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Forest Biomass and Bioenergy: Opportunities and Constraints in the Northeastern United States

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EXECUTIVE SUMMARY

There has been enormous interest in the use of forest biomass for energy in the Northeastern US. Both the federal government and most states in the region are actively engaged in assessments of the potential role of forest biomass in renewable energy standards and portfolios. This study addressed two critical components of those assessments:

- the amount of biomass that can be sustainably harvested from Northeastern forests for energy purposes, and
- which conversion technologies and end-use applications should be pursued to most effectively reduce greenhouse gas emissions, reduce dependence on foreign oil, and promote the rural economy of the region.

Our analyses relied on data on forest biomass supply from the U.S.D.A. Forest Service Forest Inventory Analysis (FIA) program and the Timber Products Output (TPO) database, and on data from the Energy Information Administration (EIA) for the energy analysis.

Our analyses yield significantly lower estimates of the sustainable supply of biomass feedstocks from Northeastern forests than the estimates from a number of previous studies. The primary reasons for the differences are due to differences in:

- Estimates of forest productivity: many previous studies use values for forest biomass productivity from a limited number of research sites, and those estimates are typically higher than estimates derived from a fuller analysis of the network of FIA plots across each state. The most likely reason for the difference is that the more localized studies sample forests on sites that are more productive, on average, than the forestland base as a whole.
- Estimates of the available forestland base: recent studies have made a wide range of assumptions about how biological, physical, legal, social, and economic factors limit the amount of the region's forestland that is available for harvest. There is still a great deal of uncertainty about a number of these factors. We present a range of scenarios of sustainable biomass supply given explicit assumptions about the magnitudes of different constraints on the available forestland base.

Estimating forest biomass availability for energy production in the Northeast

- Forestland makes up slightly over 67% of the total land area of the northeastern states. While the area of forestland has increased significantly over the past century, recent studies suggest that the current forestland base represents a high-water mark, and is unlikely to increase.

- Despite assumptions that northeastern forests are even-aged, maturing, and declining in growth rates, the data show a very different picture, with (a) forests managed primarily by partial harvesting (rather than clearcutting), (b) stands with a wide range of tree biomass, and (c) a landscape that is very close to optimal in terms of net forest growth and accumulation of carbon in aboveground tree biomass.
- Timber harvests during recent years (2004-2008) have been below net growth calculated over the entire forestland base (63% of net growth over the entire region, but with significant variation from state to state). Both the sustainability of the current harvest rates, and the degree to which harvest rates could be sustainably increased for biomass energy production, however, depend critically on the fraction of the total forestland base that is available for harvests.
- Less than 6% of the region's forestlands are legally reserved from harvests, but a wide variety of biophysical, economic and social constraints place additional limits on the forestland base that is available for harvest. Two of the potentially most significant of these are (a) parcelization – the subdivision of forestland into small land holdings that are too small for efficient harvest operations, and (b) landowner unwillingness to harvest because of higher priority interests. Unfortunately, there is a great deal of uncertainty about the impact of both of these factors on the available forestland base. The magnitude of this uncertainty can be underlined by the fact that 10% of all unreserved forest land is located in private parcels of under 8 ha (20 acres).
- We considered two sets of assumptions about the magnitudes of the biophysical, economic and social constraints on the available forestland. Under our conservative ("Low") scenario, only 63% of the total northeastern forestland is available for harvests (with substantial variation from state to state), and recent harvest rates have consumed effectively all of the sustainable yield. However the recent harvests recover only a small fraction of logging residue, and some additional fraction of this material could be harvested sustainably for biomass energy. Under a much less restrictive set of assumptions (our "High" scenario) – in which 78% of the forestland base is available for harvest, recent harvests represent only 82% of total net growth on available forestland, and there is a more significant potential for additional harvests for biomass energy, though the most advantageous strategy is to produce additional wood products where possible and use the remainder for bioenergy.
- We used these different sets of assumptions about the area of available forestland, and whether biomass currently used by the pulp and paper industry would be diverted to energy production, to calculate a set of 5 different scenarios for the sustainable quantity of biomass that could be harvested and devoted to energy production in the region (in metric tons of dry biomass, per year) (Table 4). Three of the scenarios assume that all of the current pulp wood harvests would be dedicated to

biomass energy supply, which would cause additional carbon emissions (leakage) in regions outside the Northeast to make up for the lower local supply of biomass for pulp and paper products.

- If (a) all current pulp harvests are diverted to biomass energy use, and (b) recent harvest rates are increased to the point where they meet recent forest net growth (a limited but intuitive estimate of sustainability), under our two different sets of assumptions about forestland availability, we estimate that biomass production for energy use would range from 13.7 – 15.8 million metric tons per year over the 8-state region (Pennsylvania – Maine, excluding New Jersey) (Table 4).
- If biomass currently used in the pulp and paper industry is not diverted to energy production, we estimate that the region can only sustainably produce 4.2 – 6.3 million metric tons/yr of biomass. This better reflects the potential for net reductions in greenhouse gas emissions (Table 4).

Substituting Fossil Fuels with Biomass in the Northeast

- Assuming that all of the estimated sustainable forest biomass supply - ranging from 4.2 – 15.1 million metric tons/yr under the different scenarios - was used in the most efficient current technology (combined heat and power plants), ***forest biomass energy would constitute 1.4 – 5.5% of the entire region's current energy consumption.***
- The proportion of the energy portfolio contributed by forest biomass, however, would vary significantly among states, with a higher percentage in states with large forestland bases and low energy consumption.
- Biomass can be used in many different energy sectors and with different efficiencies. Using the conservative estimate of 4.2 million metric tons of forest biomass supply for energy, the Northeast could either:
    - Replace 6% of its coal consumption (used for electricity); or
    - Provide 4 to 6% of its total electricity mix from biomass[1], with an additional 14% replacement potential of the liquid fossil fuels used in the commercial and industrial heating sector if Combined Heat and Power (CHP) technology is used; or
    - Replace 28% of the liquid fossil fuels used in the commercial and industrial heating sector; or

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[1] Based on a 25 or 40% net electrical efficiency.

  - Replace 16% of the liquid fossil fuels used in the residential heating sector; or
  - Replace 5 or 2% of its current highway diesel or gasoline consumption, if future liquid transport biofuels become commercially available.

- Replacing one metric ton of coal with biomass (e.g. by cofiring) is over three times more efficient in terms of endpipe CO_2 emission reductions than substituting gasoline with cellulosic ethanol. Combined heat and power plants reduce close to five times more endpipe CO_2 emissions when replacing coal (for electricity) and liquid fossil fuels (for heat) than substituting gasoline with cellulosic ethanol.
- Despite having limited if any potential for sustainable increases in timber harvests (over levels recorded from 2004-2008), Maine shows the most promising fossil fuel substitution potential from increased recovery of logging residue. We estimate that Maine could replace up to 42% or 49% of its current use of liquid fossil fuels in the commercial/industrial or residential heating sector, respectively, through this source of biomass energy. New Hampshire also shows favorable substitution potentials across all scenarios. For instance, it could replace 84% of its current use of liquid fossil fuels in the industrial and commercial heating sector with local forest biomass if all biomass would be directed into that sector only. In comparison, our analyses suggest that neither Connecticut nor Rhode Island will be able to able to substitute > 10% of any of their fossil fuel sectors (transport fuels, heating applications, electricity production) with forest-based biomass energy.
- Understanding the net greenhouse gas implications of additional forest biomass harvests and its impacts on terrestrial carbon stocks in the region will require further analyses especially those related to the CO_2 emissions of land use change associated with expanded harvesting activities (harvesting lands not currently being managed).
- Results suggest that displacing oil with biomass in commercial and industrial boilers represents the most viable short-term scenario for reducing dependence on foreign oil and net greenhouse gas emissions. Co-firing biomass with coal in existing coal electrical generating plants may also be an efficient way to replace current fossil fuel use and curb CO_2 emissions if residues are used – but it does nothing to reduce energy imports and risks a geographic mismatch of demand and availability. While cellulosic ethanol would require additional research and commercialization efforts, producing process heat in biomass boilers or co-firing biomass with coal faces much lower technology hurdles. It could therefore be implemented within a much shorter timeline, requires less investment into new infrastructure, and has immediately favorable CO_2 substitution efficiency if waste wood and logging residues are used.

- Forest-based bioenergy can play an important role in a future diversified energy mix in the Northeast even under conservative assumptions about the magnitude of the biomass resource. However, for forest-biomass derived bioenergy to matter significantly across all potential substitution scenarios, total energy demand has to be reduced dramatically by reducing overall energy consumption and increasing the efficiency of energy use, especially in the transport sector.

All of the biomass energy technologies - regardless of efficiencies, energy carrier substituted, conversion technology applied, or temporal scale of implementation - rely on a cost-efficient and pervasive biomass supply chain. The declining forest industry in the Northeast poses a major threat to the maintenance of both the physical infrastructure for forestry, and of the human resources for sound forest management (see e.g. Sherman 2007 for Vermont, Germain 2010 for New York). To spur innovation and investments in biomass supply infrastructure, there is a need for a reliable biomass market *in the short-term.* Supporting short-term bioenergy applications now (such as use in commercial boilers) might therefore also contribute to the development of more long-term technologies (such as wood-fired distributed combined heat and power systems) that can be more attractive from an energy efficiency or CO_2-offset capacity point of view. This is a strategy that Austria has applied successfully since the 1980s by first supporting biomass heating applications and then expanding biomass use for electricity production (OEMAG 2010). As a result, Austria now provides 11% of its electricity from biomass.

Conclusions

Forest biomass energy can play an important role in a diversified renewable energy portfolio for the Northeastern U.S., and can be an important source of jobs and economic growth in the region. ***Our analyses, however, show that the magnitude of the sustainable forest biomass supply is far smaller than most previous studies have suggested***.

Policies to promote forest biomass energy need to recognize the wide range of biological, physical, social, and economic constraints on the sustainable supply of forest biomass for energy, in order to avoid perverse incentives that lead to unsustainably high rates of harvest. ***Overharvesting would lead to degradation of northeastern forests - a resource of critical economic and ecological importance – and actually release more carbon to the atmosphere than would comparable energy production from fossil fuels.***

The magnitude of a forest-based biomass energy industry in the Northeast will ultimately reflect the balance of the often competing demands that public and private landowners place on forests for economic, environmental, and aesthetic benefits.

INTRODUCTION

One consequence of the imperative to reduce greenhouse gas emissions worldwide has been enormous interest in the use of various forms of biomass as an energy source, particularly for the production of liquid fuels. While potentially with low-carbon emissions - at least in principle – it is now clear that there is an extraordinarily wide range of factors that must be considered to evaluate the net carbon and climate impact of biomass energy production. Legislation and policies at both the federal and state level have created growing demand and incentives for use of biomass for energy, but generally without accounting for (1) the sustainable capacity of the natural resource base to meet energy demands, (2) a full accounting of the impact of biomass energy production on net emissions of carbon and other greenhouse gases, (3) the impact of biomass energy production on the wide range of ecosystem services provided by U.S. fields and forests, and (4) the ramifications of increased domestic production of biomass energy on ecosystems and economies worldwide.

With mounting pressure to reduce demand on traditional food crops as biofuel feedstocks (the "first generation" biofuels), attention in the Northeastern U.S. has focused increasingly on use of forest biomass as a "second generation" feedstock. However, many of the concerns that arose from very high demand for agricultural feedstocks also apply to use of forest resources. And the issues related to the broader climate impacts of forest biomass energy production are arguably even more complex than in traditional row crops. Reasons for this include the very wide range of environments from which forest biomass may be harvested, the long-term dynamics of carbon storage and release during succession following harvests, and the impacts of intensification of forest harvest on a wide range of ecosystem goods and services that are currently provided by eastern forests. For all of these reasons, there is an urgent need for a comprehensive analysis of the net climate impacts of the use of forest biomass for energy production in the eastern U.S.

The production of liquid fuels and electricity currently consumes only a small fraction of forest biomass harvests in the Northeastern U.S. The use of wood for heat (primarily in residential woodburning stoves) is, in fact, still one of the dominant uses of forest biomass as an energy source in this region. Biomass accounted for less than 6% of energy supplied in the Northeastern U.S. in 2008 (EIA 2010g). Proponents of forest biomass-based energy appear to envision a significant increase in all forms of use of woody biomass for energy (liquid fuels, electricity, and combustion for heat). A number of states have either adopted or are considering proposals to require that a significant fraction of the state's energy use come from renewable sources, including bioenergy.

Meeting these goals could put unprecedented demand on forest resources in the Northeastern U.S. Meeting these goals *sustainably* will require that there is either a currently underutilized woody biomass resource in the region, conversion of existing uses of biomass (paper, wood, etc.) to energy sources, or conversion of currently non-forested land to woody biomass production.

BACKGROUND

Assumptions and Conventional Wisdom about Northeastern Forests

There are a number of implicit assumptions that appear to have motivated the high degree of interest in expanding the use of Northeastern forest biomass for energy.

- One common assumption is that, outside of lands managed using plantation forestry, **timber harvests in most areas of the Northeastern U.S. are assumed to be far below sustainable levels**, and also below traditionally-defined “allowable cut” limits (i.e., below rates of net forest volume increment). This impression may stem, in part, from the decline in the numbers of sawmills and pulp mills in many regions, creating the appearance of a decline in the demand for and regional harvest of forest products.
- At the same time, **it is often assumed that Northeastern forests are largely even-aged**, and that most stands date from clearcutting during the peak of logging activity 80 – 120 years ago. A corollary is that these stands are **assumed to be nearing “maturity,” at which they will stop sequestering carbon** (at least in biomass of live trees). This assumption is then used to argue that harvesting such stands will reset them to younger stages that have higher annual rates of net carbon sequestration.
- Finally, a great deal of research (and venture capital) has been focused on the development of intensively managed plantations of specialized (and potentially genetically modified) woody biofuel feedstocks. **Such proposals often refer to plans to utilize fallow or abandoned farmland** (to avoid concerns about land-use conflicts that became so apparent in the corn ethanol boom). It is true that 100 years ago there were large areas of such land in the eastern U.S. However most of that land has already undergone succession to forest. These lands have, in fact, played a major role in the temperate forest carbon sink that has been so important in the global carbon cycle over the past 50 years. The abundance of fallow land going forward, however, is much more limited. Remote sensing data for the eastern U.S. suggest that there are still parts of the region where such land exists, but there are also many other parts where establishment of plantations of woody biofuel feedstocks would require conversion from existing agriculture or forestland.

Recent Assessments of Northeastern Forest Biomass Resources

A number of studies over the past decade have supported the assumption that there is a large, untapped forest biomass resource in the Northeastern U.S. (e.g., INRS 2008, Milbrandt 2008, Perlack et al. 2008). Smith et al. (2001) estimated that recent harvest levels could be more than doubled in Northeastern timberlands without reducing total standing biomass over time. Sherman (2007) concluded that Vermont's forests would be able to provide significantly more biomass on a sustained yield basis than is currently harvested. A recent assessment in New York indicated that an additional 4.8 – 6.4 million dry metric tons of biomass can be sustainably harvested over and above current levels of harvest for traditional forest products (Volk et al. 2010). Similar studies have been done for Maine (Maine Forest Service 2008, Dickerson et al. 2007) and Massachusetts (Kelty et al. 2008, Mass DOER 2010). These estimates typically rely on USDA Forest Service Forest Inventory and Analysis (FIA) data, usually including a "discount" factor that seeks to account for land that is inaccessible, reserved from production, or otherwise not eligible for inclusion in the count of "harvestable" acreage. Some of these analyses were intended to build the case for citing biomass production facilities, and "take credit" for forested land just outside state borders. For example, the Vermont Wood Fuel Supply Study (Sherman 2007) "counts" wood in border counties in Massachusetts, New Hampshire, and New York as available wood for citing biomass plants in Vermont. A similar approach is followed by Kelty et al. (2008) for Massachusetts.

There will soon be more complete coverage of forest resources on a state-by-state level. The 2008 Farm Bill and the USDA Forest Service State and Private Forestry (S&PF) programs are requiring each state to develop a statewide Forest Resource Assessment and Strategy (FRAS) by June 2010. The reports are intended to summarize forest conditions and trends, and to identify and prioritize the issues (and threats) facing each state's forests. The reports are not specifically focused on biomass energy but will provide a variety of statistics on forest resources and current harvest levels. Reports for many Northeastern states are already available in draft form on the Web.

Current and Proposed Forest Biomass Energy Use in the Northeast

While biomass currently provides only a small fraction of current energy use in the Northeastern U.S., its use is widespread. For instance, 30% of the schools in Vermont are heated with wood (Frederick 2007). There was a total wood-fired electric capacity of 1,098 MW installed in the Northeast as of 2008 (less than 1% of total generating capacity), with over half of this located in Maine (EIA 2010f). Large quantities of the biomass used for these applications come from a well-established secondary market such as sawmill residues or municipal waste. For instance, one of the largest biomass power plants in the region, the 50 MW McNeil station in Burlington, VT, receives as much as 30% of its total biomass use from such secondary markets (BED 2010). It should be noted that a recent study has concluded that there is not much additional recoverable material from such sources, even on a national scale (Perlack et al. 2005). Thus, the potential for these secondary sources to support expansion of biomass energy production may be quite limited.

Northeastern policy makers have been calling for significant increases in the use of forest-derived biomass for energy production. For example, Vermont officials have called for a doubling of the forest-derived biomass that is currently used for energy production by 2025 compared to current levels (e.g., Vermont's 25x'25 Initiative 2008). That initiative also calls for a renewable electricity share of 20% from non-hydro sources by 2017 (currently 7%, Rickerson et al. 2008). New York has a similarly ambitious agenda, aiming at a non-hydro renewable energy portfolio of 11% by 2013. Consequently, state and federal agency initiatives are promoting biomass sector industries and investment such as the Clean Energy States Alliance (CESA 2010). These efforts also include publishing technology implementation guidelines (e.g., Bourgeois 2009 or Antares Group 2006 for New York, NHRCD 2009 for New Hampshire), developing biomass sustainability assessment frameworks (e.g., DOE 2009), advising local decision makers (e.g., NACD 2010, NRBP 2010), and establishing legal frameworks that promote bioenergy production, such as the Regional Greenhouse Gas Initiative (RGGI 2010). Forest policy and industry organizations are becoming active on behalf of bioenergy on national and regional levels. These include the Heinz Center (2010), the Pinchot Institute (2010), the Northern Forest Biomass Energy Initiative (2010), the Biomass Thermal Energy Council (2010) as well as forest industry organizations with a regional focus such as Atlantica BioEnergy Task Force and the New York Biomass Energy Alliance (2010).

OBJECTIVES

There has been little debate about the potential economic benefits to expanding biomass energy use in the Northeastern U.S. Recent and more thorough analyses of both the net carbon benefits and broader ecological impacts of expanding the biomass energy supply (e.g., Fargione et al. 2008, Searchinger 2009) have tempered the initial enthusiasm, but there still appears to be a great deal of interest among policy makers in a significant expansion of forest-based biomass energy in the Northeast. We would argue that what has been missing from this debate has been ***a realistic, regional assessment of the potential forest-based biomass energy supply, and the degree to which that energy could supplant current fossil fuel based energy consumption within the Northeast.***

"Multiple-use" has been a paradigm in U.S. forest management for over a century – both in legal terms for federal and state public lands, and in practical terms in the context of the values that private landowners place on their forests. The magnitude of a forest-based biomass energy industry in the Northeast will ultimately reflect the balance of the often competing demands that public and private landowners place on forests for economic, environmental, and aesthetic benefits. There seems little doubt that maximizing the biomass energy supply from the region's forests would compromise (potentially seriously) other uses and values, including a wide range of ecosystem services, conservation of native species, and economic benefits from recreation. Nonetheless, we feel that the debate about forest-based biomass energy in the Northeast would benefit from a rigorous and realistic analysis of the potential magnitude of the sustainable biomass supply from the region's forests, with "sustainable" defined in the strict sense of a renewable, biological resource (wood). In effect, this would set a realistic upper bound on the long-term magnitude of a truly "sustainable" (*sensu lato*) forest-based biomass energy industry.

Thus there were two basic objectives of this study:

- **Objective 1: Produce a rigorous, scientific assessment of the potential forest-based biomass energy supply for the Northeastern U.S.** There were three components of this assessment:
    - A. ***Analyze the extent of the Northeastern forestland base, and constraints on the availability of that land for biomass harvests.*** There is clearly an extensive forestland base in the Northeast, but there are many forms of restrictions -- including biophysical, legal, economic and social constraints – on the availability of forestland for biomass harvests. There is uncertainty about the magnitude of many of these constraints, and this represents a serious limitation on the ability to predict long-term sustainable biomass supply for energy.
    - B. ***Assess the current status of biomass stocks and net growth in the Northeastern forests, and the rates and patterns of current utilization for existing forest product markets***. This analysis focuses on the current status of biomass in Northeastern forests, and the relationship of current harvest rates to traditionally-defined "allowable cuts" (i.e., timber supply sustainability in the strict forestry sense). In particular, the analysis addresses a number of the common assumptions about the status of Northeastern forests.
    - C. ***Calculate a range of potential biomass supply for energy, under a range of scenarios.*** There are many variables that will ultimately determine the rate of supply of forest-based biomass for energy production in the Northeastern U.S. We outline a suite of scenarios that represent a range of assumptions about the strength of various constraints on woody biomass supply in the region. Each of

the scenarios is designed to represent a sustainable supply (given the assumptions), but with sustainability defined in the very strict sense of a renewable timber resource, rather than in the critical and much wider sense of sustainability that incorporates not just timber supply but the much broader range of ecosystem services and values that the public places on forests. Thus, our scenarios should be viewed as upper limits on the potential sustainable supply of biomass for energy in the region.

- **Objective 2: Provide a perspective on how this biomass resource could be used to replace current consumption of coal and liquid fossil fuels (LFFs) in the Northeast.** There were four components of this assessment:
  - A. ***Acquire consumption data on fossil fuels in the Northeast.*** We focused our analysis on coal and LFFs, as these are the two dominant fossil fuels used in the Northeast. For further analysis, we categorized consumption data by fuel and end use.
  - B. ***Convert to CO_2 endpipe emissions associated with current use.*** Based on the fossil fuel consumption data, we computed the 2008 endpipe CO_2 emissions derived from the use of each fuel.
  - C. ***Develop substitution scenarios for fuels.*** We developed a set of seven scenarios to identify different fossil fuel substitution pathways that could be pursued by increasing the use of biomass. The scenarios are based on a range of options currently being considered in the Northeast. These scenarios differ in the temporal scale and efficiency with which they replace fossil fuels with biomass.
  - D. ***Calculate total and relative CO_2 emission reductions by state when substituting fossil fuels with biomass***. For each scenario, we matched biomass availability (Objective 1) with current use of coal or LFFs to identify the potential to reduce endpipe CO_2 emissions on a state-by-state basis.

RESULTS

The Northeastern Forestland Base: Extent and Constraints on Availability for Harvest

The Forestland Base

The FIA website provides regularly updated summaries of the area of forestland by state and county, classified by a number of features (i.e., ownership, reserve status, site conditions, etc.). The FIA estimates of forestland are statistical estimates based on the fraction of plots that meet their definition of "forestland" ("land that is at least 10 percent stocked by forest trees of any size, or land formerly having such tree cover and not currently developed for a non-forest use"). The nine-state region (Pennsylvania to Maine, including New Jersey) has a total land area of 42,024,301 ha (103,844,307 acres), of which 28,225,350 ha (69,746,359 acres) are considered forestland (Appendix 1). This is slightly over 67% of the total area. Both the fraction of the land that is forested and the average biomass of forests vary widely at the county level (Appendix 2). To put this in historical context, virtually the entire region is assumed to have been forested at the time of European settlement (although there is uncertainty over the extent of Native American agriculture before their population density was significantly reduced by the introduction of smallpox and other diseases). As a result of subsequent clearing for agriculture, the extent of forestland probably reached its lowest point in the early 1900s and has rebounded dramatically since then. Recent analyses suggest that the rebound has peaked, and that the area of forestland in both the eastern U.S. and the Northeastern states has stabilized or begun to decline slightly due to development (Drummond and Loveland 2010).

Legal Limitations on Land Available for Harvests

Slightly less than 6% of the forestland is legally "reserved" (i.e., lands where logging and forest management are legally proscribed) (Appendix 1). Almost three quarters of the reserved land is found within New York State (1,198,784 ha out of 1,666,499 ha), primarily in the Adirondack and Catskill Forest Preserves. The FIA estimates of reserved land are likely to be a slight underestimate of the true acreage of legally reserved lands, because it is difficult to track local easements that may limit harvests on individual tracts of land. Many states have legal limitations on logging within specified buffers along certain water bodies, or above specified elevations, but there are no regional estimates of the magnitude of the lands restricted under these provisions (Butler et al. 2010).

Physical Constraints

There are a variety of physical, economic, and social constraints on the availability of the remaining 94% of the forestland base for biomass harvests (Butler et al. 2010). For instance, the FIA estimates of forestland include sites that would typically be defined as wetlands. Over the eight-state region[2], these "hydric" sites represent 4.2% of the plots (Appendix 2). Winter harvesting is presumably possible on only some fraction of these sites. Steep slopes (>40% slope) represent another 4.7% of the forestland (Appendix 4), although again, there are silvicultural systems that could be used to harvest many of the sites in this category.

Economic Constraints

A much more practical limitation is the cost of road building for access, given property boundaries and rights-of-way. Butler et al. (2010) consider stands >1 mile from an existing road to be only "partially" available. Our analysis of the FIA data indicates that 7.7% of the plots in the nine-state region were >1 mile (straight-line distance) from the nearest improved road.

Butler et al. (2010) also consider parcel size to be a significant factor in the availability of forestland for harvest, because of economies of scale under current harvesting methods. Their analysis assumes that an 8 ha (20 acre) stand is the "minimum operable size" for Northeastern forests. The National Woodland Owner Survey (USDA FS 2010c), however, indicates that over 50% of the area in family forests in parcel sizes of 1-4 ha (1-9 acres) for the nine Northeastern states has been harvested at least once during the tenure of the current owner. The fraction of area subject to harvest did, as expected, increase with increasing parcel size. For example, ~80% of forest area in parcels >40 ha (100 acres) had been harvested at some point in the tenure of the current owner. But these results suggest that even very small parcels may be available for some form or level of harvest under certain conditions.

This is an area of very active research. A number of studies have highlighted the long-term trend toward increasing "parcelization" of the forestland base (i.e., subdivision into ever smaller ownerships), and there appears to be widespread concern among forestry professionals that this will, over time, significantly reduce the forestland area available for commercial harvests. There appear to be ample reasons for this concern, but we do not feel that it is currently possible to provide rigorous estimates of the magnitude of this constraint.

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[2] See methods section *Compiling FIA data for Northeastern Forests* for this exclusion.

Social Constraints

Finally, Butler et al. (2010) emphasize that landowner values also play an important role in the availability of land for harvest. They suggest that these social constraints are far more significant than physical or economic constraints on the available resource base. Their analyses are based largely on surveys of owner attitudes, and may or may not predict owner behavior and willingness to harvest, particularly as economic pressures and incentives grow over time. There is compelling evidence, however, that some (potentially significant) fraction of the unreserved forestland base is effectively unavailable for harvest because of social constraints (Butler et al. 2010). Again, we do not believe that enough is known to quantify these constraints with any degree of confidence. Nonetheless, we believe that this is likely to be the single greatest source of uncertainty in the magnitude of the additional forest resource available for biomass energy in the region.

The Status and Current Utilization of Woody Biomass in Northeastern Forests

Aboveground Tree Biomass in Northeastern Forests

Based on the most recent official FIA "population estimates" for the period from 2004-2008 (USDA FS 2010n), the average "merchantable" biomass (aboveground biomass in trees, to a 4" top diameter) on forestland in the eight-state region (omitting New Jersey)[3] was 85.2 metric tons/hectare [106.4 metric tons/hectare of total aboveground tree biomass] (Table 1).

There is considerable variation both among and within individual states (Table 2, Figure 1 and Figure 2). Maine has the unenviable combination of the least favorable soils and climate and the highest rates of recent harvest (described later in this report), and as a result has the lowest average biomass levels (~53 metric tons/hectare). The southern New England states of Connecticut and Massachusetts have the highest average merchantable biomass (110-115 metric tons/hectare) (Table 1) and the highest total aboveground tree biomass (Figure 2). Individual counties within states also vary enormously in both the percent of land area that is forested, and the average stocking (biomass) of that land (Appendix 2).

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[3] See methods section *Compiling FIA data for Northeastern Forests* for this exclusion.

Table 1. Total aboveground tree biomass (adult trees plus saplings), and live tree "merchantable" biomass (defined by FIA as biomass above the stump and below a 10.2 cm [4 inch] top branch diameter), by state and for the region as a whole, and per unit area (hectare).

State	**Area Of Forestland** ha	**Total Live Tree And Sapling Aboveground Biomass** metric tons	**Merchantable Biomass** metric tons	**Average Merchant-able Biomass** metric tons/ha
Connecticut	697,829	108,731,556	80,489,837	115
Maine	7,145,731	602,552,693	381,242,694	53
Massachusetts	1,221,938	183,057,479	135,522,519	110
New Hampshire	1,943,857	251,365,457	177,544,327	91
New York	7,669,011	981,655,842	701,468,378	92
Pennsylvania	6,738,913	920,560,580	667,356,854	99
Rhode Island	141,001	19,944,474	14,520,667	103
Vermont	1,856,854	249,572,980	177,665,817	96
Total	27,415,133	3,317,441,061	2,335,811,095	85

Figure 1. Regional variation in adult tree aboveground biomass (metric tons/hectare) in forestland FIA plots from the most recent full census of the eight-state region.

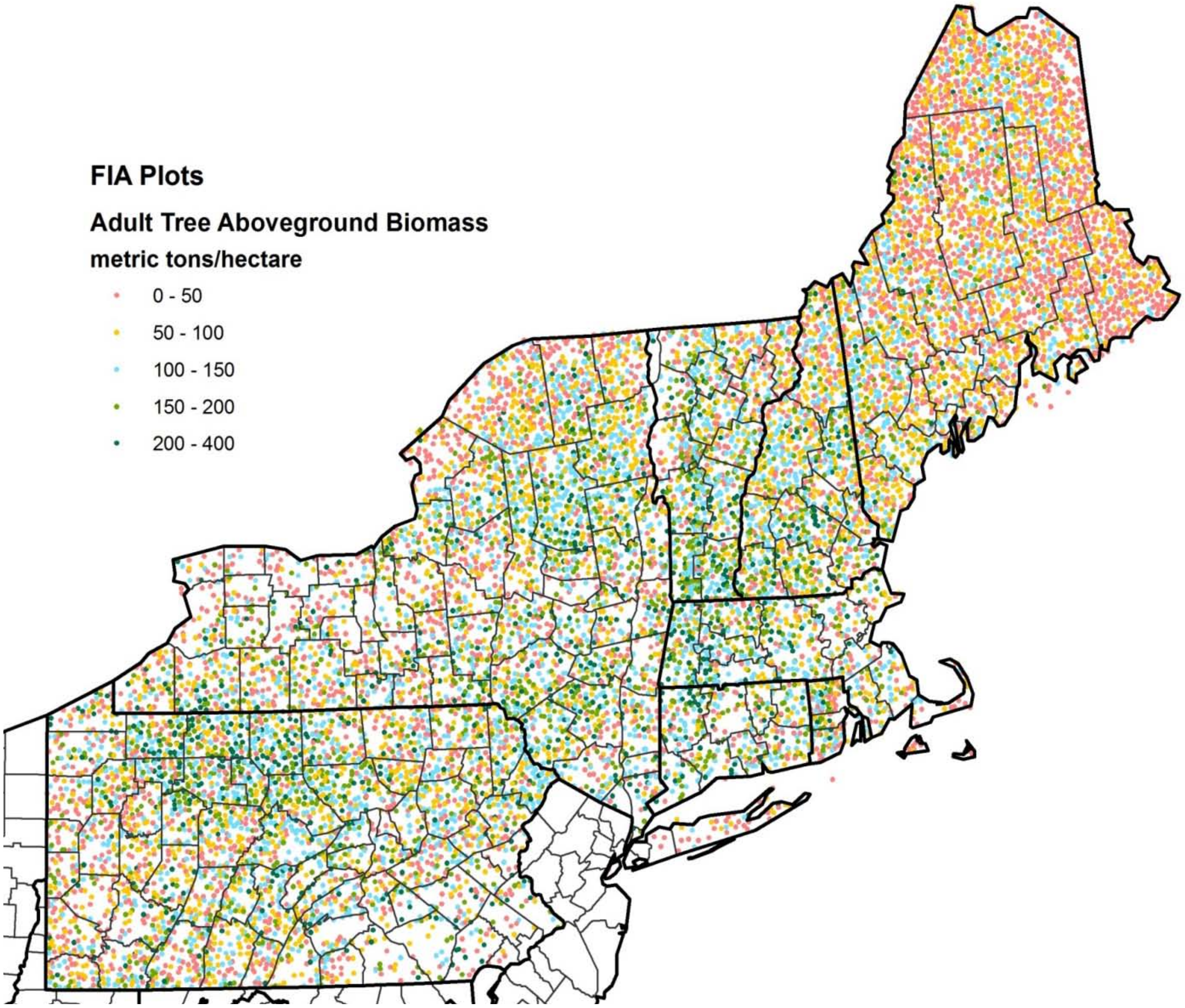
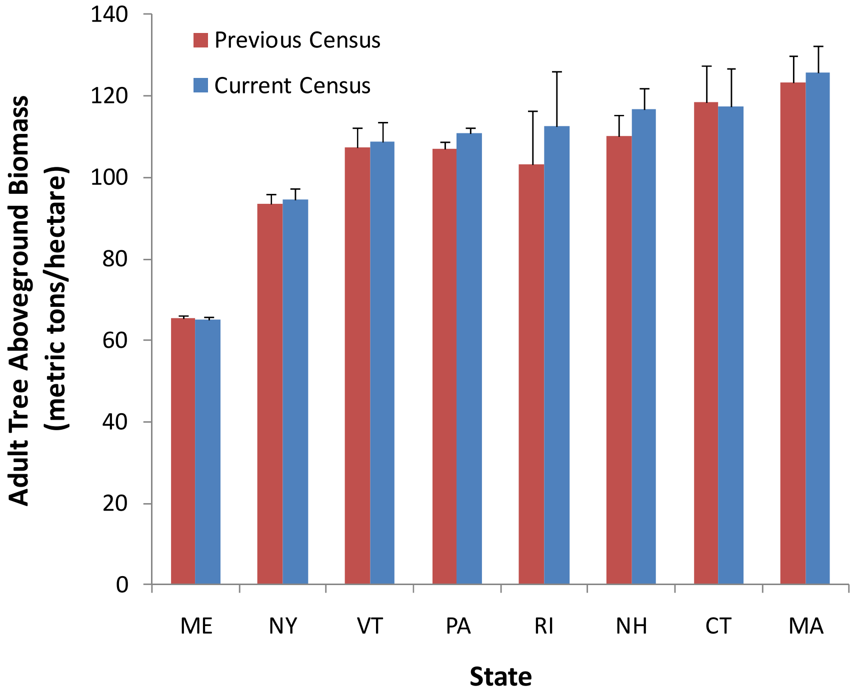


Figure 2. Variation among states in the plot-level adult tree aboveground biomass (metric tons/hectare) in the previous and current censuses for the eight Northeastern states (with standard error bars).



Regional Variation in Biomass Increment and Harvests

Table 2 summarizes the recent (2004-2008) rates of tree biomass increment and harvests, by state, (in units of m^3 per year) as reported by the FIA program in its official “population estimates” (USDA FS 2010n). “Net growth” consists of total tree growth, minus natural mortality. “Removals” are the estimate of the volume removed by logging. The figures reveal that during this period, harvesting has exceeded net growth for the state of Maine and is approximately equal to net growth in Connecticut. In the remaining six states, harvests have removed anywhere from a low of 17% of net growth in Rhode Island to 67% of net growth in Vermont. For the region as a whole, harvests have removed an average of 63% of net growth annually during this period (2004-2008) (Table 2). In approximate terms, the difference between net growth and removals equals the growth in total tree volume in a region. As a fraction of the total volume (4th column in Table 2), the growth in tree volume on an annual basis ranges from a decline by 0.1% per year in Maine to an increase of 1.8% per year in Rhode Island. For the eight-state region, these figures suggest that total tree volume over the landscape as a whole is increasing at a rate of ~0.76% per year.

Table 2. Average annual net volume growth of aboveground biomass, mortality, and removals, by state, over the period 2004-2008 from FIA program population estimates in units of tree volume (m^3/yr). "Difference as a % of total volume" is the difference between net growth and removals, as a percent of total volume of trees, and indicates the estimated annual % increase (or decrease) in total tree volume, given these rates of net growth and removal.

STATE	NET GROWTH m^3/yr	MORTALITY m^3/yr	REMOVALS m^3/yr	GROWTH - REMOVALS m^3/yr	DIFFERENCE AS % OF TOTAL VOLUME	REMOVALS AS A % OF NET GROWTH
Connecticut	1,985,171	1,206,620	1,972,099	13,072	0.01%	99%
Maine	16,585,125	9,944,035	17,381,728	-796,611	-0.11%	105%
Massachusetts	3,548,842	2,345,552	1,028,608	2,520,258	1.15%	29%
New Hampshire	5,744,156	3,508,445	2,490,233	3,253,953	1.08%	43%
New York	20,015,035	14,447,706	9,788,476	10,226,655	0.91%	49%
Pennsylvania	24,207,723	9,216,975	12,742,610	11,465,221	1.14%	53%
Rhode Island	475,929	193,091	80,258	395,675	1.78%	17%
Vermont	5,107,525	2,897,275	3,412,785	1,694,756	0.59%	67%
Total	77,669,505	43,759,699	48,896,797	28,772,980	0.76%	63%

It is critical to note that these figures represent all forestland in the region and do not exclude reserved lands or lands that are not available for harvest due to physical, economic, or social constraints. We will address the long-term sustainability of the current harvest rates and the degree to which there is potential for sustainable increases in biomass harvests in detail in a later section. As a simple illustration here, however, note that if one-third of the forestland base in Vermont was effectively "unavailable" for harvests, then the harvest rate in that state (at 67% of net growth over the entire forestland base) might well represent the highest yield that could be sustained in the long term (assuming that the available and effectively reserved lands had roughly similar net biomass increments). ***Total carbon storage in the forests would be expected to continue to increase for many years as carbon stocks in the "reserved" (legally or otherwise)***

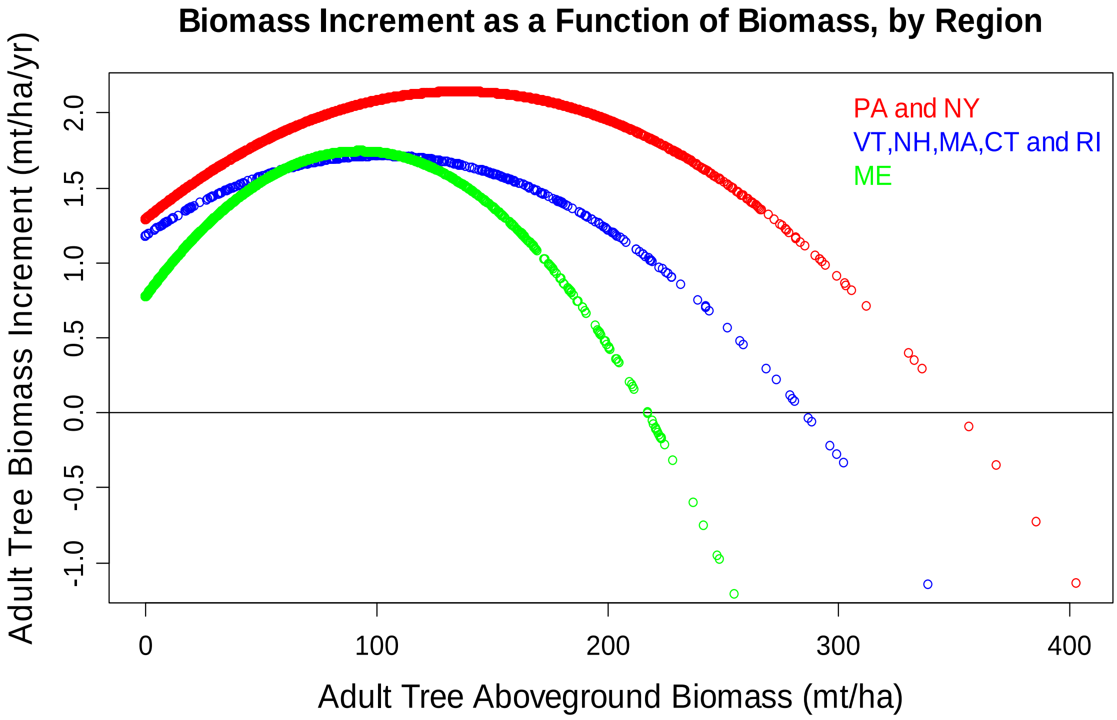
lands continued to increase, but any increase in harvests above current levels would come at the expense of a decline in the total stock of forest biomass in the working forests.

Relationship between Tree Biomass and Biomass Increment

The biomass “yield” of a forest stand (i.e., the annual increment in biomass) varies predictably as a function of total stand biomass. In principle, yield is expected to increase as stands increase in total biomass (because of the inherent scaling of tree growth to tree size), and then reach a peak at some intermediate biomass. As stands continue to increase in biomass, yields should decline and eventually reach zero. The reasons for the decline have been widely debated in the ecological literature, but the fact that the decline happens is indisputable -- forests do not continue to increase in living biomass indefinitely. The shape of this biomass increment curve (Figure 3) is central to the overall yield of a landscape or region, when combined with the information on the proportion of the landscape in stands of different total biomass (Figure 4, discussed below).

Our statistical analysis of biomass increment patterns lumped the eight states into three regions to ensure adequate sample sizes. The three regions differ in (1) the magnitude of the peak increment, (2) the level of total tree biomass at which the peak occurs, and (3) the biomass at which increment is predicted to become zero (Figure 3). Note that these analyses are for unlogged stands and represent potential yield for harvest. Vermont, New Hampshire, Massachusetts, Connecticut, and Rhode Island have a lower peak biomass increment than Pennsylvania and New York combined, and the peak occurs at lower total tree biomass. The lower yields at any given tree biomass presumably reflect some combination of the effects of less favorable climate and soils, or the result of past disturbances. As a result, maximum tree biomass (i.e., the biomass at which stands are assumed to, on average, stop accumulating biomass in the aboveground portions of live trees) varies significantly across the region, from slightly over 200 metric tons/ha in Maine to over 350 metric tons/ha in Pennsylvania and New York.

Figure 3. Estimated biomass increment (metric tons/hectare/year) as a function of total adult tree aboveground biomass in FIA plots, for three regions within the Northeastern U.S. The curves represent maximum likelihood fits of a quadratic function to the individual plot-level biomass increment data for unharvested plots averaged over the period between the current census and the previous census (see the methods section for details).



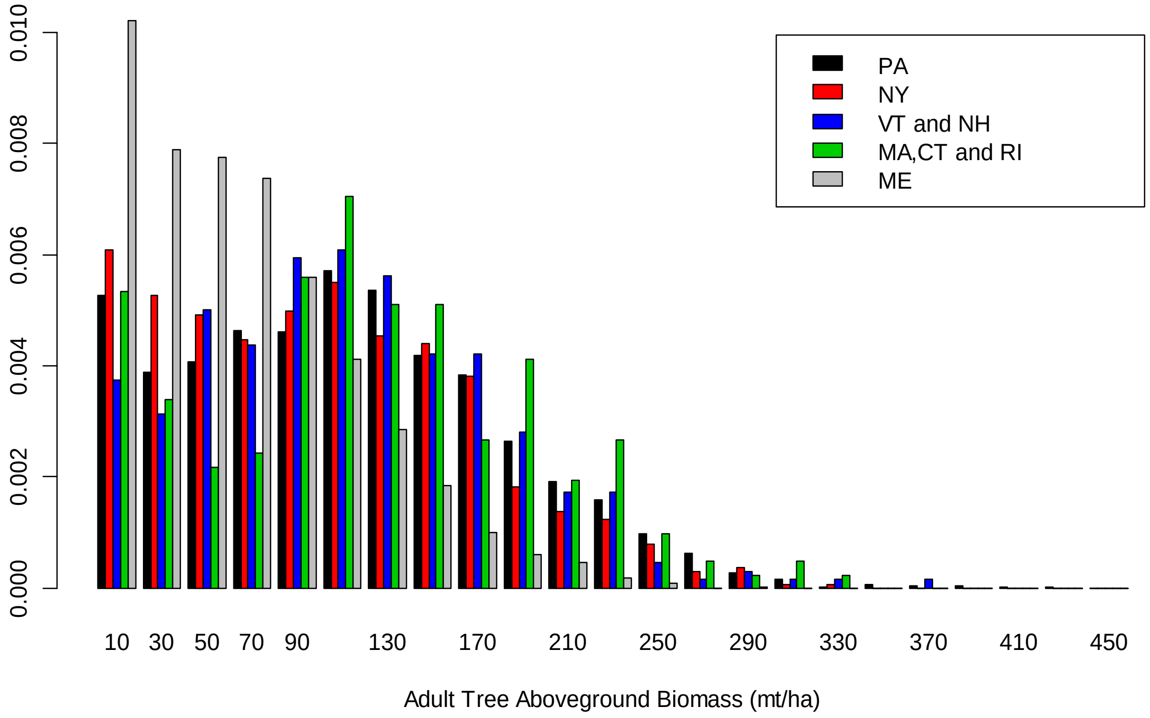
Plot-Level Distribution of Aboveground Tree Biomass, and Average Biomass Increment

The average biomass increment (yield per unit ha) in a region (Table 3) is a product of the biomass increment functions described above and the plot-level variation in aboveground tree biomass in the region (Figure 4). Despite assumptions in some quarters that Northeastern forests overall are nearing “maturity” (and zero net aboveground live biomass increment), the FIA data show a landscape with an extremely wide range of biomass, with most stands clustered in the range of adult tree biomass that has the highest rates of biomass increment. As would be expected from the high rates of harvest in Maine, the frequency distribution for that state is dominated by stands with very low biomass, and the mean biomass is dramatically lower than in the other states (Table 3). The statewide average biomass increment is also relatively low (1.35 metric tons/ha/yr). The southeastern New England states (Maine, Connecticut, and Rhode Island) have the highest average biomass, with the greatest fraction of plots in high biomass stands, but partly as a result of this, have the lowest average biomass increment (Table 3). Pennsylvania has intermediate average biomass (115 metric tons/ha on average), but the highest average biomass increment (2.08 metric tons/ha/yr, Table 3). This presumably reflects favorable soils and climates (relative to the other Northeastern states), but also reflects a distribution of plot biomass that is concentrated in the range of biomass where biomass increment is at its peak (Figure 4). ***Given that the peak predicted biomass increment is only slightly higher than the current average biomass increment, the current frequency distribution of plot-level biomass in Pennsylvania (Figure 4) appears to be near-optimal for biomass increment.***

Table 3. Biomass increment (annual growth in adult aboveground tree biomass, over the period from the previous to the current census) for FIA plots in the Northeastern states. The southeastern New England states of Massachusetts, Connecticut and Rhode Island were lumped to increase sample size. The coefficient of variation for the biomass increment is computed as the standard error of the mean, expressed as a percentage of the mean.

	Number of Plots	Mean Aboveground Biomass	Mean Biomass Increment	Coefficient of Variation
State		**mt/ha**	**mt/ha/yr**	**% of biomass increment**
Pennsylvania	1944	115	2.08	3.5%
New York	559	103	1.23	9.5%
Southeastern New England	191	121	1.07	20.2%
Vermont	134	115	1.64	12.7%
New Hampshire	143	118	1.83	10.3%
Maine	2589	68	1.35	3.0%

Figure 4. Frequency distribution of adult tree aboveground biomass (metric tons/ha) in the FIA plots from the current census for the region. The five smaller New England states are grouped into northern New England and southern New England to avoid small sample sizes in individual size classes.



Current Regional Forest Harvest Regimes

The overall pattern of forest biomass harvest in any region is an amalgam of widely different silvicultural practices, reflecting the diverse influences of variation in the forest resource, landowner interests, and market forces. Nonetheless, it is possible to characterize, statistically, the overall pattern of biomass harvest in a region, and then use that pattern to assess both the overall yield of biomass and the sustainability of the harvest regime over time.

As part of our compilation of the FIA plot biomass data, we calculated the fraction of basal area harvested ("removed" in FIA parlance) from the previous census to the current census. For the eight-state region, the time period for these harvests varied from plot to plot, but was concentrated in the years 2004-2008. The bulk of this period was during the housing boom of the past decade and before the crash of 2008, and it is likely that harvest rates in the past 18 months have declined.

Our statistical analysis simultaneously estimates the two key components of a regional harvest regime: (1) it estimates the annualized probability that a stand is subjected to any level of harvesting, and (2) it estimates the fraction of basal area that was removed, given that a stand was harvested. Both of these terms are modeled as functions of the total adult tree biomass (in metric tons/hectare) at the time of the previous census. The amount of biomass harvested can't be estimated directly because the FIA individual tree datasets don't include a calculation of the biomass of harvested trees. However, basal area (sum of the cross-sectional areas of the tree trunks, measured at breast height) is approximately linearly related to total tree biomass, so the fraction of basal area removed is effectively equal to the fraction of tree biomass harvested.

The results (Figure 5) illustrate that partial harvesting, rather than even-aged management (clearcutting), is the predominant form of harvesting in all three of the subregions. While the probability that a stand will be logged does increase slightly as total tree biomass increases, the rate of increase is modest, and even stands with relatively low current biomass are subject to harvests (Figure 5a). When a stand is logged, the fraction of basal area removed is either effectively constant or was lower in stands with higher biomass. Thus, in New York and Pennsylvania, if a stand is logged, on average 30% of the biomass is removed, regardless of how much biomass was present. There is, of course, a great deal of variation in individual harvests, but the mean does not vary with stand biomass. For the other two subregions (Vermont, New Hampshire, Massachusetts, Connecticut, and Rhode Island vs. Maine), the average fraction of biomass removed actually declines as stand biomass increases, but the heavy rates of harvest from Maine show up as the highest average % removal across all levels of stand biomass.

Figure 5. Estimated forest harvest regimes for different parts of the study region. "New England" consists of the states of Vermont, New Hampshire, Massachusetts, Connecticut, and Rhode Island: A. Estimated annual probability that a stand is logged, as a function of tree biomass (adult aboveground tree biomass, in metric tons/ha); B. The percent of adult tree basal area (as a surrogate for biomass) harvested if a stand was logged, again as a function of stand biomass (metric tons/ha).

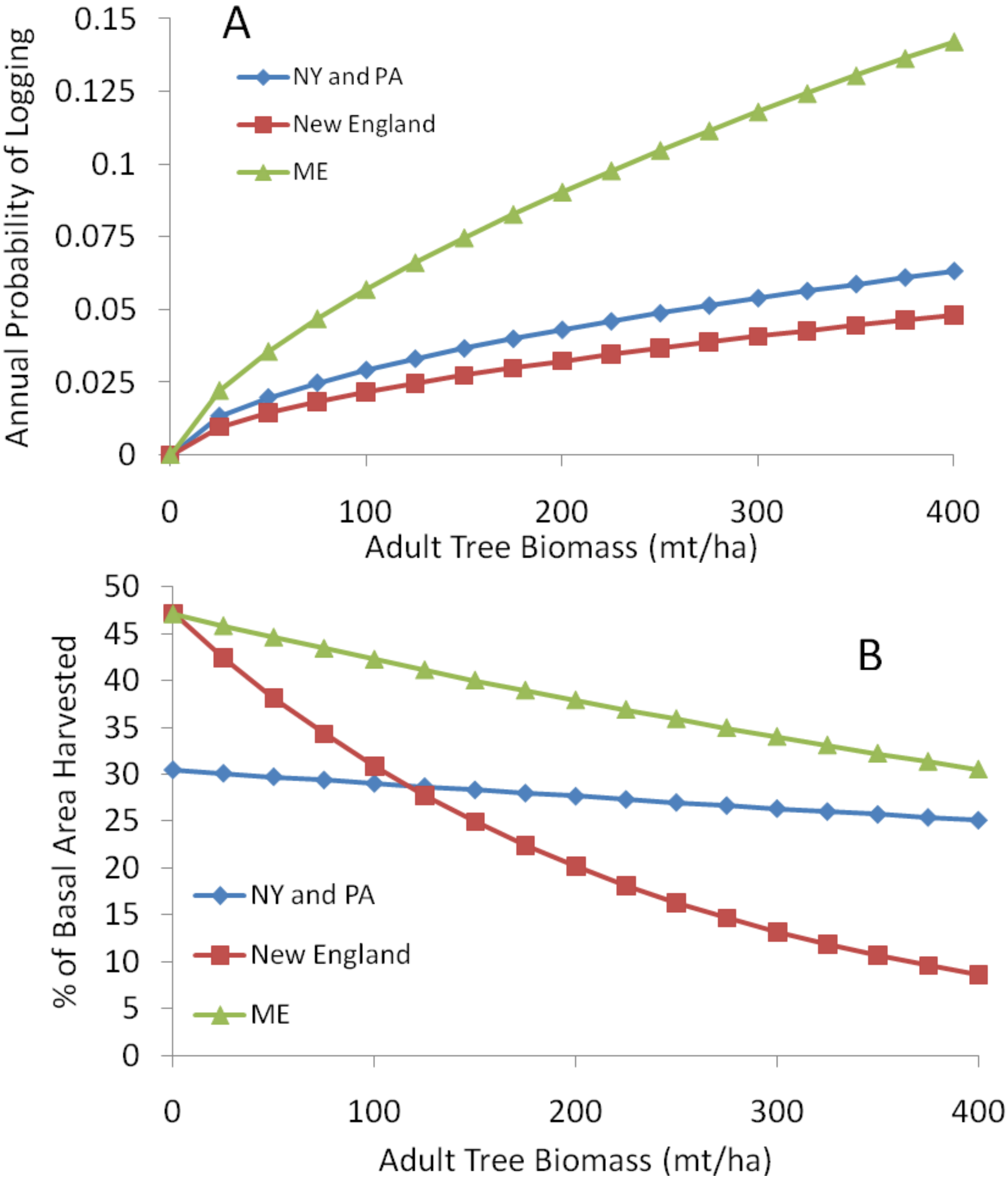
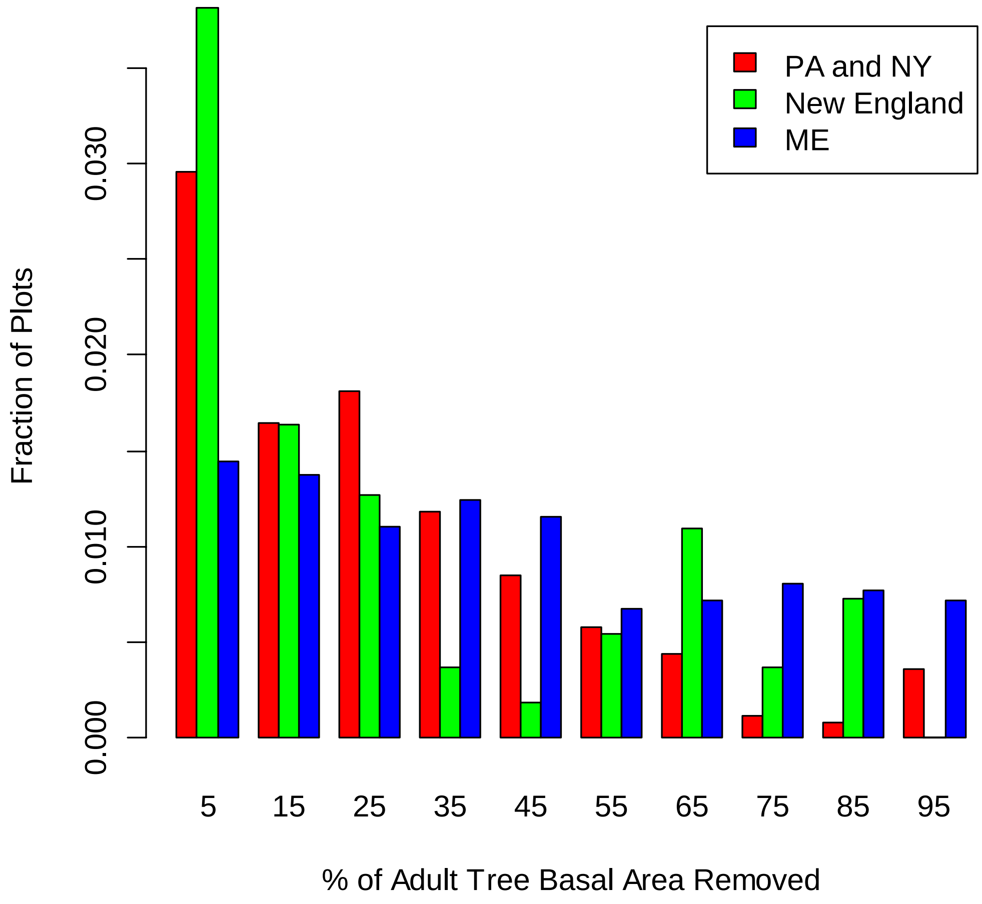


Figure 6 shows the actual frequency distribution of the % of tree basal area removed for the stands that were logged, for each of the three regions. Again, Maine has the greatest fraction of plots that have intensive harvests (i.e., >75% of biomass removed). The distribution for the other southeastern New England states is effectively bi-modal – with the majority of stands having very low intensity harvests, while a subset of stands have relatively intense harvests (i.e., >50% of biomass removed). For the states of Pennsylvania and New York, the vast majority of stands that were logged experienced harvest rates of <30% of current biomass.

Figure 6. Frequency histograms of the % of adult tree basal area removed for plots that were logged during the most recent census interval, by region. See Appendix 7 for the census periods. The Y-axis is scaled so that the area of all bars sums to 1. Since the intervals are in 10 even units, multiply the Y axis value by 10 to get the fraction of all logged plots that were in a given interval. Clearcutting was rare in all three regions. The median % basal area removed was 22.5% for Pennsylvania and New York, only 15.5% for Vermont, New Hampshire, Massachusetts, Connecticut, and Rhode Island, but 38.1% for Maine.



Long-Term Implications of Recent Harvest Regimes for Biomass Stocks and Yield

Given a current distribution of plot-level biomass in a region (as in Figure 4), the combination of the biomass increment functions shown in Figure 3 and a harvest regime as defined in Figure 5 will -- over time -- lead to a new, steady-state distribution of plot-level biomass and a relatively constant biomass yield at the landscape level. It is easy to visualize a hypothetical harvest regime that results in the highest potential sustained biomass yield from the landscape as a whole. Such a regime would be designed to cluster all stands in the landscape at the biomass level that is at the peak of the biomass increment curves in Figure 3 (i.e., ~125 metric tons/ha for PA and NY, 100 metric tons/ha for ME). Such a homogeneous landscape, however, is both impractical from an operational standpoint, and undesirable from an ecological perspective.

As described above, all of the Northeastern states have forested landscapes with a very wide range in the distribution of plot-level biomass (Figure 4). We have done extensive modeling of the long-term implications of the patterns shown in Figures 3-5, and the Northeastern states illustrate two very different futures. In the case of Maine, which has the most intensive harvest regime and where current harvests exceed recent net growth (Table 2), maintaining the current harvest regime given the current distribution of plot-level biomass shown in Figure 4 will lead, over time, ***to a continued decline in average plot-level biomass*** (and in the total carbon stocks stored in Maine's forests), and ***a decline in the landscape-average yield*** (since more and more of the landscape will be clustered in very low biomass stands that have low biomass increment [left-hand side of the graph in Figure 3). ***Note that the harvest "regime" is not defined by an absolute amount of biomass removed from a given stand, but by the fraction of biomass that is removed (*****Figure** 5***b*). Thus, as average stand biomass declines, the total amount of biomass harvested under a given regime declines.***

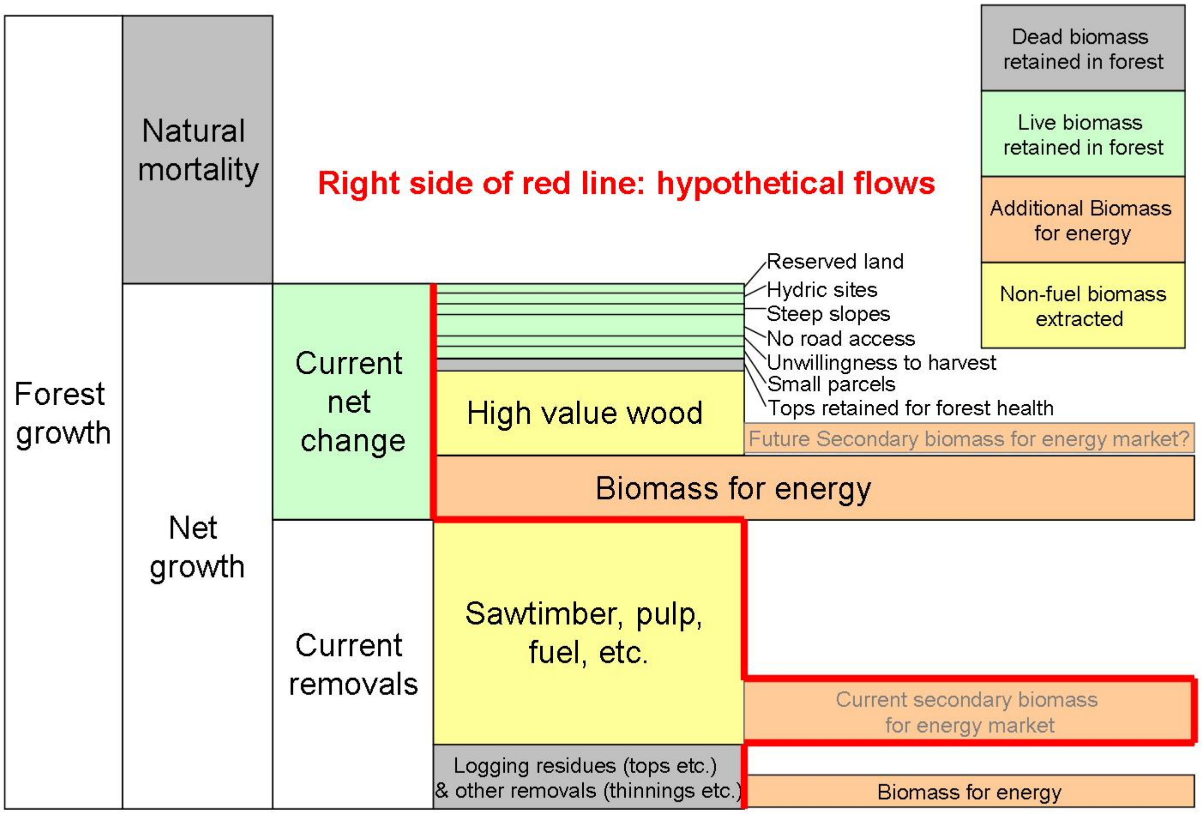
For the remaining Northeastern states, where harvest regimes are less intense, current removals do not exceed net growth (Table 2). Assuming all of the landscape is available for harvest (an overly optimistic assumption that will be considered in detail in a subsequent section), the current harvest regimes would result in ***an increase in average plot-level biomass stocks*** (i.e., the total biomass of live trees on the landscape) and ***a slight increase in the long-term average biomass yield***. The increase in biomass yield occurs because the harvest regimes are dominated by partial harvesting (rather than clearcutting), and over time, the average biomass of the stands will increase. As a result, harvesting 30% of the biomass (a typical harvest in PA and NY, Figure 5) produces a higher average yield per unit area of forestland.

Potential Forest Biomass Availability for Energy Production

We present below a range of scenarios for expansion of the Northeastern forest biomass energy supply. The scenarios illustrate the wide range of factors that have to be considered when making an attempt to estimate sustainable biomass availability, even when just incorporating the most basic forestry perspectives. For two of the scenarios, we provide a "low" and "high" supply option, with constraints that bracket a range of estimates of the magnitudes of the legal, economic, and social constraints on the available forestland base.

Figure 7 serves as an illustration of the constraints for additional harvest of biomass that we considered in this study. The height of the box "Forest growth" represents total forest growth per year in the Northeast. The boxes to the right of "Forest growth" represent real and hypothetical flows of biomass while the relative height of the boxes represent their share of this biomass flow (for hypothetical flows we used the percentages of constraints used in Scenario B Low as explained below). Currently 35% of the annual forest growth is compensated by natural mortality. Over the region as a whole, rates of harvesting during the period 2004-2008 removed 62% of the net change. Some fraction of the current "net change" in forest biomass could be potentially available for additional biomass harvest, but only after accounting for a) high-value biomass that would go to the veneer and sawlog market, and b) for land that is not available for harvest. Current cut but unused biomass (logging residues and other removals such as thinnings) could be tapped into to a certain degree for biomass extraction. We did not include biomass from secondary sources such as wood chips coming from saw mill operations in our analysis, as this market is highly uncertain.

Figure 7. Biomass allocation as fraction of annual biomass growth in Northeastern forests for Scenario B Low. The height of the boxes represent the relative ratio of the biomass flows according to the scenario assumptions as outlined below in the scenario descriptions.



Scenario A – Diverting Biomass from Paper to Energy

In this scenario we assume no increase in overall harvest regime (over the levels depicted in Table 2 for the period 2004–2008). Additional biomass for energy comes from diverting all of the pulp fraction of existing harvests to energy production, plus extracting logging residues (tops) from the existing harvests. Although the harvest regime stays the same in this scenario (the same fraction of tree biomass is being cut compared to current levels), the fate of that cut biomass will be different, with more of it removed from the stand rather than decaying in the forests, and all of the pulp supply diverted to energy rather than paper production. In effect, this scenario assumes that traditional markets will continue to capture the high-value wood products (sawlogs and veneer logs), but that biomass energy will at some point outcompete the pulp market for low-grade wood.

We assumed that:

- To calculate biomass available from current removals (see Table 2), we assume that 77% of this biomass is in the "merchantable" section of the bole, while 4% of the biomass is in stumps and not used, and the remainder (19%) represents the tops or logging residue.
- All pulp would be diverted to biomass energy (see Appendix 6), but veneer and sawlog markets would prevail with their current fraction of each state's harvest. Over the region as a whole, pulp markets capture approximately 45% of the current timber harvest (but with significant variation from state to state). The magnitude of this supply may well decline over time, since the goal of many forest landowners is to gradually increase the fraction of a harvest that goes to high-value products.
- 50% of the logging residues (tops) are extracted (assuming that 19% of the "Removals" in Table 2 are in tops). We assume that the current utilization of tops is negligible, so the 50% that is recovered under this scenario represents new utilization dedicated to biomass energy.
- The "available" land base is not a factor in this analysis. We focus on current removals which, by definition, occur only on accessible land where land owners are willing to harvest. If recent harvest rates are unsustainably high, then supply under this scenario will decline over time.

Scenario B - Biomass from New Harvests

In this scenario we assume that the current harvest regime remains devoted to the current mix of forest products (including both high-value products and pulp), but the harvest regime is increased in intensity to a level that would produce combined removals that match current estimates of net growth (i.e., harvesting all of the "allowable cut"). This could be accomplished by either increasing the frequency of harvests and/or the fraction of biomass removed when harvested. The critical issue for this scenario is how much removal rates could be increased without exceeding net growth[4] on the "available" land. Below we specify "**Low**" and "**High**" biomass supply variants of this scenario, depending on whether there are strong or weak constraints on the amount of land effectively available for harvest.

We assumed that:

- The additional harvest to current logging would tap into the net growth of the Northeast (Table 3). We assume for this scenario that all the net growth could potentially be available for energy production, restricted only by (i) leaving some fraction of the tops remaining in the forest, (ii) continued capture of the high-value products by traditional timber markets (veneer and sawlogs), and (iii) the size of the available land base on which the new harvests could take place.
    - Fraction of tops remaining in the forests: in order to maintain forest health and productivity, not all of the tops can or should be removed. The Forest Guild (Perschel and Evans 2010) suggests leaving 25-33% of the crown material in the forest. **We assume that** 50% of tops are removed in both scenarios.
    - Use of high-grade wood in traditional wood products (veneer and sawlogs): only the "pulp" fraction (Appendix 6) of the merchantable biomass of the additional harvests would be available for biomass energy use. The high-value products from the additional harvests would add to the veneer and sawlog market (same fractions for both the **Low** and **High** variants of Scenario B).
    - Restrictions on available forest land:
        - Legal restrictions[5]:

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[4] For this analysis we assume that the available land has the same average net growth as the "unavailable" land.

[5] Buffers along water bodies and forest land on high elevations were not included in this analysis but should be considered in more detailed analyses. Legal restrictions on the maximum elevation acceptable for harvests differ from state to state. Buffers vary in width depending on the water body characterization.

  - Reserved land is excluded (~5.9% of total forestland) for both the **Low** and **High** biomass variants (see Appendix 1).
- Physical constraints:
  - Exclusion of wetlands: **Low**: no logging in wetlands; **High**: 50% of forests on hydric soils available for logging.
  - Exclusion of steep slopes: **Low**: no logging on steep slopes (>40°); **High**: 50% of steep slopes available for logging.
- Economic constraints:
  - Effects of distance from roads: **Low**: no logging on stands with a distance of >1 mile to the nearest improved road (~7.7% of land, see section *Economic constraints*); **High**: half of these "remote" stands logged.
  - Effects of parcelization (see Appendix 5): **Low**: no logging in parcels <4 ha (10 acres), and 50% of parcels <8 ha (20 acres) are available; **High**: logging allowed in 50% of parcels <4 ha, and in all parcels >4 ha.
- Social constraints:
  - There is a fraction of forestland effectively "reserved" because some landowners are unwilling to log: **Low**: we assume that 10% of the unreserved forestland (over and above land unavailable for any of the constraints listed above) is unavailable; **High**: 5% of the remaining unreserved forestland is unavailable.

Only 63% of the total forestland base was estimated to be available for harvests in the **Low** variant under the assumptions listed above. Under the **High** variant, 73% of the forestland base was estimated to be available for harvests.

Note that the current rates of removal estimated for the region as a whole also happen to be 63% of net growth calculated for all forestland (regardless of legal restrictions or other constraints on availability of the land for harvests) (Table 2). A rigorous calculation of sustainable harvest rates requires a much more detailed analysis, but as a first approximation, ***these results suggest that the current harvest regime over the entire Northeast is very close to (if not greater than) a sustainable rate, when limited to the available land base.***

Scenario C – Combined

This scenario is the most liberal estimate of the three. We assume a maximum availability of biomass for energy use by combining features of Scenarios A and B. All current pulp wood harvests would be dedicated to the biomass energy supply, while also (a) increasing overall harvest levels to equal net growth on "available" forestland, and (b) harvesting some fraction of logging residues. As in **Scenario B** - ***Bioenergy from New Harvests***, we created **Low** and **High** variants for **Scenario C**, using the same weak and strong constraints outlined for **Scenario B**.

Table 4. Biomass availability by scenario and state in metric tons (dry) per year. If constraints on forestland availability are factored into the calculations, current harvest rates in both Connecticut and Maine already exceed net growth, so no additional harvests were factored into Scenarios B and C for those two states.

State	Scenario A- *Diverting Biomass from Paper to Energy*	Scenario B - *Biomass from New Harvests*		Scenario C *Combined*	
		Low	High	Low	High
Connecticut	333,014	70,225	70,225	333,014	333,014
Maine	4,563,148	962,262	962,262	4,563,148	4,563,148
Massachusetts	170,815	192,935	308,469	327,729	443,263
New Hampshire	689,094	523,020	767,218	1,066,800	1,310,999
New York	2,082,262	667,986	1,218,198	2,311,147	2,861,359
Pennsylvania	3,346,754	1,505,443	2,491,920	4,146,444	5,132,921
Rhode Island	11,554	23,938	39,460	33,056	48,578
Vermont	919,160	205,219	411,116	930,549	1,136,447
Total	**12,115,802**	**4,151,028**	**6,268,867**	**13,711,888**	**15,829,728**

Summary of Biomass Supply Scenarios

Table 4 summarizes the estimates of biomass available from forests for energy use when applying the scenario assumptions outlined above. The scenarios suggest a range of 4.2 to 15.8 million metric tons of dry biomass/year could be available for bioenergy applications in the Northeast. Scenarios A and C would compete with current uses (pulp wood), while Scenario B would not. Diverting pulp harvests to biomass energy production would require replacing the region's pulp and paper production with biomass harvests from other parts of the world. This, in turn, could significantly reduce the potential benefits in carbon emissions versus using fossil fuels (Searchinger et al. 2009).

For Scenario B, the biomass derived from an increase in overall harvest rates constitutes as little as 0% (Maine and Connecticut, Scenario B Low and High) to 94% (Rhode Island, Scenario B High) of the total biomass available, the remainder being derived from currently logged but unused sources. In the case of Connecticut and Maine all additional biomass available would come from current logging residues only.

Comparison with Previous Studies

A direct comparison of these numbers with previous studies is difficult, since assumptions about growth and residue accessibility vary widely, and spatial boundaries of other studies do not match ours. In general, our estimates of biomass supply are significantly lower than from most other previous studies. There may be a number of reasons for this, but we believe that the two most important are (1) we are using the most current data available from the Forest Inventory and Analysis program, and these data cover a period when harvest rates were relatively high, and (2) by using the FIA data from the entire region, our analyses capture the full range of variability in current forest biomass and forest growth. We feel these numbers provide the most accurate basis for estimates at the state and regional level. Many other studies base their estimates of forest growth on data from a much more limited set of sites, typically sites that are more productive than on average for all forestland in the region.

For example, Kelty et al. (2008) assume 0.5 to 0.8 million metric tons of biomass/yr are available in Massachusetts based on harvest residues and forest net growth only. The Manomet Center for Conservation Sciences (2010) estimates that up to 0.5 to 0.7 million metric tons are available in Massachusetts on a sustained annual basis from forest net growth and logging residues with high biomass prices. Our results suggest a range of 0.19 to 0.27 million metric tons/yr for Massachusetts when using logging residues and forest net growth, (Low and High Scenario B). Our estimates are lower mainly because a) our estimates of forest net growth using statewide FIA data are lower, and b) we included more reduction factors to total available land and accounted for high-value biomass of future harvests that would not go into the bioenergy market.

Volk et al. (2010) assume that 4.8 million metric tons of biomass/yr are available within New York without competing with current uses, but our results suggest a range of 0.7 to 1.0 million metric tons/yr, also without competing with current uses (Scenarios B Low and B High). Volk et al. (2010) computed this higher number largely based on higher assumptions of forest net growth, and from earlier data on harvest rates, when overall harvest levels were lower.

Fossil Fuel Substitution Analysis

Potential Forest Biomass Energy as a Fraction of Total Current Energy Consumption

The degree to which forest biomass energy can substitute for current fossil fuel consumption will depend on a great many factors, but our estimates of the sustainable forest biomass supply can, at the very least, provide estimates of the potential magnitude of the resource.

The rest of the report goes into considerable detail about fossil fuel substitution potentials under different scenarios of displacement of specific types of fossil fuels or energy sectors by different biomass utilization technologies. But it is informative to calculate the fraction of total current energy use that could be substituted by forest biomass energy, if all of the biomass was used in the most efficient, near-term technology (combined heat and power plants).

Table 5 summarizes the total energy use (in terajoules) for the 8 states for the year 2007 (EIA 2010j). We then used the forest biomass supply estimated under 4 of the biomass supply scenarios, and estimated the energy potential (as a fraction of total energy use) of that supply, assuming that it was used in a combined heat and power plant with 40% efficiency in electricity generation, and 40% efficiency in heat.

Our analysis shows that the potential for substitution of current energy use varies widely among states (assuming that each state limits it biomass energy production to biomass harvested within the state). States with large forest land bases and low energy consumption, such as Maine, New Hampshire, and Vermont, obviously have the greatest potential for replacement of fossil fuels. ***But for the region as a whole, using all of the available forest biomass in CHP applications would increase the share of forest biomass energy in the total energy portfolio[6] of the Northeast to only 1.4 – 5.5%.***

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[6] Including all sources (renewable and non-renewable) and uses (heat, transport or electricity) of primary energy.

Table 5. Energy use (in Tera Joule), by state and for the region as a whole, in 2007, and the potential fraction of that energy use that could come from forest biomass given the estimates of sustainable biomass harvests (for energy) under 4 of the scenarios presented in Table 4. The calculations assume that the biomass is used in a combined heat and power plant with an 80% overall efficiency (40% in electricity generation, and 40% in usable heat), and thus represent a best-case scenario.

		Scenario B - Biomass from New Harvests		Scenario C - Biomass from New Harvests and All Existing Pulp Harvests	
STATE	2007 Total Energy Use (TJ)	LOW	HIGH	LOW	HIGH
Connecticut	918,589	0.3%	0.3%	1.5%	1.5%
Maine	480,658	8.4%	8.4%	40.0%	40.0%
Massachusetts	1,597,903	0.5%	0.8%	0.9%	1.2%
New Hampshire	331,481	6.6%	9.8%	13.6%	16.7%
New York	4,268,847	0.7%	1.2%	2.3%	2.8%
Pennsylvania	4,226,541	1.5%	2.5%	4.2%	5.2%
Rhode Island	229,568	0.4%	0.7%	0.6%	0.9%
Vermont	171,016	5.1%	10.1%	22.9%	28.0%
TOTAL	**12,224,602**	**1.4%**	**2.2%**	**4.7%**	**5.5%**

Detailed Fossil Fuel Substitution Scenarios

While the numbers in Table 5 are sobering, forest biomass can play a much larger role in specific energy sectors. We have considered a wide range of scenarios for use of forest biomass energy to replace current fossil fuel consumption in a variety of specific energy sectors, under a range of different technologies for biomass utilization. We used the biomass supply estimate from Scenario B Low - *Biomass from New Harvests* (Table 4) as the basis for our analysis of fossil fuel substitution. Scenario B does not maximize the biomass available for energy production, largely because it doesn't assume the diversion of all current pulp wood to biomass energy production. The **Low** variant of Scenario B is clearly more conservative than the **High** variant, but there is still considerable uncertainty about many of the constraints incorporated in the two variants.

The scenarios outlined in Table 6 focus on potential for substitution of current uses of coal and liquid fossil fuels (LFF). Natural gas is an increasing component of the energy portfolio in the Northeast. However, there is less debate about reducing the consumption of natural gas as a nonrenewable fuel due to lower concerns over negative environmental consequences and supply security compared to coal and LFFs.

The scenarios are categorized based in part on infrastructure challenges and the developmental stage of conversion technologies (e.g., in development or commercially available and proven) (Table 6). For instance, co-firing coal plants with a low percentage of wood requires relatively little additional infrastructure and is therefore categorized as a short-term option. Short-term scenarios are characterized by the fact that no major changes in current technology infrastructure are necessary, and a proven conversion technology is available. Medium-term scenarios rely on substantive adaptations in energy-use infrastructure and a widespread replacement of conversion technology, but also rely on proven and available conversion technology. Long-term scenarios rely on a conversion technology that is not commercially available in the near future.

Table 6. Scenarios analyzed for the potential for substitution of coal and liquid fossil fuels (LFFs) with forest biomass. For conversion factors applied and units used in the analysis see Table 7 and 8.

Scenario name	Scenario time horizon	Fuels to be substituted	Description
10% co-firing with coal for electricity	Short-term	Coal	10% co-firing of biomass in coal-fired electric power plants
Wood electricity, 25% efficiency	Short-term	Fuels used in the current electricity mix	Substitution of fuels used in the current electricity mix by producing electricity from wood chips with net efficiency of 25%
Wood electricity, 40% efficiency	Medium-term	Fuels used in the current electricity mix	Substitution of fuels used in the current electricity mix by producing electricity from wood chips with a net efficiency of 40%
Combined Heat and Power (CHP), 40% efficiency for electricity and usable heat	Medium-term	Fuels used in the current electricity mix; Diesel, residual fuel[a], and kerosene for heat	Substitution of fuels used in the current electricity mix by producing electricity from wood-fired combined heat and power (CHP) plants with a 40% net electric and 40% usable heat efficiency. Process heat substitutes for LFF use in the residential and commercial (heating) sector
Wood chips for commercial and industrial heat	Short-term	Diesel and residual fuel, kerosene	Substitution of LFFs used in the commercial and industrial sector (mainly for heating)
Pellets for residential heat	Short-term	Diesel and residual fuel	Wood pellets substituting for LFF use in the residential heating
FT diesel for transport	Medium/long-term	Diesel	Diesel derived from cellulosic biomass using Fischer-Tropsch synthesis (CHOREN 2010) for ground transport substituting current diesel use
Cellulosic ethanol for transport	Long-term	Gasoline	Cellulosic ethanol for ground transport substituting current gasoline use

[a] Residual fuel is also known as No. 5 and No. 6 fuel oils.

Fossil Fuel Units and Substitution Factors for Wood

Table 7 gives an overview on the units used to specify energy contents, endpipe CO_2 emissions, and specific gravity of coal and the liquid fossil fuels (LFFs) analyzed.

Table 7. Units and conversion factors for fossil fuel and wod-derived energy carriers. Empty cells were not required for the calculations. All units are based on data retrieved from ORNL 2010 unless noted otherwise. Although this report uses dry tons as unit for biomass, reduced efficiencies in conversion technologies due to wood moisture content (green tons) is factored into the scenarios.

Energy carrier	Energy content	End-pipe fossil fuel CO_2 emissions	Specific gravity
	GJ/mt	mt CO_2/t	mt/m^3
Gasoline	47.06	3.17	0.73
Diesel[g]	46.02	3.20	0.84
Residual fuel	42.03	3.15	0.99[a]
Kerosene[e]	46.06	3.16	0.817
Coal	23.66[b]	2.19	
Cellulosic ethanol	29.73[c]		0.79
FT diesel[f]	40[d]		
Wood	20		

[a]) Source: DOE 2010.

[b]) Mean energy content of coal consumed in the US in 2008 (EIA 2010c).

[c]) Source EIA 2010d.

[d]) Source CHOREN 2010.

[e]) Same units for kerosene applied to aviation and non-aviation kerosene. Naphta (aviation) fuel consumption has not been reported by EIA for the Northeast and was therefore not included in the analysis.

[f]) FT diesel based on cellulosic biomass using Fischer-Tropsch synthesis (CHOREN 2010).

[g]) In this study we used diesel as a synonym for distillate fuel as used in the EIA data.

Current Use of Coal and Liquid Fossil Fuels[7]

Figures 8 and 9 show the 2008 endpipe CO_2 emissions as well as total energy use associated with coal-derived electricity production and all Liquid Fossil Fuel (LFF) use in the Northeast, respectively. In 2008, there were 382 million metric tons of endpipe CO_2 emissions and a total energy consumption of 5,534 Peta Joule (10^{15}) associated with LFF use and coal-fired power plants in the Northeast. The biggest endpipe CO_2 emitters across

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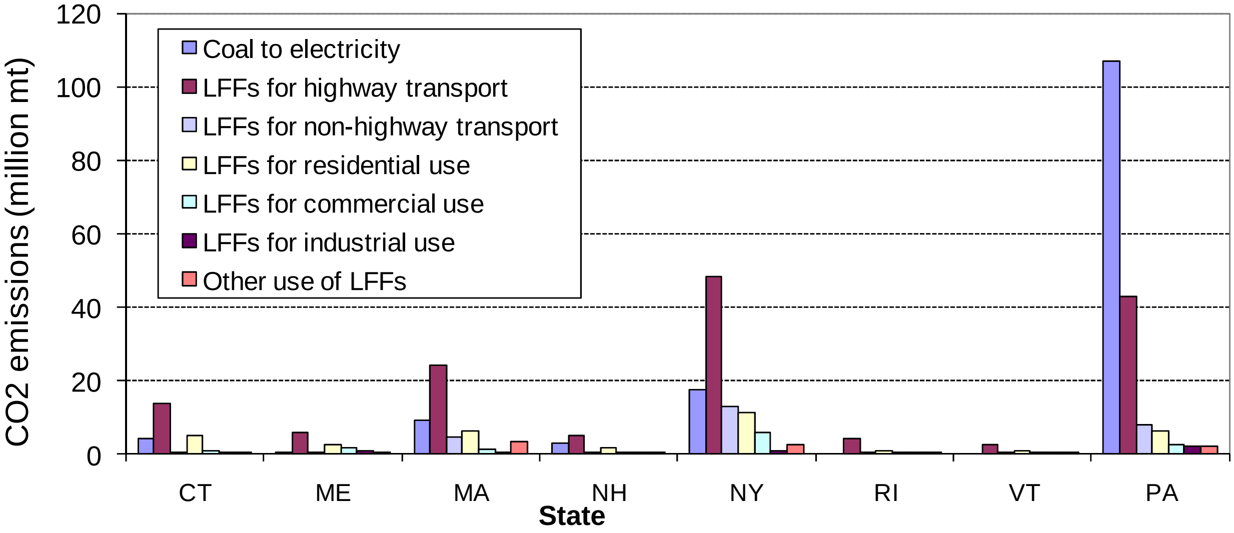
[7] This analysis considers use of coal only for production of electricity, and ignores coal use for heating and industrial processes

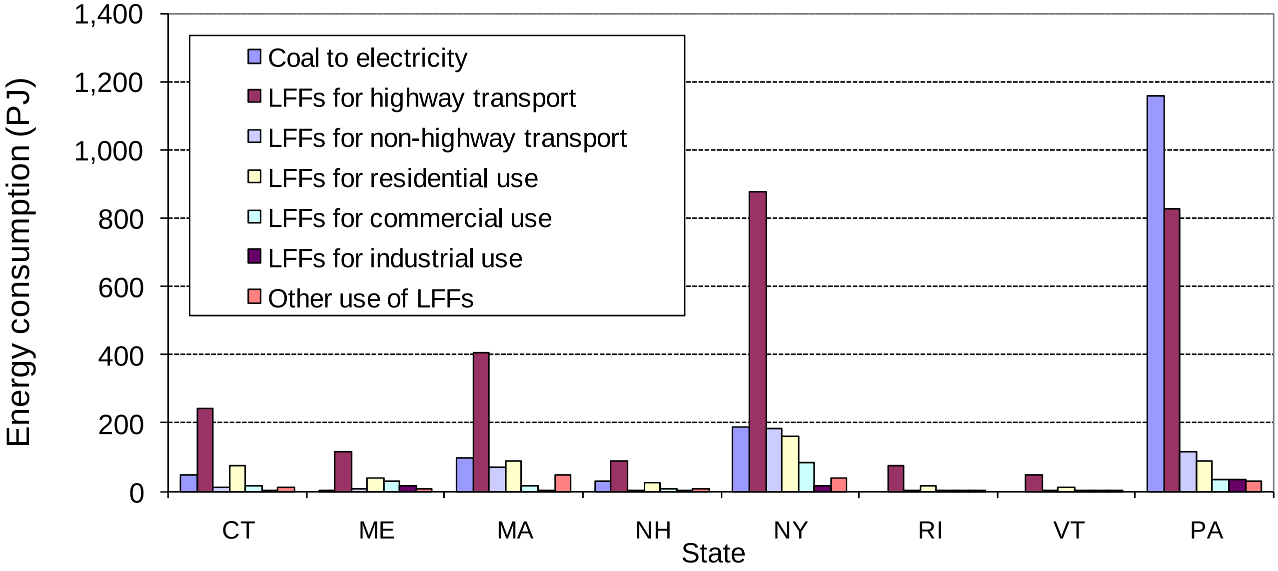
all states' energy use sectors are LFFs used for highway transport, except for Pennsylvania with its heavy reliance on coal-fired power plants. LFF use in aviation played a minor role in the transport sector. However, it has to be noted that some smaller states withheld aviation fuel information due to confidentiality reasons (EIA 2010a).

The residential, commercial and industrial heating sectors in the Northeast are responsible for 23% of all endpipe CO_2 emissions from LFFs in the region, led by Maine where 45% of all LFF endpipe CO_2 emissions come from the heating sector. Measured in energy content, 19% of all LFFs consumed in the Northeast end up in the heating sectors. While coal for electricity generation is the single largest energy use sector for both graphs, it also becomes apparent in the two graphs that coal emits more CO_2 for each energy unit consumed as its relative share is higher in CO_2 emissions than in energy use. Under a strict CO_2 emissions reduction goal it might therefore be advisable to target specifically coal consumption. ***But if energy independence is a consideration the substitution of wood biomass for LFF used for process heat optimizes both carbon emissions reductions and the need for oil imports.***

We acknowledge that not all of the LFFs used in the residential, commercial, and industrial sector are used for heating applications but also for cooling and to a very small extent as material input (industrial sector). The material input sector is assumed to be negligible, we also assume that the cooling sector could be as readily converted to wood-based systems as the LFF heating sector. Other uses in Figures 8 and 9 include military, farm, construction, and other end uses, but are negligible in terms of their total contribution to endpipe CO_2 emissions compared to other LFF uses included in the figures.

Figures 8 and 9. CO$_2$ emissions (in million metric tons) and energy consumption (in Peta Joule) from coal for electricity production and liquid fossil fuels (LFFs) in 2008 by state. Non-highway transport use of LFFs includes rail, vessel, and aviation. While residential use of LLF is largely restricted to heating applications, commercial and industrial use of LFF can include some use for cooling and in the case of industrial use a negligible number as a material input in production processes. Other use of LFF includes use in military, off-highway, farm, electric power production, etc. Source: EIA 2010a,b.





Analysis of the Fossil Fuel Substitution Scenarios

Table 8 depicts the conversion factors used to calculate how many metric tons of Liquid Fossil Fuels (LFFs) or coal could be substituted by one metric ton of biomass assuming different biomass conversion routes as they are applied in the substitution scenarios (Table 6). We assumed a constant energy content of 20 GJ/metric ton for forest biomass. These conversion factors show that there are significant differences in how many units of energy (by weight) can be replaced with one unit of biomass. Highly efficient biomass power plants (even without utilizing process heat) and co-firing biomass with coal show significant substitution potentials. For instance, the use of one metric ton of biomass in a 40% efficient bioelectricity sector would replace over one metric ton of coal, while using the same amount of biomass to substitute any LFF would substitute less than one-fifth of a ton of liquid fossil fuel**. *Replacing one metric ton of coal with biomass (e.g,. by co-firing) is close to four times more efficient in terms of endpipe CO_2 emission reductions than substituting gasoline with cellulosic-biomass derived liquid fuels[8]. However, this scenario might not reduce dependence on foreign fossil fuels. Combined heat and power plants reduce close to five times more endpipe CO_2 emissions when replacing coal (for electricity) and liquid fossil fuels (for heat) than substituting gasoline with cellulosic ethanol.***

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[8] The conversion rate is 4.0 for biomass derived cellulosic ethanol and 3.7 for biomass derived diesel substitute, see also Table 7 for CO_2 emissions associated with fossil fuel consumption.

Table 8. Substitution factors for fossil fuels when substituted with wood-derived fuels. All units are in metric tons of fossil fuel substituted by one metric ton of wood. An energy content of 20 GJ/mt was assumed for wood. Only cells with relevance to substitution scenarios are populated. Although this report uses dry tons as unit for biomass, reduced efficiencies in conversion technologies due to wood moisture content (green tons) are factored into the scenarios.

	Substituted fossil fuel in metric tons replaced by one metric ton of wood				
Wood conversion route	Gasoline	Diesel	Residual fuel	Kerosene	Coal
10% co-firing with coal[a]					0.859
Heat – wood chips[b]		0.386	0.423	0.386	
Heat – wood pellets[c]		0.435	0.476		
Electricity – 25% efficient[d]					0.643
Electricity – 40% efficient[d]					1.029
FT diesel[e]		0.174	0.190	0.174	
Cellulosic ethanol[f]	0.185				

a) A mean 2008 electric conversion efficiency of coal to electricity of 32.9% was used (EIA 2010e); for co-firing wood with coal we applied a reduction of overall efficiency of 0.53% (Heller et al. 2004).

b) An 80% conversion efficiency of wood chips to heat was assumed. In case several fuels were substituted for the same purpose, fossil- to wood-fuel conversion numbers were weighted by the respective share each fossil fuel represented in the sector.

c) It was assumed that one metric ton of wood can be converted to one metric ton of pellets without changes in energy content. A 90% conversion efficiency of pellets to heat was assumed.

d) Efficiency rates are based on current plant data and cover a range from older installations using boiler technology (as low as 25%) to more recent findings on gasification technology (as high as 40% (Paisley et al. 2001).

e) It was assumed that one metric ton of wood can be converted to 0.2 metric tons of FT diesel based on cellulosic biomass using Fischer-Tropsch synthesis (CHOREN 2010).

f) It was assumed that one metric ton of wood can be converted to 0.27 metric tons of cellulosic ethanol (EIA 2010d).

While Table 8 gives information on substitution efficiencies, Table 9 presents data on total substitution capacity by sector. In other words, Table 9 depicts the fossil fuel substitution potential in energy units and in percent of the specific fossil fuel sector for the different biomass conversion scenarios. The biomass estimates used for this analysis correspond to Scenario B Low - *Biomass from New Harvests* in Table 4. If the available biomass would be used in the Northeastern commercial and industrial liquid fossil fuel (LFF) heating sector only, for example, as much as 28% of this sector's LFF use could be replaced. In contrast, ***LFF use in the transport sector would be reduced by only 2% for***

the whole region if all available forest biomass was converted to cellulosic ethanol to fill gasoline tanks.

On a state level, Maine shows the most promising fossil fuel substitution potential. Despite its very limited potential to increase (or even sustain) biomass harvests (see Table 4), its comparatively low total energy consumption makes biomass a potentially significant source of its future energy portfolio. For instance, Maine could replace its current use of LFF in the commercial/industrial or residential heating sector by up to 42% or 49%, respectively. Alternatively, Maine could cover 38% of its current electricity use when installing highly efficient biomass power plants (with a net electric efficiency of 40%) or substitute 28% of its current road diesel use once (cellulosic) biomass-to-diesel technology becomes commercially available. New Hampshire also shows favorable substation potentials across all scenarios. For instance, it could replace 84% of its current use of LFFs in the industrial and commercial heating sector with local forest biomass under Scenario B Low – *Biomass from New Harvests*. In comparison, the states with a high population to area ratio (Connecticut, Massachusetts, Rhode Island) are unable to substitute any of their individual fossil fuel sectors by more than 10%, with the exception of Massachusetts which could replace 16% of its current use of LFFs in the commercial and industrial heating sector. In particular, the scenarios substituting liquid transport fuels show low substitution potentials due to their low substitution efficiencies (Table 8) and the high total energy consumption in the transport sector (Figure 9).

Under the Combined Heat and Power (CHP) scenarios, 6% of the electricity for the whole region could be provided from forest biomass while substituting at the same time up to 14% of current LFFs in the commercial and industrial heating sector. All other scenarios analyzed in Table 9 would contribute a lower figure to a total energy portfolio. It also becomes apparent that some scenarios might be more attractive from a regional rather than a state perspective. For instance, 20.2 out of 26.4 GW of coal-fired electric generating capacity in the Northeast is located in Pennsylvania. Subsequently, Pennsylvania might be interested in reducing coal consumption, and would have the potential to burn all the forest biomass available in the Northeast without exceeding a 10% co-firing limit. Such an approach might make sense from a regional view to reduce overall endpipe CO_2 emissions. However, some states with no coal-fired power plants (e.g., Rhode Island, Vermont) or states where the biomass potential exceeds co-firing capacities (e.g., Maine, see Table 9) might prefer in-state use of its biomass for reasons such as to reduce transport costs and emissions, to stimulate in-state economies, or to reduce energy dependence. Therefore, while we assumed for the sake of analysis that all available forest biomass would go into one specific sector depending on the scenario, we acknowledge the critical importance of other factors, including energy independence, besides fossil fuel reduction efficiencies or total reduction potential when choosing fossil fuel substitution strategies.

Table 9. Biomass energy production potential by fossil fuel substitution scenarios and state. Energy production potential is given in TeraJoule (10^{12} J)/yr. Percentages indicate how much of a given fossil fuel sector (in 2008 consumption numbers, see Appendix 8) could be substituted if all biomass would be devoted to this sector. For a description of the substitution scenarios see Table 6.

State	**10% co-firing with coal**	**Wood electricity 25% efficiency**	**Wood electricity 40% efficiency**	**CHP wood electricity 40% efficiency**[a]	**Wood chips for heat**	**Pellets for heat**	**FT diesel for transport**	**Cellulosic ethanol for transport**
Connecticut	1,428 3%	1,069 1%	1,710 2%	1,710 / 624 2% / 4%	1,248 7%	1,404 2%	562 1%	610 0%
Maine	19,561 718%	14,646 24%	23,433 38%	23,433 / 8,553 38% / 21%	17,107 41%	19,245 49%	7,698 28%	8,359 9%
Massachusetts	3,922 4%	2,936 2%	4,698 3%	4,698 / 1,714 3% / 8%	3,430 16%	3,859 4%	1,543 2%	1,676 0%
New Hampshire	10,632 33%	7,960 10%	12,736 15%	12,736 / 4,649 15% / 42%	9,298 84%	10,460 42%	4,184 28%	4,543 6%
New York	13,579 7%	10,167 2%	16,267 3%	16,267 / 5,938 3% / 6%	11,875 12%	13,360 8%	5,344 2%	5,802 1%
Pennsylvania	30,603 3%	22,913 3%	36,660 5%	36,660 / 13,773 5% / 21%	27,545 41%	30,109 33%	12,044 5%	13,077 2%
Rhode Island	487 N/A	364 1%	583 2%	583 / 213 2% / 5%	426 9%	479 3%	192 2%	208 0%
Vermont	4,172 N/A	3,123 13%	4,997 20%	4,997 / 1,827 20% / 29%	3,655 58%	4,104 25%	1,642 18%	1,783 5%
Total	84,382 6%	63,178 4%	101,085 6%	101,085 / 37,292 6% / 14%	74,584 28%	83,021 16%	33,208 5%	36,058 2%

The first total number in each cell represents the bioenergy production potential for electricity generation while the second number represents the substitution capacity for liquid fossil fuels used in the commercial and industrial heating sector. The same logic applies to the percentages.

Full Greenhouse Gas Emissions Analysis: Incorporating Emissions from Biomass Conversion and Land Use Change

The data presented above focus on fossil fuel substitution potentials and efficiencies. Another important aspect of fossil fuel substitution is CO_2 emission reduction. This analysis did not consider CO_2 emissions associated with the final use of fossil fuels (endpipe emissions), nor did we consider CO_2 emissions associated with the sourcing, refining, or transporting of biomass, coal, and Liquid Fossil Fuels (LFFs). When optimizing for CO_2 emission reductions, the fossil fuel substitution scenarios might produce a different picture. For further analysis, a full CO_2 Lifecycle Analysis (LCA) would be necessary to consolidate the total CO_2 reduction potentials associated with the scenarios presented here. For instance, when focusing on *endpipe* emissions only, one metric ton of wood pellets can substitute more LFF *endpipe* CO_2 emissions in the heating sector than one metric ton of wood chips (Table 8). However, wood pellets require a substantial amount of energy in the production process (~4 GJ of energy are used to produce one metric ton of pellets, Craven 2008) and are often shipped over long distances. In contrast, wood chip production is less energy intensive and transport distances are often kept at a minimum. The overall CO_2 balance of wood chips might therefore be more favorable than a comparable biomass of wood pellets when looking at the whole life cycle.

Additionally, the production and substitution of other potent greenhouse gases (GHGs) associated with the scenarios also need further study. For instance, N_2O and CH_4have global warming impacts 298 and 25 times higher, respectively, than that of one metric ton of CO_2 emissions, respectively over 100 years (IPCC 2006). LCA results from Raymer (2006) suggest that including several GHGs in a wood to energy analysis as well as including emissions occurring in the production process would reduce the fossil fuel substitution capacity of wood by 2% to 19%. In the Raymer study (2006) differences in GHG emissions were mainly explained by the different technologies applied.

Further refinement of scenario descriptions could yield further improvement in offsetting CO_2 emissions through gains in efficiencies. For instance, distributed wood-fired Combined Heat and Power (CHP) plants might have lower grid losses than current centralized coal plants, thus further increasing the overall CO_2 substitution capacity of this scenario (see also Buchholz and Volk 2010 for a discussion on scales and efficiencies in renewable energy analysis). In contrast, transport distances do not necessarily impact GHG and energy balances of bioenergy projects as much as often anticipated -- especially when rail- and waterways are used. For instance, Hamelinck et al. (2005) and Raymer (2006) showed that even biomass power plants with global supply chains can still be attractive from a CO_2 and energy efficiency point of view compared to fossil fuel-derived power production.

A major set of concerns in the overall carbon cycle of bioenergy applications are the carbon fluxes associated with changes in land use. In the case of forest-based bioenergy applications discussed in this study, “activities that keep otherwise regenerating forests to constant levels of carbon reduce that sink relative to what would have occurred without those activities” (Searchinger et al. 2009). Additional CO_2 emissions from the increased use of logging residues which are removed from the live forest biomass pool anyway would presumably not change a carbon flux balance dramatically. One could expect a minor difference in carbon release on a temporal scale where the carbon is released instantly through combustion when used for bioenergy compared to a ~10 year release during decomposition of tops in the forest (Manomet Center for Conservation Sciences 2010). ***However, cutting biomass that would have not been cut under current conditions, such as the biomass characterized in this study as forest net growth, might alter the overall carbon balance of bioenergy projects drastically and deserves further analysis***.

For instance, a recent study on the energetic use of forest biomass use in Massachusetts found that the initial carbon debt of replacing coal-fired power plant with forest biomass fueled power plants takes over 50 years to be “paid off” in terms of avoided CO_2 emissions from coal burning (Manomet Center for Conservation Sciences 2010). Similarly, it might be misleading to assume that the pulp fraction of current removals (Scenario A - *Diverting Biomass from Paper to Energy* and C- *Combined*) might be accounted for as $C0_2$ neutral biomass available for energetic use with the further decline of the Northeastern pulp industry. Assuming a constant consumption of pulp products in the U.S., the sourcing of pulp wood would most likely be only shifted to other regions, adding the resulting CO_2 emissions to the total equation. The choice of a baseline scenario on the forest management side as well as the fossil fuel reference scenario becomes therefore a major factor in the overall GHG analysis of forest-based bioenergy systems to substitute current coal, oil, or natural gas use.

METHODS

Forest Biomass Estimates

Compiling FIA Data for Northeastern Forests

The U.S. Forest Service Forest Inventory and Analysis (FIA) network of plots represents the most comprehensive sample of forest biomass and resources available. The FIA website provides a range of standard summaries of forest resources from the data, but compiling detailed estimates of tree biomass currently requires downloading individual plot data for analysis. We compiled FIA data for the two most recent census intervals for the eight-state region from Maine to Pennsylvania. There has not yet been a recensus of New Jersey using the new national standard FIA sampling protocol. As a result, estimates of growth, mortality, and removal were not available for that state. We downloaded the tree, plot, and plot condition files from the FIA Datamart website (USDA FS 2010k), using files available as of March 1, 2010. For each state we retrieved the plots from the first full census done under the new national standard (post 1999) and the plots from the current (subsequent) census cycle. In most states, the current census cycle is still underway (census cycles typically take 5-6 years), so the set of "current" cycle plots is only a subset of the number of plots censused in the previous cycle (Appendix 7). Only plots with at least some portion of the plot in an "accessible forestland" condition at the time of a census were used.

FIA protocol defines adult trees as stems >12.4 cm (5") DBH. We summed the adult aboveground carbon estimates across all live trees in each plot in each census cycle and multiplied by 2 to estimate live, adult tree aboveground biomass in each plot. For the subset of current plots that were recensused from a previous plot, biomass increment was calculated as the difference in biomass from one census to the next, divided by the length of the census interval at that plot (in years).

For each plot, we computed an estimate of the amount of biomass harvested during the most recent census interval in a given plot by calculating the percent of live basal area of adult trees at the time of the previous census that was recorded as "removed" during the census interval. Regressions of biomass on basal area confirmed the very tight and linear relationship between these two variables. When diameter measurements were missing from harvested trees at the time of a census, we used diameters recorded for those trees in the previous census. It is also possible that some harvested trees were simply recorded as dead. Thus, in all likelihood our estimate is a slight underestimate of actual harvest levels.

Statistical Analyses of Regional Variation in Biomass Increment and Harvest Regimes

In addition to reporting summaries of current forest biomass by state and county, we have used the dataset to explore the expected growths in regional forest biomass resources given (1) the current frequency distribution of stand-level biomass across a region, (2) estimated rates of biomass increment as a function of current biomass, and (3) the current regional harvest regime (fraction of plots logged, and fraction of biomass removed if logged). The two functional relationships (2 and 3, above) come from two regression equations parameterized from the compiled FIA dataset. The first equation describes the current harvest regime in Northeastern forests: i.e., the annual probability that a given plot is harvested, and if harvested, the proportion of aboveground biomass removed. Both of these are estimated simultaneously as a function of adult tree aboveground biomass. The second function describes the increment in adult aboveground tree biomass, again as a function of current adult tree aboveground biomass.

Because of relatively low sample sizes for logged plots in some of the states, we have grouped the eight states into three regions: (1) Pennsylvania and New York, (2) New England (Vermont, New Hampshire, Massachusetts, Connecticut, and Rhode Island), and (3) Maine.

For each of these regions, our statistical model for the harvest regime estimates both components (probability of being logged, percent of basal area removed if logged) simultaneously, using maximum likelihood methods. We used a zero-inflated gamma distribution for the likelihood function, since the dataset contains many zeros (unlogged plots), and the distribution of percent of basal area removed (if logged) is skewed and better fit by a gamma distribution than a normal distribution. Zero-inflated likelihood functions typically estimate a constant zero inflation term, but in our case we also tested a model in which the zero term (probability of not being logged) varied as a function of the independent variable (adult tree biomass).

We tested several flexible function forms for the relationship between the independent variable and both the zero-inflation term and the percent of basal area removed (if logged). A negative exponential function was the most parsimonious functional form for both relationships. Thus, the predicted percent of BA removed from plot i (BAR_i), given that the plot was logged during the census interval, was fit to the equation:

$$BAR_i = \alpha\, e^{-\mu X_i} \qquad \text{(Eqn. 1.)}$$

where X_i was adult aboveground tree biomass (in metric tons/ha) and α and μ were estimated parameters. The predicted probability that a plot was logged during census interval (P_Z) was modeled as:

$$P_Z = \left[a\, e^{-mX_i^{\,b}} \right]^{N_i} \qquad \text{(Eqn. 2)}$$

where again Xi was adult aboveground tree biomass in the ith plot, Ni was the census interval (in years) for that plot, and *a*, *m*, and *b* were estimated parameters. As a result of raising the function to the power *N*, the parameters specify the effective annual probability of being logged.

The likelihood function for the model was:

$$Prob(y_i \mid \theta) = \begin{cases} P_z \ if\ y_i = 0, \\ (1 - P_z) Gamma(y_i \mid \theta)\ if\ y_i > 0 \end{cases} \qquad \text{(Eqn. 3)}$$

where y_i was the observed percent of BA harvested, θ is the vector of parameters in the model (including the shape parameter for the gamma distribution), and Gamma(y_i/θ) was the probability of observing y_i under a gamma distribution with parameters θ. We solved for the maximum likelihood values of the parameters using a global optimization routine (simulated annealing). All analyses were done using the R statistical software package.

There is enormous variability among FIA plots in net growth in adult tree biomass from one census to the next. Plot biomass changes as a result of (1) growth of previously measured trees (i.e., trees that were bigger than 5" DBH at the time of the previous census), (2) "ingrowth" of new adult trees (i.e., trees that are now >5" DBH and are measured, but were not measured in the previous census), and (3) death of previously measured trees. Since the plots are relatively small, the death of several large trees or the ingrowth of a cluster of new small trees can cause a large change in the biomass measured on a plot. In principle, the average annual increment in adult tree biomass should peak at some intermediate level of total plot biomass, and then decrease and ultimately reach zero, since aboveground tree biomass does not increase indefinitely. Thus, we used a quadratic function (Eqn. 4) to describe adult tree biomass increment (TBI_i) of plot i as a function of total tree biomass (TB_i) in that plot :

$$TBI_i = a + b * TB_i + c * (TB_i)^2 + \varepsilon \qquad \varepsilon \approx N(0, \sigma^2) \qquad \text{(Eqn. 4)}$$

Where *a*, *b*, and *c* are the regression coefficients, and the error (ε) is normally distributed with mean = 0 and variance = δ^2. Again, we solved for the maximum likelihood values of the parameters using a global optimization routine (simulated annealing), using the R statistical software package.

Conversion Factors, and Competing Uses of Biomass from Forest Net Growth

Some parts of a tree such as the stump will be less likely to be harvested for biomass due to economic or ecological reasons. Using FIA data for New York (EVALIDator 4.01, USDA 2010a), we determined that 4% of the total aboveground live biomass (excluding saplings) is located in the stump (30.5 cm or 1 ft above ground), 77% in the bole (diameter >10.2 cm or 4 inches), and 19% in the crown/top. While we analyzed overall biomass availability on its sensitivity to different levels of crown biomass extraction, we excluded stump biomass for all calculations in this study.

To convert volumetric TPO data to weight units, we used a specific gravity of 0.549 t/m^3 (weighted by share for the region's soft- and hardwood species with 0.552 and 0.626 t/m^3, respectively).

Not all biomass located in the bole is likely to be used for biomass. High quality sections will be used for veneer or sawlogs, while lower quality sections are currently used for pulp or energy purposes. To account for the share of forest biomass growth that is unlikely to be available for energy purposes, we calculated the percentage of the bole that was allocated to pulp wood based on 2006 TPO data (Appendix 6). Biomass for pulp or energy use is to a large degree overlapping in price structure and quality standards. The current state of the declining pulp industry in the Northeast suggests no further expansion of the biomass demand. Therefore, we assumed that pulp wood sections would be potentially available for energy use in biomass that would be cut in addition to current harvest levels.

Not all of the additional growth of forest biomass is likely to go into the biomass to energy supply chain. Some of the growth currently occurring in the Northeast is of veneer or sawlog quality, so this fraction of forest biomass growth needs to be subtracted from biomass supply estimates as it fetches higher prices on the veneer or sawlog market. We assume that the boles of pulpwood quality would be available for the biomass market. Appendix 6 shows the most recent Timber Product Output Reports (TPO, USDA FS 2010) data available for 2006 on the distribution of bole (roundwood) products by state[9]. Using this data as an estimate, there might be as little as 0% of the forest net growth in roundwood available in Rhode Island for biomass and up to 54% in Maine with a regional average of 45%. Some of this biomass would become available through the secondary

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[9] Considering that TPO data relies on self-reported data from the loggers and forest landowners and is not based on statistical samples, there are doubts to what extent this data should be used. But in light of the fairly small share of its total contribution to the biomass pool besides biomass from forest net growth we assume that these uncertainties do not question the study's results substantially.

market as by-products from sawmills. However, this potential biomass is not considered in this study.

Fossil Fuel Offsets and Substitution Scenarios

We retrieved data on liquid fossil fuel consumption for the Northeast from the U.S. Energy Information Administration (EIA 2010a). Using the most recent 2008 data, we retrieved consumption numbers for gasoline from the “Prime Supplier Sales Volumes” and all other liquid fossil fuel from the “Adjusted Sales of Fuel Oil and Kerosene” dataset. 2008 data on coal consumption and total electricity generated in the Northeast was derived from the EIA as well (2010b and w, respectively).

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Appendix 1: Forestland Area, by State and Ownership

Area of unreserved and reserved forestland, by ownership and state and for the entire nine-state region, and the % of each state's land area that is forested. Estimates from FIADB 4.0, for census periods 2004-2008 for all states except New York and New Hampshire (2003-2008). There can be substantial uncertainty in estimates for categories with low absolute values and for states with small areas.

State/Region	Ownership	Total (ha)	Unreserved (ha)	Reserved (ha)	% Area Forested
Entire Region	Federal	989,034	824,528	164,506	
	State/Local	5,206,734	3,701,316	1,505,418	
	Private	22,030,197	22,027,552	2,645	
	Total	28,225,965	26,553,396	1,672,569	67.2%
Connecticut	Federal	6,229	6,229		
	State/Local	185,985	183,131	2,854	
	Private	505,631	505,631		
	Total	697,845	694,991	2,854	55.6%
Maine	Federal	72,558	49,735	22,824	
	State/Local	431,695	330,329	101,366	
	Private	6,641,633	6,641,633		
	Total	7,145,887	7,021,697	124,190	89.4%
Massachusetts	Federal	32,869	19,781	13,088	
	State/Local	358,144	345,096	13,049	
	Private	830,951	830,951		
	Total	1,221,964	1,195,828	26,137	60.2%

State/Region	Ownership	Total (ha)	Unreserved (ha)	Reserved (ha)	% Area Forested
New Hampshire	Federal	317,314	269,774	47,539	
	State/Local	149,269	146,621	2,648	
	Private	1,477,317	1,477,317		
	Total	1,943,900	1,893,713	50,187	83.7%
New York	Federal	56,704	48,860	7,844	
	State/Local	1,817,681	622,374	1,195,307	
	Private	5,794,793	5,794,793		
	Total	7,669,178	6,466,027	1,203,151	62.7%
Pennsylvania	Federal	255,766	232,446	23,321	
	State/Local	1,706,385	1,546,590	159,795	
	Private	4,776,909	4,774,263	2,645	
	Total	6,739,060	6,553,299	185,760	58.1%
Rhode Island	Federal				
	State/Local	37,181	35,540	1,641	
	Private	103,823	103,823		
	Total	141,004	139,363	1,641	52.1%
Vermont	Federal	198,083	165,232	32,851	
	State/Local	173,005	173,005		
	Private	1,485,806	1,485,806		
	Total	1,856,894	1,824,043	32,851	77.5%

Appendix 2: Area of Unreserved Forestland and Forest Biomass Estimates, by County

Area of unreserved forestland (in hectare), the % of the total land area in forestland, the average aboveground tree biomass (metric tons/hectare), and the total aboveground tree biomass (metric tons) by county for the nine-state region. Biomass estimates are not available for the state of New Jersey. Note that 1 short ton/acre equals approximately 2.24 metric tons/hectare. "Merchantable" biomass averaged over the region is approximately 81.3% of total aboveground tree biomass. "Merchantable" biomass is defined by FIA as biomass above the stump and below a 4" top branch diameter.

County	Unreserved Forestland (ha)	% Land Area in Unreserved Forestland	Average Aboveground Tree Biomass (mt/ha)	Total Aboveground Tree Biomass (metric tons)
CONNECTICUT	694,991	55%		
Fairfield	57,417	35%	123.0	7,062,531
Hartford	81,889	43%	112.1	9,180,913
Litchfield	159,289	67%	147.8	23,550,945
Middlesex	58,118	61%	82.1	4,773,391
New Haven	72,466	46%	57.8	4,191,799
New London	101,130	59%	120.9	12,228,168
Tolland	82,659	78%	136.5	11,287,137
Windham	82,023	62%	109.0	8,948,066
MAINE	7,021,697	88%		
Androscoggin	83,698	69%	73.8	6,179,035
Aroostook	1,555,449	90%	54.0	84,053,650
Cumberland	147,720	68%	102.4	15,125,655
Franklin	398,664	91%	76.5	30,527,895
Hancock	352,555	86%	66.3	23,387,954
Kennebec	156,962	70%	82.4	12,931,769
Knox	68,613	72%	66.7	4,580,817

County	Unreserved Forestland (ha)	% Land Area in Unreserved Forestland	Average Aboveground Tree Biomass (mt/ha)	Total Aboveground Tree Biomass (metric tons)
Lincoln	87,248	74%	89.5	7,816,046
Oxford	492,714	92%	93.1	45,868,542
Penobscot	804,148	91%	57.2	46,023,071
Piscataquis	915,554	89%	61.2	56,065,047
Sagadahoc	44,103	67%	103.9	4,583,699
Somerset	952,691	94%	62.5	59,570,504
Waldo	154,995	82%	75.7	11,739,885
Washington	617,025	93%	45.2	27,893,355
York	189,557	74%	96.4	18,279,444
MASSACHUSETTS	1,195,828	59%		
Barnstable	25,760	25%	59.7	1,538,019
Berkshire	180,183	75%	174.0	31,362,443
Bristol	80,886	56%	88.2	7,140,143
Dukes	13,178	49%	37.6	495,239
Essex	62,873	48%	96.6	6,074,249
Franklin	142,272	78%	135.3	19,252,146
Hampden	101,529	63%	150.0	15,240,155
Hampshire	97,692	71%	145.3	14,196,235
Middlesex	85,512	40%	106.7	9,131,553
Nantucket	5,031	41%		
Norfolk	47,789	46%	104.3	4,988,386
Plymouth	83,210	49%	98.7	8,217,260
Suffolk	-	0%		
Worcester	269,914	69%	135.0	36,442,643

County	Unreserved Forestland (ha)	% Land Area in Unreserved Forestland	Average Aboveground Tree Biomass (mt/ha)	Total Aboveground Tree Biomass (metric tons)
NEW HAMPSHIRE	1,893,713	82%		
Belknap	79,468	76%	107.2	8,522,404
Carroll	207,958	86%	144.6	30,091,175
Cheshire	156,552	85%	115.1	18,030,633
Coos	416,510	89%	82.5	34,355,855
Grafton	369,686	83%	108.4	40,107,907
Hillsborough	166,896	74%	127.3	21,262,031
Merrimack	197,142	81%	132.9	26,217,184
Rockingham	115,870	64%	162.7	18,857,558
Strafford	64,535	68%	132.0	8,520,586
Sullivan	119,097	86%	101.0	12,033,480
NEW JERSEY	764,435	40%		
Atlantic	78,852	54%		
Bergen	9,081	15%		
Burlington	109,594	53%		
Camden	17,537	30%		
Cape May	33,694	51%		
Cumberland	62,159	49%		
Essex	-	0%		
Gloucester	15,029	18%		
Hudson	907	8%		
Hunterdon	39,372	35%		
Mercer	21,121	36%		
Middlesex	18,190	23%		
Monmouth	37,745	31%		
Morris	49,367	41%		

County	Unreserved Forestland (ha)	% Land Area in Unreserved Forestland	Average Aboveground Tree Biomass (mt/ha)	Total Aboveground Tree Biomass (metric tons)
Ocean	95,192	58%		
Passaic	22,906	48%		
Salem	26,792	31%		
Somerset	14,850	19%		
Sussex	71,235	53%		
Union	-	0%		
Warren	40,811	44%		
NEW YORK	6,466,027	53%		
Albany	69,898	52%	105.0	7,342,505
Allegany	191,886	72%	94.0	18,044,225
Bronx	5,463	50%		
Broome	105,672	58%	105.7	11,176,392
Cattaraugus	214,758	63%	71.8	15,420,727
Cayuga	69,811	39%	88.9	6,206,956
Chautauqua	150,289	55%	71.7	10,781,606
Chemung	64,472	61%	115.4	7,443,249
Chenango	154,383	67%	132.0	20,391,169
Clinton	191,812	71%	49.6	9,512,189
Columbia	81,920	50%	115.9	9,500,379
Cortland	87,114	67%	108.4	9,444,853
Delaware	271,390	72%	121.1	32,877,175
Dutchess	107,807	52%	104.7	11,296,758
Erie	101,968	38%	84.8	8,654,531
Essex	216,469	47%	115.4	24,985,457
Franklin	253,890	60%	77.6	19,705,895
Fulton	73,251	57%	131.4	9,627,124
Genesee	45,499	36%	24.7	1,125,940

County	Unreserved Forestland (ha)	% Land Area in Unreserved Forestland	Average Aboveground Tree Biomass (mt/ha)	Total Aboveground Tree Biomass (metric tons)
Greene	99,106	59%	150.2	14,887,974
Hamilton	130,844	29%	111.1	14,545,098
Herkimer	139,391	38%	98.1	13,685,977
Jefferson	169,739	52%	72.2	12,257,458
Kings	-	0%		
Lewis	233,463	71%	84.9	19,839,875
Livingston	45,934	28%	107.0	4,915,354
Madison	94,641	56%	44.3	4,193,443
Monroe	40,939	24%	34.8	1,426,396
Montgomery	37,123	35%	61.6	2,287,604
Nassau	3,691	5%	22.8	84,368
New York	1,787	30%		
Niagara	35,683	26%	160.9	5,744,988
Oneida	197,915	63%	94.7	18,740,657
Onondaga	93,110	46%	102.4	9,539,279
Ontario	69,047	41%	61.0	4,215,820
Orange	93,893	44%	77.7	7,301,731
Orleans	32,656	32%	94.6	3,092,104
Oswego	165,650	67%	118.6	19,659,375
Otsego	168,045	65%	110.9	18,649,243
Putnam	33,594	56%	100.8	3,389,107
Queens	-	0%		
Rensselaer	114,357	68%	118.8	13,592,990
Richmond	1,947	13%		
Rockland	6,472	14%	189.9	1,229,762
St. Lawrence	451,662	65%	67.1	30,308,217
Saratoga	139,688	66%	106.0	14,813,288

County	Unreserved Forestland (ha)	% Land Area in Unreserved Forestland	Average Aboveground Tree Biomass (mt/ha)	Total Aboveground Tree Biomass (metric tons)
Schenectady	29,349	55%	109.0	3,201,696
Schoharie	102,697	64%	136.3	14,001,400
Schuyler	52,759	62%	123.8	6,532,387
Seneca	18,550	22%	61.6	1,142,766
Steuben	225,078	62%	96.9	21,815,591
Suffolk	45,895	19%	52.2	2,398,763
Sullivan	194,624	77%	100.2	19,500,294
Tioga	79,414	59%	73.0	5,797,141
Tompkins	60,226	49%	101.1	6,090,758
Ulster	163,119	56%	123.4	20,133,096
Warren	119,812	53%	132.6	15,897,009
Washington	120,176	56%	101.7	12,229,042
Wayne	60,704	39%	92.1	5,593,608
Westchester	41,151	37%	135.9	5,595,819
Wyoming	59,817	39%	100.5	6,012,716
Yates	34,530	39%	75.6	2,611,336
PENNSYLVANIA	6,553,299	56%		
Adams	47,003	35%	82.6	3,883,049
Allegheny	70,465	37%	68.3	4,813,974
Armstrong	103,662	61%	98.1	10,174,229
Beaver	41,614	37%	95.7	3,981,997
Bedford	157,084	60%	101.9	16,018,264
Berks	63,034	28%	122.9	7,748,219
Blair	80,438	59%	112.6	9,057,697
Bradford	164,391	55%	93.0	15,296,005
Bucks	35,933	23%	119.2	4,286,638
Butler	96,415	47%	74.9	7,225,035

County	Unreserved Forestland (ha)	% Land Area in Unreserved Forestland	Average Aboveground Tree Biomass (mt/ha)	Total Aboveground Tree Biomass (metric tons)
Cambria	105,859	59%	96.4	10,208,416
Cameron	86,114	84%	143.5	12,359,100
Carbon	61,646	62%	97.0	5,982,161
Centre	214,749	75%	113.6	24,407,773
Chester	46,324	24%	126.8	5,877,994
Clarion	105,727	68%	88.2	9,324,296
Clearfield	212,189	71%	81.0	17,192,493
Clinton	166,963	72%	129.2	21,580,564
Columbia	52,870	42%	102.5	5,421,474
Crawford	142,575	54%	100.1	14,275,504
Cumberland	44,770	31%	119.1	5,335,271
Dauphin	63,520	47%	115.2	7,318,544
Delaware	3,471	7%	12.9	44,956
Elk	195,190	91%	128.3	25,057,551
Erie	102,792	49%	104.7	10,763,924
Fayette	111,017	54%	107.7	11,959,129
Forest	106,590	96%	151.9	16,201,281
Franklin	74,363	37%	97.7	7,264,753
Fulton	74,744	66%	78.8	5,889,813
Greene	90,325	61%	88.5	7,995,124
Huntingdon	158,555	70%	122.5	19,430,750
Indiana	122,991	57%	103.7	12,756,741
Jefferson	101,035	60%	133.7	13,514,062
Juniata	52,902	52%	110.6	5,853,375
Lackawanna	74,137	62%	73.9	5,481,336
Lancaster	42,597	17%	130.9	5,578,858
Lawrence	40,879	44%	89.4	3,658,138

County	Unreserved Forestland (ha)	% Land Area in Unreserved Forestland	Average Aboveground Tree Biomass (mt/ha)	Total Aboveground Tree Biomass (metric tons)
Lebanon	30,123	32%	140.0	4,219,897
Lehigh	25,391	28%	161.4	4,099,224
Luzerne	143,680	62%	97.9	14,067,843
Lycoming	232,433	73%	132.8	30,890,394
McKean	222,650	88%	146.3	32,587,834
Mercer	79,361	46%	62.8	4,986,390
Mifflin	73,135	69%	124.5	9,110,792
Monroe	101,769	65%	107.4	10,937,322
Montgomery	8,844	7%	91.3	807,580
Montour	7,673	23%	45.8	351,613
Northampton	23,893	25%	142.8	3,413,677
Northumberland	62,739	53%	95.2	5,972,597
Perry	90,053	63%	121.8	10,970,566
Philadelphia	0	0%		
Pike	111,100	78%	131.8	14,650,228
Potter	229,819	82%	147.3	33,862,160
Schuylkill	131,019	65%	101.2	13,258,449
Snyder	39,796	46%	98.2	3,911,375
Somerset	172,904	62%	89.5	15,485,118
Sullivan	94,120	81%	103.5	9,745,393
Susquehanna	126,834	60%	100.2	12,710,088
Tioga	186,471	64%	124.6	23,245,900
Union	43,797	53%	162.5	7,121,386
Venango	135,252	77%	109.2	14,781,654
Warren	181,805	79%	148.4	26,994,899
Washington	98,911	45%	76.3	7,549,320
Wayne	130,183	69%	116.5	15,172,861

County	Unreserved Forestland (ha)	% Land Area in Unreserved Forestland	Average Aboveground Tree Biomass (mt/ha)	Total Aboveground Tree Biomass (metric tons)
Westmoreland	132,732	50%	102.7	13,640,660
Wyoming	66,584	65%	100.0	6,660,803
York	55,295	24%	110.9	6,134,184
RHODE ISLAND	139,363	51%		
Bristol	2,219	35%	80.7	179,178
Kent	19,170	43%	159.1	3,051,437
Newport	6,544	24%	88.7	580,871
Providence	61,618	58%	145.2	8,948,601
Washington	49,812	58%	77.9	3,882,469
VERMONT	1,824,043	76%		
Addison	101,502	51%	95.8	9,730,305
Bennington	133,190	76%	153.3	20,425,942
Caledonia	138,671	82%	88.3	12,250,870
Chittenden	87,001	62%	69.1	6,017,081
Essex	161,182	94%	91.5	14,747,066
Franklin	108,609	66%	105.5	11,460,423
Grand Isle	4,387	21%		
Lamoille	98,214	82%	132.4	13,007,180
Orange	147,319	83%	94.7	13,952,747
Orleans	136,131	75%	83.7	11,398,697
Rutland	194,686	81%	124.4	24,226,669
Washington	137,924	77%	91.9	12,677,238
Windham	173,029	85%	140.6	24,336,165
Windsor	202,197	80%	115.5	23,359,388

Appendix 3: Hydric Forestland

Fraction of the FIA plots, by state, that were classified as “hydric.” The statistics were compiled from the last full census for each state (i.e., the “previous cycle” Appendix 7). Most of this land would qualify as “wetland” (forested swamps) under state and federal regulations. Some portion of this land could still be harvested (particularly in winter over frozen soils), but we assume that much of it would be unavailable for harvests.

State	# Plots	% of Plots that are Hydric[1]
Connecticut	317	5.7%
Maine	552	10.0%
Massachusetts	3182	5.8%
New Hampshire	874	3.0%
New York	3362	4.5%
Pennsylvania	3149	1.4%
Rhode Island	128	10.2%
Vermont	866	2.9%
Overall	12430	4.2%

[1] "Sites with normally abundant or overabundant moisture all year."

Includes swamps, bogs, small drainage channels, and beaver ponds.

Appendix 4: Distribution of Forestland, by Slope

The percent of FIA plots by slope class, by state. We assume that some portion of the steepest slopes (>40%) would be unavailable for harvests.

	Slope		
State	**0-20%**	**20-40%**	**>40%**
Connecticut	81.6%	17.1%	1.3%
Maine	84.2%	13.3%	2.6%
Massachusetts	91.1%	7.8%	1.0%
New Hampshire	71.7%	22.7%	5.6%
New York	77.8%	17.5%	4.7%
Pennsylvania	67.1%	24.5%	8.4%
Rhode Island	93.8%	6.3%	0.0%
Vermont	59.7%	33.4%	6.9%
Overall	77.4%	18.0%	4.7%

Appendix 5: Small-Scale Private Forest Parcels in the Northeast

Results from the Woodland Owner Survey (USDA FS 2010c.).

State	**Private forest <4 ha[b]**		**Private forest >4 ha and <8 ha[c]**	
	ha	in % of forestland	ha	in % of forestland
Connecticut	102,388	14%	32,780	5%
Maine	182,517	3%	130,716	2%
Massachusetts	227,438	18%	84,176	7%
New Hampshire	89,842	5%	81,748	4%
New York	564,144	7%	438,689	6%
Pennsylvania	358,155	5%	332,659	5%
Rhode Island	39,660	28%	12,546	9%
Vermont	77,701	4%	60,704	3%
Total	1,641,845	6%	1,174,018	4%

b) ~10 acres; data exhibits high standard errors ranging from 21% (New York, Pennsylvania) to 56% (Vermont). Source: USDA FS 2010c.

c) ~20 acres; data exhibits high standard errors ranging from 23% (Pennsylvania) to >100% (Connecticut, Rhode Island). Source: USDA FS 2010c.

Appendix 6: Share of Pulp Wood in the Roundwood Market in 2006

Share of pulp wood in the roundwood market in 2006 (source: TPO database USDA FS 2010). The pulp wood share of the biomass that can be harvested in addition to current cuts is assumed to be potentially available for bioenergy applications. Roundwood is defined as the bole section of a tree with the top and branches cut off.

State	**Sawlogs and Veneer**	**Pulp**	
	m3	m3	% of total roundwood products
Connecticut	147,501	5,465	4%
Maine	5,740,309	6,776,611	54%
Massachusetts	205,097	31,262	13%
New Hampshire	735,863	319,581	30%
New York	2,430,978	2,160,866	47%
Pennsylvania	3,916,976	1,817,556	32%
Rhode Island	36,387	0	0%
Vermont	928,840	290,811	24%
Total	14,141,951	11,402,152	45%

Appendix 7. FIA Census Cycles for the Northeastern States

	Previous Cycle			Current Cycle		
State	Cycle	# Plots	Census Years	Cycle	# Plots	Census Years
Connecticut	5	531	2003-2007	6	110	2008
Maine	5	3586	1999-2003	6	3563	2004-2008
Massachusetts	5	868	2003-2007	6	172	2008
New Hampshire	6	994	2002-2007	7	199	2008
New York	5	5279	2002-2007	6	1065	2008
Pennsylvania	5	4861	2000-2004	6	3904	2005-2008
Rhode Island	5	257	2003-2007	6	50	2008
Vermont	6	1097	2003-2007	7	211	2008

Appendix 8. 2008 Energy Consumption Data Used in the Substitution Scenarios

All numbers in Tera Joule (10^{15} Joule). Source data came from EIA 2010a for Liquid Fossil Fuels (LFF), from EIA 2010b for coal consumption, and from EIA 2010h for total electricity generation. For Scenario 4 (combined heat and power from biomass), the first number represents current electricity consumption, and the second number represents current use of LFFs in the industrial and commercial heating sector.

Scenario Name	**10% co-firing with coal**	**Wood chips for heat**	**Wood electricity, 25% efficiency**	**Wood electricity, 40% efficiency**	**CHP wood electricity, 40% efficiency**	**Pellets for heat**	**FT diesel for transport**	**Cellulosic ethanol for transport**
State	**Coal**	**Mix of LFFs**	**Electricity mix**	**Electricity mix**	**Electricity mix/Mix of LFFs**	**Mix of LFFs**	**Mix of LFFs**	**Gasoline**
Connecticut	47,663	18,618	109,383	109,383	109,383/18,618	74,799	43,755	201,548
Maine	2,725	41,738	6,1490	6,1490	6,1490/41,738	39,190	27,615	88,596
Massachusetts	98,309	21,064	152,892	152,892	152,892/21,064	90,208	67,743	352,415
New Hampshire	31,783	11,127	82,289	82,289	82,289/11,127	25,131	14,684	75,227
New York	190,674	98,750	504,739	504,739	504,739/98,750	161,529	232,744	712,670
Pennsylvania	1,158,745	67,919	799,796	799,796	799,796/67,919	90,771	235,001	632,350
Rhode Island	0	4,696	26,572	26,572	26,572/4,696	16,752	11,601	66,528
Vermont	0	6,323	24,532	24,532	24,532/6,323	16,752	9,139	38,081
Total	**1,529,899**	**270,236**	**1,761,693**	**1,761,693**	**1,761,693/270,236**	**515,131**	**642,281**	**2,167,414**