SILVICULTURAL AND ECOLOGICAL CONSIDERATIONS OF FOREST BIOMASS HARVESTING IN MASSACHUSETTS

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Matthew J. Kelty
Anthony W. D'Amato
Paul K. Barten

Department of Natural Resources Conservation
University of Massachusetts
Amherst, MA

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Executive Summary

One part of Task 4.0 (Forest Impact Assessment with Increased Residue Removals) of the Massachusetts Sustainable Forest Bioenergy Initiative was to assess the levels of woody biomass fuels that exist in Massachusetts forests. At the level of the individual forest stand, the question is: what is the potential quantity of biomass fuels that could be harvested from typical sawtimber stands (70-100 years old) during a standard commercial harvest for sawlogs? At the state-wide level, the question is: what is the total annual sustainable biomass harvest from Massachusetts forests (that is, the total annual harvest level that would not exceed the total annual forest growth)?

Typical sawtimber stands had 70 dry tons/acre total biomass (counting all trees) and grew just under 1 dry ton/acre/year. Subtracting the biomass of the high-value sawlogs in these stands, there would be a total harvest of biomass-fuel-grade material of 45 dry tons/acre (this includes the total biomass of trees that are too small or too poor in stem quality for sawlog production). This is the amount that could be obtained from a clearcut harvest, which is not a common practice in Massachusetts. Partial harvests (thinnings) are a more common practice, and would provide a biomass yield of 25 dry tons/acre, with a substantial residual stand being left on the site. At the state-wide level, estimates of total annual sustainable harvests are 890,000 dry tons/year if all state forestlands plus all private forest lands with ownerships ≥ 10 acres are included. If only larger ownerships ≥ 100 acres (which are more likely to be involved in biomass harvesting) are included with the public forest lands, the estimate is 500,000 dry tons/year. These levels bracket the demand for 690,000 dry tons/year of new biomass material from forest harvesting to supply the 165 MW of new biomass-fueled electricity generation planned for the state.

The second part of Task 4.0 was to review key findings in the scientific research literature related to ecological impacts of increased harvesting for biomass, as is proposed for Massachusetts. The key findings and management recommendations are as follows:

Nutrient conservation: Although clearcut harvesting is an acceptable silvicultural practice in certain conditions we do not recommend the complete removal of woody biomass in combination with a silvicultural clearcut. This kind of harvest removes substantial portions of the nutrient capital of the site in the sawlog and biomass material. This occurs for most nutrients, but calcium is the nutrient of greatest concern. It would take more than 100 years for the amount of calcium removed in a whole-tree clearcut to be replenished from natural atmospheric and rock-weathering inputs. Partial harvests that retain a healthy residual stand are recommended.

Soil properties: Biomass harvesting will likely cause increased movement of harvesting equipment across the stand. This greater traffic may cause compaction of soils, which can lead to overland flow of water and the movement of sediment and nutrients into streams. Careful layout and construction of roads, and use of slash to protect roadbeds are important practices to reduce compaction.

Streamwater and water quality: The movement of water through soils and into streams increases with increasing intensity of forest harvesting. Greater water movement can lead to greater sedimentation and nutrient export into the streams, reducing water quality. The use of Best Management Practices (BMPs) can mitigate the effects on water quality. The main factors in BMPs for controlling sedimentation and nutrient export are: 1) planning and constructing appropriate truck roads and skid trails; 2) retaining riparian forest filter strips along streams to trap sediments moving in overland flow, to stabilize stream banks, and to allow filter strip vegetation to take up nutrients moving in either overland or subsurface flow. Another practice to protect water quality is a reduction in the proportion of trees harvested within the watershed; the residual stand will maintain active uptake of water and nutrients throughout the stand, so that the mitigation of sedimentation and nutrient flow does not rely solely on the streamside filter strip.

Carbon cycling and storage: The stand that develops following a biomass harvest should be managed to quickly return to high biomass growth rates. This means that the practices outlined in previous sections for nutrient conservation and protection of soil physical properties during harvests are critical in order to maintain high site productivity, which, in turn, leads to high carbon storage. Leaving a forest stand unharvested will create the greatest carbon stores on that site. However, thinning the stand and using the forest products for long-lived products (e.g., lumber or plywood) will sequester more carbon in total (the combination of living trees sequestering new carbon in the stand, and lumber being in use as part of a house). In the future, intensive management of woody biomass crops on short rotations may become economical; these could be either agricultural-type short rotation systems, or more forest-like systems such as aspen stands.

Wildlife habitat: Heavy cutting for biomass harvests can create open areas with dense brushy vegetation that provides habitat for some wildlife species (referred to as "early successional species"). However, harvest methods should retain 10-20% of the stand area in intact forest patches, and leave coarse woody debris on the ground to create the habitat structures needed by many of the species. Partial harvests (thinnings) can provide habitat for other species that can use the structure of a thinned overstory canopy with dense understory vegetation.

Forest fire risk: Thinning hardwood stands with removal of small trees and slash for biomass fuels would reduce amount of fine surface fuels by not adding the slash to the forest floor during the harvest. That would be the main effect on the reduction of fire risk, but it would not make a great difference because fire risk is already low in most hardwood stands. However, with pine stands on dry sites, removing small trees in a thinning (plus removing logging slash) would reduce both surface fuels and ladder fuels, thus providing a substantial reduction in fire danger.

The planned increase of biomass harvesting will be occurring in a region where forests are owned and managed largely for the ecosystem services they provide, such as habitat conservation, clean air and water, recreation, and rural home sites. Biomass harvests can be applied in a manner that sustains ecological processes, if partial harvests rather than clearcut harvests are used, leaving healthy, vigorous, residual stands that will continue to grow and sequester carbon at high rates after the harvest. Biomass harvests must be designed to be economically viable but also leave post-harvest forest stands in a condition that still provides these ecosystem services. If harvests are designed to fit into current forest management practices that protect these non-commodity values from forests (thereby promoting social sustainability), public support may be strong. But this support could quickly wane if the program appears to focus too closely on industrial-scale harvesting.

For decades, forest managers have been trying to find ways to create markets for small trees and low-grade wood in order to curtail "high-grading"--the harvest method in which only the high-value trees are cut and the small and low-value trees are left. The practice of high grading degrades the stand for future timber production and for many other forest values as well. Because biomass harvesting will create those markets for small trees and low-grade wood, with proper planning and practices it can both increase renewable energy production in the state and improve forest management for sawtimber production which can lead to reduced consumption of non renewable resources.

Table of Contents

1. Scope and introduction

Report context and content

Widespread support has developed among the American public for expanding renewable energy sources, including wood-based bioenergy (Sample 2007). This is based upon general environmental concerns about global climate change and its link to carbon emissions. However, public support may not last long if the impacts of harvesting biomass fuels appear to create other environmental problems. This kind of backlash has occurred with wind power. The development of markets for biomass fuels must be planned to avoid these kinds of unintended negative consequences. Most forests in Massachusetts are owned and managed for their ecosystem services, which include provision of clean water, biodiversity conservation, open space, recreation, and (for private lands) privacy for the landowner's home. Biomass harvests must be designed to be economically viable but leave post-harvest forest stands in a condition that still provides these ecosystem services. If this can be done, then biomass harvesting can both increase renewable energy production in the state and improve forest management for sawtimber production. For decades, forest managers have been trying to find ways to create markets for small trees and low-grade wood in order to curtail "high-grading"--the harvest method in which only the high-value trees are cut and the small and low-value trees are left. This kind of harvest degrades the stand for future timber production and for many other forest values as well.

The Massachusetts Sustainable Forest Bioenergy Initiative was created to promote forest resources as an environmentally sound source of renewable energy in the state (DiMaio and O'Connor 2007). The Initiative is funded by the U.S. Department of Energy and the Massachusetts Technology Collaborative, Renewable Energy Trust. This report deals with two aspects of the Initiative's objectives. First, it examines the levels of biomass fuels available in Massachusetts forests at the stand-level (i.e., an individual harvest area generally 10 to 100 acres), and at the state-level (i.e., all forestland in Massachusetts likely to be involved in timber harvesting). Second, the impact of biomass harvesting on forest ecological processes is examined in a series of literature reviews. Topics include the impacts on nutrient cycling and conservation, soil physical properties, streamflow and water quality, carbon cycling and storage, wildlife habitat, and forest fire risk. Within the Initiative framework, this report is Task 4.0: Forest Impact Assessment with Increased Residue Removals, Subtask 4.1: Research and assess impacts of biomass harvesting and sustainable removals on forest health.

Incorporating biomass harvests into current silvicultural practice in Massachusetts

Forestland comprises 62% of the total land area of Massachusetts, and a majority of that forestland (72%) has grown into the sawtimber size-class (i.e., stands stocked with trees that meet or exceed the minimum diameter for use as sawtimber) (Alerich 2000). Most of these stands had regenerated in the early to mid-1900s following clearcutting or hurricane blowdown, so they are roughly even-aged. The incentive for large-scale clearcutting in the early 1900s was the existence of industrial markets for charcoal, boxboards, tanbark, and chemical wood (which could use trees of all sizes), but these markets were all replaced by coal, oil, and petroleum-based chemicals by 1920-1950 (Kelty and D'Amato 2006). The highest level of lumber production in Massachusetts occurred in 1890-1910, but then declined to about 40% of that peak by 1940 (Kittredge et al. 2003). Although markets for small trees were quite limited at that time, some clearcutting continued simply because it was a "deeply ingrained practice" (Cline 1944). The expanding timber markets at that time were for high-grade hardwoods and white pine for furniture, flooring, and finish material (Gordon 1988). As a result, most harvesting began to shift to diameter-limit cutting, in which only sawtimber trees larger than a fixed diameter (often about 10 inches diameter at breast height--dbh) were cut.

This pattern of clearcut harvesting in the early 20th century created the maturing forests that now dominate the Massachusetts landscape. Current harvesting practices have not continued the heavy cutting that had led to the establishment of most of these stands. Instead, they generally are selective harvests--a continuation of the trend that had become common when the markets for small-diameter trees were sharply reduced. This approach to harvesting is occurring in spite of the fact that the most efficient and successful silvicultural practices for treating mature stands of most of the forest types in southern New England (particularly those dominated by oaks and white pine) are even-aged shelterwood methods (Hibbs and Bentley 1983, Lancaster and Leak 1978). Much of the current interest in partial cutting is not concerned with meeting optimum silvicultural goals, but rather is focused on a larger set of landowner objectives. About 54% of Massachusetts forestland is owned by non-industrial private individuals (Alerich 2000). Most of these landowners do not have timber harvest income as a major goal. Their modest goals for timber cutting often consist of producing enough income to meet the costs of maintaining ownership of the forestland, or harvesting enough timber to allow the land to be enrolled in a property tax reduction program for forestlands. The highest priorities of a majority of these landowners are for maintaining an intact forest that provides for nature conservation, scenery, outdoor recreation, and privacy for their home (Finley and Kittredge 2006).

A study of cutting practices carried out in the North Quabbin Region (NQR) of Massachusetts documented the prevalence of partial cutting in the period of 1984-2000 (Kittredge et al. 2003). NQR consists of 19 towns with an area of 415,730 acres in north-central Massachusetts. A mean of 1.5% of the forest land base per year was harvested during the 17-year period, with a mean timber volume removal of only 27% of the total stand volume. This study also showed that partial cutting was not restricted to private family forest owners with predominant conservation interests. The industrial ownerships in the NQR study conducted harvests over more land area (4% of their land base per year), but also had a low harvest intensity, with a mean of only 16% of the stand volume removed in harvests. It is clear that the large value differential among tree sizes and species is leading to a selective removal of the high-value sawtimber-size oaks and white pine, as well as other valuable species such as sugar maple, yellow birch, white ash, and black cherry (Alerich 2000).

These partial cutting practices are often described as thinning, selection, or shelterwood. These practices tend to be similar during the first harvest in a stand, because in all three cases, the overstory canopy is thinned, and the smaller understory and midstory trees are often left uncut (although in the selection and shelterwood regeneration methods, the understory and midstory trees should be thinned or removed entirely to promote new seedling establishment). The removal of these small trees has been difficult to carry out because of the limited markets for small trees and the reluctance of many landowners to invest in forest treatments.

The principal timber objective in southern New England stands is the production of high-value sawtimber trees. Optimal silvicultural practice for producing these sawtimber trees would be to conduct one or more thinnings over the life of a stand to identify the best individuals as crop trees and remove a portion of the other large trees of poorer quality to give more space for the crowns of the crop trees. Thinning could start early in the life of the stand (the recommended stand age to begin thinning is 50 years) (Hibbs and Bentley 1983). However, the first thinning is often delayed until about age 70 years, when the harvested trees would be large enough to produce income from the timber sale. During these treatments, some poor quality trees with no timber value because of decay, large branches, or poor stem form (called "cull" trees) are girdled so that they will die and open growing space for crop trees.

Clearcut harvests do occur in southern New England, but they are not common on either public or private lands. Clearcuts are generally small--only 2 to 3 acres in size. Massachusetts cutting regulations limit the size of clearcuts to 10 acres (except in special circumstances). The clearcutting method is used mostly for creating specific wildlife habitat structures or for restoring stands where poor previous management methods have removed most trees of value and it is deemed best to start over with new regeneration.

This description of current stand conditions and harvest practices indicates that most stands receive partial cuts that are focused mainly on the overstory, so small trees and poor-quality sawtimber-size trees tend to build up in many of these stands. Thus, the greatest potential for harvesting woody biomass fuels from Massachusetts is as an addition to conventional partial harvests that focus on sawtimber.

2. Assessment of potential biomass harvest levels in typical Massachusetts forest stands

Analysis objectives and approach

The general objective of this first part of the assessment of potential biomass harvests is to determine, at the stand level, the biomass fuels that would be available for harvest in typical stands in Massachusetts. The data for describing these typical stand conditions were taken from existing inventory plots on Massachusetts public and private forest lands.

The specific objectives of this analysis are to determine:

1. the total stand biomass per acre for a range of forest types and site qualities in Massachusetts; this includes trees of all species, sizes, and stem quality.

2. the potential harvestable biomass in a stand, as if it were clearcut (using whole-tree harvest methods). This calculation is designed to determine the baseline of the total biomass harvest, excluding all trees of sawtimber size and quality; it is not included as either a common or preferred silvicultural method.

3. the potential harvestable biomass in a stand that receives a conventional crown thinning (i.e., thinning of the overstory trees). There are two variations--one in which only the overstory crown thinning is conducted; the other includes (in addition to the crown thinning) the use of low thinning, which removes small understory and midstory trees for biomass. This distinction is important because small trees are more expensive to harvest per unit of wood volume or biomass, but they may contain a substantial portion of biomass in some stand types.

Analysis methods

To determine the typical stand conditions, we used data from state and private forests in the western half of the state (i.e., Worcester Plateau Ecoregion westward), where most timber harvests occur. Continuous Forest Inventory (CFI) plots are located on most State Forests and Watershed Protection Areas, administered by the Massachusetts Department of Conservation and Recreation (Massachusetts DCR 1998); these provide data available from 2000 for public forest lands. Inventory plots from the Forest Inventory and Analysis (FIA) program of the U.S. Forest Service (Alerich 2000) are located across the entire state, with data available from 1998. Since most of the land area of Massachusetts is privately owned (76%), the FIA plots provide data mainly for private lands. In our analysis, we refer to the CFI data as representing public lands and FIA data as representing private lands. The forest inventory data include the species, diameter, volume, and tree grade (stem quality) of all trees in each plot, as well as the site quality of the plot (based on site index measurements).

The five most common forest types in the two sets of plots (i.e., Mixed Oak, White Pine, Northern Hardwood, Hemlock, and Mixed Hardwood) were chosen for these analyses. For each forest type, all inventory points were divided into low, medium, and high site quality. Only those plots that were in the 70-100 year age class were selected, because stands of this age class are the most likely to be harvested; they are also the majority of the Massachusetts landscape. This created 30 combinations of 5 forest types x 3 site quality levels x 2 ownership classes. The number of inventory plots for each combination of forest type and site quality ranged from 2-18 points, with an average of 5 inventory points per forest type-site quality-ownership combination. For each combination, the average stand condition was determined for stocking (number of trees), species composition, tree size distributions, and tree grade distributions.

For each of these 30 average stand conditions, aboveground biomass was calculated for each tree in the inventory plots, using the regression equations developed by the U.S. Forest Service (Jenkins et al. 2003). These equations calculate biomass in dry tons, based on tree diameter and species groups. Trees that were 10 inches dbh and greater were classified as sawtimber size. Stem quality of sawtimber-size trees was assigned in two classes: acceptable or cull. Cull trees had no value for sawlogs because of substantial decay or poor stem form. The proportion of trees ≥ 10 inches diameter that were classified as culls in our analysis was based on field classifications of tree grade on CFI and FIA plots (Table 1).

Then, harvest removals were modeled by removing trees from the current stands, based on tree size and quality as determined by the harvest rules for each of the three silvicultural options (below). The main stems of all acceptable sawtimber-sized trees (i.e., those that were not classified as culls) were utilized for lumber rather than biomass fuel; their stem volume was calculated in board foot units. The potential biomass removals are in three categories: 1) cull trees (trees ≥ 10 inches diameter that have no value as sawtimber); 2) small-diameter trees (all trees < 10 inches); 3) harvest residues or slash (the upper stem and branches of the sawtimber trees that were cut for sawlogs). These three categories were measured in biomass units of dry tons.

1. *Clearcutting:* all trees are cut, with all trees of sawtimber size that are not cull being used for lumber, and cull trees, small trees, and harvest residue used for biomass.

2. *Crown thinning:* harvest of approximately 50% of the sawtimber-size trees in the stand; of these, acceptable trees (not cull) were used as sawlogs, and cull trees were used for biomass (as whole trees); the harvest residues from the trees cut for sawlogs were used for biomass.

3. *Crown thinning + low thinning:* this harvest is similar to crown thinning (above) but the low thinning also included all small trees being cut and used for biomass.

Results

Total standing biomass across all 30 combinations of forest type-stand quality-ownership class ranged from 21 to 101 dry tons/acre, with stands averaging 71 and 69 dry tons/acre on public and private lands, respectively (Table 2). Note that these values do not represent harvestable biomass, but are totals that include all trees, whether sawtimber quality or biomass fuel quality. The mean levels of standing biomass were generally quite similar among forest types (approximately 70-78 dry tons/acre) except for the Mixed Hardwood stands, which were composed largely of paper birch and red maple; these had the lowest average levels of standing biomass at 55 dry tons/acre. Two differences can be seen in public vs. private ownerships: Mixed Oak stands are substantially lower in biomass on the private lands compared to public lands, and Hemlock stands are higher in the private lands compared to public lands. This is likely a result of heavier cutting of the valuable oak and lighter cutting in the low-value hemlock on private land ownerships.

A summary of biomass and sawlog volume removals associated with the three harvest methods of: 1) clearcutting, 2) crown thinning, and 3) crown thinning + low thinning are presented in Tables 3, 4, and 5, respectively. Sawlog volume removals in the clearcutting treatment ranged from 1 to 12 MBF/acre among all stand conditions (MBF = 1000 board feet) and averaged 6 MBF/acre on both public and private lands (Table 3). The White Pine forest type and the high-site-quality Northern Hardwood forest type had the highest sawlog volumes. Biomass removals from the clearcut, which were a combination of cull trees, small trees, and harvest residues, were generally greater on private lands due to the higher proportion of cull trees on those lands (Tables 1 and 3). The biomass harvest from the clearcut provides a mean of 41 and 50 dry tons/acre for the public and private lands, respectively, which amounts to 58% and 72% of the total standing biomass being converted to harvestable biomass fuel in each case.

The crown thinning harvest generated much lower levels of biomass, with total biomass removals averaging 9 dry tons/acre on both public and private lands (Table 4). Harvest residues (the tops of trees cut for sawlogs) were lower than with clearcutting because fewer sawtimber trees were cut. Cull tree biomass was lower because this was a thinning of the overstory, not a complete removal of cull trees, as in a clearcut. In addition, no small trees were cut. In contrast, average biomass levels harvested in the crown thinning + low thinning treatment (Table 5) were 2.5 to 3.0 times greater than the crown thinning treatment, with total biomass removals of 27 and 23 dry tons/acre for public and private lands, respectively. Since the only difference between the two thinning harvests was the removal of small trees, this indicates that a large stock of small trees (5-10 inches dbh) exists in typical mature stands. These small trees add 17 and 14 dry tons/acre in biomass harvest for public and private lands, respectively, and account for 63% and 61% of the total biomass harvest for the crown thinning + low thinning treatment.

Thus, using mean values from this analysis, an assessment of potential biomass harvest levels can be made. A typical Massachusetts forest stand of age 70-100 years contains 72 dry tons/acre; this accounts for trees of all species, sizes, and quality in the stand. A clearcut using whole-tree harvesting methods could produce 45 dry tons/acre of biomass fuels (with the remaining 27 dry tons/acre being harvested as sawlogs), but a harvest of this type would generally not be acceptable due to impacts on soil nutrient conservation, wildlife habitat conditions, and stream water quality (see literature reviews). Partial cutting (thinning, selection cutting, or shelterwood cutting) could produce approximately 9 to 25 dry tons/acre, with the difference being whether small trees (5-10 inches dbh) are included in the harvest; much of the available biomass for harvest is contained in these small trees.

Table 1. Mean percentage of trees ≥ 10 inches dbh that were cull (not suitable for use as sawtimber) in public and private forests. Cull designation is based on field assignments of tree grade in CFI and FIA plots. All trees receiving a grade 4 and above were considered cull.

	Percent Cull	
Stand type	**Public**	**Private**
Mixed Oak	19	23
Mixed Pine	26	32
Northern Hardwood	25	34
Hemlock	25	40
Mixed Hardwood	29	28

Table 2. Total standing biomass on state and private forest lands in western Massachusetts, based on CFI data from Massachusetts DCR and FIA data from the U.S. Forest Service. Mean values are given for the 5 most common forest types, separated into 3 site quality classes (low, medium, and high) and 2 ownership classes (public and private). CFI data were used for public lands and FIA data were used for private lands.

	Standing biomass (dry tons/acre)	
Stand Type	Public	Private
Mixed oak (low)	62	34
Mixed oak (med)	77	61
Mixed oak (high)	71	67
Mixed oak (all)	***70***	***54***
White pine (low)	75	73
White pine (med)	72	66
White pine (high)	77	89
White pine (all)	***75***	***76***
Northern hardwood (low)	73	45
Northern hardwood (med)	75	72
Northern hardwood (high)	76	101
Northern hardwood (all)	***75***	***73***
Hemlock (low)	72	94
Hemlock (med)	88	97
Hemlock (high)	75	75
Hemlock (all)	***78***	***89***
Mixed hardwood (low)	53	73
Mixed hardwood (med)	59	21
Mixed hardwood (high)	59	66
Mixed hardwood (all)	***57***	***53***
OVERALL AVERAGE	**71**	**69**

Table 3. Sawlog volume and biomass totals associated with clearcut harvesting on state and private forest lands in western Massachusetts. All sawtimber trees (those ≥ 10 inches dbh) were harvested; of these, cull trees were converted to biomass; all other trees of that size were converted to sawlog volumes. Small trees (5 - 10 inches dbh) and harvest residues from tops of sawlog trees were converted to biomass.

	Clearcut Treatment									
	Sawlog volume (MBF/acre)		**Cull biomass** (dry tons/acre)		**Harvest residues** (dry tons/acre)		**Small tree biomass** (dry tons/acre)		**Total harvested biomass** (dry tons/acre)	
Stand Type	Public	Private	Public	Private	Public	Private	Public	Private	Public	Private
Mixed oak (low)	4	2	9	16	6	3	20	12	35	31
Mixed oak (med)	7	5	13	22	10	7	12	13	35	42
Mixed oak (high)	6	6	12	18	8	8	14	11	34	37
White pine (low)	9	8	18	28	10	10	13	12	41	50
White pine (med)	8	7	17	24	10	9	14	9	41	42
White pine (high)	10	12	19	31	11	14	11	8	41	53
No. hardwood (low)	6	3	18	21	9	5	15	12	42	38
No. hardwood (med)	7	6	18	29	9	9	16	12	43	50
No. hardwood (high)	7	10	19	36	9	14	15	8	43	58
Hemlock (low)	5	8	17	41	8	14	24	14	49	69
Hemlock (med)	8	7	25	50	11	12	19	28	55	90
Hemlock (high)	7	6	21	38	9	9	17	20	47	67
Mixed hardwood (low)	2	4	6	40	3	6	30	34	39	65
Mixed hardwood (med)	4	1	9	13	6	1	23	12	38	21
Mixed hardwood (high)	5	8	11	22	6	9	17	9	34	40
AVERAGE	**6**	**6**	**15**	**29**	**8**	**9**	**17**	**14**	**41**	**50**

Table 4. Sawlog volume and biomass totals associated with crown thinning treatment on state and private forest lands in western Massachusetts. Approximately 50% of sawtimber-size trees (those ≥ 10 inches dbh) were harvested; of these, cull trees were converted to biomass; all other trees of that size were converted to sawlog volume. Harvest residues from tops of sawlog trees were converted to biomass. Small trees were not harvested.

	Crown Thinning Treatment							
	Sawlog volume (MBF/acre)		**Cull biomass** (dry tons/acre)		**Harvest residue biomass** (dry tons/acre)		**Total harvested biomass** (dry tons/acre)	
Stand Type	Public	Private	Public	Private	Public	Private	Public	Private
Mixed oak (low)	2	1	4	2	2	1	6	3
Mixed oak (med)	3	2	6	4	3	2	9	6
Mixed oak (high)	3	2	5	4	3	3	8	7
White pine (low)	4	3	8	7	3	3	11	10
White pine (med)	3	3	7	7	3	2	10	9
White pine (high)	4	5	8	10	3	3	11	13
No. hardwood (low)	3	1	8	4	3	1	11	5
No. hardwood (med)	3	2	8	8	3	2	11	10
No. hardwood (high)	3	4	8	12	3	3	11	15
Hemlock (low)	2	3	8	12	2	3	10	15
Hemlock (med)	3	3	11	11	3	3	14	14
Hemlock (high)	3	2	9	9	3	2	12	11
Mixed hardwood (low)	1	2	3	4	1	2	4	6
Mixed hardwood (med)	2	0	4	1	2	0	6	1
Mixed hardwood (high)	2	3	5	6	2	2	7	8
AVERAGE	**3**	**2**	**7**	**7**	**3**	**2**	**9**	**9**

Table 5. Sawlog volume and biomass totals associated with crown thinning + low thinning treatment on state and private forest lands in western Massachusetts. Approximately 50% of sawtimber-size trees (those ≥ 10 inches dbh) were harvested; of these, cull trees were converted to biomass; all other trees of that size were converted to sawlog volume. Small trees (5 - 10 inches dbh) and harvest residues from tops of the sawlog trees were converted to biomass.

	Crown Thinning + Low Thinning Treatment									
	Sawlog volume (MBF/acre)		**Cull biomass** (dry tons/acre)		**Harvest residue biomass** (dry tons/acre)		**Small tree biomass** (dry tons/acre)		**Total harvested biomass** (dry tons/acre)	
Stand Type	Public	Private	Public	Private	Public	Private	Public	Private	Public	Private
Mixed oak (low)	2	1	4	2	2	1	20	12	26	15
Mixed oak (med)	3	2	6	4	3	2	12	13	21	19
Mixed oak (high)	3	2	5	4	3	3	14	11	22	18
White pine (low)	4	3	8	7	3	3	13	12	24	22
White pine (med)	3	3	7	7	3	2	14	9	24	18
White pine (high)	4	5	8	10	3	3	11	8	22	21
No. hardwood (low)	3	1	8	4	3	1	15	12	26	17
No. hardwood (med)	3	2	8	8	3	2	16	12	27	22
No. hardwood (high)	3	4	8	12	3	3	15	8	26	23
Hemlock (low)	2	3	8	12	2	3	24	14	34	29
Hemlock (med)	3	3	11	11	3	3	19	28	33	42
Hemlock (high)	3	2	9	9	3	2	17	20	29	31
Mixed hardwood (low)	1	2	3	4	1	2	30	34	34	40
Mixed hardwood (med)	2	0	4	1	2	0	23	12	29	13
Mixed hardwood (high)	2	3	5	6	2	2	17	9	24	17
AVERAGE	**3**	**2**	**7**	**7**	**3**	**2**	**17**	**14**	**27**	**23**

3. Assessment of statewide sustainable biomass harvest levels

Analysis objective and approach

The objective of the second part of the analysis of potential biomass harvest levels is to provide an estimate of the sustainable level of biomass harvesting for the entire forest land area of Massachusetts. The requirement for harvest sustainability (i.e., sustained yield) is that the total harvest per year does not exceed the total net growth per year on the land base of interest. Therefore, determination of sustainability for the state requires estimates of 1) mean forest growth rate per acre across state forestlands, and 2) the total land area in the state that is likely to be managed for forest products; in this case, it would include all land that may be managed for a range of objectives, but with harvesting forest products being included as one of those potential objectives.

Analysis methods

Mean forest growth rates were determined by using a standard growth projection model developed by the U.S. Forest Service--the Northeast Forest Vegetation Simulator (also called NE-TWIGS) (Teck and Hilt 1991). This growth model was run using the Landscape Management System (LMS) software (http://lms.cfr.washington.edu). The model was used to determine 50-year growth rates for each of the 30 forest type-site quality-ownership class combinations (as described in the previous section), based on the CFI and FIA databases. The mean growth rate of each stand condition over this 50-year period was used as the estimate of growth for the sustainability analysis.

The forestland area for public lands in Massachusetts (including state, county, municipal, and federal) is available from FIA data (Alerich 2000); the total is 554,200 acres. The area for private lands is available from Kittredge et al. (in press). The likelihood of timber harvesting on private forest land declines with ownership size. Therefore, we included two levels of private land area in the analysis: a) only larger private ownerships (≥ 100 acres) which are more likely to consider biomass harvests (582,690 acres), and b) all ownerships ≥ 10 acres (1,647,685 acres). From these initial land areas, we conducted a “net-down” analysis in which social, policy, and operational constraints were applied to the public and private forest land bases to remove lands that are not likely to be harvested. This will result in an estimate of the net total of forestland from which biomass harvesting might occur in the future.

The following constraints were used for this analysis:

1. *Operational constraints*: Information on landscape-level operational constraints (e.g., steep slopes, wetlands) was derived from forest plans of the Quabbin Forest (the first FSC-certified public land in North America). Based on the patterns of

these operational limitations in this large forested landscape, we removed 7% of both the public and private land bases from consideration for harvesting.

2. *Public forest reserves:* The area of newly established forest reserves on state lands (50,203 acres) was deducted from the total public land area to generate an estimate of total public lands available for biomass harvests. The remaining public land area includes some parks and other recreational areas that are not off-limit to harvesting, but will likely not receive heavy harvesting; these acreages were not available, so were not removed from the total.

3. *Landowner willingness to harvest biomass*: Information from Massachusetts private woodland owner surveys conducted by Dr. David Kittredge were used to assess the willingness of landowners to harvest wood on their land. From this survey, it was determined that 70% of private landowners would consider harvesting timber in the future. Therefore, we removed 30% of the private ownership land base from consideration for biomass harvesting.

These reductions were applied to each land base (public and/or private, appropriate) to derive an estimate of the total land base for harvesting. The overall mean growth rates ((dry tons/acre)/year) for public and private lands were then multiplied by the land base (acres) to determine the total annual forest biomass growth and the potential sustainable biomass harvest, both in units of dry tons/year.

Results

The results of the 50-year growth projections for each of the 30 stand conditions are shown in Figures 1 and 2. These were the basis for the mean annual growth rates in Table 6. There were no major trends that could be identified in growth rate differences among the various stand types. Differences were a result of complex interactions among the species, site conditions, and previous harvest trends that created the initial conditions that were used for the growth projections. The mean growth rates for all forest types and site qualities combined were 0.94 and 0.89 (dry tons/acre)/year for public and private lands, respectively, with an overall mean of 0.92 (dry tons/acre)/year.

The net land area available for biomass harvesting in Massachusetts varies substantially based on the smallest private ownership size that is likely to be harvested for biomass fuel. If only large private ownerships ($\geq$ 100 acres) are considered, the estimate of the net private land base available is 379,000 acres (Table 7). In contrast, the inclusion of smaller ownerships (10-99 acres) increases the net private land base to 1,072,000 acres. Because biomass harvesting has not been common in Massachusetts, it is difficult to predict the level of acceptability of this management activity to private owners of small forest tracts. Therefore, we used both definitions for determining the private land areas available for biomass harvest, and provide harvest assessments for both scenarios. The estimate of public land area available for harvest is 465,000 acres (Table 7).

The multiplication of the land area and the biomass growth rate provides an estimate of the total annual biomass growth of that land area (Table 7). However, this cannot be considered the potential sustainable biomass harvest level, because a mean of 36% of all forest growth is in the form of trees of sawlog size and quality. These trees would not be harvested for biomass. Therefore, the public, private, and total statewide estimates of total annual biomass growth were reduced by 36% to determine the estimate of the potential annual biomass harvest.

The data in Table 7 were presented at high precision levels (to one-acre precision) in order to make the calculations transparent. Using appropriate precision (rounding) levels, the statewide total forest biomass growth is 1,390,000 dry tons/year if all private lands ≥ 10 acres are included, and 770,000 dry tons/year, if only larger private holdings ≥ 100 acres are included. Similarly, the statewide potential annual biomass harvest is 890,000 dry tons/year if both small and large private holdings are included, and 500,000 dry tons/year if only the large private holdings are included.

The estimated demand of chips from in-state forestry operations is 1,000,000 green tons or 526,000 dry tons (assuming 1.9 green tons per dry ton). This would account for 60% of the total annual biomass fuel needed for 165 MW electricity production, with the remainder coming from forestry operations out of state, and waste wood from sawmills and land clearing. This demand for in-state chips would be 59% of the sustainable annual harvest, counting forest ownerships of 10 acres and greater. If only ownerships 100 acres and greater are considered, the demand exceeds the sustainable annual harvest level by 5%.

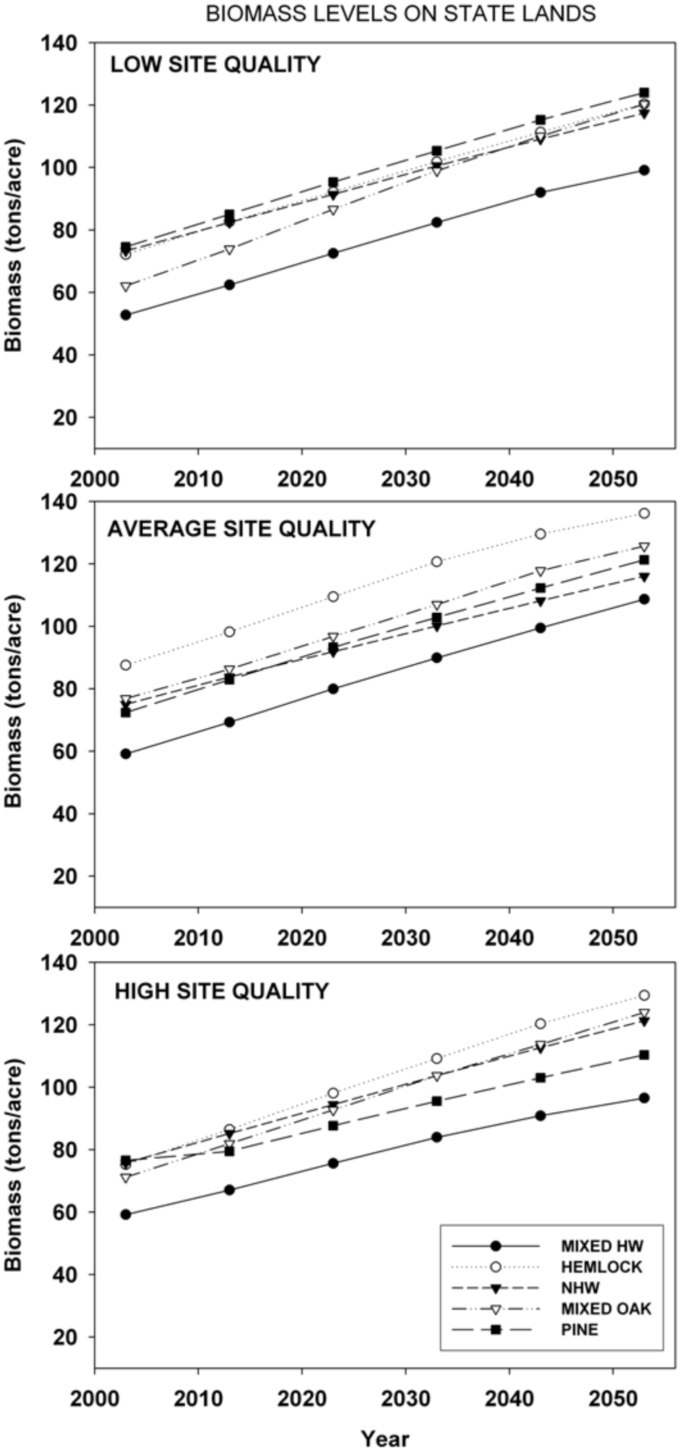

Figure 1. Total standing biomass (dry tons/acre) for common Massachusetts forest types on a) low, b) average, and c) high site quality sites in public *(state)* forest lands. Biomass represents aboveground woody biomass in all stems ≥ 1 inches dbh. Initial conditions are from CFI data, and growth trends are from Northeast Forest Vegetation Simulation projections.

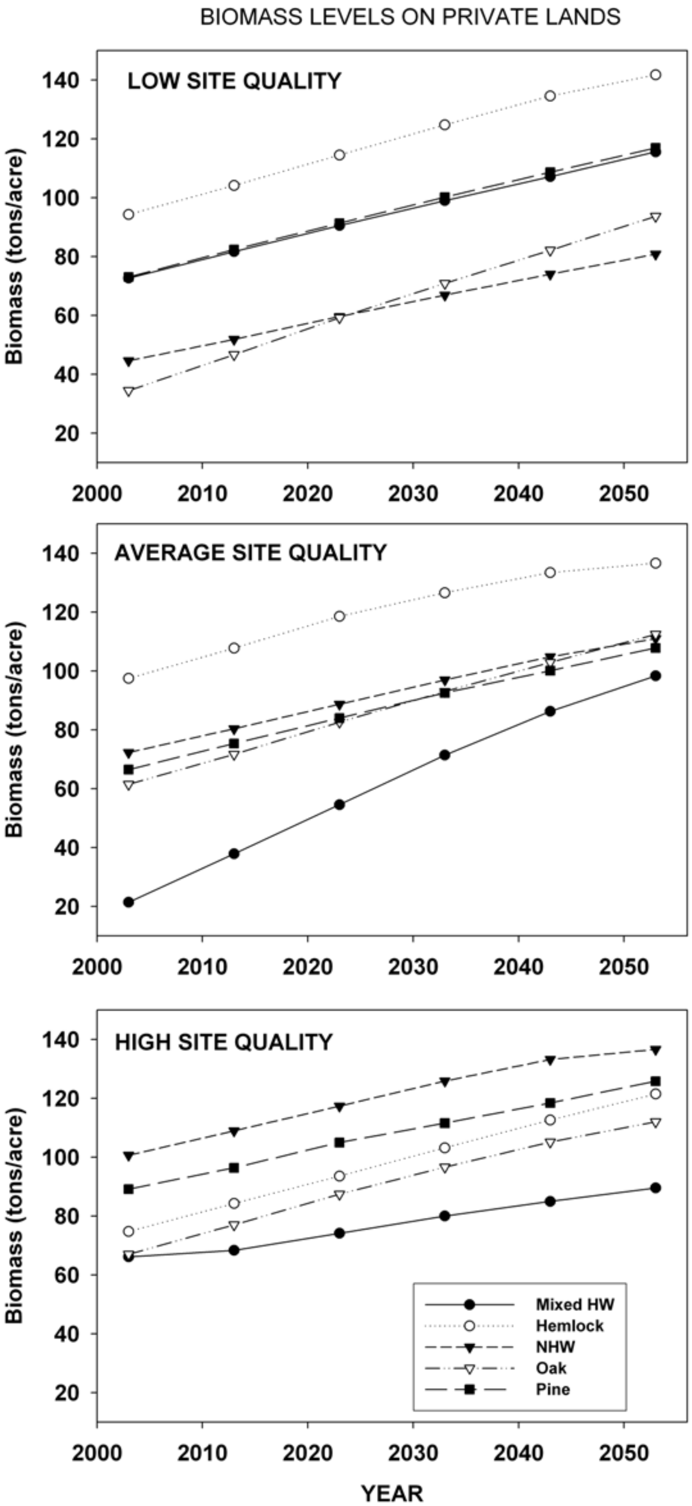

Figure 2. Total standing biomass (dry tons/acre) for common Massachusetts forest types on a) low, b) average, and c) high site quality sites on *private* forest lands. Biomass represents aboveground woody biomass in all stems ≥ 1 inches dbh. Initial conditions are from FIA data, and growth trends are from Northeast Forest Vegetation Simulation projections.

Table 6. Total standing biomass and annual rates of biomass growth (based on 50 year projections) on state and private forest lands in western Massachusetts. Standing biomass figures are from Table 2. Annual biomass growth rate values are from the 50-year growth simulations from the Northeast Forest Vegetation Simulator model, shown in Figures 1 and 2. Mean values are given for the 5 most common forest types, separated into 3 site quality classes (low, medium, and high) and 2 ownership classes (public and private). CFI data were used for public lands and FIA data were used for private lands.

	Standing biomass (dry tons/acre)		**Biomass growth rate** ((dry tons/acre)/year)	
Stand Type	Public	Private	Public	Private
Mixed oak (low)	62	34	1.16	1.19
Mixed oak (med)	77	61	0.98	1.02
Mixed oak (high)	71	67	1.06	0.9
Mixed oak (all)	***70***	***54***	***1.07***	***1.04***
White pine (low)	75	73	0.99	0.88
White pine (med)	72	66	0.98	0.83
White pine (high)	77	89	0.68	0.73
White pine (all)	***75***	***76***	***0.88***	***0.81***
Northern hardwood (low)	73	45	0.88	0.72
Northern hardwood (med)	75	72	0.82	0.77
Northern hardwood (high)	76	101	0.91	0.72
Northern hardwood (all)	***75***	***73***	***0.87***	***0.74***
Hemlock (low)	72	94	0.96	0.95
Hemlock (med)	88	97	0.97	0.78
Hemlock (high)	75	75	1.08	0.93
Hemlock (all)	***78***	***89***	***1.00***	***0.89***
Mixed hardwood (low)	53	73	0.93	0.86
Mixed hardwood (med)	59	21	0.99	1.54
Mixed hardwood (high)	59	66	0.75	0.47
Mixed hardwood (all)	***57***	***53***	***0.89***	***0.96***
AVERAGE	**71**	**69**	**0.94**	**0.89**

Table 7. Biomass growth rates, net forest land base, annual forest biomass growth, and sustainable annual harvest levels for the state of Massachusetts. The annual forest biomass growth levels include all trees in the inventory plots; annual biomass harvest was reduced by 36% from the annual forest biomass growth to account for the proportion of the trees that would be harvested for sawtimber, and thus not be available for biomass harvest. The biomass growth rates and net land base areas were the same for both annual forest biomass growth and sustainable annual biomass harvest estimates.

Biomass growth rates ((dry tons/acre)/year)		**Net land base** (acres)			**Annual forest biomass growth** (dry tons/year)		
Public	Private	**Scenario for private lands**	Public	Private	Public	Private	**Total**
0.94	0.89	All ownerships (≥ 10 acres)	465,203	1,072,642	437,291	954,651	**1,391,942**
0.94	0.89	Large ownerships only (≥ 100 acres)	465,203	379,331	437,291	337,605	**773,427**

Sustainable annual biomass harvest (dry tons/year)		
Public	Private	**Total**
279,866	610,977	**890,843**
279,866	216,067	**495,933**

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4. Literature Review: Forest impacts associated with biomass harvesting

Review topics

The objective of this literature review is to provide a concise description of the current state of knowledge about the impacts of biomass harvesting on forest ecosystem structure and function. The topics include: a) nutrient cycling and retention, b) soil physical properties, c) streamflow and water quality, d) carbon cycling and storage, e) wildlife habitat, f) forest fire risk.

Biomass versus conventional harvesting

Most current forest harvesting activities in Massachusetts are best described as *conventional* or *stem-only harvests* in which only commercial sawlogs are removed from a harvest area. While *biomass harvests* utilize much of the same equipment and the same principles as conventional harvests, there are some important differences between these approaches that make the impacts of biomass harvesting potentially greater. In particular, biomass harvesting removes harvest residues, including branches and foliage, and nonmerchantable trees that are normally left on site following conventional harvests. In addition, many traditional forest products, such as dimensional lumber, require larger trees for their production. As a result, conventional harvesting occurs over long rotations allowing trees to reach larger, financially mature sizes. In contrast, biofuels can be produced from any size tree and hence forests managed for biomass production can be harvested on much shorter rotation cycles. The impacts of the intensity and frequency of biomass harvests will be included in the following discussion of the potential impacts of this practice.

4a. Nutrient cycling and retention

Nutrient dynamics in forest ecosystems

Long-term forest productivity depends on conservation of the nutrient capital (inherent fertility) of a site. The major nutrients in forest ecosystems are nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), and magnesium (Mg). Input and output rates of these nutrients are generally much lower than the internal cycling rates in the ecosystem. Vegetation plays a central role in forest nutrient cycling. Nutrients are taken up by roots from soil solution and are incorporated into living biomass, including woody stems and roots, foliage, and fine roots. Each year, a portion of live biomass dies, forming litter that adds organic matter to the forest floor. Nutrients in the litterfall are in organic form, but are mineralized to inorganic form through decomposition processes (Gosz et al. 1973). The inorganic form of nutrients are available for plant root uptake from soil solution. This cycle does not add or remove nutrients from the ecosystem; it cycles them between organic form in vegetation and inorganic form in soils.

Biomass harvesting is one output for nutrients; it directly impacts forest nutrient cycling through the removal of aboveground biomass--stemwood, branches, and foliage. Stemwood generally contains relatively low concentrations of nutrients, compared to the higher levels in fine branches and foliage (Whittaker et al. 1979). As a result, the removal of the nutrient-rich components from the forest can lead to a reduction in the nutrient capital of a site (Pierce et al. 1993). The overall impact of these removals is a function of the intensity of the harvests (how much is removed) and the length of the cutting cycle (the time until the next harvest).

The release of nutrients from organic matter is largely controlled by soil microbial activity. The activity level of these microorganisms increases as a function of soil temperature and moisture (Oades 1988). Because harvesting removes all or part of the canopy, it generally leads to higher soil temperatures from increased sunlight and higher moisture conditions from reduced evapotranspiration (Aber et al. 1978) and more rain and snow reaching the forest floor. N is often the focus of nutrient research because it is required in relatively high concentrations in vegetation, it affects the function of the cycling of other nutrients, and it creates pollution problems when it leaches into stream water. When N is mineralized by microbial activity, it initially occurs in the inorganic form ammonium (NH_4) in soil solution. If conditions are good for microbial activity, ammonium is then transformed (nitrified) to nitrate (NO_3). N in the form of nitrate is highly mobile, and can readily leach from the site following harvesting or other disturbance (Hornbeck et al. 1987). Base cation nutrients (Ca, Mg, K, and others) follow the same pattern, but they stay in cation form and do not form multiple compounds as N does. The leaching losses of all nutrients are fairly short-lived after a harvest. Subsequent revegetation of the site results in increased nutrient uptake levels; leaching rates generally return to pre-harvest levels within five years (Martin and Pierce 1980, Martin et al. 1984, Mann et al. 1988). These leaching losses into stream water are the second output of nutrients from the ecosystem.

The inputs of nutrients to the ecosystem are not as obvious as the cycling of nutrients in vegetation growth, litterfall, and decomposition. The balance of inputs to outputs is the factor that controls nutrient conservation. The input of N is from the atmosphere (in precipitation and dry deposition), and from biological fixation of gaseous N_2 in soil pores, by microbes in the soil or on roots of legumes and other plant species. The atmospheric deposition of N has increased in the Northeast (and other parts of the industrialized world) from emissions caused by burning of fossil fuels in vehicles and production of fertilizers (Driscoll et al. 2003). This annual input has caused some forest sites to reach N saturation, in some cases causing forest decline (Aber et al. 2003). These high levels of N accumulate in the forest floor, and may cause increased leaching into stream water as well. These concerns outweigh those of depletion of N from harvesting. The input of P from atmospheric deposition and weathering of rock is generally sufficient to maintain stocks. P is tightly bound to organic and mineral soil compounds, so it has low leaching rates in forested ecosystems (P levels in streams even after harvesting are often below the level of detection) (Federer et al. 1989). The inputs of the base cation nutrients Ca, Mg, and K are also from atmospheric deposition and chemical weathering of rocks, but they do not form the same kinds of chemical bonds as P, so they can be leached from the soil solution much more readily than P (Mann et al. 1988, Federer et al. 1989, Sverdrup and Rosén 1998).

Of these base cations, Ca has become the nutrient of greatest concern in New England forests (Tritton et al. 1987, Federer et al. 1989), and in other forests as well (Mann et al. 1988). It is often stored in plant biomass in greater concentrations than other nutrients; the accumulation of Ca is high even in stemwood, with particularly high levels in the stemwood of some oak species (Tritton et al. 1987). Ca also may be leached to streams in high concentrations. The high mobility of Ca and the other base cations is affected by acid precipitation (Lawrence et al. 1995). Acid conditions in soil water break the weak ionic bonds that hold the base cations to soil and humus particles, and increase the leaching rates of those nutrients (Hornbeck 1989). In addition, elevated levels of nitrification following harvesting can also promote leaching losses of other soil nutrients (Hornbeck and Kropelin 1982), because the nitrification process increases soil acidity. These processes are the likely causes of undisturbed watersheds showing losses of these cations with little or no loss of N or P (Hornbeck et al. 1990).

Impacts of biomass harvesting on nutrient budgets--experimental results

A study of biomass and nutrient removals in both a whole-tree clearcut and a thinning was conducted in Connecticut in the 1980's (Tritton et al. 1987, Hornbeck 1989, Hornbeck et al. 1990, Federer et al. 1989). This study is of particular interest because it quantifies conditions that are quite similar to those of biomass harvests in Massachusetts. Three adjacent first-order watersheds (stands) were used, each about 16 acres in area. The coarse loamy till soils were shallow on ridgetops, ranging to deep, well-drained soils on lower slopes. The stands were 80 years old, and consisted mainly of oaks (red, black, white, and chestnut), hickories, red maple, black birch, and mountain-laurel. One watershed was left untreated as the reference (control). The second was clearcut with removal of all tree biomass (all trees > 1 inch dbh were cut and were either chipped or removed as sawlogs). The third was commercially thinned, with slash from harvested trees left on site. The harvest was carried out in winter. Precautions were taken during logging to minimize soil erosion and stream sedimentation, by minimizing logging equipment disturbances close to streams. However, no filters were left (i.e., all trees were cut along streams).

Table 8 presents results for biomass and Ca removals for the three watersheds in the Connecticut study. Initial aboveground biomass in the Connecticut study was similar to the average of Massachusetts stands--ranging from 74 to 83 dry tons/acre in the Connecticut stands, compared to the mean value of 70 dry tons/acre from Massachusetts data (see Section 2). The whole-tree clearcut removed 88% of the biomass; the remainder consisted of shrubs and partially decayed coarse woody debris that could not be used. The thinning treatment, which was a stem-only harvest, removed only 10% of stand biomass.

Total ecosystem Ca includes the Ca levels in three components: 1) the Ca incorporated into living and dead plant biomass, 2) the plant-available Ca that is in the forest floor and soil and is in the mobile cation form, and 3) the Ca in the forest floor and soil that is in the form of minerals in rock and till, and therefore is not mobile or available for plant uptake. The Ca that is contained in rock and till fragments can become mobile after being chemically weathered from the rock. In this ecosystem study, the Ca bound in fine fragments in the soil (< 2mm particle size) has been measured and is included in the total ecosystem Ca value. The Ca in gravel, boulders, and bedrock is not counted. When weathering occurs in these larger rocks, the Ca that becomes available is considered a new input to the ecosystem.

The quantity of Ca removed in the harvest of tree biomass is clearly the main output of Ca from the ecosystem. The clearcut also increased losses of nutrients that leach into stream water, because the removal of most vegetation results in a lack of nutrient and water uptake from the soil. These leaching losses were measured for 3 years after the harvest--the period of time when greatest losses occur. There was no increase in leaching losses from the thinning treatment. The total Ca losses for the whole-tree clearcut (both harvest removals and nutrient leaching) amounted to 13% of the total ecosystem Ca; the Ca loss from the thinning treatment was 2% of total Ca (Table 8).

Although the leaching losses are a small portion of the total Ca loss, this portion comes from the soil solution--the fraction that is most readily available for uptake by plant roots. There is some evidence that initial rapid growth of vegetation in the first few years after a whole-tree clearcut may be temporarily limited by a shortage of available nutrients, but this has not been clearly documented (Hornbeck et al. 1990).

Table 8. Results of a Connecticut study of the effects of whole-tree clearcutting and stem-only thinning treatments on calcium (Ca) budgets. In addition, estimates of the Ca budget for a hypothetical thinning with biomass harvest using initial Massachusetts stand data. Recovery period is the length of time without further harvest that is required for the ecosystem to recover the Ca lost in the harvesting.

	Connecticut study results			**Hypothetical Massachusetts stand**
	Reference (uncut)	**Clearcut (whole tree)**	**Thinning (stem-only)**	**Potential thinning**
Biomass (dry tons/acre)				
Pre-cut biomass	83	81	74	70
Harvest removal	0	71	7	35
Loss as % of pre-cut	0	88%	10%	50%
Calcium stocks (kg/ha)				
Plant biomass Ca, pre-cut	825	825	825	825
Plant-available Ca, pre-cut	176	176	176	176
Total ecosystem Ca, pre-cut	4239	4239	4239	4239
Calcium losses (kg/ha)				
Harvest removal	0	530	96	250
Leaching loss for 3 yrs post-cut	0	28	0	~ 0
Total losses	0	558	96	250
Loss as % of total Ca	0	13%	2%	6%
Calcium input rates (kg/ha/yr)				
Atmospheric input	2	2	2	2
Weathering input	1.5	1.5	1.5	1.5
Total inputs	3.5	3.5	3.5	3.5
Recovery period (years)				
Time to return to pre-cut levels of total ecosystem Ca	---	159	27	71

TABLE NOTES:

- The Ca budget is presented in in metric units; the standard nutrient unit for ecosystem studies is kg/ha. These are used only for comparison among values with the same units; percentages are the main values of interest.
- Citations for the Connecticut study: Tritton et al. 1987, Hornbeck 1989, Hornbeck et al. 1990, and Federer et al. 1989.
- Leaching losses to stream water are the differences between treatment and reference watersheds. The loss in the reference watershed was set to zero for this calculation regarding harvest effects, but the actual loss for the reference watershed for the 3 years was 32 kg/ha/yr, and the actual loss for the whole-tree clearcut was 60 kg/ha/yr.

Calcium (Ca) inputs come from two sources. Atmospheric deposition adds 2 (kg/ha)/yr; this input can be measured accurately. Chemical weathering of large rocks and fragments (which makes Ca available for uptake) is difficult to measure; estimates of weathering rates for New England ecosystems are 1.5 (kg/ha)/yr (Federer et al. 1989). This makes it possible to estimate the length of time without additional harvesting that is needed for Ca to recover to pre-cut levels. The site with the thinning treatment will recover in 27 years, but the whole-tree clearcut will take 159 years to recover to the pre-cut Ca level, which is longer that the normal rotation length.

Because the stem-only thinning in the Connecticut study was such a light harvest, a hypothetical thinning was added (Table 8), which was a heavier cut that included biomass harvesting. The hypothetical thinning was described in Section 2 of this report; it involves both crown thinning and low thinning, which includes a partial cut of the sawtimber-size trees, and complete removal of small understory trees. Whole-tree harvest methods for biomass are used for all cut trees except for the sawlog portions of sawtimber trees. The same Ca concentrations in plant biomass in the Connecticut study were used for this hypothetical stand. There was a 50% removal of biomass in the thinning, and 250 kg/ha of the initial 500 kg/ha of Ca were lost in the harvest removals (Table 8). If it is assumed that the hypothetical stand is on the same Connecticut site, the harvest removed 6% of the total Ca. Following this harvest, the Ca site capital would recover to pre-cut levels in 71 years, which is less than the typical rotation length and approximately the time for a first thinning if management is focused on sawtimber.

It should be noted that these calculations of recovery time are based on the replenishment of the Ca removed in the harvested biomass and of the Ca lost in the increased leaching that was caused by the harvest (that is, the leaching loss that was greater than the background leaching loss of the uncut reference watershed). It is important to note that with current conditions of acid precipitation and nitrogen deposition, the leaching output exceeds atmospheric and weathering inputs such that Ca capital has a low but continual net loss in many Northeastern streams, even with no harvesting disturbance (Hornbeck et al. 1990).

Management recommendations regarding nutrient conservation

1. Avoid combining whole-tree removal with clearcutting, especially on sites with low inherent fertility. These include sites with coarse-textured sandy soils, with shallow soils over bedrock, or with moist organic soils. Estimates of the length of time to replenish calcium removed in the harvest are greater than 100 years, even for average sites. Other nutrients (nitrogen, phosphorous, potassium, magnesium) are also removed, but the rapid loss of calcium is of greatest concern. When a large clearcut is planned, stem-only harvesting will result in leaving 20% of the biomass on the site in the form of fine branches, which would also leave a large fraction of nutrients--from 18% (for Ca) to 64% (for P)--on the site, that otherwise would have been removed in the harvest.

2. Reduce the intensity of biomass harvests of stands dominated by oaks. Oak species tend to sequester greater amounts of calcium in their stemwood compared to other species, so calcium is depleted more quickly in harvests of oak stands.

3. Use whole-tree removal biomass harvests with standard silvicultural methods that employ partial harvests (patch selection, shelterwood, thinning). Whole-tree harvests used with partial cutting methods will have smaller ecological effects because they remove a smaller fraction of site nutrients and have smaller leaching losses.

4. Use methods such as shelterwood to establish advance regeneration; established understories will minimize leaching losses during subsequent harvests.

5. Plan intensive harvests to occur in the dormant season after leaves have already fallen. Foliar nutrients will be cycled into forest floor organic matter instead of being removed in the harvest, and will add further to the retention of nutrients described in the first recommendation above.

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4b. Soil physical properties

Impacts of harvesting on soil compaction

Soil physical properties, such as bulk density, porosity, and texture (particle size distribution of sand, silt, and clay), strongly influence patterns of soil water retention, aeration, drainage, and tree root penetration within forest soils (Brady and Weil 1996, Ballard 2000). These soil attributes are a primary control over long-term site productivity. As is the case with conventional harvesting, the effects of biomass harvesting on soil compaction are a function of several factors, including the ground pressure and total load exerted by harvesting equipment, soil type, and harvest season. For example, moist, fine-textured soils are most susceptible to compaction, but frozen soils are generally resistant to changes in structure caused by equipment passes (Braise and Camiré 1998, Ballard 2000). However, even coarse-textured soils increase in bulk density from the ground pressure of harvesting equipment. The glacial till and outwash soils of southern New England are predominantly sandy loams or loamy sands, so they are intermediate in susceptibility to excessive compaction.

Bulk density is a primary measure for determining harvest effects on soils. The greatest changes in bulk density often occur after the first pass of harvesting equipment, but further increases do occur with multiple passes, and additional changes occur, including the collapse of large pores to smaller sizes--thus affecting drainage (Ballard 2000, Armpoorter 2007). One of the most effective means to reduce soil compaction from harvesting equipment is to spread a mat of slash as a covering for harvest trails (McDonald and Seixas 1997, Armpoorter 2007). (This also has the advantage of retaining nutrients on-site.)

These impacts can occur with conventional harvesting, but there are several attributes of biomass harvesting that could potentially lead to greater soil compaction levels. Multiple passes on harvest areas are more likely with combined sawlog and biomass harvests, particularly if different equipment is used to cut sawtimber trees and small understory trees, and this can increase compaction problems (McNabb et al. 2001, Zenner et al. 2007). In addition, the removal of slash for biomass fuel, if carried to an extreme, will reduce the protection that is provided by a ground cover of slash.

New England study of soil disturbance during biomass harvesting

A study of soil disturbance during whole-tree clearcutting was conducted in the Northeast by Pierce and colleagues (1993). There were four study sites, located in Connecticut, New Hampshire, Maine, and Vermont. The Connecticut site was the same that was used in the nutrient cycling study, described previously in Section 4a. Soil condition after the whole-tree clearcut was measured at points along transects throughout the harvest areas. Soil condition was separated into five classes: undisturbed, scarified, exposed mineral soil, compacted, and heavily compacted with ruts > 4 inches deep.

The Connecticut harvest was carried out in winter with feller-bunchers and grapple skidders, but with chainsaw felling on parts of the stand where there were steep slopes. The percent area for the Connecticut harvest for each of the soil conditions was: 28% undisturbed, 8% scarified, 8% exposed mineral soil, 52% compacted, and 4% heavily compacted (rutted). The researchers indicated that the condition of "compacted" was slight to moderate compaction that would probably be alleviated by frost and water action is a few years (Pierce et al. 1993). The heavily compacted (rutted) areas are the areas that would have long-term impacts.

The New Hampshire and Maine sites both had higher proportions of the harvest areas with heavy compaction (26% and 20%, respectively). The New Hampshire site had level topography, so skidder operators could easily access the entire area; the high level of compaction was the result, even though half of the harvest was done with snow cover. The Maine site was a spruce-fir stand with about twice the basal area of the other sites; this would have required more passes of the grapple skidders and forwarders (both were used); the harvest was conducted in summer. These results agree with the principles identified above--that multiple passes throughout a harvest area can cause excessive compaction on a substantial portion of the area.

Management recommendations regarding soil properties

1. Use designated harvest trails for multiple passes to and from landings; protect these trails with a layer of slash, especially in stretches that are likely to be compacted.

2. Use one-pass harvesting systems to limit successive entries on a site, and use equipment with low ground pressures.

3. Restrict biomass harvesting to frozen-ground conditions on susceptible soils (generally on moist, fine-textured soils).

4. Reclaim and restore areas with excessive compaction as needed (remove ruts, prepare a seedbed, and seed with annual rye to quickly establish plant cover, add organic matter, and foster natural regeneration by native plant species).

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4c. Streamflow and water quality

The quality of water in streams that flow from forest ecosystems is of great importance for maintaining the biota of aquatic ecosystems (fish, invertebrates, amphibians, and other organisms) and for protecting public drinking water supplies throughout the region. Undisturbed forests produce water of high quality, but these same forests produce sawtimber, pulpwood, and biomass fuels which require harvest disturbances if they are to be used. This review will deal with questions of how forest harvesting for biomass (such as whole-tree clearcutting or thinning with whole-tree removals) may affect water yields and the movement of sediment and nutrients into streams.

Basics of the hydrologic cycle in forests

A brief description of the hydrologic cycle in an undisturbed forest will be presented, based on de la Cretaz and Barten (2007). The input of water into the forest ecosystem through precipitation is affected by the forest canopy. Some of the precipitation (rain and snow) falls directly to the forest floor through gaps in the canopy, but much of it is intercepted by the foliage. Some of this intercepted water then drips off the branches to the forest floor or flows down branches and stems, but a portion of it is evaporated directly from the canopy--thus never reaching the forest floor. This interception loss occurs year-round for forests dominated by evergreen species, but only during the growing season for deciduous species. Thus, evergreen conifers can reduce total water reaching the forest floor by 20-30%; total interception by deciduous broadleaf species may account for 5-15% of annual precipitation.

When water reaches the forest floor, some may be evaporated directly from the litter layer, but canopy shading limits this direct evaporation. The rest of the precipitation moves into the soil. Even heavy rainfall events and snowmelt rarely exceed the infiltration capacity of undisturbed forest soils. The factors that produce this capacity include the highly permeable layer of litter and humus (decaying organic matter) on the forest floor, the generally stony, coarse-textured soils of New England, and the channels formed by roots of woody plants. Some of the water that flows into the soil profile is stored in fine pores and on the surface of soil particles. Some soil moisture (with dissolved nutrients) is absorbed by plant roots and used in photosynthesis and transpiration by the canopy foliage—this releases water vapor and oxygen to the atmosphere. Water that is not held in the soil or absorbed by plants for transpiration continues to flow vertically down through the soil profile until it reaches bedrock, a dense till layer, or a saturated zone. These impermeable or slowly permeable layers cause lateral subsurface flow at a rate that is influenced by soil properties (hydraulic conductivity) and slope (hydraulic gradient).

However, high infiltration capacity is not always present--where one or more of these conditions exist: compacted soils, fine-textured soils (large proportion of clay or silt), frozen soils, saturated soils (no available storage for "new" water), or lack of protective litter/humus layers. In these cases, some, perhaps all of the rain or snowmelt does not enter the soils, but instead it flows overland. Overland flow causes soil particles to be lifted and carried downslope (that is, it causes surface erosion). These eroded soil particles are now sediment particles that travel downslope along the path of least resistance where they may enter streams and degrade water quality.

The central reason that water quality is high in streams flowing from forests is high infiltration capacity—often exceeding the maximum rainfall intensity or snowmelt rate during extreme hydrologic events. High infiltration capacity enables water to move through the soil matrix as subsurface flow. This water will be free of sediment when it reaches a stream, although it may carry dissolved nutrients. The movement of water is rapid in New England forests because most soils are shallow to bedrock, dense till, or saturated soils. Flows will increase in headwater streams in only minutes or hours during and rainfall or snowmelt events.

Harvesting effects on streamflow

A harvest of any kind will cause a set of changes in the magnitudes of various components of the hydrologic cycle, because of the removal of a portion or all of the trees on the site. A greater amount of precipitation will reach the forest floor because of lower evaporation of intercepted water in the canopy. There will also be greater evaporation from the forest floor. The largest change is likely to be the reduced transpiration of the forest canopy. Any degree of cutting (measured in proportion of basal area removed) will in principle increase streamflow. However, the harvest removal must be at least 20-30% of the stand basal area to cause a streamflow increase that is detectable (Hornbeck et al. 1997). Above that cutting level, increased streamflow begins promptly after cutting, and it increases with increasing proportion of basal area (biomass) that is removed from the watershed. This temporary increase in water yield declines rapidly as the total leaf area and transpiration of forest regeneration approaches the pre-harvest condition (three or more growing seasons).

Comparisons among watersheds with different cutting treatments show the magnitude of streamflow increases (Hornbeck et al. 1997). In this case, three watersheds in the White Mountains of New Hampshire were used. The first was a watershed that had been experimentally deforested (all trees cut and left in place) followed by 3 years of herbicide application to eliminate regrowth. (This was an extreme ecological experiment to determine the maximum change from removing all plants; it was not a simulation of a forest management treatment.) The percent increase in water yield due to the treatment was 41, 29, and 26% during the three years when regrowth was prevented with herbicides, and then 22, 17, and 6% in subsequent years, showing the importance of regrowth in returning the streamflow nearly to pre-treatment levels. The other two watersheds received potential forest management treatments. The whole-tree clearcut harvest had a 23% increase in water yield the first year, but the next two years showed no significant changes due to the treatment. The third treatment was strip cutting, with a total of 1/3 of the watershed area harvested each year for 3 consecutive years. For the 3 years of cutting, the change in streamflow due to cutting was 3, 4, and 8%, and then for three years after the final cut (when 100% of watershed had been cut) these increases were 8, 4, and 9%. This progressive cutting treatment shows that the increase in streamflow was barely detectable when only 1/3 of the stand was cut (only 3% higher after the first year of cutting). Many selection cutting methods remove about 1/3 of the stand basal area, but the interval between harvests is 30 years or more to create an uneven-aged stand. There would likely not be a detectable increase in streamflow with that kind of cutting. A more detailed description of harvesting effects on water yield and water quality in the northeastern U.S. can be found in Chapter 6 of de la Cretaz and Barten (2007).

Harvesting effects on water quality--sedimentation

New England forests generally have very low erosion (sediment production) rates because of their high infiltration capacity. In undisturbed forests, the soil and stream channel erosion that does occur is from low-frequency events when high intensity rainfall, rapid snowmelt, or rain-on-snow events occur during the dormant season. Sediment production and transport occurs along with overland flow. The greatest impacts of harvesting on sedimentation occur if truck roads and skid trails create these overland flows. In the whole-tree clearcutting experiment in New Hampshire (discussed above), 96% of the biomass was removed and 70% of forest floor was disturbed in the harvest. However, there were restrictions on the slopes of roads and skid trails, and filter strips were retained along the streams. Sediment loads were elevated for 3 years after the harvest, but returned to mean pre-cut levels after that (Martin and Hornbeck 1994). In only 1 of those 3 years did the sediment level substantially exceed the maximum levels during the pre-harvest measurement period. In another study of sedimentation and harvesting (Pierce et al. 1993), turbidity measurements were taken in streams at the base of the watersheds of 3 whole-tree clearcuts located in Maine, New Hampshire, and Connecticut. Nearly all measurements were below the EPA standard for drinking water except for very high values at the New Hampshire site that coincided with the failure of a culvert on a skid road.

These and other studies (summarized in de la Cretaz and Barten 2007) indicate that after heavy cutting that includes streamside vegetation the volume and velocity of streamflow increases. This leads to channel erosion and substantial increases in sediment transport. Riparian forest buffers along streams provide root support that helps to stabilize stream banks (especially during stormflow events) and adds coarse woody debris that protects the channel.

The influence of forest roads, landings, and skid trails or forwarder roads on water movement, surface erosion, and sediment transport can be substantial or negligible. Due diligence with road and skid trail layout coupled with proactive stormwater management can minimize adverse effects. Limiting the total length of roads and trails, avoiding sensitive areas (e.g., wetlands, vernal pools, fine-textured soils, steep slopes, etc.), and minimizing the number of stream crossings are important first steps. Dispersing stormwater off road surfaces by maintaining a centerline "crown" and removing ruts that channel flow limits the generation and transport of sediment (and adsorbed nutrients) to acceptable levels. Diverting stormwater on to undisturbed (high infiltration capacity) soil in adjacent forest before it enters streams or wetlands at road crossings eliminates the most significant component of nonpoint source pollution.

Harvesting effects on water quality--nutrients

Nutrient export through streamflow was described in Section 4a; it dealt with nutrient conservation for maintaining forest site productivity. However, high nutrient exports (especially nitrogen in nitrate form) can also increase algal and other plant productivity in streams, ponds, and lakes, leading to eutrophication and degradation of those ecosystems. In addition, the U.S. drinking water standard for nitrate concentrations is 10 mg/L, so limiting nutrient export concentrations is important for public drinking water supplies.

In contrast to sediments, dissolved nutrients can be transported to streams via subsurface flows. This movement may be increased after harvest because of reduced uptake of water and nutrients. The leaching of nutrients is generally very low in undisturbed forests. A group of watersheds in New Hampshire were studied to determine whether harvesting elevates the nutrient concentrations in stream water. Three watersheds had the following treatments: 1) clearcut with no filter (riparian forest buffer) strips retained along streams; 2) clearcut with 60-ft-wide strips streams, reducing the area cut to 70% of the total stand; 3) strip cuts with 33% of the stand cut each year for 3 consecutive years, and with filter strips as described above (Martin and Pierce 1980). The stream water concentrations of the two most mobile nutrients--nitrate and calcium--were measured for each watershed for 2 to 4 years after the harvest. Mean concentrations (in mg/L or parts per million, ppm) were determined for each year, and concentrations for the year with maximum levels are reported below for each watershed. Untreated reference watersheds had stream water concentrations of 2 for nitrate and 2 for calcium. The clearcut stand with no filter strips had maximum concentrations of 18 for nitrate and 4 for calcium. Concentrations were lower for the clearcut with filter strips, with 9 for nitrate and 3 for calcium. These results show the importance of the filter strip in having established vegetation to take up nutrients from soil solution (in subsurface flows), preventing those nutrients from entering the stream. The watershed with the progressive strip cuts had concentrations of 6 for nitrate and 2 for calcium; each of the cut strips was revegetated by the time the next strips were cut the next year, so nutrients were lost mainly from only 1/3 of the harvest area at any time. The nutrient loss after the first-year cutting had concentrations of 4 for nitrate and 2 for calcium, barely detectable above the reference watershed concentrations. This indicates that partial cuts with long cutting cycles (a common occurrence in Massachusetts stands) will likely produce nutrient losses that are barely detectable.

Similar harvesting studies of nutrient leaching have been carried out across the United States. Binkley (2001) reviewed the results of 43 such studies for harvesting effects on nitrate concentrations in stream water. Of these, 30 studies showed nitrate increases in stream water, but only 4 had nitrate levels greater that 0.5 mg/L (de la Cretaz and Barten 2007). Some of the best-known watershed studies have been done in the White Mountains of New Hampshire--on or near to the Hubbard Brook Experimental Forest (including the study described above). It appears that those sites, with sandy. podzolic soils on sites that are shallow to bedrock, have unusually high rates of nutrient leaching. The untreated reference watersheds in the Hubbard Brook studies had higher nitrate concentrations in streams than most of the harvested watersheds in other regions. However, the relative changes in stream water concentrations with varying harvesting treatments are expected to be similar for those watersheds, so the principles of reducing nutrient loss with riparian forest buffers and reduced cutting areas would hold.

Management recommendations regarding streamflow and water quality

These studies of stream water quantity and quality show that there are harvesting practices that can limit sedimentation and nutrient export, even when the harvest removes enough forest cover to increase total water yield (i.e., increasing streamflow quantity). These practices have been assembled into Best Management Practices (BMPs) in many states. Their application to harvests is mandatory in some states, and voluntary in others (de la Cretaz and Barten 2007). The main factors in BMPs for controlling sedimentation are: 1) planning and constructing truck roads and trails by limiting steep slopes, installing water control structures, keeping roads away from streams where possible, and using appropriate stream crossings; 2) retaining riparian forest buffer strips along streams to trap sediments moving in overland flow, and to stabilize stream banks and channel with the living roots and coarse woody debris that falls into the stream. The main factor in BMPs for limiting the export of nutrients to streams is maintain adequate riparian forest buffer strips along streams to take up nutrients moving in either overland or subsurface flow. Another factor not explicitly in BMPs but important to reduce nutrient losses is reducing the proportion of land area or basal area to be harvested within the watershed in order to maintain active uptake of water and nutrients throughout the stand, rather than relying solely on the stream buffer.

Details of forest harvesting BMPs are available for many states. A review of BMPs throughout the U.S. is available in de la Cretaz and Barten (2007). Massachusetts BMPs are contained in the Massachusetts Forest Cutting Practices regulations (Kittredge and Parker 1996). The US Forest Service Northeastern Area and several states (including Massachusetts) have recently completed a performance-based BMP monitoring protocol. Along with other design and implementation resources, this protocol can be used to maximize the effectiveness of BMPs to protect water quality and aquatic ecosystems (http://www.na.fs.fed.us/watershed/bmp.shtm).

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4d. Carbon cycling and storage

Carbon dynamics in forest ecosystems

Forests represent the primary terrestrial carbon sink, storing over 80% of global terrestrial aboveground carbon (Dixon et al. 1994). Over the course of stand development, carbon is fixed from the atmosphere through the photosynthesis of forest vegetation and is stored in these ecosystem components: living biomass, dead woody biomass (coarse woody debris), forest floor organic matter (from foliage and twig litterfall), and soil organic matter (from root decomposition and dissolved organic matter) (Pregitzer and Euskirchen 2004). Overall, the amount of carbon fixed by a given forest ecosystem and stored in organic matter is related to forest net primary productivity (NPP). NPP is defined as gross (total) plant photosynthesis minus plant respiration. Thus, annual rates of NPP include all plant matter produced in a year (foliage, fine roots, woody stems and branches, and woody roots); mortality of whole trees or of parts (branches, leaves, roots) is not subtracted. Net ecosystem productivity (NEP) is defined as gross (total) photosynthesis minus total ecosystem respiration (Janisch and Harmon 2002). Ecosystem respiration includes the respiration of microbes, insects, and all other fauna that consume and decompose biomass. Thus, annual rates of NEP include all plant matter produced in a year *minus* all decomposition in that year.

NPP measurements are useful for understanding the pattern of carbon sequestration over time. However, the ultimate measure of carbon sequestration rate is NEP, because it is the balance of carbon input through biomass production to carbon output through biomass decomposition. When photosynthetic rates are greater than ecosystem respiration rates (i.e., NEP is positive), biomass accumulates, and the forest ecosystem is considered to be a carbon sink. A forest ecosystem is considered to be a carbon source when respiration exceeds photosynthesis and there is a net flux (loss) of carbon dioxide from the ecosystem (Dixon et al. 1994).

The pattern of carbon storage (sequestration) over the period of stand development is of great interest for planning forest management. A world-wide review and analysis of field studies of carbon cycling and storage (Pregitzer and Euskirchen 2004) determined average rates of NPP and NEP over stand ages from just after a stand-replacing disturbance to old-growth status. This review grouped forest studies into three biomes: boreal, temperate, and tropical, and grouped stand ages into five age classes: 0-10, 11-30, 31-70, 71-120, 121-200 years. The graphs in Figure 3 show the trends in NPP and NEP for temperate forests, as presented in this review. The growth trend in NPP shows an increase from 0-10 years to 11-30 years, and then a gradual decline with increasing stand age. The initial rise in growth is related to canopy closure. During the establishment phase (the first 10 years) the stand has an open canopy, so maximum biomass growth rates have not yet been attained. When the canopy is fully closed (age class 11-30 years), the maximum rates occur. Then a gradual decline in growth occurs with increasing age. This pattern of decline is well documented, although the causes and mechanisms are not fully understood.

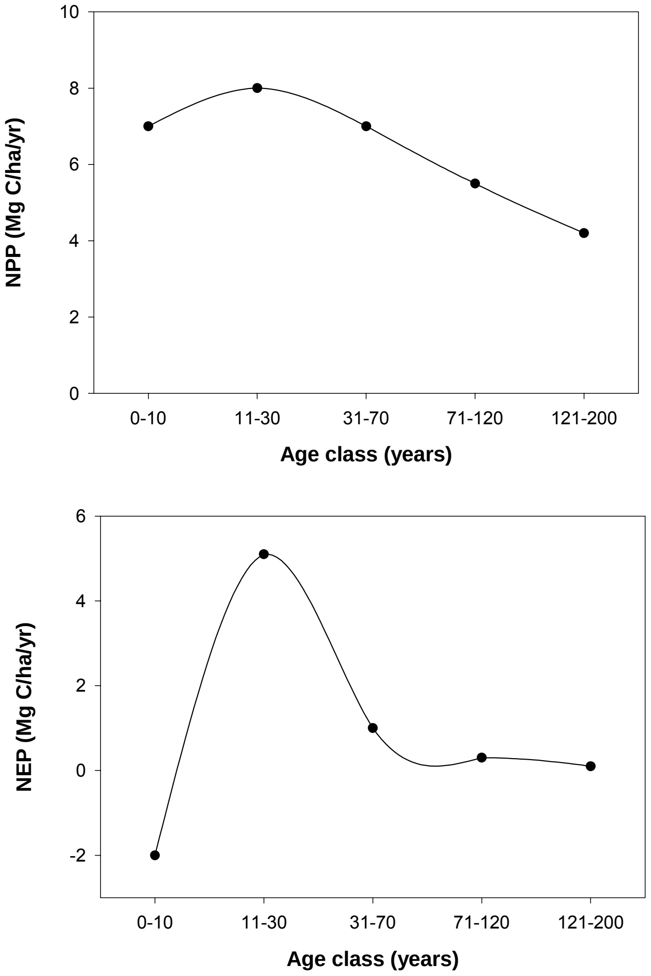

Figure 3. Patterns of net primary productivity (NPP) and net ecosystem productivity (NEP) over time, beginning with a stand-replacing disturbance at age 0 and progressing to old-growth status. The values are averages from many field studies in the temperate zone, based on the review of Pregitzer and Euskirchen (2004).

Some of the hypotheses for explaining this decline are: 1) canopy density is reduced as trees grow taller and sway in the wind; this causes breakage of fine twigs, leading to gaps between crowns and causing the total leaf area to decline; 2) nutrients become stored in woody portions of living biomass, reducing the nutrients available for leaf function; 3) stand structure containing dominant and suppressed trees is not as efficient in biomass production as the structure of younger stands with a single canopy layer of trees of relatively uniform crown size; 4) plant maintenance respiration rates increase as trees grow larger, but photosynthesis remains constant (Ryan et al. 1997).

The NEP trend (Figure 3) shows young forests (0-10 years) as carbon sources (having negative NEP), as ecosystem respiration rates exceed primary production in these systems (Pregitzer and Euskirchen 2004). This results from the forest canopy being partially open, which reduces total photosynthetic rate and increases the rate of decomposition of forest floor and coarse woody debris (the increased decomposition is caused by warmer temperatures and increased moisture because of reduced evapotranspiration). In contrast, forests in the 11-30 year age class (young closed-canopy stands) have the highest net rates of carbon fixation (with high NPP and lowered decomposition rates). Intermediate-aged (30-120 years) and older (120-200 years) forests then show gradually declining NEP values. The decline in NPP (described above) and the decomposition of dead trees reduce the total ecosystem carbon fixation of these older stands, but they still act as carbon sinks. However, the question of whether old-growth forests act as carbon sinks or sources (or are neutral) has not been resolved (Ryan et al. 1997, Suchanek et al. 2004). Climatic fluctuations make this difficult to determine; old-growth stands can shift from sinks to sources from year to year as temperature and rainfall vary. Long-term data are needed to determine the net status of carbon sequestration.

This description of NPP and NEP trends (which represent annual rates of carbon balance) should not be confused with the change in the total amount of carbon stored in a stand over time. Total carbon stocks in temperate forests over the age classes described above show a steady increase after the 0-10 year establishment stage. The mean values for temperate forests (including all ecosystem components described earlier) range from about 100 Mg C/ha in the 0-10 year stage to 500 Mg C/ha at 121-200 year stage (Pregitzer and Euskirchen 2004). These units are metric tons of carbon. An approximate conversion to English units of biomass would give a range of 90 to 450 dry tons/acre of total ecosystem biomass over that time period. Of that total biomass, the living plant biomass portion ranges from 35 dry tons/acre in the 0-10 year age class to 115 to 350 dry tons/acre in the 121-200 year age class (there was great variability in biomass levels in this oldest age class). This overall pattern from a world-wide review is also shown directly in Northeastern stands, where the size of forest ecosystem carbon pools have been found to generally increase with stand age (Curtis et al. 2002, Hooker and Compton 2003, Yanai et al. 2003).

Forest management impacts on carbon cycling and storage

The general pattern of stand growth measured in terms of NPP relates directly to ideas of forest management. A basic management method for analyzing growth rates and stand rotation lengths involves current annual increment (CAI) and mean annual increment (MAI). CAI and NPP are both current annual stand growth rates. They differ in that NPP measures all growth above and below ground. CAI measures growth in biomass (or timber volume), subtracts tree mortality, and includes only aboveground growth, but the general pattern of growth is similar to NPP. MAI is defined as the mean annual growth rate over the total age of the stand. The units for measuring CAI and MAI can be for any forest product (i.e., tons, board feet, cubic meters, etc.). If the units are for biomass ([tons/acre]/year), the peak in CAI will occur at a young stand age--close to the age when NPP would peak (Figure 4). The CAI peak (and the MAI peak) would be shifted to older ages if measurements were in total wood volume ([ft^3/acre]/year) or in sawn lumber ([board feet/acre]/year).

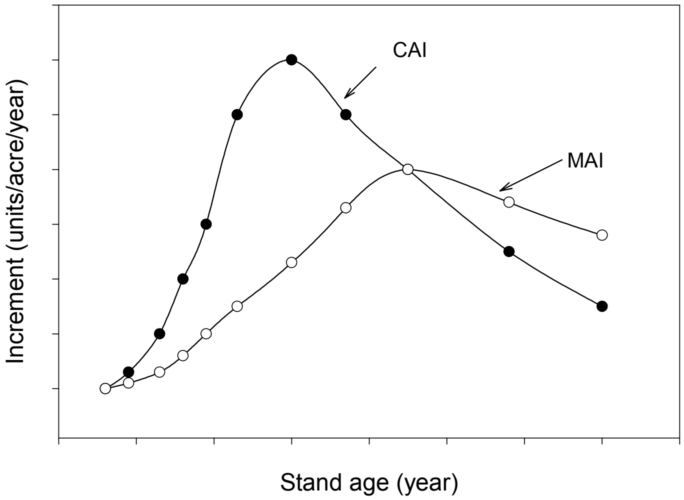

Figure 4. Generalized graph of current annual increment (CAI) and mean annual increment (MAI) to determine the rotation age (peak of MAI curve) that will give the maximum yield. Units can be biomass ([tons/acre]/year) or volume ([ft^3/acre]/year) or other.

The peak of MAI identifies the age at which the stand should be harvested and regenerated in order to maximize total wood yield from the stand over multiple rotations. This principle has guided intensive management of woody biomass production. The key to maximizing biomass yield is to achieve closed canopies very quickly, and then harvest at the peak of MAI. The main species that have been chosen for intensive biomass production have rapid juvenile growth and are prolific stump-sprouters (green ash, sycamore, willow, sweetgum) or root sprouters (aspen, cottonwood, hybrid poplar). Once the root stocks are established, some of these plantations reach closed-canopy status in 2-3 years, with MAI peaking at 10 years or less. The best known study of short-rotation biomass crops in the Northeast is at the State University of New York at Syracuse (Volk et al. 2004). These experimental plantations use willow species that are grown at high density to achieve canopy closure and high growth rates quickly; the rotation age is 3 or 4 years. A key management step is to harvest after leaf fall in the autumn in order to return foliar nutrients to the soil. Even with that practice, it is still necessary to add N to replace the nutrients removed in the harvest (Volk et al. 2004); other short-rotation systems must fertilize with other nutrients as well (Ranger and Nys 1996).

When managing stands on more traditional rotation lengths for sawtimber production, thinning (control of stand density) is the main treatment of interest for obtaining biomass fuels. The basic silvicultural principle relating to the effect of thinning on growth rates (Smith et al. 1997) is that thinning cannot increase the total stand growth. The main purposes of thinning are: 1) to increase the growth rate of individual trees in order to move them into larger sizes and therefore greater values as sawtimber trees; 2) to salvage trees that are likely to die from competition, and turn that portion of growth into usable yield rather than leave it to become coarse woody debris. The earliest form of thinning (low thinning) was designed only to meet the second goal--to cut only the overtopped and intermediate trees, without having much effect on the growth of the larger trees. The purpose was to assure that all biomass in the stand was used for a product (older textbooks referred to this as "salvaging mortality"). With this kind of thinning, the canopy gaps produced by the harvest are small, and the canopy would close in just a few years. Thus, the growth rate would be maintained nearly constant (Savill and Evans 1986). If stands in Massachusetts were managed using light to moderate thinning in this way, the result would be to 1) decrease the total carbon stored in the stand in the removal of wood products , 2) leave the future rate of carbon sequestration in the stand unaffected, and 3) increase the total biomass yield from the stand (a combination of the trees in the residual stand and the biomass fuels and lumber products). The increase in total carbon sequestration occurs because natural tree mortality has been reduced or eliminated by giving more growing space to the trees left in the stand. Thus, dead trees are not decomposing, releasing carbon dioxide. Instead, they are forest products that are either being stored for long periods as furniture or construction lumber or being burned for electricity production, substituting for burning of fossil fuels.

Species effects on carbon sequestration rates

Differences among species in biomass growth rates can be affected by foliage retention (evergreen vs. deciduous) or tolerance level (shade-intolerant vs. shade-tolerant). Evergreen species would be expected to have greater annual production rates because the retention of foliage creates the potential for a longer growing season compared to deciduous species. This is true in some situations. The highest biomass growth rates reported in the temperate zone are for evergreen species growing in wet, mild, maritime climates, which can have nearly 12-month growing seasons. One of the highest growth rates measured was in a young stand of western hemlock and Sitka spruce on the Oregon coast, which produced 14 (tons/acre)/year (Fujimori 1971). Similarly rapid rates are found with conifer species in Great Britain and Ireland. However, in climates that occur in New England (and much of the temperate zone), there is a distinct shift to a cold season that causes evergreen tree species to become dormant for much of the same period that deciduous species are leafless. Conifer species generally produce greater basal area and stemwood volume per acre than hardwood species, but conifer wood generally has lower density than hardwoods, so the comparison of conifers and hardwoods is more similar for biomass than for volume. There appears to be no consistent trend between evergreen and deciduous species in biomass production (e.g., Alban et al. 1978).

Shade-tolerant species (such as beech and hemlock) produce canopies that have greater density (higher leaf area index) than shade-intolerant species (such as paper birch and red pine). The shade-tolerant species have greater biomass growth rates than intolerants, if the species are compared with fully closed canopies (Smith et al. 1997). However, shade-tolerant species have much slower initial growth in the establishment stage, so a fully closed canopy is produced at a later age. For most purposes of management for biomass, management decisions favor rapid development of a closed canopy to attain high growth rates sooner, even though the production rate at full canopy may be lower. Most studies of species-related growth rates are conducted with pure (single-species) stands to reduce the variables involved. However, mixed-species stands with stratified canopies of intolerant species growing above tolerant species have been shown to have higher stand growth rates than single-species stands of the component species (Assmann 1970, Kelty 1989).

It is difficult to determine trends in biomass growth rates among species because it is unusual to find a range of species growing on the same site. The study by Alban et al. (1978) is one example where a comparison could be made of stands of 3 conifers and 1 hardwood species on a single site. But even that experimental design does not answer an important question: what is the maximum growth rate of each species growing on the site to which it is best adapted? A stand growing on land with a high site index for that species will have greater biomass growth than on land with a low site index (that is essentially the definition of the site index concept). The matching of a species with an appropriate site is a key part of attaining high growth rates.

Management recommendations regarding carbon cycling and storage

Removal of biomass (carbon) from the forest to use as fuel directly competes with the function of the forest as a carbon sink. Biomass harvesting will have negative impacts on forest carbon storage, largely through the removal and combustion of carbon stores from the harvested site. These harvests not only remove carbon stored in living biomass, but also limit the development of large standing dead trees and downed logs, which are important forest carbon sinks. An additional negative impact comes from the removal of harvest residues from the site. These residues are important for maintaining post-harvest forest floor carbon pools and their removal could lead to reductions in soil carbon sinks (Yanai et al. 2003). Finally, the combustion of fossil fuels by biomass harvesting equipment increases the levels of CO_2 emissions at a given site, potentially impacting the carbon neutrality of biomass harvests (Eriksson et al. 2007). Ideally, biomass harvesting will generate an overall positive impact on carbon cycling patterns (at the regional or global scale, rather than the stand scale) if biofuels derived from woody biomass are substituted for fossil fuels (Dixon et al. 1994). The practices to maximize carbon storage include the following:

1. Ensure that the stand that develops following a biomass harvest has high biomass growth rates, so that carbon sequestration begins promptly on that site. This means that the practices outlined in previous sections for nutrient conservation and protection of soil physical properties during harvests are critical in order to maintain high site productivity, which, in turn, leads to high carbon storage.

2. When choosing tree species to favor in regenerating a stand, it is more important to match species to appropriate sites, than to choose species with high biomass growth rates to promote on all sites. Of the species that are well-adapted to a given site, the most productive stand structure is to have shade-intolerant species growing above a lower canopy of shade-tolerant species.

3. In the future, intensive management of woody biomass crops on short rotations may be economical. In that case, the choice of appropriate high-biomass-producing species is critical, and the site may be amended for that species in an agricultural approach. However, not all intensive management for biomass is in agricultural-like systems; forest-like systems such as aspen stands are an intermediate step.

4. With conventional forest stands, leaving the stand unharvested will build up the greatest carbon stores on that site. However, thinning the stand and using the forest products for long-lived products (e.g., lumber or plywood) will sequester more carbon in total (the combination of living trees sequestering new carbon in the stand and lumber in use as part of a house (not decomposing in the forest). A series of moderate thinnings in a stand to provide long-lived wood products will provide the highest level of carbon storage.

5. Substitute biofuels for fossil fuels in harvesting equipment when possible.

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4e. Wildlife habitat

Components of wildlife habitats

Maintaining native biological diversity is an important part of forest management that strives for ecological sustainability. Harvesting of any kind will alter forest structure and may alter composition as well, thus changing the habitat conditions for animals, plants, fungi, and other organisms. There is not a specific forest condition that is "good habitat." Each forest condition provides habitat for a particular set of species. Biomass harvesting will have differential effects on forest wildlife depending on the habitat requirements of each species or suite of species (Cook et al. 1991). Forest structure refers to a set of vegetation elements (live trees, standing dead trees (snags), down dead wood > 4 inches diameter (coarse woody debris), down dead wood ≤ 4 inches diameter (fine woody debris), and low woody vegetation (shrubs, herbs, tree seedlings and sprouts). The numbers, sizes, and spatial distribution of these habitat elements create the structure of the habitat. Plant species composition also contributes to the habitat quality; for example there are critical food sources (nuts or fruits) that are produced by specific mast-bearing tree species; also, winter cover can be provided only by evergreen species such as hemlock, pine, cedar, and spruce.

Forest habitats are frequently classified by stand age, such as these four stages: 1) early successional forest (seedling/sapling stage); 2) intermediate-aged forest (pole stage); 3) mature forest (sawtimber stage); 4) old-growth forest. Because of the history of heavy forest cutting 70-100 years ago in southern New England, Massachusetts forests are now predominantly in the mature forest stage (72% of forestland is defined as sawtimber stands; Alerich 2000). The habitat stages that are the least common in Massachusetts are early successional and old-growth forests.

This review will describe the changes in habitat conditions and wildlife species occurrence that occur for the types of silviculture that may be used for biomass harvests--whole-tree clearcuts and overstory thinning with removal of small trees.

Habitats created by clearcutting

Stands that have been recently clearcut are characterized by the low, woody vegetation of early successional habitat, including shrubs, tree regeneration, and herbaceous plant species. Several mammal species are positively associated with the abundant browse from shrubs and tree seedlings present in these forests, including beaver, moose, and deer (DeGraaf and Yamasaki 2001, Potvin et al. 2005a). A landscape of regenerating clearcuts has been identified as important foraging habitat, with moose and deer browsing on the tender leaves, twigs, and bark of deciduous trees and hemlock. When located near water sources, the increased food base of early successional habitats is also beneficial for beaver who feed on young hardwoods (Thompson 1988, DeGraaf and Yamasaki 2001).

Early successional habitat is also utilized by many small mammal species (Potvin et al. 1999, Constantine et al. 2004, Potvin and Bertrand 2004). Some mammals are dependent on this habitat. For example, the range of the New England cottontail has recently been reduced to only 14% of its historical distribution, with forest maturation thought to be the leading cause in the species decline (Litvaitis et al. 2006a). Increased creation of early successional habitat has been recommended as a method to ensure the long-term viability of this species as well as other species that extensively utilize this habitat (Litvaitis et al. 2006a, Tash and Litvaitis 2007). Some carnivores are also dependent on early successional habitats owing to their dependence on small mammal prey. Decreasing bobcat populations in New England coincided with maturing forests that no longer supported abundant small mammal prey (Litvaitis et al 2006b). Raptors also use early successional areas for hunting small mammals. Other mammal species such as the red squirrel, northern flying squirrel, and eastern chipmunk appear largely undisturbed by clearcuts, retaining high population levels in early successional vegetation but continuing to utilize the habitat as it matures (Potvin et al. 1999, Potvin and Bertrand 2004).

A large number of bird species also require shrubland habitat provided by clearcuts (Titterington et al. 1979, Fink et al. 2006, Wallendorf et al 2007). The lack of clearcuts in the region has resulted in the decline of many bird species that are dependent on early successional habitats (Hunter et al. 2001). Generalist species such as the American robin and the ruffed grouse are associated with open landscapes (Drolet et al. 1999, Endrulat et al. 2005). Shrubland species such as the blue-winged warbler, the Eastern towhee, the field sparrow, the yellow-breasted chat, and the chestnut-sided warbler are abundant in openings with low vegetation and few trees, independent of the size of the opening (Krementz and Christie 2000, Fink et al. 2006, Askins et al. 2007). In addition to these shrubland specialists, Potvin and Bertrand (2004) found that a large number of the bird species that were present in uncut forest also utilized the clearcut landscape, and sometimes occurred at higher densities with this mixture of habitats across the landscape. For those species that are dependent on shrubland habitat, succession necessitates the continual creation of new, open areas (Askins et al. 2007), as the tree regeneration matures into the pole-sized stage, with the canopy shade eliminating the low vegetation.

Although some bird species depend on clearcut landscapes, others cannot use these kinds of habitat. Species such as the Acadian flycatcher, ovenbird, solitary vireo, worm-eating warbler, and bay-breasted warbler were found to be significantly affected by clearcutting (Potvin and Bertrand 2004), with occurrence negatively correlated to increased amounts of open area (Drolet et al. 1999). The density of these species decreased after clearcutting (Wallendorf et al. 2007, Drolet et al. 1999).

For the bird, mammal, and other species that do benefit from early successional habitat, whole-tree removal of biomass during clearcutting does not provide ideal habitat.

An open area with little or no coarse or fine woody debris on the ground does not provide habitat for many species. Dense vegetation will develop within 5 years, but even then, the species that use the habitat may be limited. The silvicultural regeneration method that is recommended for creating early successional habitat in New England (Scanlon et al. 2000) is "clearcut with reserves" (also called "aggregate retention harvest", or "clearcut with structural retention"). In this method, a standard clearcut is modified by retaining forest patches that are representative of the mature forest in various shapes and sizes. In total, 10 to 20% of existing forest cover is retained in clusters of live trees and snags. The retention of patches that contain a combination of large live trees, cavity trees, understory shrubs and downed logs are prioritized. Aggregate retention harvesting has been shown to maintain the abundance of cavity nesters such as woodpeckers (Gunn and Hagan, 2000) and also provides microhabitats for various amphibians (Dupuis et al. 1995). It is also important to retain down woody debris both in and out of the patches, as it provides habitat for 30% of the small mammal species, 45% of amphibians, and 50% of reptiles native to the region (DeGraaf et al. 1992).

Habitats created by overstory thinning with small tree removal

The silvicultural treatment of overstory thinning with complete removal of all small trees for biomass has not been a common practice. Consequently, wildlife research on this kind of habitat has not been conducted. However, a silvicultural method similar to this technique is shelterwood cutting, in which a first cut removes 50-70% of the canopy and all or most of the sapling and pole trees (Smith et al. 1997). The rest of the canopy is left for 10-30 years in order to shade and protect the regenerating stand; the shelterwood overstory is eventually removed completely (or reserve trees or patches are retained, as for clearcuts) to release the established regeneration. Using the available literature on shelterwood cuts and wildlife habitat preferences, we can infer the potential effects of this shelterwood or thinning method for biomass harvesting.

Several years after the first shelterwood cut, dense tree and shrub regeneration will have become established and will provide an important food source for deer and moose. The combination of browse and a partial canopy overhead (which provides thermal cover and reduced snow depths) makes it particularly good winter habitat (Kelty and Nyland 1983).

Comparisons between clearcutting and partial cutting (shelterwood) have shown that changes in bird communities are most likely driven by changes in the vegetative structure (Webb et al. 1977, Freedman et al. 1981, Annand and Thompson 1997, Hagan et al. 1997). These vegetative changes may impact foraging and nesting habitat (King and DeGraaf 2000). Some bird species require mature closed-canopy forests, and they nest at different heights in the vegetation, from ground and shrub levels up to the canopy; they also forage for insects and fruits throughout the vegetation. When the canopy is thinned, changes in the habitat suitability for these species occur. Canopy dwellers may exhibit reduced foraging efficiency when canopy trees are thinned, simply because there are too few trees. Additionally, increased light penetration to lower levels in the forest may reduce suitable nesting habitat for ground and shrub-dwelling species (King and DeGraaf, 2000). The species that cannot maintain populations in the shelterwood structural habitat are referred to as mature forest specialists (such as the brown creeper, and other species mentioned above), just as there are early successional specialists (such as the alder flycatcher) that require the post-clearcut shrubby vegetation.

However, several studies have shown that shelterwood cutting provides habitat for many species that include both early-successional and mature forest birds that are not strict specialists for their preferred habitat (King and DeGraaf 2000, Webb et al. 1977, DeGraaf et al. 1991, Annand and Thompson 1997). That is, some species that are found mostly in either young vegetation or mature forests, can take advantage of the structure that contains both a thinned forest canopy in the overstory and dense low vegetation in the understory. As with clearcutting, the habitat provided by shelterwood and thinning will provide for many more wildlife species if the structural elements of snags, cavity trees, and coarse and fine woody debris are retained as part of the shelterwood or thinned stand.

Management recommendations regarding wildlife habitat

1. Whole-tree clearcutting creates open areas that will regenerate to dense brushy vegetation within 5 years, and this provides habitat for some wildlife species. However, modifying harvest methods to use clearcutting with reserves (or aggregate retention harvest) that retains 10-20% of stand area in intact patches, and leaves coarse woody debris on the ground will provide habitat for larger populations of many more species.

2. Thinning (or shelterwood) with removal of small trees will lead to regeneration of the understory, and will provide habitat for many animal species that are not habitat specialists for either early successional structure or mature forest structure; these species can use the structure of a thinned canopy with dense understory. However, some species require the early successional structure with little or no overstory, and others require closed-canopy structure that is managed with single-tree selection or no cutting at all.

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4f. Forest fire risk

Forest fuels and treatments for reduction

Fuel-reduction treatments are standard practice for reducing the probability of wildfire in forests. Biomass harvesting removes more woody biomass from a stand than a conventional sawtimber harvesting does, so it may serve to reduce fire danger in stands that are prone to burning. The types of fuels that are most important with regard to biomass harvesting and fire are: 1) fine surface fuels (leaves, needles, and small-diameter branches on the forest floor or in slash piles), which cause the initial spread of nearly all forest fires; 2) ladder fuels (small trees, especially those that retain dead branches on lower stems or have flammable live crowns), which spread surface fires up into the canopy; 3) crown fuels (branches, leaves, and needles, both live and dead, in the crowns of overstory trees) which can form the most intense type of fire because of the large amount of fuels in a non-compact structure (Brown and Davis 1973). However, the importance of each kind of fuel differs among forest types and climates. The standard treatment to reduce surface fuels has been to use prescribed fire (i.e., controlled burning).

Many conifer forests in the western United States in regions with dry summers are highly flammable. Decades of successful suppression of wildfires in these forests has resulted in the buildup of all of these fuel types. Fuels are now so plentiful that prescribed fire is too dangerous to use in many stands, because it may turn into an uncontrollable wildfire. An alternative method is to thin these stands, removing whole trees (including branches and upper stem) to extract these ladder fuels, without adding new surface fuels. This has led to a major U.S. Forest Service management program, "The Healthy Forest Initiative". In addition, a U.S. Forest Service research project (The Fire and Fire Surrogate Project) has been established on 13 sites across the U.S. (Youngblood et al. 2005). Its goal is to compare prescribed fire, thinning, and the combination of the two, for fuel reduction in a range of forest types and climates. (Prescribed fire is so common for fuels reduction in the West that thinning is referred to as a "fire surrogate".) One problem with the implementation of thinning for fuel reduction is that only the smaller trees are removed, and this is expensive because of the poor markets. The existence of a biomass fuels market would be beneficial.

Fire risk in Massachusetts forests

Most forests in Massachusetts are not subject to fires of high frequency *or* high intensity. With regard to fire behavior, the forests of the region can be classified into the following types: *northern hardwoods* (sugar maple, beech, birch); *transition hardwoods* (dominated by red, black, white, and other oak species, with hickory, red maple, birch); *pine-oak* (pitch pine, white pine and dry-site oaks, including scarlet, black, and scrub oaks). The two hardwood types may also contain white pine and/or hemlock.

The two hardwood-dominated types generally have a low risk of fire. With northern hardwoods, the leaves of the main species are thin and decompose readily, so they have lower accumulation rates than other types. They also tend to mat down on the forest floor; this compaction does not allow oxygen to mix with the fine fuels, so it also reduces fire risk. In addition, dead branches on the lower stems of hardwoods decompose rapidly and fall to the ground, so the small trees do not act as ladder fuels. And finally, the live canopy of hardwood stands ordinarily do not carry a fire, because of the high moisture content of the leaves, and the high air humidity caused by transpiration of the trees. In contrast to the western U.S. where annual precipitation occurs mainly as snow during the dormant season, eastern temperate forests receive rain and snow in relatively consistent (and larger) amounts throughout the year.

In the transition hardwood stands with a large component of oak, much of the same pattern occurs, but there is an important difference in the structure of oak leaves. They are thicker than leaves of the northern hardwood species, and as they dry, they tend to curl up rather than form a compact mat on the forest floor (Brown and Davis 1973). This increases the risk of fires starting in these surface fuels, but this forest type still does not have high fire risk--largely due to the climate.

In both types of hardwood stands, there are two periods of each year when fire danger is greatest: 1) in the spring, after snow is gone but before the growing season has begun (typically late-March through early-May); 2) in the autumn, after leaf fall. In both periods, the lack of an overstory canopy exposes surface fuels to wind and sun. But for most of the year there is either canopy shade or cold air temperatures, and precipitation occurs rather uniformly throughout the year. The historical record suggests that Native Americans took advantage of the fire weather in these two periods. They would burn hardwood stands to create hunting areas with open canopies with sparse understories; this led to shifting northern hardwood stands to oak and chestnut, which sprout prolifically after fire (Lorimer and White 2003).

The third forest type (pine-oak forest) is the only one of the three that has a substantial risk of wildfire. These stands generally grow on sandy soils on the Massachusetts coastal plain and islands (and along the coast from New Jersey to Maine). They also occur inland on scattered glacial outwash plains with sandy soils. Evidence from sediment cores show abundant charcoal in the pre-settlement record (Lorimer and White 2003), indicating that fire was frequent in these forests, likely ignited by the resident tribes of Native Americans. A number of factors lead to the high risk of fire in this type: 1) the pine component of the fine surface fuels (pine needles and twigs) do not decompose as readily as hardwood leaves (especially on dry sites) so these surface fuels tend to accumulate; 2) dead branches persist on trees, creating ladder fuels; 3) the moisture content of needles can decrease to the point that a fire can carry through the pitch pine crowns.

Fires in Massachusetts were more common in the late 19th and early 20th centuries compared to today. At that time, white pine stands dominated much of the landscape; these were on sites more suited to hardwood species, but the pines had become established on abandoned pastures and farm fields on these sites. Clearcutting of the mature pine stands was common, and it left large areas of slash in the open sun--branches with needles still attached, in slash piles several feet tall. These fuels did not decompose quickly and were very flammable (Smith et al. 1997). To reduce the danger of wildfires starting in slash, it was common at that time to pile and burn post-logging slash.

The use of prescribed fire is the most commonly used practice to reduce surface fuels in the U.S.--for burning slash piles or for broadcast burning of slash and/or natural accumulation of fuels. Generally, hardwood stands do not accumulate enough fuels to make this practice necessary, but it is used in pine stands on the coastal plain. The Massachusetts Slash Law (Kittredge and Parker 1996) is constructed on the principle that all slash should be disposed of in a manner that will minimize danger from fire. However, controlled burning of slash is not required and is not commonly done. The basic approach of the law is to use public roads that bound a timber harvest as fire breaks. Softwood slash cannot be left on the ground within 40 feet of a public road and can be left in piles no higher than 2 feet for the next 60 feet from the road. Hardwood slash can be in the first 40 feet, but piles can be only 2 feet in height. Most harvests in Massachusetts leave a partial canopy that shades the forest floor and most stands are hardwood-dominated, so this approach is generally satisfactory with the forest types, harvest methods, and climate of the region.

An interesting aspect of the Fire and Fire Surrogate study (described above) is that of the 13 sites, 8 are in the West, 3 are in the Southeast (all in conifer forest types), with only 1 in the Northeast hardwoods. This site is in southern Ohio in an oak-dominated forest. The same treatments of prescribed fire, thinning, and the combination are used here, but the objective for this site is not focused on reduction of fire danger by fuels control (because the fire danger is already so low)--but rather as a way to create a fire that is hot enough to reduce the abundance of maple and other hardwood species in order to foster oak recruitment (Iverson et al. 2004). Thus, the objective is to maintain the forest type created by Native Americans and continued by European settlers by burning.

Management recommendation regarding forest fire risk

The conclusions about the effects of biomass harvesting on fire risk in Massachusetts is as follows:

1. Thinning of hardwood stands using whole-tree removal methods for the tops of sawtimber trees and for small trees and large cull trees would reduce amount of fine surface fuels by not adding slash to the forest floor during the harvest. That would be the main effect on the reduction of fire risk--but it would not make a great difference because fire risk is already low in such stands.

2. With pine stands on dry sites, removing small trees in a thinning (including removing logging slash) would reduce both surface fuels and ladder fuels--thus providing a substantial reduction in fire danger.

3. With clearcut stands, whole-tree harvesting would reduce fire danger compared to stem-only harvests; again, this would mainly be important in conifer stands.

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5. Conclusions

Massachusetts forests contain substantial amounts of low-quality wood that could be harvested for use as biomass fuels; these trees have accumulated in stands because there have been very few markets for this kind of wood for many decades. Our analyses of stocks of biomass fuels were focused on sawtimber stands 70-100 years old. These make up 72% of forestland in Massachusetts, and are the stands most likely to be harvested. The average stand in this category has a total of 70 dry tons/acre of biomass (this includes all trees of any size or stem quality). The average stand has a growth rate of just under 1 dry ton/acre/year.

At the state level, the estimate of the forest land base for harvesting on private ownerships of 10 acres or larger is approximately 1,100,000 acres. The public forest land base for harvesting is 460,000 acres. Given average stand growth rates (and subtracting the biomass of sawlogs harvested for higher-value markets), the sustainable harvest for biomass fuels on the public and private land base together is 890,000 dry tons/year. Owners of larger tracts of forestland are more likely to engage in more intensive harvesting on their land; if the private land base is modified to include only ownerships 100 acres or larger, the sustainable harvest would be approximately 500,000 dry tons/year.

Most stands in Massachusetts (in both public and private ownership) are managed primarily for the ecosystem services they provide. For those owners who also have timber income as part of their management objectives, the goal is generally to produce high-quality sawlogs. The combination of these objectives leads to silvicultural methods that employ partial harvests: *thinning* to foster the growth of the best sawtimber trees, and *shelterwood* or *selection* methods to harvest the crop trees and begin the regeneration process. These methods produce different residual stand structures, but they are similar in that they remove part of the overstory in the harvest. The opportunity for biomass harvests is to remove the small trees, the large cull trees, and the upper stems and branches of the trees cut for sawlogs. If all of these were harvested, together they would provide 25 dry tons/acre of biomass fuels as part of a partial harvest in an average Massachusetts stand (that would also include 3,000 board feet/acre of sawlogs).

Clearcuts with whole-tree removal would produce 45 dry tons/acre in biomass fuels, along with 6,000 board feet/acre of sawlogs. However, whole-tree clearcutting removes substantial portions of the nutrient capital of the site, particularly by removing fine branches (and sometimes leaves) with high nutrient concentrations. Calcium, potassium, and magnesium have the greatest depletion rates. Calcium is of greatest concern; it would take more than 100 years for the amount of calcium removed in a whole-tree clearcut to be replenished from atmospheric deposition and rock weathering. This problem is recognized throughout the Northeast. The problem is exacerbated by acid precipitation and excess nitrogen deposition, which acidifies soils, and thus increases the loss of nutrients from soils into stream water.

In either a clearcut or a partial cut, there will likely be increased movement of harvesting equipment across the stand. This may cause excessive compaction of soils—leading to reduced infiltration capacity (the rate at which water enters the soil), overland flow, surface erosion, and sediment transport to streams. However, the Massachusetts Forest Practices Act regulates the harvest process through implementation of Best Management Practices, administered by Service Foresters. The requirements for filter (riparian forest buffer) strips along streams, careful layout and construction of roads and stream crossings, and other practices serve to avoid or mitigate these potential problems and adverse impacts on aquatic ecosystems and public water supplies.

Young dense vegetation that develops following clearcutting is important habitat for a number of bird, mammal, and other wildlife species. Because this habitat is not common in Massachusetts, wildlife managers seek to increase the area of this habitat by clearcutting. However, a whole-tree clearcut falls short of creating ideal habitat conditions. Retention of patches of trees (living and dead) and of a substantial amount of woody debris on the ground during the clearcutting is needed to include these important elements of the early successional habitat. Thinning or shelterwood harvesting (with the small trees removed for biomass) provides habitat for many species that are neither early successional or mature forest specialists.

Biomass harvests that remove small trees and slash will reduce the fuels that can lead to the spread of surface fires through a forest stand. However, most of the stand types in Massachusetts already have low fire risk, so the benefit from fuel reduction is small. There is one forest type where biomass harvests would be quite helpful; it is in stands dominated by pitch pine and oaks on dry sandy soils. These stands have a significantly higher fire risk, and fuel reduction programs are already in place in some of these areas; prescribed fire is generally used, but fuel harvesting may be a useful alternative.

Harvests of any products from forests are often examined for sustainability by considering three overlapping areas (Floyd 2002): 1) economic sustainability (maintenance of companies, communities, and families dependent on forests); 2) ecological sustainability (maintenance of biological diversity and integrity of ecological processes and systems); and 3) social sustainability (maintenance of private forest ownership and public participation in decision-making for public lands; ensuring forest benefits for future generations).

This report has provided estimates of the stock of biomass fuels available in average stands and of the total sustainable harvest level state-wide. Biomass harvests appear to be feasible based on the stock of low-quality wood in Massachusetts stands, and a substantial part of the new wood chip demand for the proposed 165 MW electricity generation plants could come from these harvests. However, this level of electricity generation (with the current technology) is close to the total sustainable harvest of biomass, and may exceed it, depending on how many owners of small woodlots (< 100 acres) will engage in biomass harvesting. Other research groups are examining additional aspects of economic sustainability.

These biomass harvests can be applied in a manner that sustains ecological processes, if partial harvests rather than clearcut harvests are used, as has been detailed in the report. Good silvicultural planning is needed in order to retain healthy vigorous residual stands that will continue to sequester carbon at high rates after the harvest. The social responses to biomass harvesting are uncertain. If harvests are designed to fit into current forest management practices that protect the flow of ecosystem services from forests (promoting social sustainability), public support may be strong. But this support could quickly wane if the program appears to focus too closely on industrial-scale harvesting.

Reference for Section 5

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