NATURAL CAPITAL INITIATIVE AT MANOMET **REPORT**

# Biomass Sustainability and Carbon Policy Study

## Chapter 5

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# CHAPTER 5

# FOREST CARBON MODELING: STAND-LEVEL CARBON DYNAMICS AND IMPLICATIONS OF HARVESTING FOR CARBON ACCUMULATION

We evaluated the carbon dynamics of five common forest cover types throughout Massachusetts (Mixed Oak, White Pine, Northern Hardwoods, Hemlock, Mixed Hardwood). We had two primary objectives with this task: (1) to achieve an understanding of Massachusetts forest carbon dynamics and implications of different harvest intensities at the stand level; and (2) to support the forest carbon life cycle accounting analysis (Chapter 6) by providing data on the total carbon recovery rates of forest stands following harvests of varying intensity. Below we summarize the methods used to evaluate forest carbon dynamics and discuss the implications of varying harvest intensities on the carbon volume response by forest stands in Massachusetts.

## 5.1 FOREST MANAGEMENT AND CARBON SEQUESTRATION

Practices that increase the amount of biomass retained on a given acre over time can be seen as having a carbon benefit. This is particularly true when the removal of the retained biomass (e.g., for pulp wood for paper making) would have generated carbon emissions in a relatively short period of time or emit methane when ultimately disposed. Increased stand-level retention practices consistent with an ecological forestry approach are considered an appropriate mitigation strategy as well. Also appropriate are reduced impact logging practices that minimize soil disturbance and residual damage to stands, thereby reducing mortality and maintaining stand vigor. Under such approaches, late-successional forest structures are seen as beneficial to forest health and resiliency, as well as achieving the biomass levels needed to yield carbon benefits (NCSSF 2008). The relative value of extending rotations is being debated, but there is evidence accumulating that older forests continue to sequester carbon well beyond stand ages we are likely to see in the northeastern forests any time soon (Massachusetts: Urbanski et al., 2007; Globally: Luyssaert et al., 2008). Extending rotation lengths serves to enhance structural complexity, thereby accumulating more biomass on a given acre (Foley et al., 2009). This strategy could also serve to sequester more carbon offsite in long-lived wood products through the production of larger diameter trees suitable for use in these products. However, Nunery and Keeton (2010) showed that even when offsite storage was considered in Northern Hardwood stands, the unmanaged stands still accumulated more carbon over a 160 year time frame. Perez-Garcia et al. (2005) also concluded that offsite storage could not surpass onsite storage unless product substitution was considered. The assumptions made around product conversion efficiencies, decay rates, and the certainty around substitution effects will drive the conclusions about the significance of offsite carbon as a long-term sink associated with forest harvesting (e.g., Van Deusen, in press).

Our modeling of forest carbon dynamics only includes estimates of onsite storage. Chapter 6 incorporates a more complete carbon life cycle accounting of the substitution implications associated with using wood for energy. The role of offsite storage in products is minimal when you consider that only 3.5% of hardwood sawlogs are estimated to be still in use after 100 years in the Northeast (Smith et al., 2006). A significant amount of hardwood sawlogs (28%) is estimated to remain in landfills after 100 years (Smith et al., 2006), but without methane capture technologies in place emissions associated with landfill storage would far exceed the benefits of other offsite storage. Landfill emissions are especially problematic since methane has a Global Warming Potential 25 times worse than carbon dioxide (IPCC, 2007). Without a comprehensive life cycle assessment for products derived from Massachusetts forests we felt it was not productive to speculate on the role of offsite storage, particularly for the time periods we are considering below. More importantly for our analyses however, Chapter 6 assumes that the increase harvest intensity for biomass energy wood doesn't change the disposition of materials that would be harvested absent biomass extraction.

Below we describe the widely-accepted models and inventory data we used to understand the role of forest management in stand-level forest carbon dynamics. Where appropriate, we describe the limitations of the models and data and how they were used to inform the analyses in Chapter 6. Models are a representation of a complex ecological reality and are best used to investigate trends and likely outcomes, not predetermined certainty. Data are generally presented in aggregate to show broad trends, but specific examples are also given to illustrate points.

## 5.2 INVENTORY DATA AND FOREST CARBON MODELS

Data used in the analyses were based upon Forest Inventory and Analysis (FIA) data from the U.S. Forest Service. We obtained inventory data from the FIA DB version 4.0 Data Mart from 1998–2008.[4] FIA plot data (including tree lists) were imported into the Northeast (NE) Variant of the US Forest Service Forest Vegetation Simulator (FVS)[5] and are accepted as compatible with the model (Ray et al., 2009). FVS is a widely-accepted growth model within current forest carbon offset standards (e.g., Climate Action Reserve Forest Project Protocol 3.1[6] and the Chicago Climate Exchange Forest Offset Project Protocol [7]) and as a tool to understand carbon implications of forest management within the scientific community (e.g., Keeton 2006; Ray et al., 2009; Nunery and Keeton, 2010). The modeling package relies

4 http://fia.fs.fed.us/tools-data/default.asp

5 http://www.fs.fed.us/fmsc/fvs/

6 http://www.climateactionreserve.org/wp-content/uploads/2009/03/Forest-Project-Protocol-Version-3.1.pdf

7 http://www.chicagoclimatex.com/docs/offsets/CCX_Forestry_Sequestration_Protocol_Final.pdf

on NE-TWIGS (Hilt and Teck, 1989) as the growth and yield model to derive carbon biomass estimates in the Northeast. These growth and yield models are based on data collected by the USFS's Forest Inventory and Analysis unit from the 1950s through the 1980s. Developed by the US Forest Service and widely used for more than 30 years, the FVS is an individual tree, distance independent growth and yield model with linkable modules called extensions, which simulate various insect and pathogen impacts, fire effects, fuel loading, snag dynamics, and development of understory tree vegetation (Crookston and Dixon 2005). FVS can simulate a wide variety of forest types, stand structures, pure or mixed species stands, and allows for the modeling of density dependent factors.

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

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

## 5.3 MODEL SCENARIOS

FIA data for both private and public lands from inventories between 1998–2008 were imported into a database for manipulation into the FVS model. The most current inventory year from each plot was used in the analysis and grown to the year 2010 using the model described below. Plots were categorized by forest cover type based on tree species list from each plot (Exhibit 5-1).

We selected a subset of the FIA plots that met a condition of having ≥ 25 Metric Tons of Carbon (MTC) per acre of aboveground living biomass ("aboveground live carbon") prior to any harvest in 2010 to represent stands that are typically harvested across the state. This was important to match the assumptions made in the Chapter 3 supply analysis and is consistent with the approach of Kelty et al. (2008). These plots represented a mean aboveground live carbon stocking of 31 MTC/acre (or approximately 124 green tons per acre). We refer to these plots as "operable" stands as they represent the majority of 70-100 year old stands with a likelihood of being harvested in the near term. A total of 88 FIA plots were used for the analyses of operable stands (Mixed Oak n=4; Northern Hardwood n=31; Mixed Hardwood n= 29; Hemlock n=3; White Pine n= 21).

The model scenarios we tested were designed to understand the carbon implications of varying intensity of harvest (i.e., removal rates) including an evaluation of "no management" or "let it grow" scenarios. In particular, we were interested in the implications of harvests that were defined as "biomass" harvests that removed the majority of tops and limbs (65%) and represented higher rates of total removal than that defined as "Business as Usual" (BAU) in supply analysis (Chapter 3). FVS allows the user to

**Exhibit 5-1: Cover Type Classification for FIA Plots**

| Cover Type | Cover Type Code | Dominant Species | Parameter |
|---|---|---|---|
| Mixed Oak | MO | *Quercus* spp. (hickories secondary) | > 50% trees > 5" dbh are *Quercus* spp. |
| White Pine | WP | Eastern White Pine | > 50% trees > 5" dbh are *Pinus strobus* |
| Northern Hardwoods | NH | Red and Sugar Maple, Beech, Yellow Birch, Black Birch | > 50% trees > 5" dbh are northern hardwood spp. |
| Hemlock | HE | Eastern Hemlock | > 50% trees > 5" dbh are *Tsuga canadensis* |
| Mixed Hardwood | MH | Northern Hardwoods/Mixed Oak | default classification (can contain pine and hemlock) |

select and customize forest management scenarios based on input criteria such as target residual basal area (BA), target percent removal, specification of diameter and species preferences, and tops and limbs retention preferences. Twenty scenarios were run using data from all FIA plots representing a range of intensity from no management to a silvicultural clearcut that removed all trees > 2" DBH (Exhibit 5-2). Scenarios are categorized as follows: (1) Unmanaged Accumulation; (2) Business as Usual Harvest (BAU); (3) Biomass Harvests; and (4) Sensitivity Analysis Harvests. The sensitivity analyses were designed to elucidate the carbon dynamics associated with retaining versus removing tops and limbs in biomass harvests and to understand the dynamics of conducting harvests with silvicultural objectives that included promoting crop tree development and moving towards uneven-aged silvicultural systems.

We chose to model carbon accumulation within a period between 2010 and 2100. Modeling on such a time frame comes with a degree of uncertainty and we acknowledge the limitations of this approach. In particular, projections do not include the impacts on carbon accumulation from stochastic natural disturbances, climate change, or the influence of exotic species. However, using these data to understand the potential long-term trajectories is appropriate and can tell us a great deal about response trends.

**Exhibit 5-2: Summary of FVS Treatment Scenarios Analyzed**

| Scenario | Name | Harvest Scenarios | Category | Tops and Limbs Removed From Site (%) | Regeneration Scenario (see Exhibit 5-3) |
|---|---|---|---|---|---|
| MS1 | Unmanaged | Unmanaged | Unmanaged | 0 | 1 |
| MS2 | BAU 32% | Common Partial Harvest (Business As Usual), Thin 25% of stand BA from Above | BAU | 0 | 2 |
| MS3 | BAU 32% Light Biomass | BAU with 65% Tops and Limbs Removed | Biomass | 65 | 2 |
| MS4 | BAU 32% Heavy Biomass | BAU with 100% of Tops and Limbs Removed | Biomass | 100 | 2 |
| MS5 | Heavy Harvest BA 40 | Heavy Harvest, Thin from Above to 40 ft2/acre BA | Sensitivity | 0 | 3 |
| MS6 | Heavy Harvest BA 40 Light Biomass | Heavy Harvest w/ Light Biomass | Biomass | 65 | 3 |
| MS7 | Commercial Clearcut (Tops and Limbs left) | Commercial Clear Cut | Sensitivity | 0 | 4 |
| MS8 | Commercial Clearcut | Commercial Clearcut with 65% Tops and Limbs Removed | Biomass | 65 | 4 |
| MS9 | Selection Cut | "Quality" Individual Tree Selection (75 ft2/acre BA retained) | Sensitivity | 0 | 2 |
| MS10 | Selection Cut Light Biomass | "Quality" Individual Tree Selection (75 ft2/acre BA retained), 65% Tops and Limbs removed | Sensitivity | 65 | 2 |
| MS11 | Silvicultural Clearcut | Silvicultural Clearcut No Legacy (>2" DBH trees removed) | Sensitivity | 0 | 4 |
| MS12 | Silvicultural Clearcut No Regen | Commercial Clearcut, No Legacy Trees Left, No Regen | Sensitivity | 0 | x |
| MS13 | DBH BA60 | Thinning through diameter classes to BA 60 ft2/acre of trees > 8" DBH | Sensitivity | 65 | 3 |
| MS14 | DBH All BA60 | Thinning through diameter classes to BA 60 ft2/acre | Sensitivity | 65 | 3 |
| MS15 | Biomass BA60 | Thin from Above to BA 60 ft2/acre | Biomass | 65 | 3 |
| MS16 | BAU 20% | Common Partial Harvest, Thin from Above (15% BA removed = 20% volume) | BAU | 0 | 2 |
| MS17 | BAU 20% Light Biomass | Common Partial Harvest, Thin from Above (15 % BA removed = 20% Volume), 65% Tops and Limbs Removed | Sensitivity | 65 | 2 |
| MS18 | BAU 35% Light Biomass | Common Partial Harvest, Thin from Above (20% BA removed = 35% volume removed), 65% Tops and Limbs removed. | Sensitivity | 65 | 2 |
| MS19 | BAU 40% Light Biomass | Common Partial Harvest, Thin from Above (30% BA removed = 40% volume removed), 65% Tops and Limbs removed. | Biomass | 65 | 2 |
| MS20 | BAU 15% | Common Partial Harvest, Thin from Above (10% BA removed = 15% volume) | Sensitivity | 0 | 2 |

Shorter-term projections (ca. 30 to 50 years) have been verified to have a higher degree of confidence since the impacts of these uncertainties are minimized by low probability of occurrence (Yaussy, 2000). We also focused on the stand-level response following a single harvest event at Time = 0 (i.e., 2010) rather than conduct a more complicated series of repeated harvest entries. We can infer a "sawtooth" response from repeated entries to a target basal area or residual condition, but single entry scenarios provided us the best information to evaluate the short-term impacts and response of stands following "biomass" harvests needed to inform Chapter 6.

The FVS NE Variant does not add regeneration elements by default (except for stump sprouting for appropriate species following harvest). Regeneration inputs were required to more appropriately reflect the behavior of forest stands following harvest. We followed the methods of Nunery and Keeton (2010) and adapted conservative regeneration inputs that were designed to be appropriate to the cover type and disturbance intensity but still within a range of natural variability (Exhibit 5-3). Conceptually, seedling inputs were periodically entered into the simulation throughout the time period to mimic baseline regeneration rates in an unmanaged stand. In harvested stands, larger numbers of seedlings were input immediately post harvest to mimic the pulse of regeneration that would be expected to follow a disturbance. Exhibit 5-3 shows the number of seedling inputs relative to the harvest scenario. Greater removal of overstory trees promotes the opportunity for larger numbers of seedlings to become established. The mix of species in heavier harvests was weighted more heavily to shade intolerant and intermediate shade tolerant species as would be expected following an actual harvest (after Leak et al. 1987 and Leak 2005). Regeneration inputs in harvested stands were then gradually reduced over time to mimic a stand initiation period followed by baseline regeneration. Site indices were inconsistently available for the FIA dataset so we used the default FVS value set to sugar maple with a site index of 56.

| | Shade Tolerance | | | |
|---|---|---|---|---|
| Cover Type | Intolerant | Intermediate | Tolerant | Total |
| HE | 16% | 21% | 63% | 100% |
| MH | 33% | 40% | 27% | 100% |
| MO | 23% | 43% | 34% | 100% |
| NH | 18% | 54% | 28% | 100% |
| WP | 32% | 31% | 37% | 100% |
| Mean | 24% | 43% | 33% | 100% |

*Note: Species were allocated based on proportional representation within each cover type and weighted to reflect a higher proportion of intolerant and intermediate shade tolerant species in the Heavy Partial Harvest and Commercial Clearcut scenarios.*

## 5.4 GENERAL RESULTS AND MODEL EVALUATION

### 5.4.1 GENERAL RESULTS

All values below are expressed in terms of Metric Tons of Carbon per Acre (MTC/acre). Approximately 50% of dry wood weight is considered to be made up of carbon (or 25% of green wood weight). We also present values either in terms of Total Stand Carbon (TSC) or Aboveground Live Carbon (AGL). AGL is simply the carbon biomass associated with the aboveground elements of a live tree. TSC is comprised of aboveground live and dead trees, belowground live and dead roots, lying dead wood, forest floor, and shrub and herb carbon pools. AGL dynamics reflect behavior foresters would be more accustomed to and are analogous to stand basal area and merchantable volume response. Basal area to AGL

**Exhibit 5-3: Regeneration Inputs Used in FVS Model Scenarios**

| Regeneration Group | Harvest Scenarios | Year | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2015 | 2025 | 2035 | 2045 | 2055 | 2065 | 2075 | 2085 | 2095 | 2105 | 2115 |
| 1 | Unmanaged Baseline Regeneration | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 |
| 2 | Light Partial Harvest Response | 2,500 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 |
| 3 | Heavy Partial Harvest Response | 5,000 | 2,500 | 2,500 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 |
| 4 | Commercial Clearcut Response | 20,000 | 5,000 | 2,500 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 |

*Note: Regeneration is expressed in trees (seedlings) per acre. Inputs based on methods described in Nunery and Keeton (2010) and regeneration response to harvests described in Leak et al. (1987), Hornbeck and Leak (1992), and Leak (2005) (5-3a).*

relationships are typically more linearly related than AGL and merchantable volume (Ducey and Gunn, unpublished data).

Not surprisingly, unmanaged stands result in greater onsite carbon storage than any of the management scenarios we simulated when both TSC and AGL are considered over the 90 year horizon (Exhibits 5-4a and 5-4b). Here, a range of management scenarios (including unmanaged) are shown to illustrate the response of a light diameter-limit partial harvest, a heavy harvest that removes 65% of the tops and limbs, and a commercial clearcut that removes all trees greater than 5" DBH. The mean values include both public and private landowners, and all cover types are aggregated. These patterns were also observed by Nunery and Keeton (2010) in Northern Hardwood stands and even held true when offsite storage of carbon was considered. There were a few plots where managed stands met or exceeded the unmanaged scenario by 2100. These plots were typically understocked at the time of harvest and a heavy harvest was able to "release" the advanced regeneration and promote the growth of the intolerant and intermediate shade tolerant species that were input following the harvest. These fast growing species begin to decline after 40 to 50 years and it is likely that a decline would be observed beyond our modeling period as a result of mortality in these short-lived species. If longer-living shade tolerant species were present in the pre-harvest canopy or mid-story, it is likely that these species would persist longer than the intolerants in the managed scenario.

**Exhibit 5-4a: Total Stand Carbon Accumulation over Time**
(see next page)

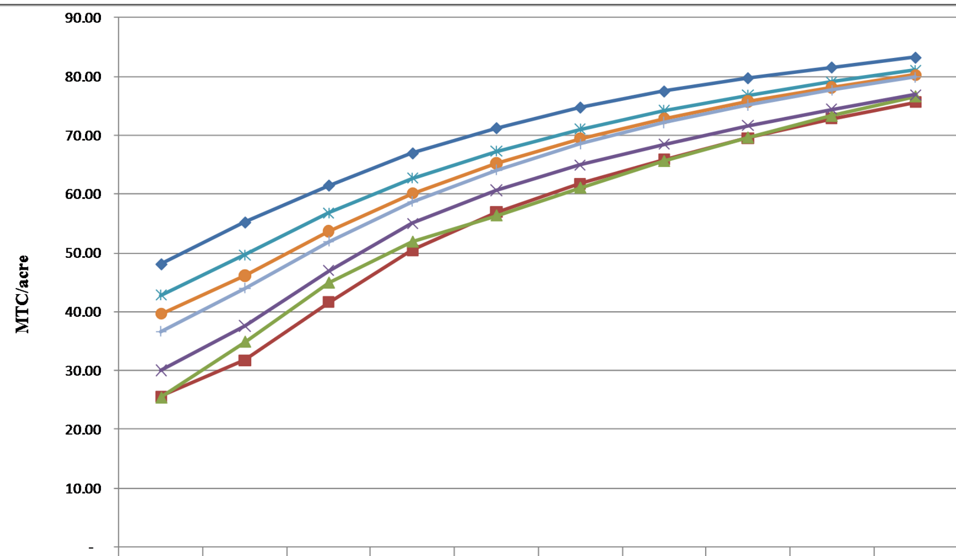
**5-4b: Aboveground Live Carbon Accumulation over Time**
(see next page)

Light partial harvests in stands that remove larger diameter trees recover slowly and roughly parallel to unmanaged stands, but gradually approach unmanaged volumes over a 90-year period. This is likely because residual mean diameter is still relatively high following the harvest and the associated growth response is slow. These light diameter-limit partial harvests (e.g., BAU 20% and BAU 32%) represent the mean harvest intensity across Massachusetts. The light harvest in the canopy increases the growth rate in the initial ten year period, but very quickly returns to approximately the same as the unmanaged growth rate. Over time these BAU stands approach unmanaged stocking but don't quite catch up after 90 years. This finding is consistent with work in the Harvard Forest by O'Donnell (2007) who found that carbon uptake in live biomass following a light partial harvest recovered quickly after an initial decline to equal the un-harvested control site's carbon uptake rates. If this relationship holds into the future, the onsite stocks would not catch up to the unmanaged site. In contrast, the scenarios we defined as "biomass" harvests (Biomass 40%, Biomass BA40, Biomass BA60) maintain high growth rates for several decades. Because of this increased growth rate, even the heavier harvested stands can reach almost 90% of the volume that could have been achieved in an unmanaged scenario. So, over a long period of time, biomass harvests have an opportunity to recover a large portion of the carbon volume removed during the harvest. However, this assumes no future harvests in the stand as well as an absence of any significant disturbance event. Both are unlikely. This return interval, or cutting cycle, in a silvicultural system will clearly play a role in the recovery of onsite carbon storage over time. If stands are consistently entered prior to achieving complete recovery, the result will be a declining "sawtooth" pattern of growth and recovery of carbon volume stored onsite. With planning and monitoring, uneven-aged silvicultural systems can be implemented that allow adequate time for recovery while maintaining a basal area that promotes quality sawlog production (Hornbeck and Leak, 1992).

Canopy and sub-canopy density plays an important role when the harvest is not heavy enough to reduce the crown completion factors. Heavy harvests create light and space for fast growing intolerant hardwood species to succeed, which can create a pulse of fast growing AGL. The heavy harvest also generates more lying dead wood from the tops and limbs. This may keep the initial post-harvest TSC value high, until this material decays and is lost from subsequent carbon pools. However, this loss is very rapidly recovered by the fast growing species. The curves in Exhibits 5-4a and 5-4b show the general pattern of a faster growth rate in the periods immediately following a harvest event, followed by a gradual slowing at the end of the modeling period. This is not surprising particularly for the unmanaged scenario which would represent plots that are reaching ages around 200 years old by the end of the modeling period. The FIA data that forms the basis of the NE Variant modeling would have had few plots that represented stands of this age, so accumulation behavior this far out in time is uncertain and requires further research (e.g., Keeton et al., In Press).

The Heavy Harvest (BA40) and Commercial Clearcut harvest scenarios behave very similarly to each other. This is largely because the Commercial Clearcut retained trees greater than 5" DBH which effectively brought the stand to 40 $ft^2$/acre of basal area. Depending upon the density of trees > 5" DBH in the plot, the Heavy Harvest could actually be a heavier harvest than the Commercial Clearcut—which may explain the greater carbon accumulation after 2020. Note that Total Stand Carbon is actually higher for a time in the Commercial Clearcut plots, possibly a product of mortality from the regeneration inputs that are lost through density competition within the smaller stems in that scenario. When we look at the impacts of a Silvicultural Clearcut that removes trees down to 2" DBH, it becomes obvious that there are immediate carbon benefits (AGL) to leaving behind advance regeneration when it is available (Exhibit 5-5). Even though 20,000 seedlings per acre are being input into the stand following harvest, it takes some time before those stems contribute significantly to the AGL, eventually the curve approaches the Commercial Clearcut, but not before 100 years.

### Exhibit 5-4a: Total Stand Carbon Accumulation over Time

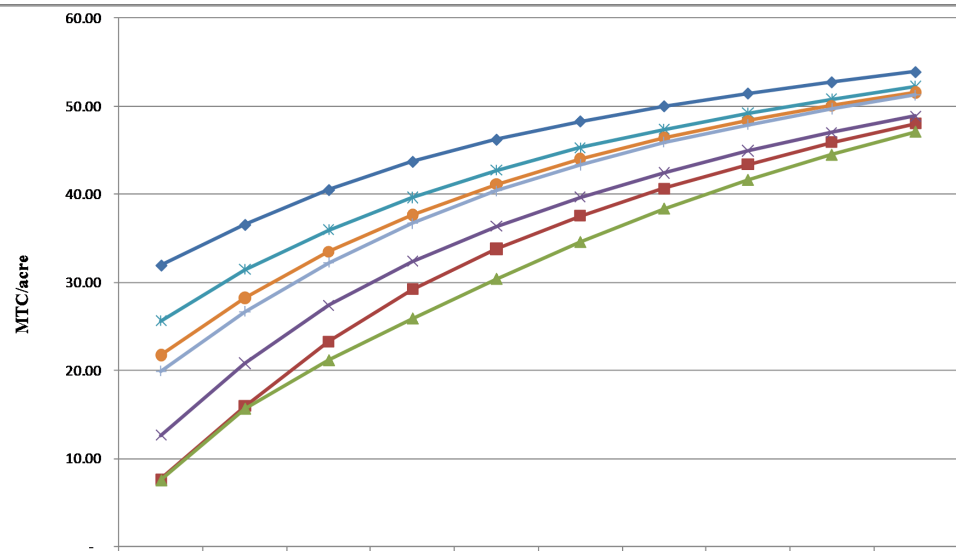



| | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|
| Unmanaged | 48.09 | 55.21 | 61.50 | 66.97 | 71.27 | 74.78 | 77.52 | 79.77 | 81.60 | 83.27 |
| Biomass BA40 | 25.61 | 31.74 | 41.63 | 50.44 | 56.91 | 61.78 | 65.90 | 69.51 | 72.86 | 75.60 |
| Commercial Clearcut | 25.35 | 34.88 | 44.92 | 51.89 | 56.36 | 61.08 | 65.61 | 69.61 | 73.28 | 76.61 |
| Biomass BA60 | 30.01 | 37.58 | 46.97 | 55.00 | 60.62 | 64.92 | 68.47 | 71.63 | 74.42 | 76.89 |
| BAU 20% | 42.81 | 49.66 | 56.82 | 62.69 | 67.25 | 71.05 | 74.18 | 76.81 | 79.05 | 81.06 |
| BAU 32% | 39.62 | 46.12 | 53.68 | 60.08 | 65.18 | 69.43 | 72.84 | 75.74 | 78.11 | 80.27 |
| Biomass 40% | 36.67 | 44.00 | 51.94 | 58.74 | 64.10 | 68.50 | 72.17 | 75.12 | 77.64 | 79.87 |

Year - MTC/acre (Total Stand Carbon)

*Note: Plots included are from FIA plots with >25 MTC/acre of Aboveground Live Carbon (pre-harvest) in 2010. Private and public owners and all cover types are aggregated (see Exhibit 5-2 for harvest scenario descriptions).*

### Exhibit 5-4b: Aboveground Live Carbon Accumulation over Time

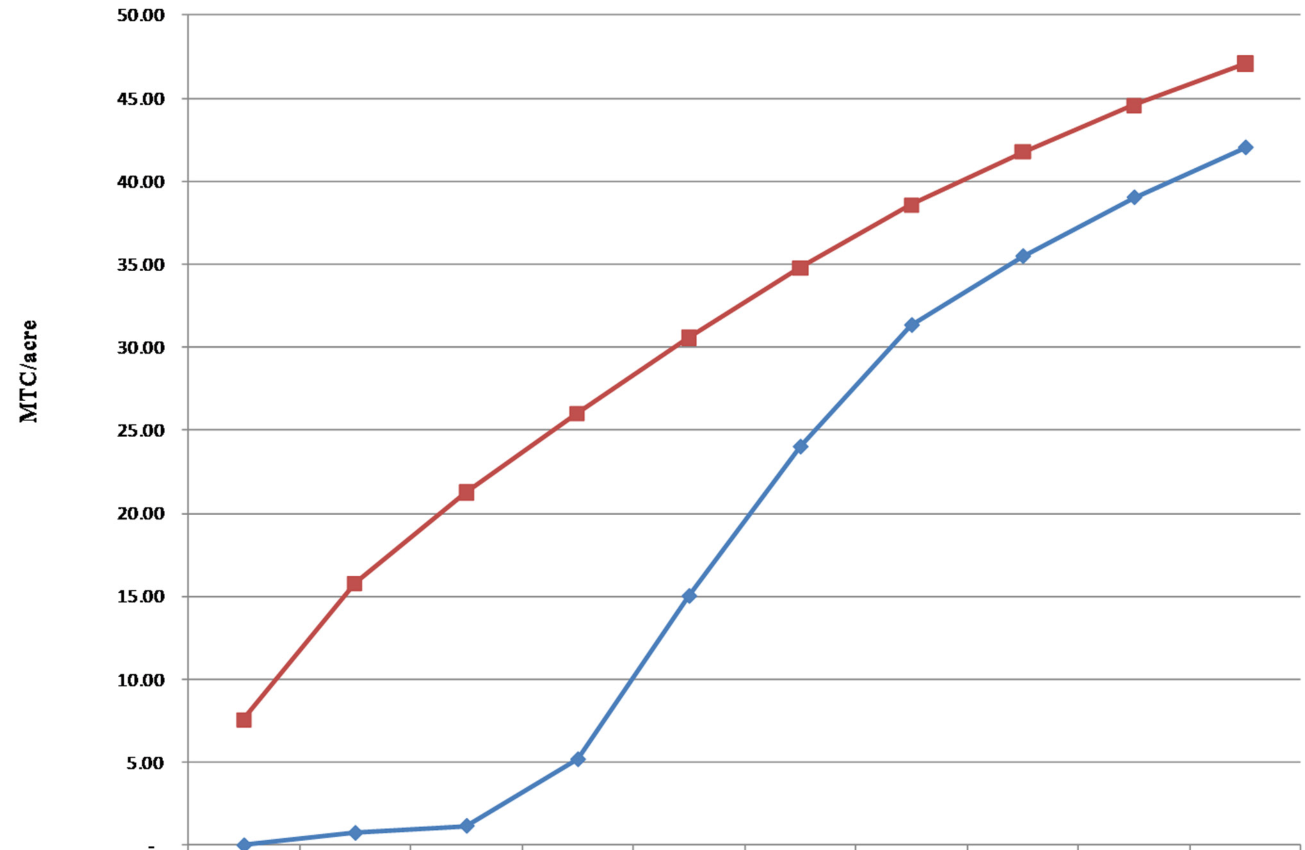



| | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|
| Unmanaged | 31.91 | 36.53 | 40.49 | 43.70 | 46.22 | 48.30 | 50.02 | 51.47 | 52.75 | 53.90 |
| Biomass BA40 | 7.66 | 15.93 | 23.29 | 29.22 | 33.81 | 37.53 | 40.66 | 43.37 | 45.92 | 48.01 |
| Commercial Clearcut | 7.53 | 15.65 | 21.16 | 25.90 | 30.39 | 34.57 | 38.37 | 41.62 | 44.47 | 47.09 |
| Biomass BA60 | 12.62 | 20.83 | 27.40 | 32.40 | 36.38 | 39.67 | 42.42 | 44.91 | 47.01 | 48.87 |
| BAU 20% | 25.64 | 31.47 | 35.98 | 39.64 | 42.71 | 45.27 | 47.38 | 49.20 | 50.80 | 52.22 |
| BAU 32% | 21.76 | 28.22 | 33.49 | 37.63 | 41.15 | 44.01 | 46.38 | 48.34 | 50.05 | 51.56 |
| Biomass 40% | 19.93 | 26.67 | 32.27 | 36.68 | 40.39 | 43.36 | 45.88 | 47.90 | 49.71 | 51.26 |

Year - MTC/acre (Aboveground Live Carbon)

*Note: Plots included are from FIA plots with >25 MTC/acre of Aboveground Live Carbon (pre-harvest) in 2010. Private and public owners and all cover types are aggregated (see Exhibit 5-2 for harvest scenario descriptions).*

**Exhibit 5-5: Aboveground Live Carbon Accumulation Following Clearcut Harvests**




| | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|
| Silvicultural Clearcut | - | 0.75 | 1.17 | 5.18 | 15.01 | 23.99 | 31.31 | 35.46 | 39.00 | 42.00 |
| Commercial Clearcut | 7.57 | 15.77 | 21.25 | 26.01 | 30.56 | 34.77 | 38.56 | 41.76 | 44.54 | 47.07 |

**Year - MTC/acre Aboveground Live Carbon**

*Note: Comparison is between a Commercial Clearcut (removing trees >5" DBH) vs. Silvicultural Clearcut (removing trees > 2" DBH).*

Aboveground Live Carbon typically follows a pattern of faster growth when mean diameters are small and densities are not limiting; then slows down as basal area maximums are reached and the lifespan maximums are approached. This is typical of what would be expected based on principles outlined in Oliver and Larson's classic Forest Stand Dynamics text (1996). Total Stand Carbon provides interesting insight primarily in the short term responses of stands as carbon pools are influenced by material left on the site. Later in the trajectory, the TSC becomes interesting again as mortality occurs and contributions of material to the dead standing and lying dead pools can vary.

### 5.4.2 COVER TYPE AND OWNERSHIP DIFFERENCES IN CARBON ACCUMULATION

Species response rates can vary depending upon silvical characteristics and this can be illustrated in some variation among cover type responses. Below are some examples of variation among cover types (Exhibits 5-6a through 5-6c). In general, the patterns are similar. The differences occur in terms of starting carbon volume and then become more pronounced near the end of the modeling period. For example, the Hemlock cover type accumulates the greatest amount of carbon over the long term as would be expected from a shade tolerant and long-lived species. However, these curves are based on only 3 plots, so a larger sample might bring it in line with other types. In addition, the future of Hemlock in Massachusetts is highly uncertain given the current status of the Hemlock Woolly Adelgid. For the other cover types, response to harvests (Exhibits 5-6b and 5-6c) generally follows the same trends with the real differences being accentuated late in the model period as with the Hemlock. Though there are minor differences among the cover types, we generally will report the results in Chapter 6 in aggregate.

Likewise, for the purposes of this analysis, we aggregated plots regardless of ownership type (Public and Private). Ownership does not result in major differences in terms of carbon trajectories and response to harvests (e.g., Exhibit 5-7). Minor differences do occur in starting carbon volume, but the plots behave similarly over time. Kelty et al. (2008) documented differences in growth between ownership types but were using two different data sets to make those comparisons (FIA for private lands and MA DCR Continuous Forest Inventory for public lands). Utilizing the Continuous Forest Inventory Plots from the MA DCR proved to be logistically challenging to integrate into FVS with the FIA plots data. Since data were available for both Public and Private lands within FIA, we decided to maintain consistency by only using FIA data.

**Exhibit 5-6a: Unmanaged TSC Accumulation by Cover Type** (see page 91)

**Exhibit 5-6b: BAU 32% Removal TSC Accumulation by Cover Type** (see page 91)

**Exhibit 5-6c: Heavy Harvest BA40 TSC Accumulation by Cover Type** (see page92)

**Exhibit 5-7: Ownership Similarities in Carbon Accumulation Over Time by Cover Type (TSC)** (see page 92)

### 5.4.3 REGENERATION CONTRIBUTION TO CARBON ACCUMULATION

Appropriately reflecting a realistic regeneration scenario is an important component of extending the time frame in which the FVS model results can be meaningful. Simply put, regeneration fills space made available by disturbances or natural mortality. In our simulations, we have followed the basic principle that heavier disturbances create more space and light, and therefore allow increasing larger numbers of seedlings to become established. Lighter harvests create less space and light in which regeneration will be successfully established. The successful seedlings will be appropriate to the amount of shade they can tolerate. Regeneration species composition is generally related to species already present within a stand and adjacent stands. But heavy harvests in the NE would typically result in 2/3 of the regenerating species being either shade intolerant or intermediate tolerance. Biologically relevant amounts and species composition were integrated into our approach.

The silvical characteristics of the regeneration are the primary factor contributing to forest carbon dynamics over time. Shade intolerants are typically faster growing species, but they are shorter lived. Thus, they can be responsible for an immediate increase in carbon biomass but will slow and decline after 50–60 years, whereas shade tolerant and intermediate shade tolerant species would persist in the stand and continue accumulating carbon for a longer period. However, Exhibit 5-5 above illustrates that the interaction between starting condition and the amount removed during a harvest are major drivers of carbon accumulation after a harvest.

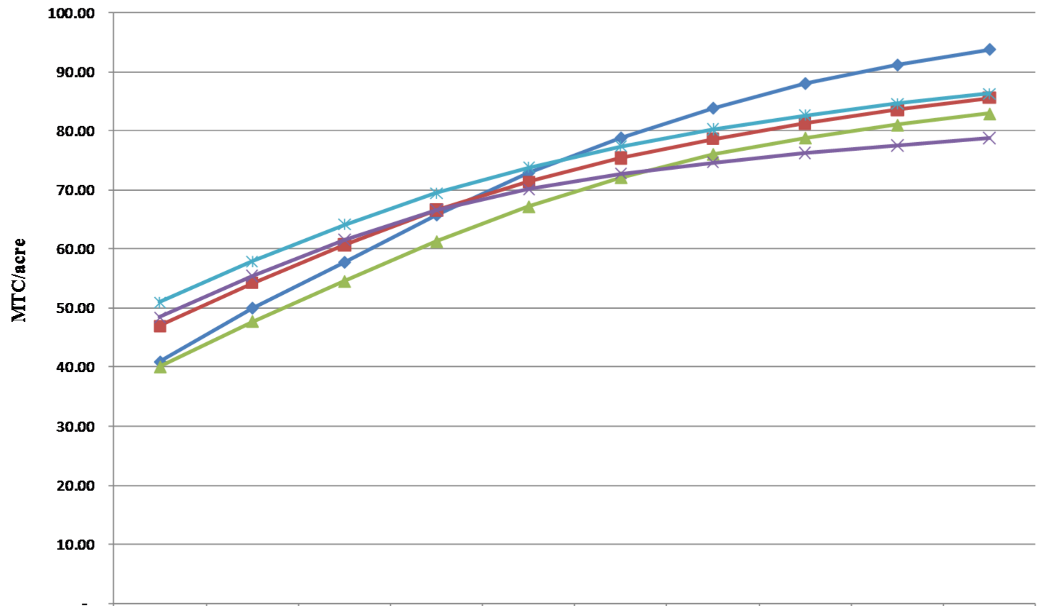
### 5.4.4 ROLE OF TOPS AND LIMBS IN CARBON BUDGET

We evaluated the carbon implications of the removal of tree tops and limbs during a harvest. We chose to simulate a removal rate of 65% tops and limbs based upon the standards recommended in Chapter 4 and the operability limitations described in Chapter 3. Removal of 65% tops and limbs generates on average between 1.23 MTC/acre and 4.22 MTC/acre depending on the intensity of the overall harvest. This carbon volume decays very rapidly if left on the forest floor, but is compensated for by new growth generally within 10 years following the harvest (Exhibit 5-8). The tops and limbs left in the forest can be observed as a pulse of carbon in the "lying dead" carbon pool, but it moves relatively quickly into the forest floor and ultimately is mostly lost to the atmosphere within a short time period (e.g., Exhibit 5-9). Thus, if tops and limbs are harvested in one scenario, and left in another, Total Stand Carbon in both scenarios will nearly converge within one decade. This recovery of carbon lost from tops and limbs could theoretically be faster if there is significant material left onsite suppressing regeneration. Overall, the model results indicate that the removal of tops and limbs is generally a minor stand level carbon issue; however, as shown in Chapter 6, they can have a significant impact on carbon recovery profiles if they represent a significant proportion of the total harvest.

**Exhibit 5-8: Tops and Limbs Contribution to Total Stand Carbon** (see page 93)

**Exhibit 5-9: Carbon Pool Comparison** (see page 93)

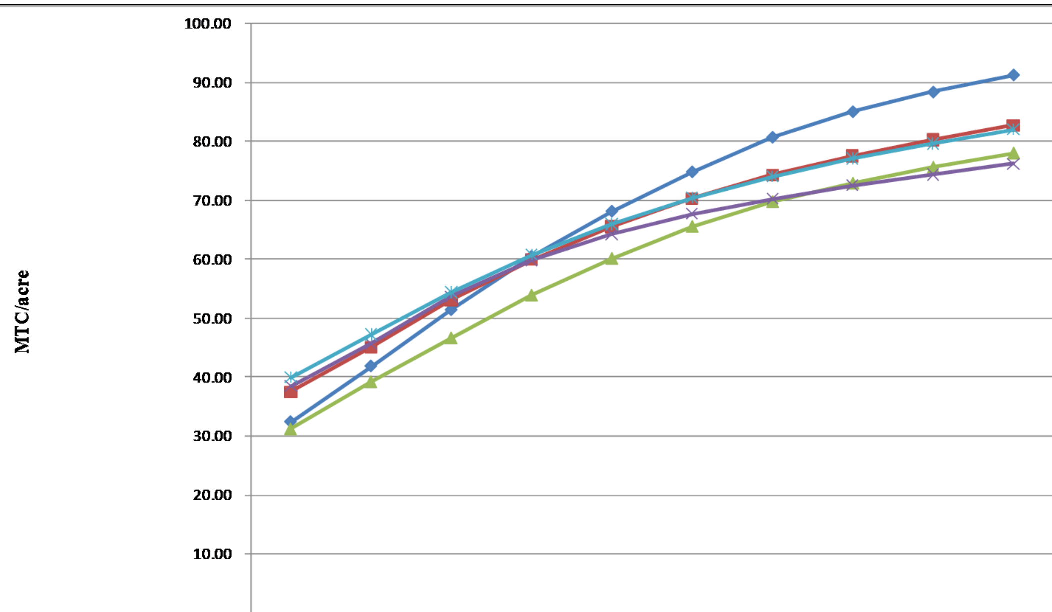
### Exhibit 5-6a: Unmanaged TSC Accumulation by Cover Type




| | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|
| HE - Unmanaged | 40.89 | 50.01 | 57.77 | 65.77 | 72.94 | 78.82 | 83.85 | 88.02 | 91.15 | 93.79 |
| MH - Unmanaged | 46.98 | 54.24 | 60.72 | 66.60 | 71.38 | 75.46 | 78.68 | 81.34 | 83.57 | 85.61 |
| MO - Unmanaged | 40.02 | 47.77 | 54.54 | 61.30 | 67.21 | 72.16 | 76.12 | 78.89 | 81.07 | 82.98 |
| NH - Unmanaged | 48.45 | 55.44 | 61.56 | 66.58 | 70.11 | 72.75 | 74.70 | 76.31 | 77.58 | 78.78 |
| WP - Unmanaged | 50.94 | 57.92 | 64.15 | 69.46 | 73.82 | 77.40 | 80.26 | 82.64 | 84.61 | 86.33 |

Year - MTC/acre Total Stand Carbon

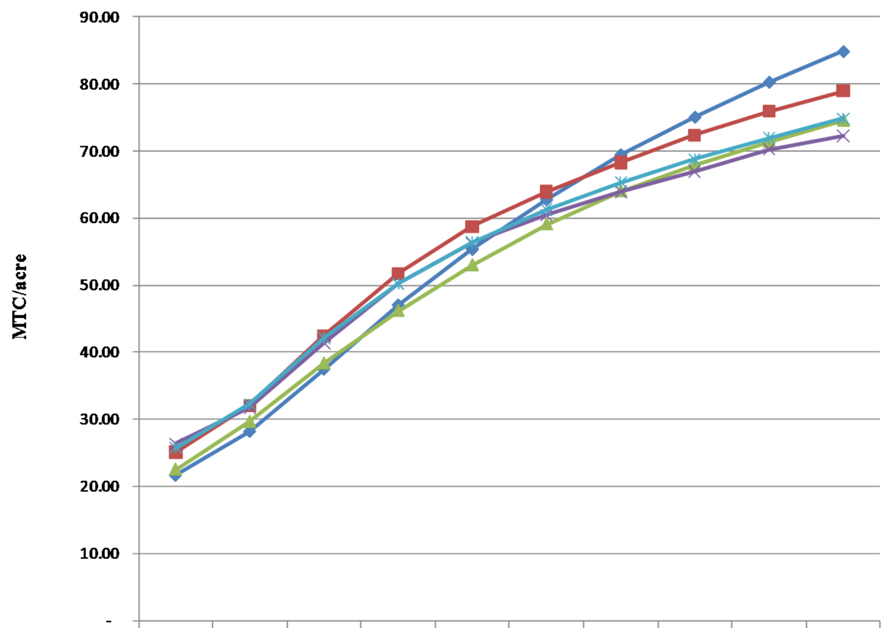
### Exhibit 5-6b: BAU 32% Removal TSC Accumulation by Cover Type




| | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|
| HE - BAU 32% (65% T&L Removed) | 32.40 | 41.86 | 51.42 | 60.49 | 68.17 | 74.85 | 80.73 | 85.06 | 88.40 | 91.32 |
| MH - BAU 32% (65% T&L Removed) | 37.48 | 45.04 | 53.10 | 59.98 | 65.55 | 70.33 | 74.30 | 77.58 | 80.31 | 82.72 |
| MO - BAU 32% (65% T&L Removed) | 31.19 | 39.21 | 46.63 | 53.88 | 60.13 | 65.56 | 69.75 | 72.89 | 75.59 | 77.99 |
| NH - BAU 32% (65% T&L Removed) | 38.46 | 45.70 | 53.72 | 59.86 | 64.32 | 67.76 | 70.26 | 72.56 | 74.38 | 76.19 |
| WP - BAU 32% (65% T&L Removed) | 39.98 | 47.28 | 54.42 | 60.79 | 65.98 | 70.47 | 74.07 | 77.16 | 79.68 | 82.00 |

Year - MTC/acre Total Stand Carbon

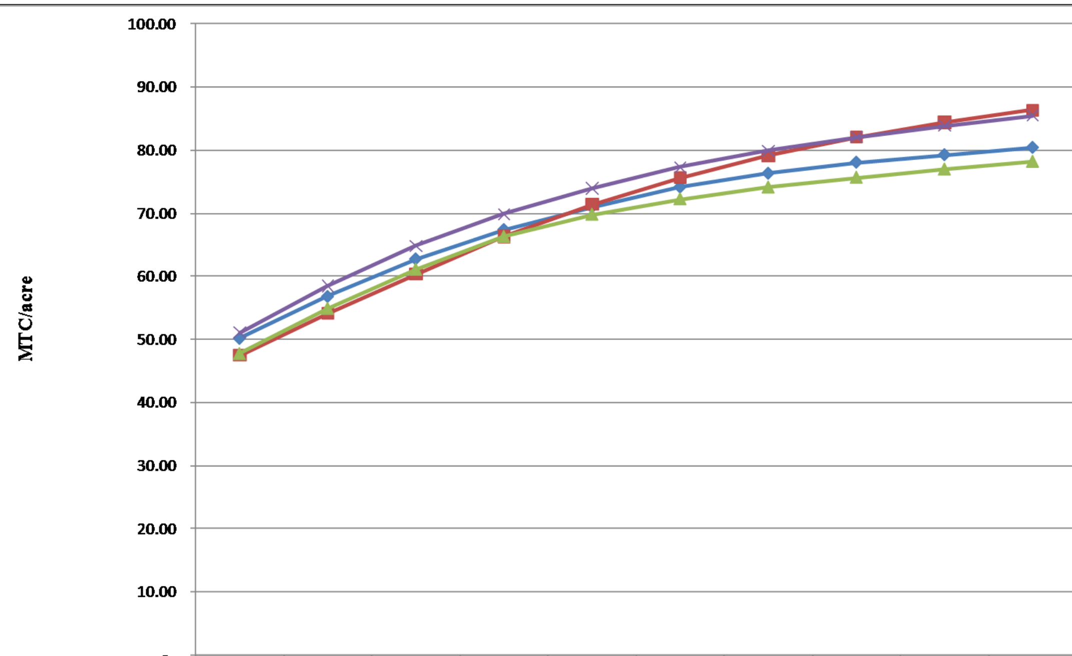
## Exhibit 5-6c: Heavy Harvest BA40 TSC Accumulation by Cover Type




| | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|
| HE - Heavy Harvest BA40 (65% T&L Removed) | 21.60 | 28.16 | 37.46 | 47.03 | 55.32 | 62.73 | 69.47 | 75.07 | 80.29 | 84.87 |
| MH - Heavy Harvest BA40 (65% T&L Removed) | 25.09 | 32.02 | 42.46 | 51.75 | 58.73 | 63.90 | 68.28 | 72.40 | 75.92 | 78.92 |
| MO - Heavy Harvest BA40 (65% T&L Removed) | 22.53 | 29.63 | 38.34 | 46.19 | 52.98 | 59.08 | 64.02 | 67.99 | 71.33 | 74.52 |
| NH - Heavy Harvest BA40 (65% T&L Removed) | 26.36 | 31.70 | 41.37 | 50.25 | 56.28 | 60.45 | 63.91 | 66.95 | 70.26 | 72.27 |
| WP - Heavy Harvest BA40 (65% T&L Removed) | 25.73 | 32.23 | 42.13 | 50.20 | 56.37 | 61.28 | 65.32 | 68.78 | 71.93 | 74.83 |

Year - MTC/acre Total Stand Carbon

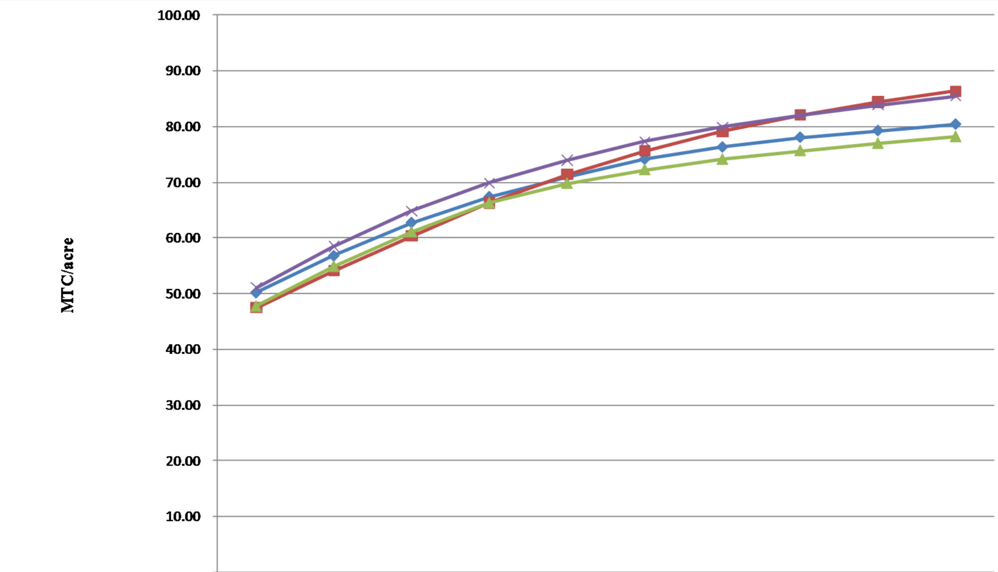
## Exhibit 5-7: Ownership Similarities in Carbon Accumulation Over Time by Cover Type (TSC)




| | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|
| Public - NH - Unmanaged | 50.17 | 56.78 | 62.72 | 67.35 | 70.92 | 74.07 | 76.25 | 77.99 | 79.18 | 80.33 |
| Public - WP - Unmanaged | 47.45 | 54.11 | 60.35 | 66.32 | 71.40 | 75.61 | 79.10 | 82.04 | 84.39 | 86.32 |
| Private - NH - Unmanaged | 47.74 | 54.89 | 61.08 | 66.27 | 69.78 | 72.22 | 74.07 | 75.62 | 76.92 | 78.14 |
| Private - WP - Unmanaged | 51.11 | 58.44 | 64.79 | 69.86 | 73.96 | 77.30 | 79.91 | 82.04 | 83.86 | 85.49 |

Year - MTC/acre Total Stand Carbon

### Exhibit 5-8: Tops and Limbs Contribution to Total Stand Carbon

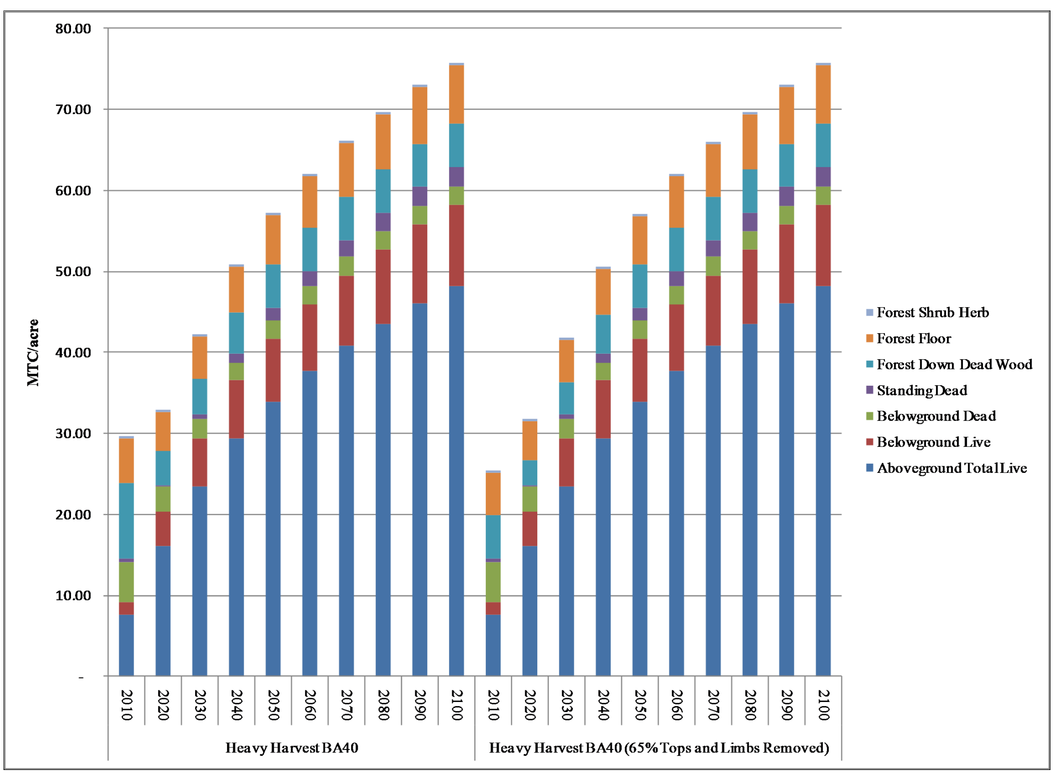



| | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|
| Public - NH - Unmanaged | 50.17 | 56.78 | 62.72 | 67.35 | 70.92 | 74.07 | 76.25 | 77.99 | 79.18 | 80.33 |
| Public - WP - Unmanaged | 47.45 | 54.11 | 60.35 | 66.32 | 71.40 | 75.61 | 79.10 | 82.04 | 84.39 | 86.32 |
| Private - NH - Unmanaged | 47.74 | 54.89 | 61.08 | 66.27 | 69.78 | 72.22 | 74.07 | 75.62 | 76.92 | 78.14 |
| Private - WP - Unmanaged | 51.11 | 58.44 | 64.79 | 69.86 | 73.96 | 77.30 | 79.91 | 82.04 | 83.86 | 85.49 |

Year - MTC/acre Total Stand Carbon

*Note: Comparison of harvest scenarios with all tops and limbs retained onsite following harvest versus removing 65% of tops and limbs (BAU 32%, Heavy Harvest BA40, and Commercial Clearcut). Total Stand Carbon values reflect the movement of carbon from tops and limbs into the down dead and forest floor carbon pools over time.*

### Exhibit 5-9: Carbon Pool Comparison




*Note: Carbon pools after a Heavy Harvest (BA40) when 100% of Tops and Limbs are retained vs. 65% removed.*

## 5.5 CONCLUSION

What do we know about modeling carbon accumulation patterns with and without harvesting?

- The basic elements of stand dynamics (and thus carbon dynamics) are the interaction among: space, light, species silvical characteristics (how they grow, regenerate, light tolerance, moisture tolerance), and site characteristics. The FVS model handles the first three elements quite well. We have held the fourth element constant throughout.

- Starting condition matters. No two acres of "natural" forest will be exactly alike. Stand development (particularly in the form of carbon growth and yield) is the reflection of the unique attributes of a given acre, but broad patterns are somewhat predictable based on what we know about the silvical characteristics of individual species and how they interact with each other. Starting diameter distribution (or mean diameter) is a driver of carbon accumulation rates since growth rates will depend on the current diameter of the individual trees making up the stand.

- Basal Area (square feet per acre) in combination with Trees Per Acre (density) is a driver of carbon accumulation rates since it reflects the space available to grow and regenerate.

- Species composition of a plot/stand is also a driver. Differential rates of growth drive differential rates of carbon accumulation. Allometric equations of hardwood vs. softwood are also a factor (e.g., taper, tree architecture).

- The above elements all relate to the influence of stand history on current conditions as well. This history includes the impacts of prior harvests and stand origin (e.g., old field, fire, 1938 hurricane). From a modeling and stand dynamics perspective, stand age (and tree age) also influences biomass/carbon growth rates. Some opportunities exist to "reset" an understocked or degraded stand. Conventional wisdom of foresters often says you would be better off starting over; it appears that can be true if regeneration yields desirable species—but it may just be a carbon/biomass response and the quality species mix for long-term growth may be sacrificed.

- The removal of tops and limbs generally has little impact on stand level carbon dynamics in Massachusetts forests. Tops and limbs that are not removed during a harvest decay quickly, generally within 10 years. If tops and limbs are a small proportion of the total harvest, then new growth will compensate for the removal within 10 years as well.

- Apart from severely understocked or degraded stands, carbon accumulation onsite in unmanaged stands will exceed onsite storage in managed stands in the long term (i.e., greater than 90 years).

- The current "business-as-usual" light harvest in the canopy increases the growth rate in the initial ten-year period, but very quickly returns to approximately the same as the unmanaged growth rate. Over time these BAU stands approach unmanaged carbon stocking but do not quite catch up after 90 years. When considered in the context of the amount of forest harvested annually in Massachusetts there is little impact of harvesting on the onsite forest carbon balance across the state.

- The scenarios we defined as "biomass" harvests (Biomass 40%, Biomass BA40, Biomass BA60) maintain high growth rates for several decades. Because of this increased growth rate, even the heavier harvested stands can reach almost 90% of the volume that could have been achieved in an unmanaged scenario. So, over a long period of time, biomass harvests have an opportunity to recover a large portion of the carbon volume removed during the harvest. However, this assumes no future harvests in the stand as well as an absence of any significant disturbance event. Both are unlikely.

- The FVS NE Variant is an effective tool to evaluate stand-level response of forest carbon to harvesting for relatively long time periods in Massachusetts. The model has known limitations but generally reflects what we know about trends in forest stand dynamics.

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