rates to use in this context' (EPA 2014, page B-14). The Stern Review of the Economics of Climate Change (Stern, 2006) used a relatively low social discount rate of 1.4% in concluding that the benefits from avoiding climate change outweigh the costs of avoiding it, although the Stern Review was much criticized for this choice of discount rate (Nordhaus, 2007).

A common construction of a social discount rate is based on Ramsey (1928; as described in IPCC, 2014), where the social discount rate (ρ) is based on a pure rate of social time preference (δ), the expected per capita rate of growth in the economy (g), and the elasticity of the marginal utility of consumption (η):

$$\rho = \delta + \eta g \tag{1}$$

The pure rate of time preference, δ, reflects the social desirability of present as compared to future consumption. The g parameter reflects the possibility that the economy and per capita consumption may continue to grow over time, making future generations wealthier than us. If so, our willingness to sacrifice now for our possibly wealthier descendants might have limits. The magnitude of those limits is captured by the η factor, which reflects the decreased utility (or benefit) obtained from each additional increment of consumption. Beckerman & Hepburn (2007) call δ and η the ethical parameters, and these parameters have received most attention in the climate change debate.

The Intergovernmental Panel on Climate Change fifth Assessment Report presents values of δ, η, and g used in recent analyses of climate change economics, as shown in Table 1 (IPCC 2014). There appears to be near unanimity about a zero or near-zero rate for δ. A common argument is that the consumption of future generations should not be discounted simply because these generations happen to be born later. Most recent climate change studies have assumed economic growth rates (g) of about 2%, with a mean value from the IPCC data of 2.1% (IPCC 2014). Along with other mean values from the IPCC report, this implies a social discount rate of 4.5% (Table 1).

In addition to ethical questions about δ and η, another question regards the g parameter, or future per capita economic growth (Ackerman *et al.*, 2009). Although the assumptions shown in Table 1 reflect global growth experience of the last decades, there is no guarantee that per capita economic growth will continue unabated for centuries into the future. Ecological economists would in fact argue that infinite growth of physical resource use on a finite planet is impossible (Daly, 1974). If Earth has a maximum human carrying capacity, then population growth and all economic growth must eventually approach zero, at least for growth of physical resources (as opposed to growth of intellectual or cultural resources). If long-term growth must approach zero and δ is zero, then the social discount rate approaches zero for long time horizons.

Another question is whether carbon emissions themselves may significantly affect the future growth rate g. Clearly, loss of land from sea-level rise, greater damages from extreme weather, ocean acidification, etc., all have the potential to slow real economic growth in the future. When consumption growth causes environmental externalities such as climate change, Dasgupta *et al.* (1999) show that social discount rates can be zero or even negative.

With respect to climate change damage, we assume below that marginal cost of damage per metric ton of atmospheric carbon (Mg C) is constant over time. In fact, the marginal damage per Mg C may rise over time, due both to more extreme effects of climate change and to a growing population who incur damages. Tol (2009) notes that discounting does not reduce the present value of future climate effects if the costs of such effects grow faster than the discount rate. For example, if marginal damage per Mg C was to grow at the discount rate, there would be no difference between the present value of carbon damages today and in the future, implying an effective discount rate of zero:

$$\begin{aligned} &\text{if } \mathrm{PV}(\mathrm{MCC}_t) = \frac{\mathrm{MCC}_t}{(1+r)^t} \text{ and } \mathrm{MCC}_t = \mathrm{MCC}_0(1+r)^t \\ &\text{then } \mathrm{PV}(\mathrm{MCC}_t) = \frac{\mathrm{MCC}_0(1+r)^t}{(1+r)^t} = \mathrm{MCC}_0 \end{aligned} \tag{2}$$

where PV is present value, MCC_t is the marginal cost of carbon emissions at some time t in the future, MCC_0 is the marginal cost of carbon emissions now, and r is a discount rate and growth rate of the marginal cost of carbon emissions. We have little knowledge of future climate change marginal damages and less knowledge of their cost paths over time. A precautionary approach suggests this and other possible justifications for zero or near-zero discount rates, treating future emissions damages as equivalent to present damages.

Table 1 Parameter values for construction of social discount rate from recent studies

	Pure rate of time preference (δ), percent	Elasticity of marginal utility of consumption (η)	Economic growth rate (g), percent
Cline (1992)	0.0	1.50	1.0
IPCC (1996)	0.0	1.75	4.8
Arrow (1999)	0.0	2.00	2.0
UK Green Book (2003)	1.5	1.00	2.0
Rapport Lebegue (2005)	0.0	2.00	2.0
Stern (2007)	0.1	1.00	1.3
Arrow (2007)		2.50	
Dasgupta (2007)	0.1	3.00	
Weitzman (2007)	2.0	2.00	2.0
Nordhaus (2008)	1.0	2.00	2.0
Mean of studies	0.5	1.88	2.1
Ramsey rule discount rate based on mean values:	0.5 + (1.88*2.1) = 4.5		

Source: Intergovernmental Panel on Climate Change (IPCC, 2014).

Using a system dynamics model that replicates results of the Manomet report, we calculate internal rates of return (IRR) for carbon emissions from forest biomass energy. IRR is a common financial metric, which we use to evaluate the greater short-term carbon emissions and decreased long-term emissions from forest biomass energy as compared to fossil energy. IRR is the discount rate at which the cost of initial carbon emissions is exactly equal to the present value of future carbon reductions. The IRR estimates can be compared to private and/or social discount rates to determine optimum biomass policy. If biomass IRR is greater than the discount rate, forest biomass energy is preferred to fossil energy.

Materials and Methods

Data

We use data from Massachusetts, USA, compiled in a report by the Manomet Center for Conservation Sciences (Walker *et al.*, 2010, 2013). The Manomet report is based on Forest Inventory and Analysis (FIA) data from the US Forest Service. These FIA data are used as inputs to a simulation model, the US Forest Service Forest Vegetation Simulator (FVS) for the northeast region. The FVS model predicts forest growth and mortality along with changes in various forest carbon pools.

Model input data include 88 FIA plots in Massachusetts that have at least 61.8 metric tons of carbon per hectare (Mg C ha^{-1}) aboveground (live), indicating that these plots are sufficiently stocked for possible timber and biomass harvest. Plots contain mixtures of tree species including oak, other hardwoods, hemlock, and white pine. All results are aggregated and expressed in Mg C ha^{-1} for this representative Massachusetts forest.

The Manomet report develops a number of harvest scenarios to estimate the impact of different harvest levels on forest carbon pools. We use two of the harvest scenarios, comparing both to a business as usual (BAU) scenario. The BAU harvest represents forest management practice typical in Massachusetts today, removing on average about 20% of above-ground live carbon or 15.6 Mg C ha^{-1}. The light biomass harvest scenario removes an additional 14.1 Mg C ha^{-1} over the BAU cut, with 38% of carbon removed including 65% of tree tops and limbs. The heavy biomass harvest scenario removes 44.5 Mg C ha^{-1} more than BAU, with 76% of carbon removed, again including 65% of tops and limbs. Results below reflect these differences between the BAU harvest and either a heavy or light harvest aimed at securing forest biomass for energy.

The FVS model simulates the specified harvest in the year 2010 followed by forest plot growth and carbon accumulation to 2100. The Manomet report provides estimates of total forest plot carbon for each harvest scenario at 10-year intervals until 2100. From these data, we first estimate parameters of growth curves for the biomass harvests and then calculate the BAU carbon levels based on Manomet-reported differences between the BAU harvest and biomass harvests.

To compare carbon impacts of forest biomass energy use to continued fossil fuel use, the Manomet report considers several different energy applications. In each application, results depend on the efficiency of forest biomass energy in this use, the efficiency of the reference fossil fuel, and the energy and carbon contents of forest biomass and fossil fuels. Here, we consider all four biomass applications for which results are available in the Manomet report: (1) forest biomass in a commercial-scale heating application compared to heavy (#6) fuel oil; (2) forest biomass in a commercial-scale heating application as compared to natural gas; (3) forest biomass for electricity generation as compared to coal-fired electricity; and (4) forest biomass electricity compared to natural gas-fired electricity.

Forest biomass carbon dynamics model

To replicate results from the Manomet study and to develop better intuition about the structure of the biomass energy utilization problem, we develop a biomass system dynamics model using STELLA software. System dynamics models have been widely used where effects over time are of primary interest (Sterman, 2000). Figure 1 depicts the core features of the model, which represents one hectare of typical Massachusetts forest and carbon dynamics associated with utilizing forest biomass energy and fossil fuels. Rectangles in Fig. 1 represent stocks or quantities, which include stocks of fossil carbon (still in the ground), atmospheric carbon in the form of CO_2, and aboveground forest biomass carbon (omitting forest mineral soil carbon, which is not modeled in the Manomet report). The double-line arrows with valve symbols represent flows, or derivatives of stocks with respect to time. Circles represent other parameters or outputs, and single-line arrows indicate origins and uses of parameters and outputs.

The equation for the forest biomass carbon stock estimated from data in the Manomet report is as follows:

$$C_f(t) = e^{\left[a-\left(\frac{b}{t}\right)\right]} \tag{3}$$

where C_f is total forest biomass carbon in Mg C ha^{-1} and t is time in years. Table 2 shows the estimated parameters a and b for biomass growth ($R^2 > 0.99$). Using equation 3 to simulate forest carbon from establishment (with no harvest) produces in the familiar sigmoid-shaped forest carbon stock curve shown in Fig. 2. Initially, forest carbon increases exponentially, but growth later slows and asymptotically approaches the maximum stock level over time.

In the Fig. 1 model, the *forest C absorption* flow is the time derivative of the stock function:

$$\frac{\mathrm{d}C_f(t)}{\mathrm{d}t} = \left(\frac{b}{t^2}\right)e^{\left[a-\left(\frac{b}{t}\right)\right]} \tag{4}$$

In Fig. 1, the flow of carbon from *forest biomass combustion* is determined by *biomass harvest quantity* (in metric tons carbon, Mg C) and the *biomass fraction of energy* (1 or 0 for the scenarios modeled here). We base the flow of carbon for scenarios using *fossil fuel combustion* on the amount of energy provided by *biomass harvest quantity* and use the carbon contents of different

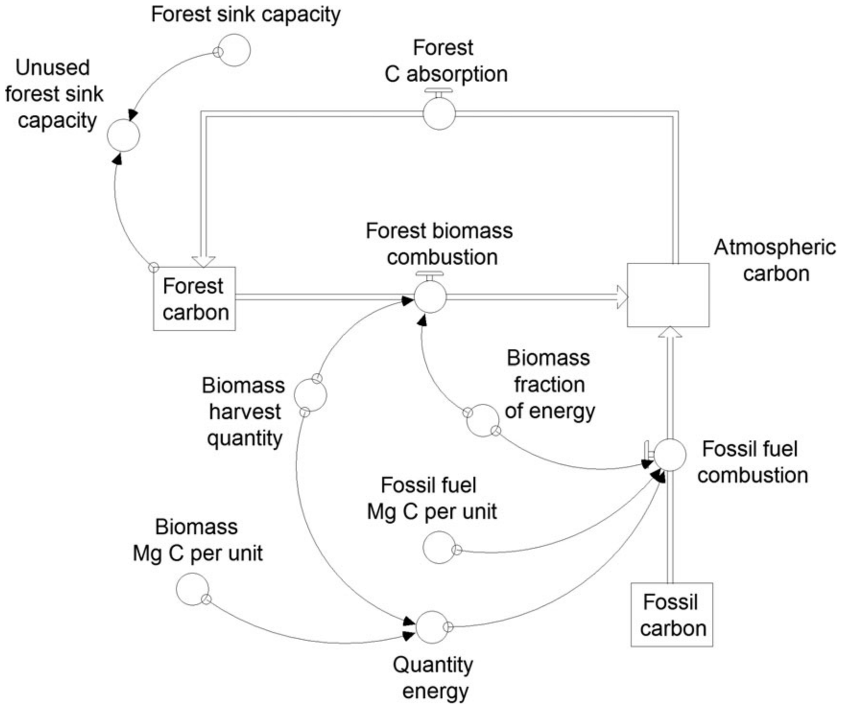

Fig. 1 STELLA model stocks (rectangles), flows (double lines with valves), parameters, and outputs (circles).

Table 2 Parameter estimates for forest growth curves in Manomet report (equation 3)

Biomass Harvest	Parameter a	Parameter b
Heavy: 61.8 Mg C ha^{-1}	5.72	63.60
Light: 44.5 Mg C ha^{-1}	5.75	66.41

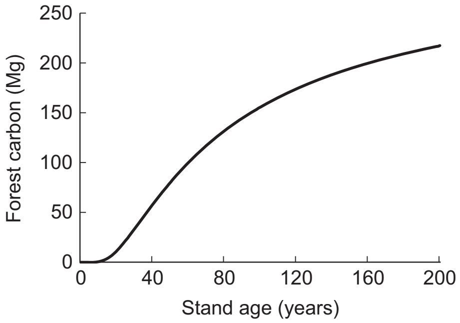

Fig. 2 Aboveground forest carbon development from 0 to 200 years without harvest for representative hectare of Massachusetts forest.

fossil fuels to calculate the carbon emissions resulting from this fossil fuel use. The model runs in one-year time steps, calculating annual carbon flows and resulting new stock levels for forest carbon and atmospheric carbon in each year. We change biomass harvest and fossil fuel parameters as necessary to produce results for the different scenarios shown below.

From equation 3, we calculate a maximum forest carbon sink capacity. Using the heavy harvest parameter *a* in Table 2, we estimate the following:

$$C_f(t \to \infty) = e^a = e^{5.72} = 304.9 Mg\, C\, ha^{-1} \tag{5}$$

In the absence of forest harvest or other disturbance, forest carbon asymptotically approaches such a maximum carbon sequestration level over many years.

There is considerable uncertainty about the long-term accuracy of forest growth models. The Manomet report notes that the FVS simulator and similar models provide a high degree of accuracy for growth periods of only 30–50 years, and the FVS simulator has been shown to be an unreliable predictor of aboveground live carbon accumulation rates in northeastern US late-successional and old-growth forests (Gunn *et al.*, 2014). Small changes in parameter assumptions or measurements have also been shown to greatly affect results in such models (Buchholz *et al.*, 2013). A system dynamics model as used in this study focuses on the structure of the problem, yielding similar qualitative results under a wide range of possible parameter values. As shown in Fig. 1, with biomass energy use, there is a circular flow of carbon from forests to the atmosphere and back to forests, while with fossil fuel use, there is a one-way flow of carbon from the Earth to the atmosphere. Although forests absorb atmospheric carbon, a forest carbon sink is essentially finite, and net carbon absorption is greatly reduced as the carbon sink fills. These characteristics are critical aspects of the problem, and given this problem structure, the model ultimately yields similar results regardless of specific assumptions about forest growth rates or capacities of forest carbon sinks.

We first consider a single biomass harvest followed by forest regrowth, or an impulse response function as modeled in the

Manomet report and by others (Cherubini *et al.*, 2011). For each harvest scenario, we calibrate the model to match Manomet estimates for carbon debt, payback, carbon dividend in 2050, and carbon dividend in 2100 for biomass thermal energy compared to oil. As shown in Table 3, our results for other technology scenarios are substantially the same as the Manomet results, and any differences are not large enough to affect conclusions or policy implications. For each scenario, we generate estimates of initial carbon release (a current cost) and subsequent annual carbon sequestration (future benefits). From these carbon changes, we then calculate internal rates of return (IRR) for each technology and harvest scenario.

While analyzing a single forest biomass harvest is analytically convenient, it is not necessarily representative of actual policy choices. If biomass is an attractive energy source now, it may be in the future as well. Periodic forest harvest may continue, with some forest regrowth and carbon sequestration taking place between harvest events. Besides being more realistic, such a long-term perspective also illustrates more clearly the difference between using fossil fuels compared to forest biomass, and the implications of discounting future carbon flows. Holtsmark (2012) demonstrates that when one considers a continuing series of forest harvests, the atmospheric carbon increase is ongoing. Under active management for biomass energy (and/or timber), forest plots never reach their maximum carbon sequestration levels. We model a series of 10 harvests over a 220-year simulation. We compare the atmospheric carbon results of using forest biomass to different fossil fuel alternatives, modeling an initial atmospheric carbon stock of zero, without considering any other sources or sinks of carbon. To make a clear comparison, we model fossil fuel use only at 22-year intervals, in the same years as biomass harvest and combustion.

Quantifying temporal values of carbon emissions

With the carbon debt–dividend analysis alone, it is difficult to compare the option of forest biomass energy to using fossil fuels. For some forest biomass energy scenarios, we trade increased atmospheric carbon in the short run for decreased levels in the long run. But it is not clear how to value the short-term carbon losses against the long-term gains from future carbon sequestration. Conventional economic tools are well suited to this purpose.

Conceptually, the problem is identical to making a capital investment now in order to obtain a flow of benefits at points in the future. Several economic metrics are available to assess the value of such capital investments. All depend on the concept of discounting, or assessing the present value of a future benefit at some fraction of its future value, because we must wait to receive a future benefit. The annual rate at which we discount future benefits is the discount rate. In this analysis, we calculate the internal rate of return (IRR) for carbon emissions, which is the discount rate at which net present value is equal to zero. At this discount rate, the cost of the initial carbon release is exactly balanced by the present value of benefits from future carbon sequestration. A project with an IRR greater than the discount rate is considered desirable, that is, the returns from the project are greater than required. The choice of an appropriate discount rate then becomes the key question to assess the temporal value of carbon emissions, as discussed above.

In this analysis, our unit of measurement is Mg C rather than a monetary value. Some previous studies have specifically recommended discounting only future financial flows and not discounting physical flows, because only perceived value can be affected by the passage of time – a ton of carbon is still a ton of carbon at any point in time (EPA 2014). But in this case, we use a ton of carbon as proxy for damage caused by climate change. While the specific climate change cost of each ton of carbon is unknown (and perhaps unknowable), the IRR calculated from the carbon flows is the same for any constant price of carbon. For example, a constant price of \$1, \$10, or \$100 per ton of carbon yields the same IRR for the carbon flows modeled. We can thus derive

Table 3 Manomet report and STELLA model estimates of carbon paybacks and dividends

Heavy Biomass Harvest	Carbon payback (year)		Carbon dividend 2050 (percent)		Carbon dividend 2100 (percent)	
Technology	STELLA	Manomet	STELLA	Manomet	STELLA	Manomet
Biomass thermal vs. oil	15	15	39	39	66	66
Biomass thermal vs. gas	40	37	11	14	51	52
Biomass electricity vs. coal	35	32	19	22	55	56
Biomass electricity vs. gas	93	85	−65	−59	8	11
Light Biomass Harvest	Carbon payback (year)		Carbon dividend 2050 (percent)		Carbon dividend 2100 (percent)	
Technology	STELLA	Manomet	STELLA	Manomet	STELLA	Manomet
Biomass thermal vs. oil	10	10	53	53	76	76
Biomass thermal vs. gas	29	31	31	34	65	67
Biomass electricity vs. coal	25	27	37	40	68	70
Biomass electricity vs. gas	60	59	−27	−22	35	39

information about temporal values of carbon emissions even without specific knowledge of the damage caused by each ton of emissions. We do assume a constant marginal cost of carbon over time, which as discussed above may not be the case, and may justify using a lower social discount rate. Unlike the carbon debt and dividend metrics, the IRR for forest biomass carbon emissions is an explicit measure of the value of carbon emission and sequestration occurring at different points in time, reflecting the option value of sequestering forest carbon in the future. In general, a higher IRR or rate of return is preferred to a lower one, and a lower discount rate justifies accepting projects with lower IRR.

Results

Table 4 shows changes in carbon debt and associated IRR for the four technology scenarios and two harvest scenarios modeled. The lighter biomass harvests have higher IRR estimates, given lower initial carbon emissions and faster recovery of forest carbon. Some energy applications also have better IRRs, notably the scenarios comparing forest biomass thermal energy to oil. As natural gas has the lowest carbon content of the biomass and fossil fuels considered here, the IRR estimates for forest biomass energy compared to natural gas energy are lower than for other applications.

In Figs 3–6, we show graphical representations of forest and atmospheric carbon stocks over time, with forests harvested for bioenergy as compared to no harvest scenarios. While no harvest is not necessarily a realistic policy scenario, this assumption shows the greatest possible contrast between using and not using forests for bioenergy.

Table 4 Estimated internal rates of return (IRR) for forest biomass carbon emissions

Heavy biomass harvest	Biomass thermal vs. oil thermal 8.3% IRR*		Biomass thermal vs. gas thermal 1.6% IRR*		Biomass electricity vs. coal electricity 2.1% IRR*		Biomass electricity vs. gas electricity 0.1% IRR*	
Year	Carbon debt (Mg)	Carbon debt change (Mg)	Carbon debt (Mg)	Carbon debt change (Mg)	Carbon debt (Mg)	Carbon debt change (Mg)	Carbon debt (Mg)	Carbon debt change (Mg)
0	1.44	−1.44	6.66	−6.66	5.58	−5.58	11.88	−11.88
10	0.54	0.90	5.76	0.90	4.68	0.90	10.98	0.90
20	−0.56	1.10	4.66	1.10	3.58	1.10	9.88	1.10
30	−2.86	2.30	2.36	2.30	1.28	2.30	7.58	2.30
40	−5.16	2.30	0.06	2.30	−1.02	2.30	5.28	2.30
50	−6.46	1.30	−1.24	1.30	−2.32	1.30	3.98	1.30
60	−7.56	1.10	−2.34	1.10	−3.42	1.10	2.88	1.10
70	−8.56	1.00	−3.34	1.00	−4.42	1.00	1.88	1.00
80	−9.56	1.00	−4.34	1.00	−5.42	1.00	0.88	1.00
90	−10.26	0.70	−5.04	0.70	−6.12	0.70	0.18	0.70
100	−10.96	0.70	−5.74	0.70	−6.82	0.70	−0.52	0.70

Light biomass harvest	Biomass thermal vs. oil thermal 12.5% IRR*		Biomass thermal vs. gas thermal 2.5% IRR*		Biomass electricity vs. coal electricity 3.2% IRR*		Biomass electricity vs. gas electricity 0.5% IRR*	
Year	Carbon debt (Mg)	Carbon debt change (Mg)	Carbon debt (Mg)	Carbon debt change (Mg)	Carbon debt (Mg)	Carbon debt change (Mg)	Carbon debt (Mg)	Carbon debt change (Mg)
0	0.46	−0.46	2.11	−2.11	1.77	−1.77	3.76	−3.76
10	−0.02	0.48	1.63	0.48	1.29	0.48	3.28	0.48
20	−0.80	0.78	0.85	0.78	0.51	0.78	2.50	0.78
30	−1.68	0.88	−0.03	0.88	−0.37	0.88	1.62	0.88
40	−2.28	0.60	−0.63	0.60	−0.97	0.60	1.02	0.60
50	−2.78	0.50	−1.13	0.50	−1.47	0.50	0.52	0.50
60	−3.28	0.50	−1.63	0.50	−1.97	0.50	0.02	0.50
70	−3.78	0.50	−2.13	0.50	−2.47	0.50	−0.48	0.50
80	−3.86	0.08	−2.21	0.08	−2.55	0.08	−0.56	0.08
90	−3.93	0.07	−2.28	0.07	−2.62	0.07	−0.63	0.07
100	−3.98	0.05	−2.33	0.05	−2.67	0.05	−0.68	0.05

*Although carbon debts are only shown at 10-year intervals, IRR is calculated from annual debt change.

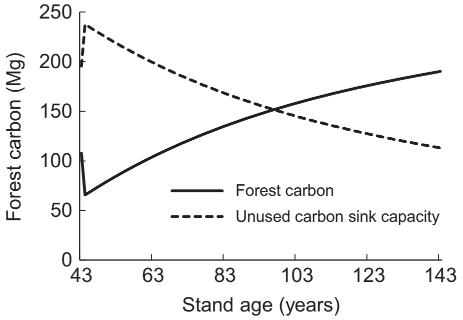

Fig. 3 Aboveground forest carbon and unused forest carbon sink capacity with heavy harvest (44.5 Mg C) at stand age of 43 years, for a representative hectare of Massachusetts forest.

The solid line in Fig. 3 shows change in the carbon stock over a 100-year simulation, with a heavy harvest followed by carbon accumulation starting at the rate of a 43-year-old plot. The initial carbon loss is partly responsible for a carbon debt which is gradually restored. Forest carbon returns to its original level 22 years after harvest in this scenario. The dashed line in Fig. 3 shows the changing capacity of the forest plot as a carbon sink – the inverse of the solid line. As the forest harvest releases carbon to the atmosphere, it also increases the capacity of the forest carbon sink, which has a value for future carbon sequestration.

Figure 4 shows effects on forest carbon of continued periodic harvests. The solid line shows forest carbon levels with continuing heavy harvests, while the dashed line shows forest carbon that would accumulate over time without harvest. The area between the lines is the foregone carbon sequestration that would have occurred without forest harvest. A baseline with BAU or light harvest levels instead of no harvest would result in a lower dashed line with a more gradual slope and would imply less foregone carbon sequestration (less area between the biomass scenario and baseline curves).

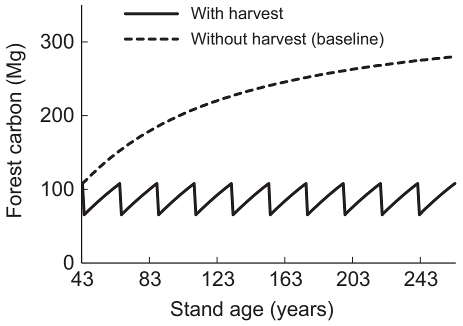

Fig. 4 Aboveground forest carbon with no harvest and with heavy harvest (44.5 Mg C) at 22-year intervals starting at stand age of 43 years, for representative hectare of Massachusetts forest.

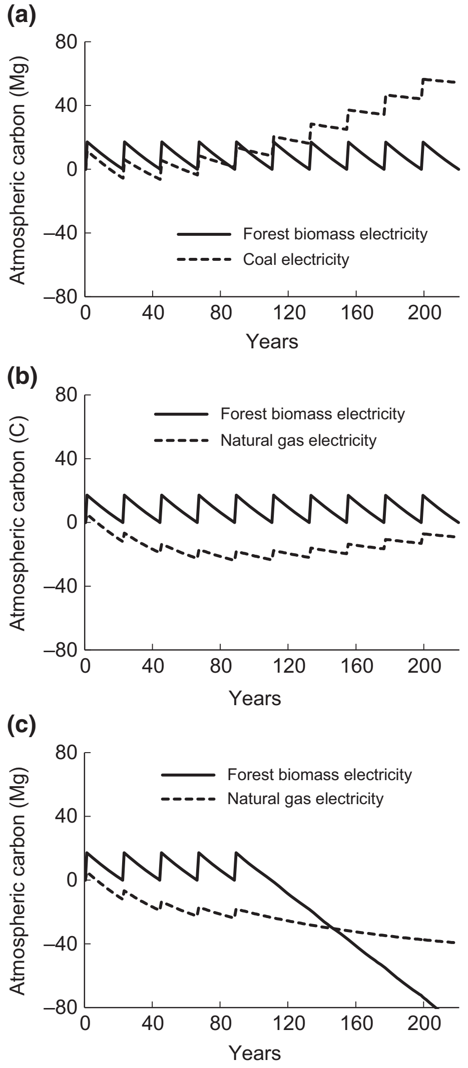

Fig. 5 (a) Atmospheric carbon using forest biomass electricity compared to coal electricity with no forest harvest. (b) Atmospheric carbon for forest biomass electricity compared to natural gas electricity with no forest harvest. (c) Atmospheric carbon for forest biomass electricity compared to natural gas electricity with no forest harvest, replacing both with carbon-free energy after 5 harvest cycles.

Figure 5a compares ongoing forest biomass electricity generation with electricity from coal. As described above, in the initial rotation the biomass option results in greater carbon emissions than coal. But the biomass carbon emissions are sequestered over one forest rotation and, importantly, never rise above the first harvest level of emissions. The ongoing increase in atmospheric carbon from biomass combustion that Holtsmark (2012) describes is a nonincreasing, fixed carbon cost of utilizing biomass energy. Atmospheric

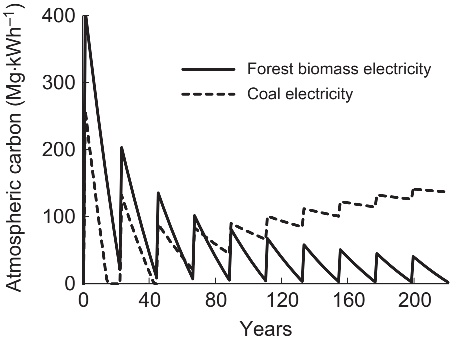

Fig. 6 Atmospheric carbon per unit of electricity produced for forest biomass electricity compared to coal electricity with no forest harvest.

carbon from burning coal is also mostly sequestered by the growing forest in the first few rotations. But recall that the forest carbon sink is finite: As the forest carbon sink fills and sequestration slows with forest age, the portion of coal emissions which can be sequestered decreases continuously. The coal carbon pattern approaches an orthogonal stairstep where each use results in an unabated carbon increase. Over the long time horizon modeled here, the paths of forest biomass energy use and coal utilization vary considerably, although this is not obvious in the first few forest rotation cycles.

While Fig. 5a compares forest biomass electricity to coal-generated electricity, Fig. 5b compares forest biomass electricity to electricity produced from natural gas. This scenario has the lowest IRR estimated, at just 0.1% (Table 4). As seen in Fig. 5b, natural gas has considerably lower initial carbon emissions than biomass. By utilizing the forest carbon sink, the atmospheric carbon levels for natural gas electricity drop below levels for forest biomass electricity. But the advantage diminishes over time, and eventually the same pattern emerges as in Fig. 5a: when the forest carbon sink fills, natural gas emissions increase atmospheric carbon in a stairstep pattern, so that atmospheric carbon from burning natural gas will eventually exceed carbon from using forest biomass (although this does not happen in the 220-year scenario modeled). By contrast, periodic carbon emissions from forest biomass combustion are always offset by subsequent growth and sequestration.

In Fig. 5c, we show the result of five forest biomass harvest cycles compared to five corresponding cycles of natural gas use for electricity generation, assuming that a carbon-free energy source replaces both biomass and natural gas after five cycles. Potential carbon-free energy sources could include wind, water, solar, and nuclear energy, combustion technologies with carbon capture and storage, and even currently unforeseen technologies. Although natural gas use appears to be preferable during the five harvest cycles, as soon as a carbon-free alternative replaces both combustion fuels, the atmospheric carbon level drops much faster in the biomass scenario than in the natural gas scenario: The five cycles of natural gas use partially filled the finite forest carbon sink, while the use of forest biomass did not.

As the ongoing increase in atmospheric carbon from continued use of forest biomass energy (Holtsmark, 2012) is fixed, the carbon emission per unit of energy produced decreases continuously with more energy production. In this sense, forest biomass carbon emissions can be considered carbon neutral over time: as shown in Fig. 6 for biomass electricity compared to coal electricity, over an infinite series of harvests biomass carbon per kWh approaches zero. By contrast, net coal emissions per kWh increase as the forest carbon sink fills and approach the unabated emissions level determined by the carbon content of coal. Filling the forest carbon sink is a one-time benefit that cannot be repeated, and its contribution to reducing carbon emissions from fossil fuels approaches zero over an infinite horizon of fossil fuel use.

Discussion

Interpreting IRR results with respect to private and social discount rates

As shown in Table 4, the atmospheric carbon IRR for forest biomass energy compared to oil in thermal applications is 12.5% for the light harvest scenario and 8.3% for the heavy harvest scenario. These returns are greater than typical private discount rates, and forest biomass energy should thus be unambiguously preferred to oil use in thermal applications as modeled here. Returns for these scenarios are also substantially greater than the social discount rate of 4.5% constructed from recent studies cited by the IPCC (Table 1).

For every application considered here except generating biomass electricity compared to an alternative of natural gas generation, the IRR exceeds Stern Review's 1.4% discount rate (Table 4). Using the Stern Review assumptions would thus favor forest biomass energy in every application except the lowest IRR scenarios. Near-zero discount rates as discussed above favor forest biomass energy in every application modeled here. As shown graphically in Fig. 5a–c, while utilizing forest biomass energy results greater initial carbon emissions than fossil fuel use, forest biomass energy (along with sustainable forest management) results in lower long-term atmospheric carbon levels in every application modeled. Note that for electricity generation, a discount rate greater than 0.1% would favor natural gas over forest biomass energy and would favor the natural gas emissions path in a scenario such as depicted in Fig. 5c. This may be preferred in the present but is clearly worse for future generations. A zero social discount rate implies that society is indifferent between benefits now or later, so with a zero social discount rate, forest biomass energy is always preferred for the options studied here.

Based on current understanding of global carbon sink dynamics, a portion of fossil fuel emissions remains in the atmosphere indefinitely: While carbon sinks like the ocean slowly absorb atmospheric carbon, the atmospheric portion of remaining emissions asymptotically approaches a level greater than zero (Cherubini *et al.*, 2011). This implies a possibly infinite stream of damages from fossil fuel carbon emissions. Thus with a zero discount rate, the net present value of choosing biomass energy over fossil fuel is infinite (as an infinite stream of damages is avoided). To the extent we discount future damages, we favor short-term gains over long-term losses.

As shown in Fig. 5a–c, biomass energy appears to have long-term advantages even when the estimated IRR is low, which may also suggest that near-zero discount rates are appropriate for the case of biomass carbon emissions. For example, Fig. 5a depicts biomass electricity vs. coal electricity, a scenario with an estimated IRR of only 2.1%. Yet graphically, it is clear that the biomass scenario is preferable to coal for reducing long-term atmospheric carbon levels. Similarly, Fig. 5b depicts biomass electricity as compared to natural gas, a scenario with only a 0.1% IRR. Even in this worst-case IRR scenario, with a long enough time horizon biomass energy use will eventually result in lower atmospheric carbon levels than fossil fuel. Figure 5c illustrates that one result of using forest biomass energy now is preserving future carbon sink capacity. If carbon-free energy is eventually adopted, these preserved carbon sinks would provide future benefits by reducing atmospheric carbon levels.

The IRR estimates presented here are specific to the Massachusetts forest growth and harvest conditions modeled. In general, forests with greater growth rates will provide greater carbon IRR and those with slower growth will provide lower IRR. Although the IRR estimates in other locations will vary, biomass technology choices with greater efficiency (e.g., thermal applications) should always have greater IRR than for lower efficiency technology, and low or near-zero discount rates should always be more favorable to forest biomass energy as compared to fossil fuel use.

Other forest biomass energy considerations

In many cases, policy decisions to support forest biomass energy will not require a near-zero discount rate. Forest biomass energy has the strongest IRR when compared to using fossil fuel in thermal applications, suggesting that thermal uses are the best candidates for using forest biomass. Given the finite and relatively small forest biomass energy resources in some regions, all available forest biomass might be consumed in high-IRR thermal applications. For example, forest biomass could replace at most 21% of Massachusetts' current use of fuel oil (assuming 1.6 million Mg per year biomass harvest, 10.5 GJ energy content per Mg at 40% moisture, and 2012 Massachusetts residential and commercial consumption of distillate fuel oil of 2067 million liters). This is based on an upper-end estimate of forest biomass availability (Kelty *et al.*, 2008), which is likely unattainable due to harvesting, price, and other supply constraints. Fuel oil replacement in thermal applications also has the highest IRR of the forest biomass energy applications studied (Table 4), with an IRR of 12.5% (with light harvest), well above the mean social discount rate suggested by the studies shown in Table 1. At least in Massachusetts, policymakers could support use of forest biomass energy for replacing heating oil and utilize the entire sustainable forest biomass energy resource, without endorsing a near-zero discount rate for carbon emissions.

The Massachusetts biomass scenarios described in the Manomet report assume an intensification of existing forest harvest to increase biomass production. But forests may be harvested primarily for timber, with only logging residues (tops and branches), mill residues, and small-dimension roundwood being used for biomass energy. If not used for biomass energy, such feedstocks would decay over time, releasing their stored carbon as CO_2 or CH_4 even in the absence of combustion. In such practice forest biomass energy may have less carbon impact than modeled here, depending in part on changes in forest detrital carbon stocks compared to a 'no use' scenario (Canham, 2013).

The IRR estimates here assume use of current technology. A portion of the initial carbon debt occurs because biomass-burning equipment is less efficient than fossil fuel equipment, especially with respect to generating electricity from biomass. Improved technology, for example, from wood gasification processes, could narrow the difference between initial fossil and biomass energy carbon emissions. Using wood fuel with lower moisture content – for example, air-dried wood at 20% moisture content rather than wood at 40% moisture content as assumed here – would also reduce biomass carbon emissions per unit of energy produced by about 6%

(assuming wood high heat value is 19.8 MJ kg^{-1}, combustion efficiency is 85%, and carbon portion of wood is 50% by weight). In general, technological constraints such as different efficiencies of converting fuels to usable energy have a limited impact on carbon effects (Buchholz *et al*., 2015).

Policy implications

The EU as a whole, EU member countries, and the United States have recognized the potential role that forest-derived biomass can play in a future energy portfolio, while at the same time, acknowledging that biomass *per se* is not carbon neutral. Accounting for time dynamics of forest-based biomass carbon emissions is perceived as a major obstacle in both regions (EPA 2014; EU 2014). Our study contributes directly to EPA's efforts in establishing an appropriate framework for forest-based bioenergy carbon discounting (EPA 2014, Appendix B).

If a policy goal is minimizing atmospheric carbon, uses of forest biomass energy that have the highest IRR should have first priority for finite forest resources. In our Massachusetts case study, this includes replacing oil for thermal applications with forest biomass. Although not specifically studied here, results suggest that forest biomass in combined heat and power systems would likely provide strong returns compared to oil, and moderate returns compared to gas, because overall system efficiencies are similar to thermal efficiencies in applications that we studied. Forest biomass is also likely to perform well compared to coal in thermal applications (e.g., in institutional central heating plants that burn coal), because coal has a higher carbon content than oil. Additional, lower return uses of forest biomass energy to replace fossil fuels could be considered in situations where the sustainable forest biomass supply is greater than needed for higher return applications. This could require policymakers to consider adopting near-zero social discount rates with respect to carbon emissions.

Public policy could be used to steer forest biomass utilization toward practices resulting in lower initial carbon emissions, especially to use of logging and mill wastes for biomass energy, and to lighter biomass harvests which have better rates of return on future carbon sequestration. Policy could also support research and development on new forest biomass utilization technology, which could shrink the carbon debt incurred when fossil fuels are replaced by forest biomass energy.

As noted above, induced market effects may mitigate carbon emissions from additional harvests (Daigneault *et al*., 2012; Galik & Abt, 2012; White *et al*., 2013) and may justify climate change mitigation policies supporting use of forest biomass energy. Yet the primary carbon emissions and sequestration effects are also relevant, as they are the main drivers of total carbon effects. Primary forest effects may also be more certain and less context dependent than macrolevel effects attributable to market forces. The forest ecosystem carbon discounting approach described above provides a stronger theoretical basis for biomass carbon policy than carbon payback, and the carbon discounting approach could also be applied in studies incorporating market effects.

Finally, if public policy supports forest biomass energy use, it must also ensure sustainable forest management in general. With such forest protections in place, utilizing forests for energy now does not preclude their use for carbon sinks later – the option value of future forest carbon sequestration can eventually be exercised. In a future change to carbon-free energy, the option of letting forests mature to reduce atmospheric carbon is still available. And if carbon-free energy never replaces forest biomass energy so that the forest carbon sink is never fully utilized, then biomass emissions approach zero per unit of energy produced. In either case, future generations are better off with forest biomass energy use now than with continued use of fossil fuels.

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References

Ackerman F, DeCanio SJ, Howarth RB, Sheeran K (2009) Limitations of integrated assessment models of climate change. *Climatic change*, **95** , 297–315.

Beckerman W, Hepburn C (2007) Ethics of the discount rate in the Stern Review on the economics of climate change. *World Economics*, **8** , 187.

Buchholz T, Friedland AJ, Hornig CE, Keeton WS, Zanchi G, Nunery J (2013) Mineral soil carbon fluxes in forests and implications for carbon balance assessments. *GCB Bioenergy*, **6** , 305–311.

Buchholz T, Hurteau MD, Gunn J, Saah D (2015) A global meta-analysis of forest bioenergy greenhouse gas emission accounting studies. *GCB Bioenergy*, (forthcoming).

Canham C (2013) Carbon cycle implications of forest biomass energy production in the northeastern United States. In: *Wood-Based Energy in the Northern Forests* (eds Jacobson M, Ciolkosz D), pp. 61–78. Springer, New York.

Cardellichio P, Walker T (2010) Why the Manomet study got the biomass carbon accounting right. *The Forestry Source*, **5**, 4–7.

Cherubini F, Peters GP, Berntsen T, Stromman AH, Hertwich E (2011) CO2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. *GCB Bioenergy*, **3** , 413–426.

Cherubini F, Stromman AH, Hertwich E (2013) Biogenic CO2 fluxes from bioenergy and climate–a response. *Ecological Modelling*, **253**, 79–81.

Daigneault A, Sohngen B, Sedjo R (2012) Economic approach to assess the forest carbon implications of biomass energy. *Environmental science & technology*, **46** , 5664–5671.

Daly HE (1974) The economics of the steady state. *The American Economic Review*, **64**, 15–21.

Dasgupta P, Maler K-G, Barrett S (1999) Intergenerational equity, social discount rates, and global warming. In (eds Portney PR, Weyant J), pp. 51–53. *Discounting and Intergenerational Equity*. Resource for the Future, Washington, DC.

EIA (2015) Total energy. Available at http://www.eia.gov/beta/MER/index.cfm?tbl=T01.03#/?f=M (accessed 4 February 2015).

EPA (2014) *Framework for Assessing Biogenic CO2 Emissions from Stationary Sources*. Environmental Protection Agency, Washington, DC.

Eriksson E, Gillespie AR, Gustavsson L, Langvall O, Olsson M, Sathre R, Stendahl J (2007) Integrated carbon analysis of forest management practices and wood substitution. *Canadian Journal of Forest Research*, **37** , 671–681.

EU (2014) *State of Play on the Sustainability of Solid and Gaseous Biomass Used for Electricity, Heating and Cooling in the EU*. European Commission, Staff Working Document 259 (final), Brussels.

European Commission (2014) *State of Play on the Sustainability of Solid and Gaseous Biomass Used for Electricity, Heating and Cooling in the EU*. Staff Working Document 259 (final), Brussels.

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. *Science*, **319**, 1235–1238.

Galik CS, Abt RC (2012) The effect of assessment scale and metric selection on the greenhouse gas benefits of woody biomass. *Biomass and Bioenergy*, **44**, 1–7.

Gunn JS, Ducey MJ, Whitman AA (2014) Late-successional and old-growth forest carbon temporal dynamics in the Northern Forest (Northeastern USA). *Forest Ecology and Management*, **312**, 40–46.

Holtsmark B (2012) The outcome is in the assumptions: analyzing the effects on atmospheric CO2 levels of increased use of bioenergy from forest biomass. *Global Change Biology: Bioenergy*, **5** , 467–473.

Hudiburg TW, Law BE, Wirth C, Luyssaert S (2011) Regional carbon dioxide implications of forest bioenergy production. *Nature Climate Change*, **1** , 419–423.

IEA (2012) *Technology Roadmap: Bioenergy for Heat and Power*. International Energy Agency, Paris. http://www.iea.org/publications/freepublications/publication/bioenergy.pdf (accessed 1 June 2015).

IPCC (2014) *Fifth Assessment Report, Climate Change 2014: Working Group III, Mitigation of Climate Change; Chapter 3: Social, Economic, and Ethical Concepts and Methods*. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Johnson E (2009) Goodbye to carbon neutral: getting biomass footprints right. *Environmental impact assessment review*, **29** , 165–168.

Kelty MJ, D'Amato AW, Barten PK (2008) *Silvicultural and Ecological Considerations of Forest Biomass Harvesting in Massachusetts*. University of Massachusetts, Amherst, MA.

Lamers P, Junginger M (2013) The 'debt' is in the detail: a synthesis of recent temporal forest carbon analyses on woody biomass for energy. *Biofuels, Bioproducts and Biorefining*, **7** , 373–385.

Lucier AA (2010) A fatal flaw in Manomet's biomass study. *The Forestry Source*, **4** , 4.

Luyssaert S, Schulze E-D, Borner A *et al.* (2008) Old-growth forests as global carbon sinks. *Nature*, **455** , 213–215.

Marland G, Schlamadinger B (1997) Forests for carbon sequestration or fossil fuel substitution? A sensitivity analysis. *Biomass and Bioenergy*, **13** , 389–397.

McKechnie J, Colombo S, Chen J, Mabee W, MacLean HL (2011) Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environmental science & technology*, **45** , 789–795.

Mika AM, Keeton WS (2015) Net carbon fluxes at stand and landscape scales from wood bioenergy harvests in the US Northeast. *Global Change Biology: Bioenergy*, **7**, 438–454.

Nordhaus WD (2007) "A Review of the" stern review on the economics of climate change. *Journal of Economic Literature*, **45**, 686–702.

Ramsey FP (1928) A mathematical theory of saving. *The Economic Journal*, **38**, 543–559.

Ryan M, Binkley D, Fownes JH (1997) Age-related decline in forest productivity: pattern and process. *Advances in ecological research*, **27**, 213–262.

Schlamadinger B, Marland G (1996) The role of forest and bioenergy strategies in the global carbon cycle. *Biomass and Bioenergy*, **10** , 275–300.

Schulze E-D, Korner C, Law BE, Haberl H, Luyssaert S (2012) Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. *Global Change Biology: Bioenergy*, **4** , 611–616.

Sterman JD (2000) *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Irwin McGraw-Hill, New York.

Stern N (2006) *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Cambridge, UK.

Tol RS (2009) The economic effects of climate change. *The Journal of Economic Perspectives*, **23** , 29–51.

Walker T, Cardellichio P, Colnes A *et al.* (2010) *Biomass Sustainability and Carbon Policy Study*. Manomet Center for Conservation Sciences, Manomet, MA.

Walker T, Cardellichio P, Gunn JS, Saah DS, Hagan JM (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** , 130–158.

White EM, Latta G, Alig RJ, Skog KE, Adams DM (2013) Biomass production from the US forest and agriculture sectors in support of a renewable electricity standard. *Energy policy*, **58**, 64–74.