NATURAL CAPITAL INITIATIVE AT MANOMET REPORT

# Biomass Sustainability and Carbon Policy Study

## Chapter 6

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# CHAPTER 6

# CARBON ACCOUNTING FOR FOREST BIOMASS COMBUSTION

## 6.1 INTRODUCTION

Greenhouse gas (GHG) emissions from bioenergy systems 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 biomass instead of fossil fuels for energy generation. In most cases, the carbon emissions produced when forest biomass is burned for energy are higher than the emissions from burning fossil fuels. But over the long term, this carbon can be resequestered 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. This chapter provides analysis designed to help inform these decisions.

As discussed in Chapter 1, 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 has been that because growing forests sequester carbon, then as long as areas harvested for biomass are remain forested, the carbon is reabsorbed in growing trees and consequently the net impact on GHG emissions is zero.[4] In this context, biomass combustion for energy production has often been characterized as 'carbon neutral.'

Assumptions of biomass carbon neutrality—the view that forest biomass combustion results in no net increase in atmospheric GHG levels—have been challenged on the grounds that such a characterization ignores differences in the *timing* of carbon releases and subsequent resequestration in growing forests (Johnson, 2008). 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. In 'closed loop' bioenergy systems— for example biomass from plantations grown explicitly to fuel bioenergy facilities—energy generation will be carbon neutral or close to carbon neutral if the biomass plantation represents stored carbon that would not have been there absent the biomass plantation. Net GHG impacts of biomass from sources other than natural forests may also be carbon neutral (or close) where these materials would have quickly entered the atmosphere through decay (e.g., residue from landscaping and tree work, construction waste). But for natural forests where stocks of carbon 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—resequestering all the forest biomass carbon emitted—may occur at some point in the future if the harvested land is sustainably managed going forward, for example under one of the widely recognized forest certification programs (e.g., FSC, SFI or PEFC). How long this will take for typical Massachusetts forest types and representative energy facilities, and under what conditions, is a primary focus of this study.

### 6.1.1 BRIEF REVIEW OF PREVIOUS STUDIES

The issue of net GHG benefits from burning forest biomass has 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 and Schlamadinger, 1995; Schlamadinger and Marland, 1996a, 1996b and 1996c). This work initially was based on insights from a simple spreadsheet model, which evolved over time into the Joanneum Research GORCAM model (Marland et al., undated). A variety of other models are now available for performing similar types of bioenergy GHG analyses. These include $CO_2$Fix (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 (Cowie, 2009).

In general, the scientific literature on the GHG impacts of forest biomass appears to be in agreement that impacts will 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). 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; and the characteristics of the fossil fuel system replaced. Recent research has also raised several other site-specific issues. Cowie (2009) cites research at Joanneum on albedo effects, which in some locations have the ability to offset some or potentially all the GHG effects of biomass combustion.[5] The effect of climate change itself on carbon flows into and out of soil and above-ground live and dead carbon pools is another factor that has yet to be routinely incorporated into biomass energy analyses.

Because of the site-specific nature of biomass GHG effects, we have developed an approach to evaluating impacts using available data on the characteristics of regional energy facilities and a forest

[4] Even when lifecycle biomass production emissions are taken into account, the argument is that net impacts on GHG, while perhaps not zero, are at least very low.

[5] This has generally been considered a more serious issue for harvests in forests located at higher latitudes than Massachusetts – areas where harvests interact with longer periods of snow cover to increase reflectivity.

ecosystems model that represents conditions in Massachusetts. In the next section, we discuss the overall carbon accounting framework for our analysis.

### 6.1.2 CARBON ACCOUNTING FRAMEWORK

Energy generation, whether from fossil fuel or biomass feedstocks, releases GHGs to the atmosphere. The GHG efficiency—the amount of lifecycle GHG emissions per unit of energy produced—varies based on both the characteristics of the fuel and the energy generation technology. However, 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).[6]

At the most general level, the carbon accounting framework we employ is constructed around comparisons of fossil fuel scenarios with biomass scenarios producing equivalent amounts of energy. The fossil fuel scenarios are based on lifecycle emissions of GHGs, using '$CO_2$ equivalents' as the metric ($CO_2$e).[7] 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. Most 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 acres 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. Our approach includes the above- and below-ground live and dead carbon pools that researchers have identified as important contributors to forest stand carbon dynamics.[8]

[6] More broadly, climate and energy policies should consider the full range of alternative sources of energy. Energy conservation and sources such as wind, solar or nuclear have no or very low carbon emissions and may also provide additional, potentially competing, options for reducing GHGs.

[7] These adjustments incorporate the IPCC's normalization factors for methane and nitrous oxides.

[8] Typically wood products would also be included as an important carbon pools but because we assume 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. We also have not modeled soil carbon explicitly as recent papers suggest that this variable is not particularly sensitive to wood harvests (Nave et al., 2010).

The conceptual modeling framework for this study is intended to address the question of how atmospheric GHG levels will change if biomass displaces an equivalent amount of fossil fuel generation in our energy portfolio. With this objective, the modeling quantifies and compares the cumulative net annual change in atmospheric $CO_2$e for the fossil and biomass scenarios, considering both energy generation emissions and forest carbon sequestration. In the fossil fuel scenarios, there is an initial $CO_2$e 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 acre—which is then followed by a drawing down over time (resequestration) of atmospheric $CO_2$e by an acre 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 acre of natural forest, followed by continued future growth and sequestration of carbon in the harvested stand.

This process is summarized in the hypothetical example shown Exhibit 6-1 below. Energy emissions represent flows of carbon to the atmosphere and forest sequestration represents capture of carbon that reduces atmospheric levels. We assume the fossil fuel and biomass scenarios produce exactly the same amount of useable energy. The example is based on a fossil fuel facility that generates 10 tonnes of lifecycle C emissions and a BAU (timber cutting but no biomass removals) where total stand carbon (TSC) in all pools is rising by 0.15 tonnes per year. In the biomass scenario, lifecycle bioenergy emissions are 15 tonnes of C and TSC on the forest, which was harvested for both timber and biomass, is increasing by 0.25 tonnes of C per year, a reflection of higher rates of forest growth that can result from increases in sunlight and growing space in the more heavily harvested stand.

The bottom row of Exhibit 6-1 shows the incremental emissions from biomass energy generation (5 tonnes C) and the incremental (beyond a BAU forest management scenario) change in forest carbon sequestration (0.1 t/C/y or 1 tonne of carbon per decade). The cumulative net change (referred to hereafter as the carbon 'flux') in atmospheric C is equivalent for the two feedstocks at the point in time where cumulative TSC increases, above and beyond the accumulation for the fossil fuel scenario, just offset the incremental C emissions from energy generation. In the example this occurs at year 2060 when the forest has sequestered an additional 5 tonnes of C, equivalent to the initial 'excess' biomass emissions. Before that time, cumulative carbon flux is higher for the biomass scenario, while after 2060 the biomass scenario results in lower cumulative atmospheric C flux. In this comparison, not until after 2060 would the biomass energy option become better than the fossil fuel with respect to impact on GHGs in the atmosphere. Furthermore, in the example full carbon neutrality would not be achieved, assuming no change in growth rates, until five decades after 2110, at which point the entire 15 tonnes of biomass energy emissions will have been recovered in new forest growth.

**Exhibit 6-1: Carbon Accounting Framework (tonnes-carbon)**

| Scenario | Energy Generation Emissions | Forest Stand Cumulative Total Carbon Accumulation | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | **2010** | **2020** | **2030** | **2040** | **2050** | **2060** | **2070** | **2080** | **2090** | **2100** | **2110** |
| **Biomass** | -15 | 2.5 | 5.0 | 7.5 | 10.0 | 12.5 | 15.0 | 17.5 | 20.0 | 22.5 | 25.0 |
| **Fossil** | -10 | 1.5 | 3.0 | 4.5 | 6.0 | 7.5 | 9.0 | 10.5 | 12.0 | 13.5 | 15.0 |
| **Net Change** | -5 | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 | 7.0 | 8.0 | 9.0 | 10.0 |

Adoption of this conceptual framework allows a useful and potentially important reframing of the biomass carbon neutrality question. From a GHG perspective, environmental policymakers in Massachusetts might prefer biomass to fossil fuels even if biomass combustion is not fully carbon neutral—that is even if biomass burning increases carbon levels in the atmosphere for some period of time. For example, it is possible that over some policy-relevant time frame burning biomass for energy could result in cumulatively lower atmospheric $CO_2e$ levels than generating the same amount of energy from coal, oil or natural gas—although these levels may still represent an increase in GHGs relative to today's levels. Rather than focusing all the attention on the carbon neutrality of biomass, our approach illustrates that there is a temporal component to the impacts of biomass GHG emissions to the atmosphere. The questions then become: (1) do policymakers seek to promote an energy source that could benefit the atmosphere over the long term, but that imposes increased GHG levels relative to fossil fuels in the shorter term (perhaps several decades); and (2) do the long term atmospheric benefits outweigh the short term costs?

A useful way to understand the relative carbon dynamics is to isolate the key drivers of net carbon flux. From this perspective, the incrementally greater amount of $CO_2e$ associated with biomass energy is the relevant starting point. Following on the terminology developed by Fargione et al. (2008), we refer to these incremental emissions as the biomass 'carbon debt.'

In addition, we introduce the concept of 'carbon dividends,' which represent the longer term benefits of burning biomass. In the example in Exhibit 6-1, these dividends can be thought of as the reductions in future atmospheric carbon represented in the years after the carbon debt has been recovered (i.e., after 2060). For example, by 2100 all 5 tonnes of excess C from biomass burning have been recovered plus another 4 tonnes (the dividend) that reflects additional reductions in emissions beyond what would have resulted if only fossil fuel had been used to generate energy.

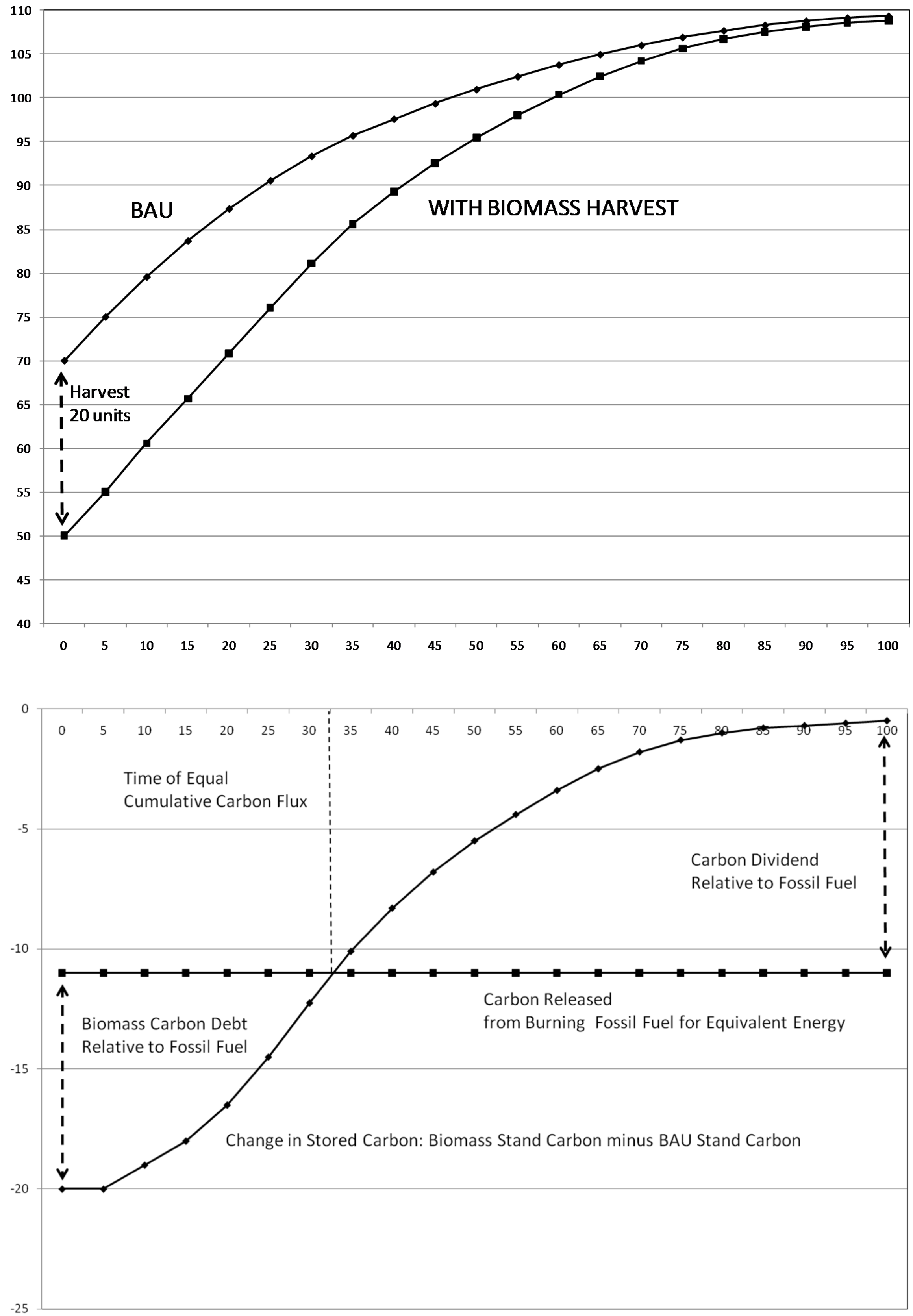
Graphically, the concepts of carbon debt and carbon dividend are illustrated in Exhibit 6-2. Exhibit 6-2a shows hypothetical carbon sequestration profiles for a stand harvested in a 'business as usual' timber scenario and the same stand with a harvest that augments the BAU harvest with removal of 20 tonnes of additional carbon. Exhibit 6-2b 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) that is needed to recover the biomass carbon debt and begin accruing carbon dividends (calculated as the difference in growth between the biomass and BAU harvests). In the 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.

**Exhibit 6-2a and 6-2b: Total Stand Carbon and Carbon Recovery Times (tonnes carbon)** (see next page)

The carbon dividend is defined in the graph as the fraction of the equivalent fossil fuel emissions (11 tonnes) that are offset by forest growth at a particular point in time. In the example, after the 9 tonne biomass carbon debt is recovered by forest growth (year 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, rising over time as the forest sequesters greater amounts of carbon relative to the BAU. Throughout this report we quantify these dividends as the percentage of the equivalent fossil fuel emissions that have been offset by forest growth. By approximately year 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.[9] In this context, a 100% carbon dividend (almost achieved in year 100 in the 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 tradeoff 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.

[9] 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.

**Exhibit 6-2a and 6-2b: Total Stand Carbon and Carbon Recovery Times (tonnes carbon)**



To see why carbon debt is an important driver of impacts, consider the hypothetical case where a biomass fuel's lifecycle $CO_2$e 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 problematic when $CO_2$e emissions from biomass are above that of the fossil fuel alternative (i.e., where the carbon debts for biomass are positive). 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 problem 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. 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.

In this context, it is also 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.

### 6.1.3 OTHER CONSIDERATIONS: LANDSCAPE OR STAND-LEVEL MODELING

A key question in developing the conceptual framework for biomass GHG analysis is whether to analyze the problem at the level of the individual stand or across the entire landscape affected by biomass harvests. A recent formulation of the biomass carbon neutrality argument focuses on the forested landscape across the entire wood supply zone for a biomass plant—as opposed to individual harvested stands—and suggests that as long as landscape-scale forest growth is in excess of harvests, then biomass is embedded in the natural carbon cycle of the forests and is causing no net increase in GHG emissions (Miner, 2010). In our view, however, this landscape approach to carbon neutrality is incomplete because it does not fully frame the issue with respect to the carbon sequestration attributes of the forested landscape in a 'business as usual' scenario. In general, the carbon accounting model should be premised on some knowledge of how lands will be managed in the future absent biomass harvests, and this becomes a critical reference point for analyzing whether burning biomass for energy results in increased or decreased cumulative GHG emissions over time.

Consequently, appropriate characterization of the BAU baseline is essential to the development of an accurate carbon accounting model of forest biomass combustion. In the case of the landscape argument for carbon neutrality, the conclusion that biomass burning has no net impact on GHG emissions does not account for the fact that in the absence of biomass harvests, the forests would likely have continued to sequester carbon anyway.[10] Therefore, a well-framed landscape analysis needs to consider the net carbon emissions of biomass burning relative to the BAU scenario of continued carbon accumulation by forests across the landscape. Framing the problem this way does not necessarily negate the landscape carbon neutrality argument—it simply recognizes that the landscape level carbon accounting problem is a more complicated one. However, when a complete representation of the baseline is taken into account, the landscape-scale and the

10 This assumes that additional biomass stumpage revenues will not dramatically alter the acreage devoted to commercial forestry activities. We believe this is a reasonable assumption given the current low prices for biomass stumpage. At $1 to $2 per green ton, few, if any, landowners would see enough change in revenue from biomass sales to alter their decisions about whether to keep forest land or sell it to someone who is looking to change the land use (e.g., a developer). As a result, we do not address the carbon issues associated with conversion of natural forests to energy plantations. We also do not address 'leakage' issues that might arise if productive agricultural land is converted to energy plantations and this leads to clearing forests somewhere else to create new cropland.

stand-level frameworks may yield the same result. The following simplified numerical example provides an illustration of why this is the case.

The example assumes an integrated energy/forest system made up of three carbon pools—the forest, atmosphere, and fossil fuel pools—each initially containing 1000 tonnes of carbon. In addition, we assume burning biomass releases 50 percent more emissions than burning fossil fuels for an equivalent level of energy production—close to the estimate of carbon debts when comparing biomass and coal-fired electricity generation. Finally, we specify that an average forest's total stand carbon across the above- and below-ground carbon pools increases by 5% per year, or 50 tonnes in our example.

In year one of a coal-fired electric scenario, we assume energy production at a level that transfers 10 units of carbon from the fossil fuel pool to the atmosphere. In the same year, the forest removes 50 tonnes of carbon from the atmosphere. The net values for each pool after one year are:

- **Fossil Fuel Carbon Pool:** 990 tonnes (1000 tonnes–10 tonnes released from energy production)
- **Forest Carbon Pool:** 1050 tonnes (1000 tonnes + 50 tonnes forest sequestration)
- **Atmospheric Carbon Pool:** 960 tonnes (1000 tonnes+ 10 tonnes emissions–50 tonnes forest sequestration).

Alternatively, we consider a change in energy production that replaces fossil fuel with biomass, in this case releasing 15 tonnes of carbon versus 10 tonnes in the equivalent energy fossil scenario. We also assume that cutting the forest does not reduce total carbon sequestration (i.e., that the harvested areas of the forest still add carbon at the 5 percent rate).[11] At the end of the first year, the carbon pools are as follows:

- **Fossil Fuel Carbon Pool:** 1000 tonnes (no change)
- **Forest Carbon Pool:** 1035 tonnes (1000 tonnes–15 tonnes biomass + 50 tonnes forest sequestration)
- **Atmospheric Carbon Pool:** 965 tonnes (1000 tonnes + 15 tonnes emissions–50 tonnes forest sequestration).

In the example, it is true that forest growth across the landscape exceeds the amount of biomass harvested (50 tonnes of new sequestration versus 15 tonnes of biomass removals)—the condition under which advocates of landscape-level carbon neutrality would argue that biomass burning is embedded in a natural cycle in which forest sequestration (50 t-C/y) exceeds removals for biomass (15 t-C/y). But it is also true that the initial effect of switching to biomass is to increase atmospheric carbon levels, in this case by 5 tonnes. The result makes clear that when the BAU baseline is correctly specified, the net change in GHG from biomass is equivalent to the biomass carbon debt, and therefore that carbon neutrality is not achieved immediately.

Introducing the assumption that additional stands are harvested in subsequent years to provide fuel for a biomass plant—while adding greater complexity to the analysis—does not alter the basic conclusions as long as stands are harvested randomly (e.g., stands with rapid carbon recovery rates are no more or less likely to be harvested than stands with slower carbon recovery). For each additional year of harvests, a carbon debt is incurred and these are additive over time. Similarly, the period required to pay off the debt is extended one year into the future for each additional year of harvests. Finally, the longer-term dividends are also additive and will accumulate over time as greater quantities of fossil fuel emissions are offset by forest growth.

The one area where landscape scale analysis might alter conclusions about carbon debts and dividends is a situation where the stands with more rapid carbon recovery profiles can be scheduled for harvest sooner than the slower recovery stands. This has the potential to accelerate the time to debt payoff and the onset of the carbon dividends. To implement such an approach, one would need to be able to identify the characteristics of the rapid carbon recovery stands and be able to influence the scheduling of harvests across the landscape. Detailed analysis to clearly identify rapid recovery stands is beyond the scope of the analysis in this report. Nonetheless, we would like to note that, while harvest scheduling may be possible for large industrial forest ownerships, it would be difficult to accomplish across a landscape like Massachusetts that is fragmented into many small ownerships. For this report, we have confined our focus to stand level analyses, which should provide useful indicators of the timing and magnitude of carbon debts and dividends in Massachusetts.

## 6.2 TECHNOLOGY SCENARIOS AND MODELING ASSUMPTIONS

### 6.2.1 OVERVIEW OF TECHNOLOGIES AND APPROACH

To illustrate the relative carbon life-cycle impacts associated with various energy scenarios, we compare the emission profiles for a representative set of biomass energy generation facilities relative to their appropriate fossil fuel baselines. Our analysis considers the following technologies:

- **Utility-Scale Electric:** A utility-scale biomass electric plant (50 MW) compared to a large electric power plant burning coal or natural gas.
- **Thermal Chips:** A thermal generation facility relying on green biomass chips relative to a comparable facility burning fuel oil (#2 or #6) or natural gas.

[11] This is likely a conservative scenario for the first year after harvest when the stand is recovering from the impacts of the cut. Assuming a lower than 5% rate of carbon growth on these acres would lower the overall average across the landscape to below 5%; the assumptions made above therefore may overstate the amount of carbon in the forest pool and understate the carbon in the atmosphere.

- **Thermal Pellets:** A thermal generation facility relying on wood pellets relative to a comparable facility burning fuel oil or natural gas.
- **CHP:** A combined heat and power (CHP) facility compared to a similar facility burning oil or natural gas.

We selected these scenarios to illustrate the range of likely wood-based bioenergy futures that we judge to be feasible in the short- to mid-term in Massachusetts. This choice of technologies reflects differences in scale, efficiency and fuel choice. The emission profiles of more advanced technologies—such as cellulosic ethanol production and biomass pyrolysis—are not modeled based on lack of commercial demonstrations, scale requirements that make development in Massachusetts unlikely, or because of a lack of available GHG emissions data.

As detailed in our conceptual framework, each scenario is made up of two primary components: a stand-level forest carbon model and an energy facility GHG emissions model. In the fossil fuel scenarios, we assume the stand is harvested for timber but not for biomass. We then track the total amount of C in the stand's various carbon pools—including above- and below-ground live and dead wood—over a 90-year time frame. For the biomass scenarios, consistent with the supply analysis discussed in Chapter 3, we assume a heavier harvest that removes additional material in the form of logging residues and low-quality trees. For each scenario, we then model the change in total stand carbon over the same 90-year time frame in order to provide comparisons of net changes in total stand-level carbon relative to the baseline 'no biomass' scenario. The energy facility emissions model is designed to take into account both the direct stack emissions of energy generation as well as the indirect emissions that come from producing, processing and transporting fuels to the facility. These are expressed as (1) biomass carbon debts, which denote the incremental percentage of carbon emissions due to harvesting and combusting wood relative to the lifecycle GHG emissions of the alternative fossil fuel, and (2) biomass carbon dividends which are the longer term benefits from reducing GHGs below fossil baseline levels. For each scenario, the combined forest and energy carbon models provide an appropriate accounting for the emissions from energy production and the carbon sequestration behavior of a forest stand that has been harvested (1) only for timber or (2) for both timber and biomass.

The details of the forest harvest scenarios are described below, followed by a discussion of the GHG modeling process for energy facilities.

## 6.2.2 FOREST HARVEST SCENARIOS

We take the individual stand as the basis for our carbon accounting process. For the fossil fuel baseline scenarios, we assume a 'business as usual' forest management approach where the stand is harvested for timber but not for biomass. The model provides a dynamic baseline for comparisons with the biomass alternative. The scenarios are summarized in Exhibit 6-3 below 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 Forest Cutting Plan data discussed in Chapter 3. We assume in the BAU that all logging residues are left in the forest.

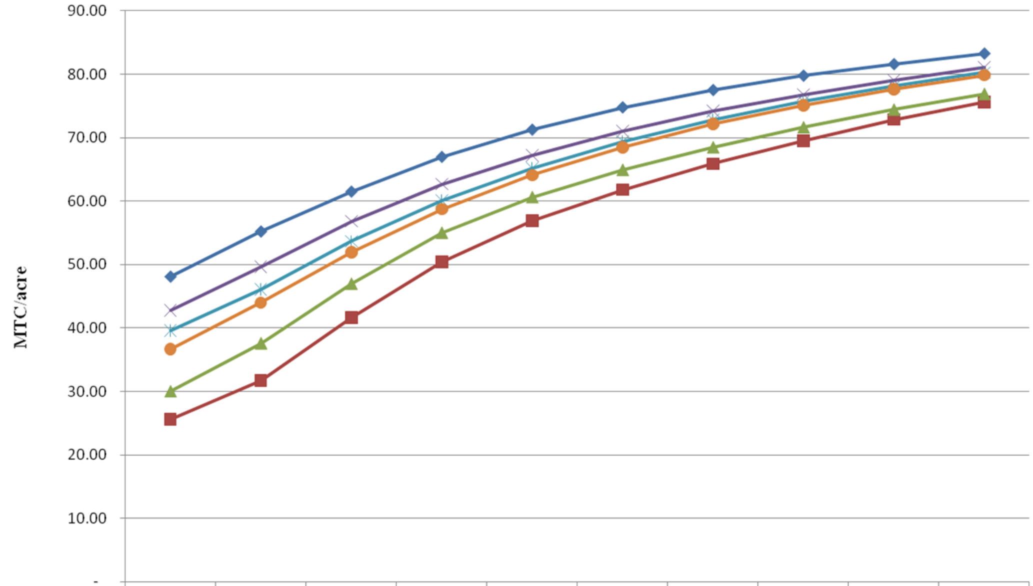
Using the FVS model, described in Chapter 5, we quantify changes in total stand carbon by decade through an evaluation of carbon in the above- and below-ground live and dead carbon pools for the following six biomass harvest scenarios. Carbon recovery profiles represent averages for a set of 88 plots in the Massachusetts FIA database with an initial volume of more than 25 tonnes of carbon per acre in the above-ground live pool.

**Exhibit 6-3: BAU and Biomass Harvest Scenarios**

| Harvest Category | Description | Carbon Removed (tonnes) | Above-Ground 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 60 ft2 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 40 ft2 of stand basal area | 24.3 | 76 | 35 |

The results of the FVS analysis provide profiles of total stand carbon and above-ground live carbon over time for the BAU and biomass harvest scenarios. These are graphed on the next page in Exhibits 6-4 and 6-5.

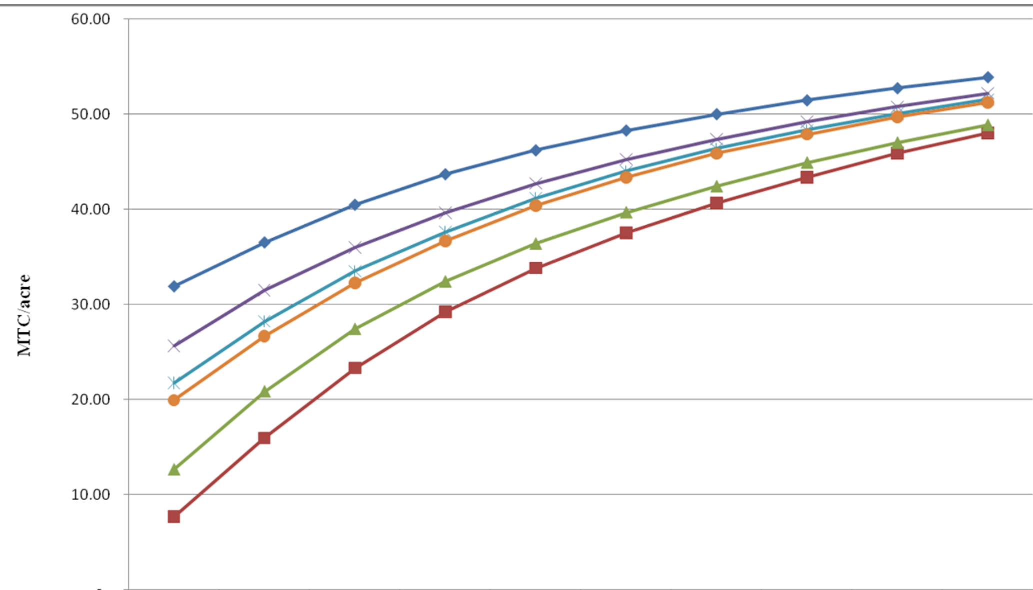
### Exhibit 6-4: Total Stand Carbon




| | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|
| Unmanaged | 48.09 | 55.21 | 61.50 | 66.97 | 71.27 | 74.78 | 77.52 | 79.77 | 81.60 | 83.27 |
| Biomass BA40 | 25.61 | 31.74 | 41.63 | 50.44 | 56.91 | 61.78 | 65.90 | 69.51 | 72.86 | 75.60 |
| Biomass BA60 | 30.01 | 37.58 | 46.97 | 55.00 | 60.62 | 64.92 | 68.47 | 71.63 | 74.42 | 76.89 |
| BAU 20% | 42.81 | 49.66 | 56.82 | 62.69 | 67.25 | 71.05 | 74.18 | 76.81 | 79.05 | 81.06 |
| BAU 32% | 39.62 | 46.12 | 53.68 | 60.08 | 65.18 | 69.43 | 72.84 | 75.74 | 78.11 | 80.27 |
| Biomass 40% | 36.67 | 44.00 | 51.94 | 58.74 | 64.10 | 68.50 | 72.17 | 75.12 | 77.64 | 79.87 |

Year - MTC/acre (Total Stand Carbon)

### Exhibit 6-5: Above-Ground Live Stand Carbon




| | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|
| Unmanaged | 31.91 | 36.53 | 40.49 | 43.70 | 46.22 | 48.30 | 50.02 | 51.47 | 52.75 | 53.90 |
| Biomass BA40 | 7.66 | 15.93 | 23.29 | 29.22 | 33.81 | 37.53 | 40.66 | 43.37 | 45.92 | 48.01 |
| Biomass BA60 | 12.62 | 20.83 | 27.40 | 32.40 | 36.38 | 39.67 | 42.42 | 44.91 | 47.01 | 48.87 |
| BAU 20% | 25.64 | 31.47 | 35.98 | 39.64 | 42.71 | 45.27 | 47.38 | 49.20 | 50.80 | 52.22 |
| BAU 32% | 21.76 | 28.22 | 33.49 | 37.63 | 41.15 | 44.01 | 46.38 | 48.34 | 50.05 | 51.56 |
| Biomass 40% | 19.93 | 26.67 | 32.27 | 36.68 | 40.39 | 43.36 | 45.88 | 47.90 | 49.71 | 51.26 |

Year - MTC/acre (Aboveground Live Carbon)

Due to model constraints, the FVS analyses rely on 'thin-from-above' harvest strategies to simulate both BAU and biomass harvests, although we conducted some limited analysis of the sensitivity of the results to alternative assumptions. For all the biomass harvests, we assume 65% of the logging residues are removed from the forest, with the remainder left on the ground.

The results were analyzed to determine how the stands harvested for biomass responded relative to their response in the BAU scenario. This analysis is designed to show relative rates of recovery of forest carbon stocks following biomass harvests.

### 6.2.3 BIOMASS AND FOSSIL FUEL GHG EMISSIONS

To estimate biomass carbon debts relative to fossil fuel technologies, we assembled estimates of GHG emissions per unit of energy produced by each technology. These estimates included both the direct combustion emissions as well as the indirect emissions related to feedstock production, processing and transportation. To the extent that data were available, we work in $CO_2$ equivalents ($CO_2e$), a metric that considers other greenhouse gases (e.g., methane from coal mines) and expresses them in terms of the amount of $CO_2$ that would have an equivalent global warming effect. The emissions estimates for both the biomass and fossil fuel technologies are shown below in Exhibit 6-6, where they have been converted to kilograms of carbon per energy unit.

**Exhibit 6-6: Carbon Emission Factors by Technology* Kilograms per Unit of Energy****

| Scenarios | Biomass | Coal | Oil (#6) | Oil (#2) | Natural Gas |
|---|---|---|---|---|---|
| **Utility-Scale Electric** | **Kilograms/MWh** | | | | |
| Fuel Prod & Transport | 7 | 9 | | | 34 |
| Fuel Combustion | 399 | 270 | | | 102 |
| Total | 406 | 279 | | | 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 |

** As discussed below, emissions factors for pellets are characterized relative to the thermal technology using green chips which is shown in this table.*

*** Sources and calculations for these data are described in the text.*

**Emissions from Biomass Harvest, Processing and Transportation:** For the biomass technologies, we include estimates of the $CO_2e$ releases associated with harvesting, processing and transporting the biomass fuel to a bioenergy facility. For green 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. We estimated harvest and chipping costs using the U.S. Forest Service's Fuel Reduction Cost Simulator (also used to estimate harvesting costs for the wood supply analysis and described in Chapter 3). We assumed chips were transported 100–120 miles (round-trip) to the combustion facility, using trucks carrying 25–30 green tonnes with an average fuel efficiency of 5 mpg. Our results were verified for consistency with other relevant studies including: CORRIM (2004); Department of Forest Resources, University of Minnesota (2008); Finkral and Evans (2008); and Katers and Kaurich (2006).

Indirect $CO_2e$ emissions make a very small contribution to the overall life-cycle emissions from biomass energy production, generally on the order of 2%. A simple way to understand this is as follows. Diesel consumption in harvesting and processing forest biomass is typically less than one gallon (we have calculated an average of 0.75 gallons per green ton based on the sources described above). Diesel consumption in transport is also assumed to be less than one gallon (we have calculated 0.85 gallons per green ton). The combustion of a gallon of diesel releases 22 pounds of $CO_2$, while the combustion of a ton of green wood (45% moisture) releases one ton of $CO_2$ [12]; thus, $CO_2$ emissions per gallon of diesel are equivalent to about 1% of stack emissions. The amount of carbon dioxide released per MWh or per MMBtu will of course depend on the green tonnes of wood required, but the ratio between indirect $CO_2e$ emissions and combustion emissions will remain the same.

**Lifecycle Emissions from Utility-Scale Electric:** For these facilities, all emissions are initially calculated as $CO_2e$ /MWh of electrical output, and then expressed as C/MWh. 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. On average, these plants release about 1.46 tonnes of $CO_2$ (399 kg of C) per MWh. When combined with the indirect emissions discussed above, lifecycle $CO_2e$ for biomass plants total approximately 1.49 tonnes per MWh (or 406 kg of C).

The comparable data for natural gas and coal have been developed by NREL (Spath and Mann, 2000 and Spath et al., 1999) and include the full lifecycle $CO_2e$ emissions. On a per MWh basis,

12 A bone-dry ton of wood is assumed to be 50% carbon. A green ton of wood with 45% moisture weighs 1.82 tons. Thus, the ratio of green wood (45% moisture) to its carbon content is 3.64 (or 1.82 / 0.5). This is essentially the same as the ratio of a ton of carbon dioxide to its carbon content (3.67, equal to the ratio of the molecular weight of CO2 to C, or 44/12). So, the combustion of one green ton of wood releases one ton of CO2.

lifecycle $CO_2e$ emissions for a large (505 MW) combined-cycle natural gas power plant are approximately 0.5 tonnes (136 kg of C) per MWh, of which 75 percent results from the combustion facility itself and 25 percent is from gas production and transportation. The comparable lifecycle estimate for a large coal generating station is approximately 1.0 tonne (279 kg of C) per MWh, with 97 percent of the emissions attributable to the generating station emissions and the remainder to mining and transportation of the coal. The natural gas plant was assumed to be very efficient at 48% due to the combined-cycle technology, while the coal plant was closer to average efficiency at 32%. These plants were selected to bracket the range of emissions of fossil fuel plants relative to their biomass electric counterparts.

We note that co-firing of biomass with coal represents another technology variant for electric utilities. The emissions characteristics of co-firing biomass with coal are expected to similar to those from a stand-alone utility scale biomass electricity plant since the biomass combustion efficiency will be similar in both types of operations. As long as this is the case, the results for utility-scale biomass electricity are indicative of the emissions characteristics of biomass emissions at electricity plants using co-firing.

**Lifecycle Emissions from Thermal Facilities:** All emissions for these facilities are expressed as C/MMBtu of thermal output. Biomass is based on a typical thermal plant with 50 MMBtu's per hour of capacity and 75% efficiency, which has heat input of 120,000 MMBtu/yr (see Chapter 2 for a more detailed description of this pathway and technology). Assuming the gross heating value of oven-dry wood to be 8,500 Btu's/lb, the total lifecycle estimate for carbon emissions is 36 kg/MMBtu.

Emissions data for heating oil and natural gas thermal plants were developed assuming that the typical capacity of the plants was also 50 MMBTH (these technologies and pathways are described in Chapter 2). The oil facilities were assumed to run at 80% efficiency, while the natural gas plants were assumed to be more efficient at 85%. We consider oil facilities that use distillate fuel oil (#2 or #4) and residual fuel oil (#6). The majority of the commercial and industrial facilities in Massachusetts use distillate oil (about 70%), but it is possible that wood biomass may compete more directly with plants burning residual fuel oil. 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). Lifecycle carbon emissions were calculated to be 33 kg/MMBtu for #6 fuel oil, 31 kg/MMBtu for #2 fuel oil, and 23 kg/MMBtu for natural gas. Because of the differences in relative combustion efficiencies, the gap between biomass and fossil fuel technologies for thermal facilities is smaller than the gap for utility-scaled electric facilities.

**Lifecycle Emissions from Pellet Applications:** Emissions for thermal pellet applications require the addition of emissions from plant operations and for transport and distribution of pellets from the plant to the final consumer. The limited analysis that we have seen for these operations (for example, Katers and Kaurich, 2006) suggest that the increased efficiencies in boiler combustion achieved with pellets approximately offsets most of the increased emissions from plant operations and additional transport of pellets from the plant to their final destination.

**Lifecycle 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. While some variations can result from the scale of facilities, the specifics of the design, and the type of heat recovery systems employed, the utility-scale electric and dedicated thermal technologies provide approximate bounds for the wide range of possibilities for CHP facilities.

**Carbon Debt Summary:** Exhibit 6-7 below summarizes the carbon debts for biomass relative to each technology and fuel. These are expressed as the percentage of total biomass-related emissions accounted for by the incremental GHG releases from biomass relative to a specific fossil fuel and technology combination. For example, using the data from Exhibit 6-6, we calculate the 31% for coal electric as ((406 – 279)/406)*100.

**Exhibit 6-7: Carbon Debt Summary Table***
**(Excess Biomass Emissions as % of Total Biomass Emissions)**

| Scenarios | Coal | Oil (#6) | Oil (#2) | Natural Gas |
|---|---|---|---|---|
| Electric | 31% | | | 66% |
| Thermal | | 8% | 15% | 37% |
| CHP | | 2% | 9% | 33% |

** See text for pellet applications.*

It is clear from this table that carbon debt depends on both the choice of fuel (and hence its heating value) and the choice of technology. Carbon debt for biomass compared to natural gas in electric power is much higher than the carbon debt in the thermal scenario. These differences are attributable to the relative efficiencies of the technologies in each scenario -- natural gas electric power has a large advantage in this case due to the assumed use of combined-cycle technology.

Carbon debts for CHP raise another important issue when comparing biomass fuel with other technological alternatives. While comparisons of biomass CHP and CHP using oil or natural gas may be straightforward, there are no data on how much fossil-fuel based CHP capacity is now operating in Massachusetts and could potentially be a candidate for replacement. Nevertheless, this comparison may still be useful in assessing the relative carbon merits of constructing a new biomass CHP plant or a new fossil fuel-fired CHP plant. On the other hand, it is interesting to note that if biomass CHP facilities were developed, it is likely that they would replace a mix of independent thermal and electric applications. Since a large amount of heat is wasted in producing stand-alone electricity, these comparisons may show biomass CHP with no carbon debt at the outset. For example, if thermal-led biomass CHP at a commercial location replaces a current mix of heat from oil and power from coal, then total carbon emissions generated at the new site are likely to decline relative to the fossil scenario as long as a significant percentage of the waste heat is utilized. In contrast, if natural gas is consumed in the current energy mix, the situation may be reversed.

## 6.3 FOREST BIOMASS CARBON ACCOUNTING RESULTS

### 6.3.1 INTRODUCTION

As discussed in the conceptual framework section, our carbon accounting analysis for biomass focuses on biomass carbon debt, biomass carbon dividends and the number of years until debts are paid off and dividends begin accumulating. These are a function of the bioenergy technology as well as the biophysical characteristics of the forest and management practices used. The transition from debt to dividend occurs at the point when the atmospheric carbon level resulting from the lifecycle biomass emissions falls to the point where it just equals the level resulting from lifecycle fossil fuel emissions.[13]

To examine the carbon debts, dividends and the timing of the transition from one to the other, we analyzed a wide array of integrated energy technology/forest management scenarios. These consider the impacts of potential differences in (1) energy technology and efficiency and (2) the biophysical characteristics of the forest and assumptions about the intensity and type of silvicultural approach used for harvests in both the BAU and biomass scenarios.

Our analysis approaches the problem by establishing integrated technology and forest scenarios that we find to be representative of average or typical conditions and management practices. Energy technologies are characterized in terms of typical lifecycle carbon emissions. Representative forest carbon recovery paths are estimated using FVS model simulations averaged across 88 actual forest stands that are included in the U.S. Forest Service's system of FIA sampling plots in Massachusetts. Overall these analyses provide guidance on the range of *average* forest carbon recovery times for each technology. It is important to note, however, that care should be exercised when translating these average results into policy. Our concern is primarily the result of three factors. First, energy technologies are continually evolving and the characteristics of any specific project proposal could differ from the typical existing configurations that we have analyzed. Second, our lack of knowledge of how stands will be harvested in response to increased demand for forest biomass may introduce substantial uncertainty in the projections of forest carbon recovery rates. Third, modeling the carbon dynamics of forest stands is complex, and although our analysis provides indications of broad general trends, these are subject to considerable uncertainty about stand-level changes in carbon pools.

In the remainder of this chapter, the presentation of results in organized around three principal topics:

- How do choices about biomass technology and assumptions about the fossil fuel it will replace affect carbon recovery times?
- How do forest management choices with respect to harvest intensity and silvicultural practice interact with the biophysical properties of forests to determine carbon recovery profiles?
- What are the carbon dividend levels associated with the various biomass energy scenarios?

To answer these questions, we first present data from our modeling of the various energy/forest scenarios. We then summarize our overall conclusions and discuss some considerations regarding how our results are most appropriately interpreted and used in energy and environmental policymaking processes.

### 6.3.2 ENERGY TECHNOLOGY AND CARBON DEBT RECOVERY

A key insight from our research is the wide variability in the magnitude of carbon debts across different biomass technologies. This results from the way specific lifecycle 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 Exhibit 6-7, 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%.

Exhibit 6-8 illustrates how debt payoff varies with technology, with detailed supporting numbers included in the table in Exhibit 6-9. The scenario represented in this exhibit is one that assumes a relatively heavy BAU harvest of timber—32% removal of above-ground 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 60 ft$^2$ per acre. Exhibit 6-8(a) illustrates the FVS model results for total stand carbon in stands harvested only for timber (BAU) and for the same stands where the BAU harvest is augmented by the additional removals of biomass including the harvest of 65% of all tops and limbs. Exhibit 6-8(b) captures the relative differences in growth between the two stands, indicating an initial harvest of 38 green tons of biomass.[14] For these scenarios,

[13] Offsetting of earlier damages from higher biomass GHG levels would require additional years of lower GHG levels (or dividends) in the biomass scenario. Full carbon neutrality would not be achieved until the point at which the entire release of carbon from burning biomass has been resequestered in the forest carbon pools.

[14] This relative difference in growth is derived by subtracting the BAU recovery curve from the biomass harvest recovery curve in Exhibit 6-8(a). In this case, the relationship in Exhibit 6-8(b) can be interpreted as the incremental growth in the stand harvested for biomass relative to growth of the BAU stand. Only through this incremental growth will carbon debts be recovered.

the graph shows that post-harvest biomass stands sequester carbon more rapidly than BAU stands harvested only for timber. In this scenario, the biomass harvest removed an additional 9.1 tonnes of above-ground live carbon from the stand (and resulted in the loss of another 0.5 tonnes of below ground carbon). After one decade of growth, the total carbon in the biomass stand has increased by approximately 1.1 tonnes compared to the BAU stand and continues to increase to a cumulative total 6.2 tonnes of carbon after 90 years. At this point in time, the biomass stand has recovered approximately 65% of the carbon removed from the stand and used for biomass energy generation (6.2 tonnes versus 9.6 tonnes harvested).

**Exhibit 6-8(a): Forest TSC Sequestration Rates under Scenario 1** (tonnes carbon)

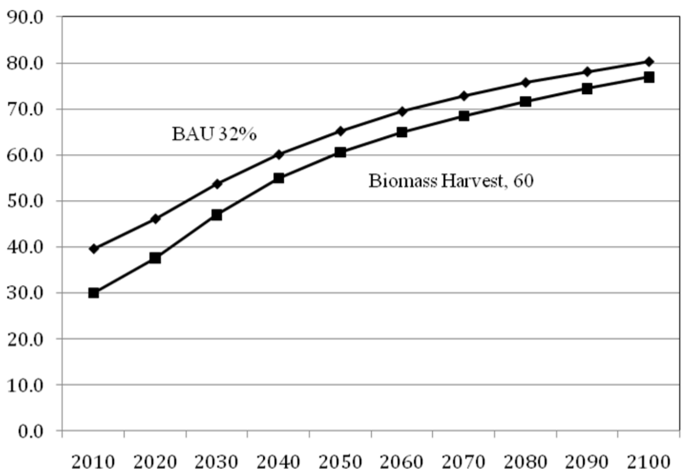
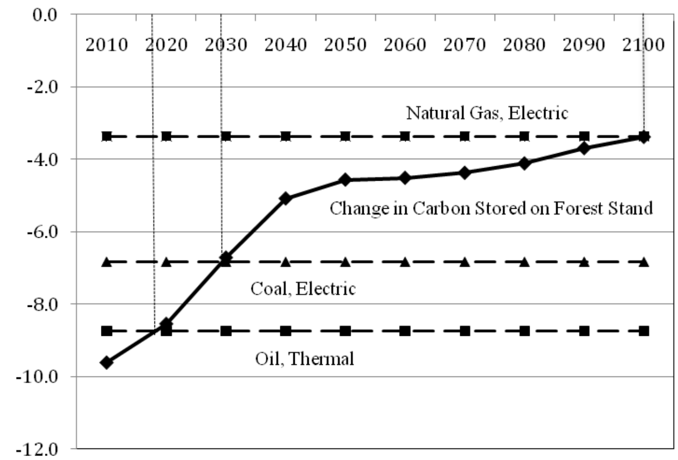



Exhibit 6-8(b) also indicates the time required on average for the stands to recover the carbon debt for various technologies. Oil-fired thermal facilities are represented by the horizontal line indicating that for the equivalent level of energy production they emitted about 12% less carbon than a thermal biomass plant when full lifecycle carbon emissions are taken into account.[15] The intersection of the thermal-oil emissions line and the forest carbon recovery curve identifies the year in which the carbon debt is fully recovered in this scenario—about 10 years for replacement of oil-fired thermal capacity with biomass. At that time, the net atmospheric levels of GHGs are equivalent for the biomass and fossil fuel technologies. Prior to that point, biomass resulted in higher GHG levels, but in later years biomass GHG levels are lower than those for fossil fuels because the forest continues to remove relatively greater amounts of the carbon than the stand in the BAU scenario. These are the benefits we characterize as carbon dividends.

[15] This represents an average of residual fuel oil (#6) and distillate fuel oil (#2).

**Exhibit 6-8(b): Carbon Recovery Rates under Scenario 1** (tonnes carbon)




The carbon debt recovery periods are also plotted in Exhibit 6-8(b) for biomass replacement of coal and natural gas electricity generation. The results make clear that technologies with higher carbon debts have longer payoff times, indicative of carbon dividends that do not appear until further in the future. Technology scenarios with shorter payoff times have lower GHG impacts than scenarios with higher carbon debts. In general, the analysis indicates that thermal carbon debts can be substantially lower than debts from large-scale electricity generation.

Our analyses also considered the carbon debt characteristics of wood pellet technology and CHP systems. In general, we find that carbon debts associated with burning pellets in thermal applications do not differ significantly from debts resulting from use of green wood chips. The differences relate primarily to location of GHG emissions associated with water evaporation from green wood rather than the overall magnitude of the lifecycle GHG emissions. For CHP, carbon debts generally fall somewhere between those of thermal and large-scale electric, depending upon whether the CHP plant is designed to optimize thermal or electric output; however, in our cases, initial carbon debts are shown to be lower than thermal because all waste heat is fully utilized and some reductions in the gross efficiency of oil and gas are recognized due to higher electrical efficiencies.

The technology scenario rankings described above generally hold true as long as the forest management and silvicultural practices are the same for the various energy generation technologies (however, as demonstrated below in Section 6.3.3.4, this may not be the case if harvesting methods preclude the removal and use of tops and limbs). Within this general hierarchy, however, the absolute and relative timing of carbon recovery for the different technologies will vary depending on the specific harvesting assumptions and results from the forest modeling process (discussed in detail in Section 6.3.3 below).

In interpreting the technology/carbon debt results, it is important to recognize that the carbon debts discussed above are based on average levels of GHG emissions per unit of energy for typical energy generation systems readily available today.[16] Biomass energy technology, however, is evolving and there are technologies that have yet to be commercialized in the U.S. that are more efficient and thus produce less GHG emissions per unit of useable energy—for example the biomass CHP gasification technologies discussed in Chapter 2. Bioenergy proposals based on new technologies with lower carbon debts are feasible and have the potential to reduce GHG impacts and associated carbon debts.

### 6.3.3 FOREST MANAGEMENT AND CARBON RECOVERY

Within the broad context of biomass carbon debts and dividends for specific technologies, the timing of carbon recovery is a direct function of two factors related to forests and forest management—(1) the biophysical characteristics of Massachusetts forests and (2) assumptions about the intensity and type of silvicultural approach used for harvests in both the BAU and biomass harvest scenarios.

As described in Chapter 5, we rely on FIA data for basic biophysical information about Massachusetts forests, and we evaluate carbon dynamics using the U.S. Forest Service FVS model. The FIA data are intended to provide a set of forest stands that is representative of the range of forest cover types, tree size distributions, species growth characteristics, and per-acre wood inventories across Massachusetts. For presentation and analysis purposes we generally characterize our results as carbon recovery rates averaged across the 88 stands in our FIA database that are at a stage in their development that makes them available for biomass harvests (i.e., stands with greater than 25 tonnes of carbon in the above-ground live carbon pool). This approach provides a reasonable basis for capturing the impact on carbon debt recovery of differences in the biophysical characteristics of the forests.

Assumptions about the nature of forest management in both the BAU and biomass harvest scenarios also have important impacts on the timing of the transition from carbon debt to carbon dividends. In order to analyze biomass harvest scenarios, we need to specify the BAU harvest level, the incremental amount of material removed in the biomass cut, the percentage of tops and limbs left on-site, and the silvicultural approaches used to harvest the material. For all scenarios, the biomass carbon calculations assume that in the absence of biomass demand, landowners will continue to manage their forests for timber and other wood products. To establish the BAU baseline, we define both the silvicultural practice used in harvesting the wood and the total quantity removed in the baseline harvest. Generally speaking, our knowledge of logging practices in the state suggests a relatively high probability that landowners would apply diameter limit, partial harvest approaches, removing the largest and best quality trees in the stand. Chapter 3 indicates that based on Forest Cutting Plan data, average harvests historically have removed between 4.5 and 6 tonnes of carbon per acre (approximately 20 to 25 green tons). Using FVS, we modeled this baseline through a removal of 20% of above-ground live stand carbon using a 'thin from above' silvicultural prescription.

We also analyzed an alternative baseline in which we assume a significantly heavier BAU harvest, one that removes approximately 32% of the above-ground live carbon. We include this BAU to account for uncertainty regarding which landowners will be more likely to harvest biomass. This scenario would be consistent with the assumption that landowners who have harvests that are heavier than statewide averages would be more likely to harvest biomass.

We then created three biomass harvest options, designed to model light, medium and heavy biomass cuts, all of which include the removal of 65% of all tops and limbs. These were combined with the two BAUs to generate six scenarios representing the impact of different management and harvest assumptions on the timing of the transition from carbon debt to carbon dividends. The results for the six scenarios are summarized in the table included as Exhibit 6-9 (next page). For each scenario, the table shows the quantity of carbon removed in the biomass harvest (i.e., the carbon removal incremental to the harvest in the timber only BAU) and statistics on the recovery by decade of this carbon through growth of the stand. For each scenario, the first row provides the difference in tonnes of total stand carbon between the BAU stand and the biomass stand in years 10 through 90. The second row indicates the tonnes of carbon recovered by the biomass stand relative to the BAU. The third row presents the cumulative percentage of the original biomass carbon recovered by decade.[17]

#### 6.3.3.1 Impacts of Alternative BAUs

The results graphed in Exhibit 6-10 demonstrate that carbon recovery times are somewhat, but not highly, sensitive to assumptions about the volume of timber removed in the BAU harvest. The graph shows carbon recovery curves for Scenarios 1 and 5, the light and heavy BAU harvests, followed by a medium-intensity biomass cut, in this case removal via a diameter limit cut of biomass down to a residual stand basal area of 60 ft2. The results indicate that the heavier BAU results in a somewhat, but not dramatically, more rapid recovery of carbon in the stand following the biomass harvest. Carbon debts resulting from biomass replacement of coal-fired electricity capacity would take about 20 years in the heavy BAU case, and about 25 years in the light BAU scenario. After these points in time, carbon dividends begin to accrue because atmospheric GHG levels are below those that would have resulted had an equivalent amount of energy been generated using fossil fuel.

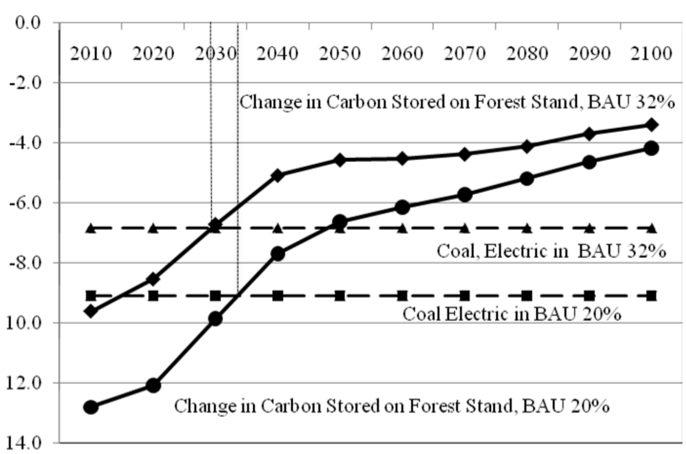
16 In the case of large-scale electricity generated by natural gas, the scenario here assumes a very efficient combined-cycle technology, and this provides a high-end estimate of carbon debts compared to biomass replacement at less efficient natural gas facilities.

17 For example, in Scenario 1, in year 1 the harvest resulted in an initial loss of 9.6 tonnes of total stand carbon (of which 9.1 tonnes is above-ground live carbon). By year 10, the difference in total stand carbon has narrowed to 8.5 tonnes, the relative differences in stand carbon accumulation between the two stands. In this case the biomass stand accumulated an additional 1.1 tonnes of carbon more than the BAU stand (9.6 tonnes minus 8.5 tonnes). This represents recovery of 11.1% of the original carbon removed in the biomass harvest (1.1/9.6).

**Exhibit 6-9: Graph of Carbon Recovery Times for Scenarios 1 and 5** (tonnes carbon)

| Scenario | | | BAU vs. Biomass Total Stand Carbon Difference by Year | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Number** | **Description** | **Harvest** | **10** | **20** | **30** | **40** | **50** | **60** | **70** | **80** | **90** |
| | BAU32%-BioBA60 | 9.1 | 8.5 | 6.7 | 5.1 | 4.6 | 4.5 | 4.4 | 4.1 | 3.7 | 3.4 |
| **1** | CumRecovered | | 1.1 | 2.9 | 4.5 | 5.0 | 5.1 | 5.2 | 5.5 | 5.9 | 6.2 |
| | %Recovery | | **11.1** | **30.2** | **47.1** | **52.5** | **53.1** | **54.5** | **57.2** | **61.6** | **64.8** |
| | BAU32%-Bio40% | 1.8 | 2.1 | 1.7 | 1.3 | 1.1 | 0.9 | 0.7 | 0.6 | 0.5 | 0.4 |
| **2** | CumRecovered | | 0.8 | 1.2 | 1.6 | 1.9 | 2.0 | 2.3 | 2.3 | 2.5 | 2.6 |
| | %Recovery | | **28.1** | **41.0** | **54.6** | **63.4** | **68.5** | **77.3** | **79.0** | **84.1** | **86.4** |
| | BAU32%-BioHHBA40 | 14.1 | 14.4 | 12.1 | 9.6 | 8.3 | 7.7 | 6.9 | 6.2 | 5.3 | 4.7 |
| **3** | CumRecovered | | -0.4 | 2.0 | 4.4 | 5.7 | 6.4 | 7.1 | 7.8 | 8.8 | 9.3 |
| | %Recovery | | **-2.6** | **14.0** | **31.2** | **41.0** | **45.4** | **50.5** | **55.5** | **62.5** | **66.7** |
| | BAU20%-Bio40% | 5.7 | 5.7 | 4.9 | 4.0 | 3.2 | 2.6 | 2.0 | 1.7 | 1.4 | 1.2 |
| **4** | CumRecovered | | 0.0 | 0.8 | 1.8 | 2.5 | 3.2 | 3.7 | 4.0 | 4.3 | 4.5 |
| | %Recovery | | **0.7** | **13.4** | **28.5** | **41.5** | **51.3** | **60.1** | **65.3** | **69.9** | **73.5** |
| | BAU20%-BioBA60 | 13.0 | 12.1 | 9.9 | 7.7 | 6.6 | 6.1 | 5.7 | 5.2 | 4.6 | 4.2 |
| **5** | CumRecovered | | 0.7 | 3.0 | 5.1 | 6.2 | 6.7 | 7.1 | 7.6 | 8.2 | 8.6 |
| | %Recovery | | **5.6** | **23.0** | **39.9** | **48.2** | **52.1** | **55.4** | **59.5** | **63.8** | **67.4** |
| | BAU20%-BioHHBA40 | 18.0 | 17.9 | 15.2 | 12.3 | 10.3 | 9.3 | 8.3 | 7.3 | 6.2 | 5.5 |
| **6** | CumRecovered | | -0.7 | 2.0 | 5.0 | 6.9 | 7.9 | 8.9 | 9.9 | 11.0 | 11.7 |
| | %Recovery | | **-4.2** | **11.7** | **28.8** | **39.9** | **46.1** | **51.9** | **57.6** | **64.0** | **68.3** |

**Exhibit 6-10: Graph of Carbon Recovery Times for Scenarios 1 and 5** (tonnes carbon)




### 6.3.3.2 Impacts of Alternative Biomass Harvest Intensities

Next we examined the impact of varying the intensity of the biomass harvest on carbon debt recovery. Exhibit 6-9 shows the impact of the light, medium and heavy biomass harvests when combined with the heavy harvest BAU and the comparable results when a lighter BAU harvest is assumed.

The results suggest that for very light biomass harvests, the time required to pay off the carbon debt and begin accumulating dividends is relatively rapid. This is evident in Scenario 2—a heavy BAU coupled with a light biomass harvest—where only 3 tonnes of biomass carbon is removed. In this example, both oil-thermal and coal-electric debts are recovered in the first decade and natural gas electric debts are paid back in approximately 50 years. As discussed in Section 6.3.3.4 below, the rapid recovery occurs because the small removal is comprised of a much greater proportion of logging residues that would have been left on the ground to decay in a BAU harvest. This relatively large magnitude of the decay losses in the BAU results in a rapid recovery of lost carbon in the biomass harvest. Such light harvest, however, would not necessarily produce the supplies forecast in Chapter 3 and may not be the economic choice of landowners.

As harvest intensity increases, however, recovery times become longer. Scenarios 1, 4 and 5, where biomass harvests range from 5.7 to 13.0 tonnes of carbon, all have carbon recovery profiles that are longer than Scenario 2, although all three show steady progress in the recovery of carbon debts. In the three scenarios, oil-thermal debts are recovered roughly between years 10 and 20 and coal-electric debts are recovered between years 20 and 30. For Scenarios 3 and 6, where the biomass removal is close to what would be considered a clearcut, the stand harvested for biomass actually loses carbon relative to the BAU stand in the first decade, creating a delay in carbon recovery that persists for many decades. This may be the result of complex interactions between regeneration and woody debris decay in the years immediately following harvest, although in the case of these more extreme harvests, we may be pushing the model to an extreme case where its results are simply less robust. Given the low likelihood that most biomass harvests will be in the form of clearcuts (see Chapter 3), we do not view the uncertainties in the Scenario 3 and 6 results as having great relevance to the overall patterns of carbon recovery.

### 6.3.3.3 Impacts of Alternative Silvicultural Prescriptions

The impact of different silvicultural prescriptions has been more difficult to evaluate using the FVS model. The present set of scenarios uses 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 likely 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 8 inches. We hypothesized that this type of harvest would result in a slower recovery compared to thinning from above. Unfortunately, the complexity of this type of harvest was difficult to mimic with FVS.

Although project resources were not adequate to manually simulate this type of harvest for all FIA stands, we did conduct a sensitivity analysis for two stands with average volumes. For each of these stands we simulated 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 Exhibit 6-11, do 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 we did not determine; it is clear however that on a stand-by-stand basis the magnitude of the slowdown can vary considerably.

### 6.3.3.4 Impacts of Harvesting Methods and the Role of Tops and Limbs

The harvest and use of tops and limbs for biomass can have an important influence on carbon recovery times and profiles: tops and limbs decay quickly if left in the forest and so their use comes with little carbon "cost" which tends to shorten carbon 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. Tops and limbs are available from two 'sources' in our biomass harvest scenarios: (1) the material left behind following an industrial roundwood harvest in a BAU scenario and (2) tops and limbs from standing trees harvested specifically for bioenergy in the biomass harvest scenarios.

As discussed in the wood supply analysis in Chapter 3, the harvest of tops and limbs would likely be economical only when harvested with whole-tree systems. Biomass harvested in this manner can be used for any type of bioenergy technology. However, biomass can also be harvested with traditional methods or cut-to-length methods when these systems are preferred due to operating restrictions and/or landowner preferences. These roundwood operations tend to be more costly, but yield higher-quality bole chips that are preferred by thermal, CHP and pellet facilities. Importantly, leaving tops and limbs behind as forest residues would increase carbon recovery times for bioenergy technologies that utilize the bole chips that are produced. The discussion that follows helps to demonstrate how the use of tops and limbs affects our carbon recovery results.

The carbon recovery times in the six scenarios presented in Exhibit 6-9 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. These 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 Exhibit 6-12.

**Exhibit 6-11: Carbon Recovery Times**
**Alternative Harvest Analyses** (tonnes carbon)

| Scenario | | | BAU vs. Biomass Total Stand Carbon Difference by Year | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Number | Description | Harvest | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
| | BAU20:Bio40DBH | 7.5 | 8.1 | 6.6 | 3.6 | 2.3 | 1.7 | 0.5 | -0.2 | -0.7 | -0.9 |
| 1 | CumRecovered | | -0.6 | 0.9 | 3.9 | 5.2 | 5.8 | 7.0 | 7.8 | 8.2 | 8.5 |
| | %Recovery | | -9.6 | 15.1 | 63.5 | 84.6 | 94.8 | 113.9 | 126.4 | 133.6 | 137.8 |
| | | | | | | | | | | | |
| | BAU20:Bio40 | 5.9 | 6.0 | 4.4 | 2.4 | 2.1 | 3.3 | 1.6 | 1.8 | -0.5 | 0.2 |
| 1 | CumRecovered | | 0.0 | 1.5 | 3.5 | 3.8 | 2.7 | 4.4 | 4.2 | 6.5 | 5.8 |
| | %Recovery | | -0.3 | 25.6 | 59.2 | 64.4 | 44.7 | 73.7 | 70.2 | 108.9 | 97.1 |
| | | | | | | | | | | | |
| | BAU20:Bio40 | 4.2 | 4.3 | 4.4 | 4.3 | 3.2 | 1.3 | 1.6 | 0.4 | 0.6 | 0.0 |
| 2 | CumRecovered | | -0.1 | -0.3 | -0.1 | 0.9 | 2.9 | 2.6 | 3.8 | 3.5 | 4.2 |
| | %Recovery | | -2.7 | -6.4 | -3.1 | 22.6 | 68.6 | 62.5 | 90.4 | 84.4 | 100.9 |
| | | | | | | | | | | | |
| | BAU20:Bio40 | 6.4 | 6.0 | 5.1 | 4.1 | 3.5 | 1.9 | 2.0 | 0.0 | 0.5 | 0.4 |
| 2 | CumRecovered | | 0.4 | 1.3 | 2.2 | 2.8 | 4.4 | 4.4 | 6.3 | 5.9 | 5.9 |
| | %Recovery | | 6.1 | 20.4 | 34.8 | 44.6 | 69.5 | 69.1 | 99.4 | 92.3 | 93.5 |

When tops and limbs are left on-site, all three scenarios show net carbon losses between the initial period and the 10-year mark; in addition, carbon losses in year 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 years (when compared to oil-based thermal), rather than occurring in less than 10 years when tops and limbs are taken in whole-tree harvests.

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

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 Exhibit 6-12) 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.

**Exhibit 6-12: The Impact of Tops and Limbs on Carbon Recovery Times in BAU32**

| 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% |

### 6.3.3.5 Impacts of Differences in Stand Harvest Frequencies

A final factor that merits consideration in interpreting the modeling results is the effect of harvest frequencies on the timing of the transition of carbon debt to carbon dividend. Frequent re-entry to the stand to remove biomass has the general effect of extending carbon recovery times. For example, if a stand is re-entered before the time at which carbon levels have recovered to the point where atmospheric concentrations are equivalent to those from fossil fuel burning, a new carbon debt is added to what remains of the initial one and the period required for that stand to reach the equivalent flux point is extended. Conversely, if a second harvest is not conducted until after the stand has begun contributing to actual reductions in GHG levels relative to a fossil fuel scenario, net benefits in the form of carbon dividends will have been positive; additional benefits will depend on the amount of carbon debt incurred in the second harvest and the growth rate of the forest following the additional removal.

As a result of this effect, it is clear that carbon recovery times are sensitive to the frequency at which a landowner chooses to harvest. Data on frequency of harvests indicates landowners who manage for timber typically cut their stands relatively frequently, which suggests our estimated carbon recovery times may be shorter than would actually occur in practice; as a result actual times to the to pay off carbon debts and begin accumulating carbon dividends may be longer.

### 6.3.3.6 Carbon Dividends

Beyond the point in time when the carbon debt is paid off, and as long as the total carbon recovery rates of stands harvested for biomass are at least as high as the recovery rates in the BAU stands, the carbon dividends from biomass energy continue to accumulate. This means that in the years after the point of carbon debt repayment, there will be less carbon in the atmosphere than had a comparable amount of energy been generated with fossil fuel. As long as the stand harvested for biomass is accumulating carbon faster than the BAU stand, this benefit—lower GHG concentrations relative to the fossil fuel scenario—continues to increase. Even if the two stands ultimately reach a point where carbon accumulates at the same rates, there continues to be a dividend in the form of an ongoing reduction in GHG levels from what they would otherwise have been. As a result, the magnitude of carbon dividends varies depending on the year in which they are evaluated. Exhibit 6-13 indicates the year in which the carbon debt is paid off and provides estimates of the percentage carbon dividend in 2050 and 2100, 40 and 90 years respectively after the modeled biomass harvest.[18]

As discussed in more detail in Section 6.1.2, the carbon dividends in the table indicate the extent to which burning biomass has

[18] FVS simulations become increasingly uncertain as they are extended over long time periods. We believe 90-year simulations represent a reasonable length of time for providing insights into long-term carbon recovery effects.

reduced GHG levels beyond what they would have been had the same energy been generated from fossil fuels. For example, if a biomass thermal plant with an initial carbon debt of 15% emitted 150 tonnes of lifecycle carbon, and the harvested forest recovered an incremental 115 tonnes of carbon over 60 years compared to a BAU scenario, the carbon dividend is 73%. This indicates that the biomass carbon debt has been completely recaptured in forest carbon stocks and in addition GHGs have been reduced by 73%[19] from what they would have been if fossil fuels had been used to generate the equivalent amount of energy. In this context, a carbon dividend of 100% indicates that biomass combustion has achieved full carbon neutrality—all the energy emissions from biomass burning have been fully offset in the form of newly sequestered carbon.

As was the case for carbon debt payoff, the dividend levels clearly indicate benefits are strongly a function of the fossil technology that is being replaced. Where whole-tree harvesting is used, replacement of oil-fired (#6) thermal by biomass thermal results in carbon dividends in excess of 38% by 2050 even in the slowest carbon recovery scenario. These reductions in GHG levels relative to a fossil fuel baseline rise to greater than 60% by 2100. With the exception of biomass replacement of natural gas electric capacity, carbon dividends after 90 years always result in fossil fuel offsets that exceed 40%. These dividends, however, are potentially reduced if stands are re-entered and additional material is harvested prior to the 90-year reference point discussed above. Carbon dividends are consistently low (and in one case negative) for biomass replacement of natural gas electricity generation.

Another way of comparing the relative contributions of carbon debts and carbon dividends is to estimate the difference in cumulative net atmospheric carbon emissions between using biomass and fossil fuel for energy at some future point in time. Due to the importance of demonstrating progress in reducing greenhouse gas emissions by 2050 as part of the Massachusetts Global Warming Solutions Act, we have provided such a comparison for our six harvest scenarios in Exhibit 6-14.

Conceptually, the analysis is perhaps best understood as follows. In the first year, a bioenergy plant consumes a specified volume of wood and establishes a carbon debt relative to the amount of carbon that would have been released in generating the same amount of energy from a fossil fuel alternative. The pattern is then repeated each year and continues until the year 2050. We then calculate the total difference in atmospheric carbon in 2050 from each harvest year and sum the results. For example, the difference in carbon from the first year is simply equal to our estimate of the carbon dividend in year 2050, 40 years after our initial harvest. The difference in carbon from the second year is the carbon dividend that we observe after 39 years, the difference in carbon from the third year is the carbon dividend that we observe after 38 years, etc. The process continues until the last year (2050) at which time the difference in carbon is equal to the difference in year one, or in other words, it is equal to the initial carbon debt.[20] This allows us to compute the total carbon 'savings' from burning biomass for a 40-year period, and then compare this value with the total amount of carbon that would have been released by using fossil fuel. When expressed in this manner, the concept is identical to our carbon dividend; however, rather than calculating a dividend at a single point in time, we now have measured the cumulative dividend in 2050, which indicates the total net change in atmospheric carbon at that time due to 40 years of biomass use.

The cumulative dividend net of forest carbon resequestration results from these calculations are shown in Exhibit 6-14: a value of 0% indicates that the carbon dividends during the 2010–2050 period have exactly offset the carbon debt; a positive value indicates that the cumulative carbon dividends have more than offset the carbon debts and have reduced atmospheric carbon compared to what would have been the case had fossil fuels been used (for example, 22% for oil (#6), thermal in harvest scenario 1 indicates that atmospheric carbon is 22% lower in 2050 due to the replacement of oil with biomass); a negative value indicates that total carbon dividends have not yet offset the cumulative debt levels (for example, -13% for natural gas, thermal in harvest scenario 1 indicates that there is still 13% more carbon in the atmosphere in 2050 as a result of having replaced a natural gas thermal plant with biomass and operating it for 40 consecutive years.

Several key observations can be made from these results: (1) the percentage carbon dividend for the entire 2010–2050 period is significantly less than the single year percentage dividend in 2050 that was based only on emissions in 2010 (shown in Exhibit 6-13, next page)—the dividend resulting from only the initial year of emissions will always be the maximum because our empirical analysis has shown that forest carbon resequestration is generally an increasing function (at least after the first few decades); (2) cumulative carbon dividends are positive for oil (#6), thermal for all harvest scenarios; using biomass to displace residual fuel oil in thermal applications would result lower atmospheric carbon levels by an average of about 20% in 2050; (3) cumulative carbon dividends are mostly negative in 2050 for the three other fossil fuel technologies indicating that 40 years is not sufficient for biomass to reduce atmospheric carbon levels using these technology/fuel combinations.

Finally, it should be noted that extending this analysis beyond 2050 will continue to show higher cumulative dividends over

[19] Carbon dividend = (total carbon recovered – carbon debt)/(total carbon emissions –carbon debt) or (115 –(0.15*150))/(150-(150*0.15)) = 73%

[20] Mathematically, there are several ways to compute these values: 1) sum the carbon differences in 2050 for each harvest year, as described above; 2) sum the total carbon released from biomass (net of forest carbon recapture) from 2010–2050 and compare this with the total carbon released from 40 years of burning fossil fuel; or, equivalently, 3) sum the total excess carbon generated from burning biomass (the excesses prior to the point of equal carbon flux) and compare these with the sum of carbon reductions relative to fossil fuel during the phase when dividends are positive.

**Exhibit 6-13: Carbon Debt and Dividends**

| Harvest Scenario | Fossil Fuel Technology | Carbon Debt Payoff (yr) | Carbon Dividend | |
|---|---|---|---|---|
| | | | 2050 | 2100 |
| 1 | Oil (#6), Thermal | 7 | 47% | 58% |
| | Coal, Electric | 21 | 32% | 46% |
| | Gas, Thermal | 24 | 26% | 41% |
| | Gas, Electric | >90 | -38% | -9% |
| 2 | Oil (#6), Thermal | 3 | 64% | 75% |
| | Coal, Electric | 12 | 54% | 68% |
| | Gas, Thermal | 17 | 50% | 65% |
| | Gas, Electric | 45 | 7% | 35% |
| 3 | Oil (#6), Thermal | 14 | 38% | 62% |
| | Coal, Electric | 30 | 21% | 52% |
| | Gas, Thermal | 36 | 13% | 47% |
| | Gas, Electric | 89 | -61% | 3% |
| 4 | Oil (#6), Thermal | 10 | 53% | 76% |
| | Coal, Electric | 27 | 40% | 70% |
| | Gas, Thermal | 31 | 34% | 67% |
| | Gas, Electric | 59 | -22% | 39% |
| 5 | Oil (#6), Thermal | 15 | 46% | 64% |
| | Coal, Electric | 25 | 31% | 54% |
| | Gas, Thermal | 28 | 24% | 49% |
| | Gas, Electric | 86 | -41% | 6% |
| 6 | Oil (#6), Thermal | 15 | 39% | 66% |
| | Coal, Electric | 32 | 22% | 56% |
| | Gas, Thermal | 37 | 14% | 52% |
| | Gas, Electric | 85 | -59% | 11% |

time. When cumulative dividends through 2100 are considered (Exhibit 6-15), they are higher than the results shown for 2050, although these longer term results will overstate benefits if biomass comes from forests that are harvested more than once or experience significant mortality-causing natural disturbance during the 2010–2100 period.

**Exhibit 6-14: Cumulative Carbon Dividends: 2010 to 2050**

| Harvest Scenario | Fossil Fuel Technology | | | |
|---|---|---|---|---|
| | 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% |

**Exhibit 6-15: Cumulative Carbon Dividends: 2010 to 2100**

| Harvest Scenario | Fossil Fuel Technology | | | |
|---|---|---|---|---|
| | 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% |

The interpretation of the carbon dividend results should recognize that neither carbon dividends nor carbon debts provide direct indications of the associated environmental benefits or damages. This would require a detailed analysis of the actual climate impacts of increased GHG levels in the period before carbon debts are paid off and lower GHG levels after that point in time. Potential non-linearity in the climate damage functions make such formal benefit-cost analysis challenging and beyond the scope of this study; consequently we leave this analysis to other researchers. Nonetheless, information on initial carbon debts, dividends accrued up to a point 90 years in the future, and estimates of the number of years needed to pay off carbon debts and begin accruing benefits should help inform the development of biomass energy policies.

### 6.3.4 DISCUSSION OF RESULTS

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. These 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.[21] The carbon recovery profile for combustion of wood pellets is roughly similar to burning green wood chips in terms of total lifecycle GHG emissions. 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 recovery times 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 our analyses provide some broad insights into biomass carbon dynamics but are also subject a number of uncertainties that are difficult to resolve.

A key finding of our work is that the magnitude and timing 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 (1) the intensity of harvests; (2) the silvicultural prescriptions and cutting practices employed; (3) the fraction of the logging residues removed from the forest for biomass; and (4) the frequency

21 Cowie (2009) draws similar conclusions in a recent presentation of work on IEA Bioenergy Task 38.

at which landowners re-enter stands to conduct future harvests. If the landowners responding to demands for increased biomass are the same ones who harvest their lands heavily today, then it is probably reasonable to assume that carbon debts are recovered relatively rapidly, along the lines suggested by our Scenario 1. In this case, the transition from debt to dividends that results from replacing oil-fired thermal with biomass is between 10 and 20 years and the biomass coal-electric transition occurs after 20 to 30 years. But if the response is more evenly distributed across all landowners and the biomass harvests are more heavily focused on removal of suppressed and understory cull trees, we expect that recoveries would likely be slower. How much slower, and the impact on subsequent carbon dividends, cannot be predicted without a better understanding than we currently have about future landowner forest management practices. While detailed landowner surveys might improve our understanding of this issue, this uncertainty cannot be completely resolved until we can observe actual landowner behavior in response to increased biomass demand.

Finally, 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 up to 85% in some scenarios relative to continued fossil fuel use. 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.

## 6.4 FINAL CONSIDERATIONS

The Massachusetts Department of Energy Resources has indicated that it hopes this study will provide valuable information to help guide its decisions on biomass energy policy. The study discusses a complex subject that is technically challenging and inevitably we have not been able to resolve all critical uncertainties. Policymakers should carefully weigh the significant uncertainties that remain, as well as other factors not addressed by our study, in deciding whether to encourage or discourage biomass development. In light of that, we conclude with some general observations on how the results of our carbon accounting analyses should be interpreted by policymakers and the public at large.

- As suggested in the discussion of carbon recovery, we have used average and/or typical values for GHG emissions from biomass and fossil fuel energy facilities. With continually evolving technology, biomass developers may be able to demonstrate lower GHG emissions per unit of useable energy. This can be expected to reduce carbon debts and change the overall time required to pay off these debts through forest growth. Consequently, our carbon debt and dividend conclusions should be viewed as representative of typical or average conditions today, a state of affairs that will likely change in the future given the evolution of technologies.

- Our carbon analysis considers only biomass from natural forests. Tree care and landscaping sources, biomass from land clearing, and C&D materials have very different GHG profiles. Carbon from these sources may potentially enter the atmosphere more quickly and consequently carbon debts associated with burning these types of biomass could be paid off more rapidly, yielding more immediate dividends. Our results for biomass from natural forests likely understate the benefits of biomass energy development relative to facilities that would rely primarily on these other wood feedstocks.

- Our 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, this 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 we have not considered, and this raises issues about generalizing our results too widely—particularly beyond Massachusetts and New England. We have 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 the Commonwealth. 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? If so, GHG impacts are likely the same as if the material were used in state. Or is there an alternative BAU for an out-of-state facility that sells renewable energy to Massachusetts—for example bioenergy facilities in Maine that may be competing for biomass supplies that would otherwise go to paper production and enter the GHG system relatively more quickly? The existence of alternative baselines would result in different carbon debts and recovery profiles than those that we have identified for Massachusetts.

- Views about how long it will take before we have truly low or no carbon energy sources 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, especially for applications where carbon debts are relatively higher and where longer payoff times reduce future carbon dividends.

- 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, we stress that our work 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 we have tried to be transparent about them. For the variety of reasons discussed above, the carbon recovery and dividend profile for a specific facility is likely to deviate from the average facilities analyzed in this report. As such, we 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.

## REFERENCES

Bauen, A., G. Berndes, M. Junginger , M. Londo, and F. Vuille. 2009. Bioenergy – A Sustainable and Reliable Energy Source: A review of status and prospects. IEA Bionenergy, ExCo: 2009:06.

CORRIM (Consortium for Research on Renewable Industrial Materials). 2004. Forest Resources: Pacific Northwest and Southeast, Phase I Final Report, Module A.

Cowie, A. 2009. Global challenges for sustainability of biofuels: life cycle assessment of GHG emissions. IEA Bioenergy Task 38. url: www.iea.org/work/2009/bangkok/2_2_Cowie.pdf.

Department of Forest Resources, University of Minnesota. 2008. Assessment of Carbon Flows Associated with Forest Management and Biomass Procurement for the Laskin Biomass Facility. Staff Paper Series No. 198.

Fargione, J., J. Hill, D. Tilman, S. Polasky and P. Hawthorne. 2008. Land Clearing and the Biofuel Carbon Debt. Science Vol. 319 1235-1238.

Finkral, A.J. and Evans, A.M. 2008. The effects of thinning treatment on carbon stocks in a northern Arizona ponderosa pine forest. *Forest Ecology and Management* 255 (2008) 2743–2750.

Gerdes, K.J. 2009. NETL's Capability to Compare Transportation Fuels: GHG Emissions and Energy Security Impacts. National Energy Technology Laboratory. http://www.netl.doe.gov/energy-analyses/pubs/Petroleum%20Fuels%20GHG%20Modeling_Feb%2025a.pdf

Hamburg, S. 2010. Biomass feedstocks and the climate implications of bioenergy. Presentation at EIA 2010 Energy Conference: Short-Term Stresses Long-Term Change. url: www.eia.doe.gov/conference/2010/session2/hamburg.pdf

Johnson, E. (2008). Goodbye to carbon neutral: Getting biomass footprints right. Environmental Impact Assessment Review

Katers, J.F. and Kaurich, J. 2006. Heating Fuel Life-Cycle Assessment. University of Wisconsin—Green Bay.

Kurz, W.A., C.C. Dymond, T.M. White, G. Stinson, C.H. Shaw, G.J. Rampley, C. Smyth, B.N. Simpson, E.T. Neilson, J.A. Trofymow, J. Metsaranta, M.J. Apps. 2008. CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecological Modeling 220 (2009) 480-504.

Marland, G. and B. Schlamadinger. 1995. Biomass Fuels and Forest-Management Strategies: How Do We Calculate the Greenhouse-Gas Emissions Benefits? Energy 20: 1131-1140.

Marland, G., B. Schlamadinger, and L. Canella. Undated. The Model GORCAM. www.joanneum.at/gorcam.htm.

Miner, R. 2010. Biomass Carbon Neutrality. National Council for Air and Stream Improvement (NCASI). url: nafoalliance.org/wp-content/uploads/NCASI-Biomass-carbon-neutrality.pdf.

Morris, G. 2008. Bioenergy and Greenhouse Gases. Green Power Institute, The Renewable Energy Program of the Pacific Institute. Berkeley.

Natural Resources Canada. 2009. RETScreen International. url:www.retscreen.net/.

Schelhaas, M.J., P.W. van Esch, T.A. Groen, B.H.J. de Jong, M. Kanninen, J. Liski, O. Masera, G.M.J. Mohren, G.J. Nabuurs, T. Palosuo, L. Pedroni, A. Vallejo, T. Vilén. 2004. CO2FIX V 3.1 - description of a model for quantifying carbon sequestration in forest ecosystems and wood products. ALTERRA Report 1068. Wageningen, The Netherlands.

Schlamadinger, B. and G. Marland. 1996a. Carbon Implications of Forest Management Strategies, pp. 217-232 in M.J. Apps and D.T. Price (eds.) Forest Ecosystems, Forest Management and the Global Carbon Cycle, Proceedings of a NATO Advanced Research Workshop, NATO ASI Series I, Volume 40, Springer-Verlag, Berlin.

Schlamadinger, B., and G. Marland. 1996b. The Role of Forest and Bioenergy Strategies in the Global Carbon Cycle, *Biomass and Bioenergy* 10: 275-300.

Schlamadinger, B. and G. Marland. 1996c. Full Fuel-Cycle Carbon Balances of Bioenergy and Forestry Options, Energy Conservation and Management 37: 813-818.

Spath, P.L. and M.K. Mann. 2000. Life Cycle Assessment of Natural Gas Combined-Cycle Power Generation System. NREL (National Renewable Energy Laboratory). NREL/TP-570-27715.

Spath, P.L., M.K. Mann, D.R. Kerr. 1999. Life Cycle Assessment of Coal-fired Power Production. NREL (National Renewable Energy Laboratory). NREL/TP-570-25119.