

Valuing Timber and Carbon Sequestration in Maryland Using MD-GORCAM

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PREFACE

Wood products can store carbon removed from the atmosphere by trees for long periods, potentially helping to offset some of the carbon dioxide emissions that are believed to be contributing to global warming and climate change. We undertook this study to examine whether harvesting practices in Maryland's state-owned forests could be modified to increase the amount of carbon that would be sequestered, and whether it would be economically justified to do so.

The study uses a carbon accounting model that is being developed by the Power Plant Research Program (PPRP) to evaluate carbon sequestration projects in Maryland. Part I of this report describes the assumptions and approximations that were used to improve the tree growth calculations included in the model and adapt them to the forests managed by Maryland's Department of Natural Resources. Parameters in the growth equations were derived from Maryland forest data, and then rules of thumb that approximate forest harvesting practices in the state were applied. The result can be characterized as the technical production function for important environmental services provided by Maryland's state-owned forests, and hence can be used as the basis for valuing those services.

Part II uses this technical production function to consider the amounts of harvested timber and carbon sequestered as joint forest products. To show the effects of different forest management practices on rates of carbon sequestration, different harvest rotation intervals are compared with respect to their expected timber production and carbon sequestration benefits. This is accomplished by making "per acre" estimates of carbon sequestration by length of the rotation interval, and similar estimates for timber. The comparisons are ultimately made between average annual increments for carbon and timber under the different rotations. Finally, we use historical timber values and likely carbon sequestration market prices to estimate the contributions of each to the value of an acre of harvested forestland.

By describing the biological processes and their economic interpretation separately in Parts I and II, the authors hope that the reader can easily navigate the study and find the results of most interest. It is our belief, of course, that the reader who reads both parts of the study will gain a more complete understanding of the complementarities between timber production and carbon sequestration. Because harvested forest land is much more readily managed for net long-term carbon sequestration benefits than other categories of forest land, these complementarities will be of great importance in developing effective carbon management programs.

The study would not have been possible without many discussions and much practical input from Jack Perdue and Dan Rider, both with the Forest Service of Maryland's Department of Natural Resources. We also gratefully acknowledge the funding provided to Robert Wieland from a USDA-CSREES Special Grant to the Harry R. Hughes Center for Agro-Ecology and to Donald Strebel through PPRP's Biology Integrator Contract with Versar, Inc.

Errata

Since the original publication of this paper, several errors have been found and corrected. The changes are as follows:

- Page 19, the figure 1,381 lb/acre has been corrected to read 1,481 lb/acre.
- Page 20, in the first line the figure “72 percent” was given as the ratio of the difference between scenario 1 and scenario 4. This has been corrected to read “38 percent”.
- In Table 2, page 21, the line titled Red Maple, Scenario 2, the value for sawdust and chips that formerly read “12” has been corrected to read “30”.

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Part I.
Adapting MD-GORCAM for DNR Forestry Applications

Donald E. Strebel

Introduction

In several previous studies, Maryland's Power Plant Research Program (PPRP) has applied a carbon accounting model to evaluate potential carbon sequestration projects in Maryland. The model, called MD-GORCAM, has consistently shown that among natural systems harvested forests have the greatest potential for removing carbon dioxide from the atmosphere. In general, this is because less biomass is allowed to decay *in situ*, growth rates are not allowed to stagnate, and wood products are frequently preserved for very long times. The model, however, has not yet incorporated species-level growth rates typical of Maryland or actual forestry management practices used in the state. In this study we introduce realistic growth parameters and management scenarios using information from several state forests managed by the Maryland Department of Natural Resources (DNR).

MD-GORCAM is an implementation of the Graz-Oak Ridge Carbon Accounting Model (GORCAM, Schlamadinger and Marland, 1996) that has been specifically adapted for carbon sequestration studies in Maryland ecosystems. GORCAM is a compartment model that tracks the flow of carbon between a number of temporary and permanent storage pools, including vegetation, litter, soil, products from harvested biomass, and landfills. A simplified conceptual diagram of the model is given in Figure 1; in practice there are many more compartments and flows than shown in this schematic. Parameterizing the model entails setting inter-compartment carbon flow rates (e.g., litter creation rates) and within-compartment process rates (such as growth or decay rates), along with specifying external factors such as harvest frequency and the fraction of harvested biomass that goes to various product categories. For details on the selection, testing, and initial parameterization of GORCAM for forest carbon sequestration studies in Maryland, the reader is referred to Strebel, et al., 2003.

One of the areas that the initial studies indicated required more work was calibrating the parameters to specific species, growth conditions, and management practices. In order to simulate the accumulation of carbon on a forest plot, MD-GORCAM requires an accurate description of the average rate at which trees grow. Ideally, the rate would be determined from a time series of measurements of individual tree age and size at the location of interest. Such data are rarely collected, so it is usually necessary to infer the growth rates from forest inventory data. These data, however, are normally aggregated over space and time, and also include the effects of harvesting and natural mortality, which co-vary with the growth rate. In the present work we have developed analysis methods and approximations that yield a unique and realistic value for the growth rate, based on broad-scale forest inventory data. Where additional tree-specific information is available from the sample plots used in the forest inventory, these approximations can be refined or eliminated.

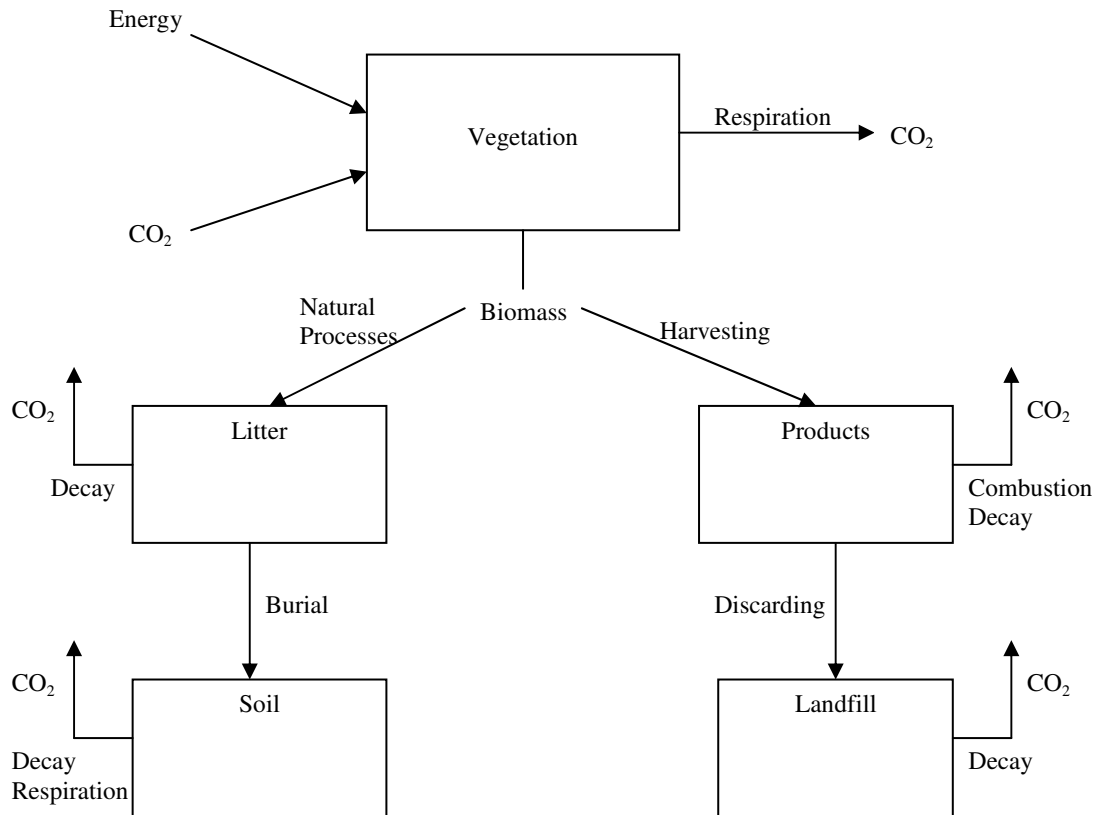


Figure 1. *Simplified Carbon Accounting Model Schematic.*

The way in which a forest plot is managed can also affect the amount of carbon stored. Strebel, et al. (2003) analyzed the amount of carbon storage predicted by GORCAM simulations under different harvest scenarios. Using soil and litter parameters for a generic deciduous hardwood community, and approximate growth rates, harvest rotation was found to be the most significant management parameter affecting the total amount of carbon sequestered (averaged over a 400-year period). To estimate the amount of carbon stored under different forest management schemes, simulations with harvest rotations of 25, 50, and 100 years, as well as continuous growth with no harvest, were run. The simulations showed that an optimized rotation schedule could provide an increase on the order of 50% more total stored carbon for the plot, even though using longer rotations would maximize individual tree biomass.

An additional factor in forests managed for commercial purposes is selective harvesting at one or more intermediate stages to reduce competition and increase the volume of marketable timber. As originally developed (Schlamadinger and Marland, 1996), GORCAM did not include such intermediate thinning options and was constrained to one growth rate (either for a single species or averaged over the plot). The focus of our current research efforts is to assess the importance of multiple species plots, rotation interval length, and harvest management regimes in Maryland forests and adapt the model accordingly. The present work improves the approach for setting single species growth parameters, incorporates a more refined version of the logistic growth model, and

includes typical thinning practices. Additional work will be required to allow integrated multi-species simulations.

The Tree Growth Models

MD-GORCAM currently provides the same two alternate growth models incorporated in the published version of GORCAM from which it was derived. These models both account for more rapid growth for younger trees and slower growth (up to a fixed biological maximum size) for older trees using basic mathematical functions. The "logistic growth" model is a bit more complex, but usually fairly realistic for biological growth processes, such as the biomass growth of individual trees. It is described by the equation

$$B(t) = (B_0 B_M) / (B_0 + (B_M - B_0) \exp\{-r (t - t_0)\}) \quad (1)$$

where $B(t)$ is the biomass at time (or age) t ,
 B_0 is the biomass at the initial time (or age) t_0 ,
 B_M is the maximum possible biomass,
and r is the intrinsic growth rate.

It is important to recognize that this is a continuous description that is intended to capture the average rate at which biomass accumulates. Although one could attempt to include the year-to-year growth variations that occur as environmental conditions fluctuate, this is not necessary when the life-cycle of the species is long compared to the duration of the fluctuations, as is true with trees (Strebel, 1980).

Most tree data are not expressed in terms of biomass, but in terms of the directly measurable parameter diameter-breast-height (dbh). Allometric relations between dbh and biomass have been determined from observations for many species, and a compendium of these relations is available (Jenkins, et al., 2004). The recommended relations for Maryland species are given by Frieswyk and DiGiovanni (1990). Table 1 indicates the relations that we have applied for the three species used in this study. Given the available data, these three species were chosen to represent the range of species

Table 1. DBH Biomass Relations

Study Species	Green Weight Reference Species	Equation	Units	Source
Red Maple	Red Maple	$\ln(B) = 1.5144 + 2.3619 \ln(\text{dbh})$	B: pounds dbh: inches	Young, et al., 1980
White Oak	White Oak	$\log_{10}(B) = \log_{10}(2.0452) + 2.7470 \log_{10}(\text{dbh})$	B: pounds dbh: inches	Wiant, et al., 1977
Loblolly Pine	Eastern Hemlock	$\ln(B) = 1.4094 + 2.3556 \ln(\text{dbh})$	B: pounds dbh: inches	Young, et al., 1980

growth rates encountered in Maryland: Red Maple is one of the fastest-growing hardwood species in the state and White Oak is one of the slowest; Loblolly Pine is the primary softwood species that is harvested.

Forest inventory data for an area provide the number of trees in each of a set of size classes. Each size class typically represents a 2" range of dbh values, although wider intervals are used for very small and very large trees. Inventories are usually conducted at an interval of 10 years, during which one of three things can happen to a tree in a specific class: (1) the tree can remain in the class; (2) the tree can be removed from the inventory by death or harvesting; (3) the tree can grow bigger and move into a larger size class. In addition, any new trees that sprout (and survive) during the interval will be added to the first class. The change in the number of trees in each class between two successive inventories is thus determined by the average growth rate and the rate of removals.¹

Using the observed class change data to recover the growth rate is possible if all of the additions and subtractions of trees between inventories can be estimated. The number of new arrivals to the first class (ingrowth) and the number of dead or harvested trees that are removed are provided by the forest inventory statistics. The approximate amount of time that a tree spends in each dbh class can then be determined algebraically given an estimate of how fast trees in the last "catch all" dbh category are removed. If, in addition, the age at some fixed size (say 6") is known or assumed, these "retention times" can be used to construct an approximate relation between age and dbh for the species in question. When the biomass relations in Table 1 are applied to the dbh values, the result is a set of biomass vs. age points that can be used to estimate the biomass growth curve (e.g., Table 2). We have used Maryland forest inventory data from Frieswyk and DiGiovanni (1988), which provides statewide statistics for several species and species groups, based on compatible sample designs for both 1976 and 1986, to derive such data sets for the three species.

We were able to improve some of the approximations in the above analysis method by using data collected in sampled plots during the Savage River Forest Inventory of 1999-2000. These data provide both age and dbh measurements for sample trees in each plot. Thus, we were able to determine the initial age (t_0), taken to be the youngest age of 6" dbh trees, and an approximate rate at which dbh changes with age for several additional dbh intervals. These approximations represent the fastest growth rate consistent with the data in that forest, and were used to recalibrate the retention times derived from the statewide inventory tables to generate the ages shown in Table 2. Similar adjustments should be made on a forest-by-forest basis, but plot level data were not yet available for the other DNR forests at the time of the analysis.

¹ In mathematical terms, this is known as a birth and death process. The formal description when many discrete classes are considered is well-known (often called the Leslie Matrix in demographics), but somewhat complex and not suitable for presentation here. Inverse analysis of the population change over a specified time interval to determine the transition rates between classes and the retention time for an individual in a class is algebraically straightforward if sufficient data are available.

Table 2. Growth Curve Data Points

Diameter Class (in.)	White Oak		Red Maple		Loblolly Pine	
	Biomass (lb.)	Age (yr.)	Biomass (lb.)	Age (yr.)	Biomass (lb.)	Age (yr.)
6	281	24.1	313	17.7	279	20
8	619	31.9	618	24.3	549	26.7
10	1142	39.8	1046	31.0	928	33.3
12	1885	47.6	1609	37.7	1426	40.0
14	2879	55.5	2316	44.3	2051	46.7
16	4154	63.3	3175	51.0	2809	53.3
18	5741	71.2	4193	57.7	3707	60.0
20	7668	79.0	5378	63.2	4751	66.7
25	14155	94.9	9109	74.0	8037	83.3
33+	30347	121.9	17550	94.7	No trees in class	

The above procedure was used for Red Maple and White Oak; Loblolly Pine is a Coastal Plain species that is not represented in the Savage River data set. We used model data from simulations reported by Wieland (2004) to set the initial age and growth rates for this species. The simulation models (ECONHDWD + PCTHIN), however, are based on actual data sets.

The biomass values and ages in Table 2 can be used to estimate the biomass at any age in the tree growth cycle. Such interpolations are useful to allow MD-GORCAM to track carbon fluxes (e.g. branch litter creation and decay) that occur on faster time scales than whole tree growth and death. Instead of interpolating linearly between each set of points, the GORCAM approach is to replace the table with an approximate mathematical function that is specified by a few key parameters. The simplification that this approach entails may result in calculated values that are near, but not exactly the same as, those in the original data table. The advantage, in addition to computational efficiency, is that the key parameters can be interpreted in terms of observable biophysical characteristics of the species, such as the average rate of growth or the maximum attainable biomass.

When the approximate growth function is parameterized from proxy data, such as the points in Table 2, there is no direct connection to the growth of individual trees in the forest, and some judgment must be used in establishing the reasonableness of the results.² We have chosen to use Equation (1), which describes most resource-limited growth processes well, and to fit it to the data points by a straightforward least-squares procedure (i.e., minimizing the sum of the squares of the biomass differences between the curve and

² The best method for determining the parameters for a mathematical model varies depending on the data and information available. When calibration data specific to the model are not available, parameters must be estimated, inferred from proxy data, or approximated using computational algorithms. A good discussion of using models for carbon sequestration accounting, along with a suggested ranking scale, is found in Section 2 of DOE 2006. Our approach is not entirely satisfactory due to the dependence on regional inventory data rather than specific forest-by-forest growth observations.

the data points). The quantitative results are given in Table 3 and the growth curves are shown graphically in Figure 2.

This "best fit" parameterization reasonably interpolates between the values in Table 2, with particularly close agreement at tree ages at which harvesting is likely to occur. The forest inventory data are not sufficiently reflective of individual trees to examine statistically whether this is the best growth curve or to explore the differences that would result from using different curve-fitting procedures. With more refined data sets, such as biomass vs. age measurements from individual trees in a specific forest, the parameters could be calibrated precisely. We would then be able to analyze the intrinsic uncertainty incorporated in modeling growth with the logistic equation and the variability expected within and among the different DNR forests.³

Table 3. Growth Equation Coefficients

Species	B_0	B_M	r	t_0 (6")	Notes
Loblolly Pine	278.7	10500	0.0752	20.0	Uses model ages from 6" to 25" dbh
White Oak	280.8	39100	0.0629	24.1	Savage field data ages from 6" to 20" dbh
Red Maple	313.0	24000	0.0689	17.7	Savage field data ages from 6" to 18" dbh

The growth curves in Figure 2 illustrate the main differences in tree species that are in the managed areas of Maryland's state-owned forests. The curves have been extended beyond the range of ages indicated in Table 2 to illustrate the maximum size values obtained from fitting the growth equation. Red Maple grows most rapidly, lives moderately long, and reaches an intermediate maximum size. White Oak initially grows the slowest, but lives the longest and reaches the largest sizes. These behaviors are consistent with the known biology of these species, and can be taken to mark the normal range of hardwood forest growth characteristics in Maryland. Most other hardwood species that are encountered in state forests would be expected to fall between these two curves. In contrast, Loblolly Pine, the main commercial softwood species in the state, initially grows relatively rapidly, but the growth slows much sooner than in hardwood species and it appears to attain smaller maximum biomass. Because the forest inventory data on Loblolly Pine is likely dominated by commercial plantations, which are managed to force rapid growth and quick turnover, these characteristics may not reflect the natural growth of Loblolly Pine in optimum environments. Note, though, that Loblolly Pine is at the northern limit of its range in the Coastal Plain areas of Maryland, so optimum growth is not expected. Overall, the three growth curves appear to exhibit reasonable tree sizes, growth rates, and lifetimes, and should be sufficient to illustrate differences due to harvesting practices.

³ We subsequently obtained a data set from Fernow Experimental Forest in West Virginia that records the dbh of individual trees at 5 year intervals. With extensive analysis, these data may allow us to refine our growth rate estimates, but still might only reflect West Virginia growth conditions and not be applicable to specific Maryland forests.

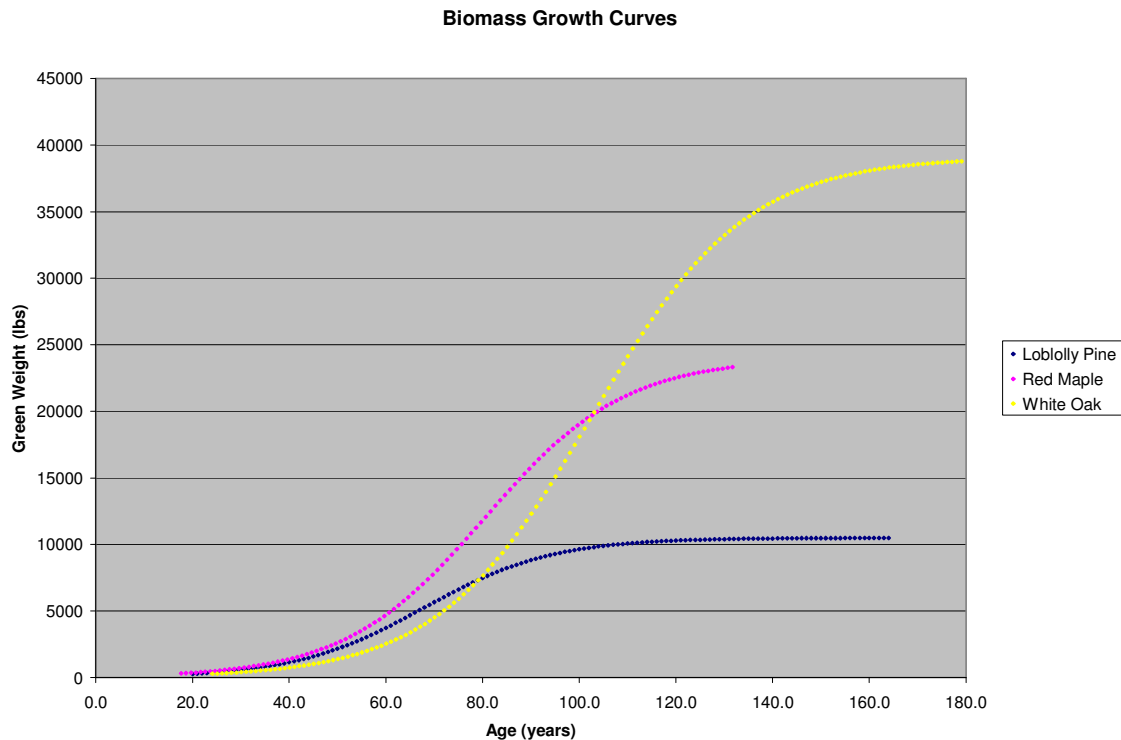


Figure 2. *Interpolated Growth Curves for Three Maryland Tree Species*

The Plot Models

The growth curve for individual trees is not sufficient to describe the net accumulation of biomass by a stand of trees in a forest. As neighboring trees grow larger, they will begin to compete for access to sunlight, water, and soil nutrients. Eventually the weaker trees will die and the remaining trees will expand into the released space. Most of the biomass of the dead trees will be lost as the branches, stems, and roots decay, and the carbon will be returned to the atmosphere. A portion of the carbon, however, will be incorporated into the permanent soil carbon reservoir. Thus, the carbon accounting system must determine how many trees die from crowding, track the decaying litter, and allow for the carbon that is immobilized in the soil.

The number of tree stems that a given area can support is limited by the available sunlight and water. It is ecologically reasonable to assume that under normal conditions the number of trees at any time will be the maximum that can be sustained by the plot's sunlight and water resources, which are approximately constant. Since the amount of sunlight and water used by an individual tree should be proportional to the tree basal area, the total tree basal area of the plot is also approximately constant over time. The crowding effect can then be determined by calculating the number of trees that can fit into available basal area at any given time.

For an even-aged stand of trees, such as might result from natural reseeded after a clearcut, all of the trees have the same size (dbh). Thus, the total basal area in the plot is the just number of trees ($N(t)$) multiplied by the basal area of an individual tree ($\pi(\text{dbh}/2)^2$). As individual trees grow, the number of trees must decrease to keep this value constant. The result of equating the expressions for the total basal area at two different times is:

$$N(t) = N_0 (\text{dbh}(t_0) / \text{dbh}(t))^2 \quad (2)$$

where $N_0 = A_b / A_0$, A_0 is the basal area of one tree at time t_0 ,
 A_b is the (constant) basal area of the plot,
and $\text{dbh}(t)$ is derived from $B(t)$ using the relations in Table 1.

Although this is a theoretical relation, it is reassuring that the number of trees reported in successive dbh intervals by Frieswyk and DiGiovanni (1988) decreases in the fashion predicted by Eq. (2), except for sudden drops at sizes at which thinning or harvesting are expected. The Frieswyk and DiGiovanni data, however, cannot be used to confirm Eq. (2) because the areas occupied by the trees are not reported. Systematic changes in area occupied by successive cohorts of a tree species, or ingrowth of other species after plot thinning, may be confounded with the crowding effect in their data.

DNR foresters (Perdue, 2006) have told us that the basal area of naturally seeded hardwood stands after thinning about 1/3 of the trees is around 70 sq. ft./acre. This implies that the pre-thinning density is approximately 100 sq. ft./acre.⁴ We have used this value for A_b in our plot simulations and calculated, on a yearly basis, the number of trees that died. The biomass from the dead trees is transferred to the "litter" carbon pool (see Fig. 1) and tracked separately as described below. The total live biomass on the plot continues to increase, of course, as shown in Figure 3 for the two hardwood species used in the study. The combined effect of crowding deaths plus logistic growth of individual surviving trees is a roughly linear rate of plot biomass increase over the time periods of interest in silvicultural operations. Note that this linear behavior may define circumstances under which the simple linear growth approximation (Marland and Marland, 1992) included in GORCAM would be appropriate.

There are two cases in which crowding as described by Eq. (2) does not apply. After a thinning operation, the plot basal area will be below A_b and crowding deaths can be ignored until the basal area increases back to A_b . Similarly, in softwood plantations the more uniform tree spacing minimizes crowding effects during most of the tree's lifespan. More frequent thinning and the application of fertilizer also help reduce crowding deaths and maintain a high basal area. It appears that the stem density in Loblolly Pine plantations is high enough to achieve a basal area of 150 to 200 sq. ft./acre at harvest.

⁴ These values are consistent with the U. S. Forest Service standard for full use of the growth potential of forest land in the Eastern United States, which is considered fully stocked at 75 - 97 sq. ft. of basal area per acre (p. 11, Frieswyk and DiGiovanni, 1988).

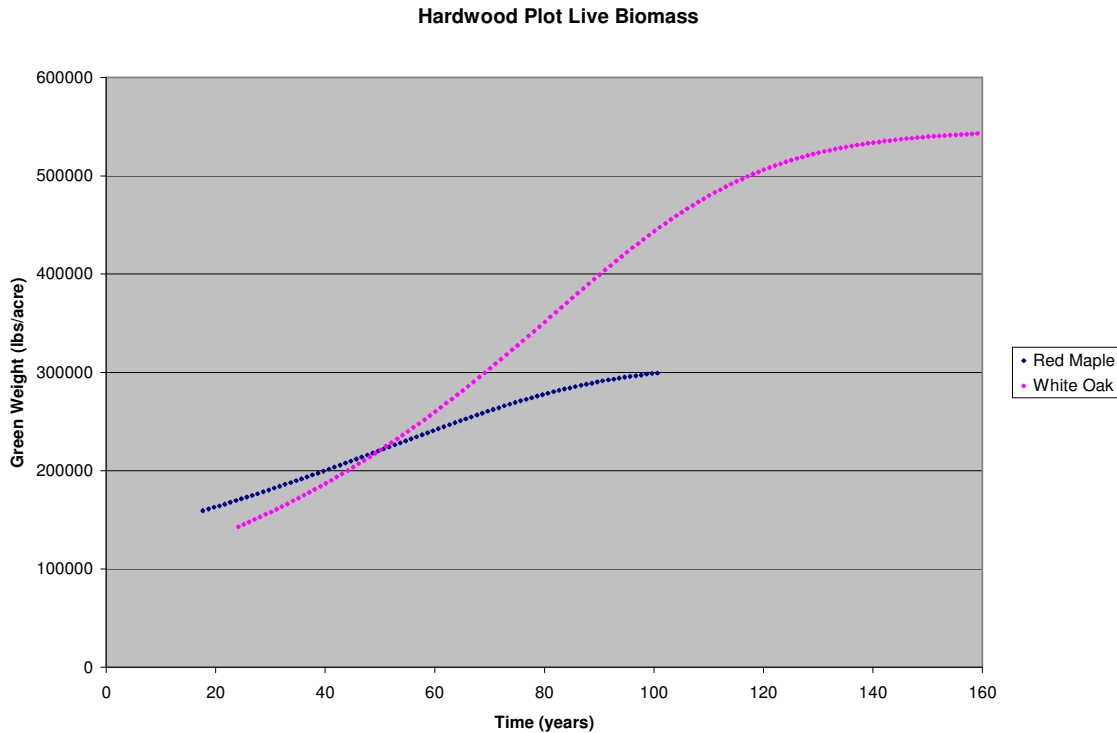


Figure 3. *Live Tree Biomass in a One Acre Plot with Constant Basal Area*

The litter decay and soil sequestration processes are dependent on many local factors, including temperature, precipitation, and soil composition. Local-scale data on these factors are only available for a few intensively studied experimental forests. Therefore, location-specific plot growth simulations are not usually possible. Fortunately, GORCAM only requires the average rates at which biomass accumulates or decays in the litter or soil pools, and the long-term results are relatively insensitive to these rates. In a previously published study (Strebel, et al., 2003, Table 4-2), sensitivity tests demonstrated that up to 50% variation around realistic average rates had only small effects (less than +/- 2%) on total carbon stored. Thus, even fairly arbitrary values for the litter decay and soil accumulation rates should yield results that are of the correct order of magnitude and show the correct trends in comparisons between scenarios.

We consider three general classes of litter:

- (1) leaves, twigs, and small branches that decay rapidly, releasing most of their carbon back to the atmosphere in 1-2 years;
- (2) branches and small stems that have about a 10 year longevity;
- (3) large stems and deadwood that decay slowly over decades.

In the plot simulations, class (1) litter biomass is treated as decaying instantaneously, while class (2) litter biomass is given a decay rate of 10% of the remaining biomass per year. Class (3) litter biomass is assumed to have a decay rate of 5% per year (e.g. about 2/3 of the biomass is gone in 20 years) and to have enough carbon (vs. nitrogen and other nutrients in the surrounding soil) to result in a small proportion (1% per year) escaping

decay and being permanently sequestered in the soil.⁵ These numbers are useful for illustrating the relative importance of the deadwood carbon pools in comparing different scenarios, but should not be taken as an accurate description of the process in any specific forest plot.

To complete the model, the proportion of deadwood that goes into the litter and soil pools must be assigned. This is another area in which actual statistics are hard to obtain because intensive, long-term observations are required. For the present simulations, we have assumed that small trees (generally ≤ 12 " dbh) that die produce a 50-50 mix of rapid-decay litter and 10-year decay litter. Larger trees are assumed to have a smaller proportion of rapid-decay litter (25%), but to have 25% of their biomass in large branches and stems that enter the 20-year decay pool when the tree dies. The soil pool gradually accumulates carbon from the 20-year decay pool and holds it unless disturbed (see harvest discussion below). The decay and sequestration assumptions are summarized in Table 4.

Table 4. Deadwood Decay Parameters

Tree Size at Death	Biomass to Atmosphere	Biomass to 10-year Litter Pool	Biomass to 20-year Litter Pool	Biomass to Permanent Soil Pool
	(instantaneous decay)	(0.1 of pool returned to atmosphere/year)	(0.05 of pool returned to atmosphere/year)	(0.01 of 20-year pool added/year)
Small (≤ 12 " dbh)	50%	50%	None	None
Large (> 12 " dbh)	25%	50%	25%	Indirect

The Harvest Scenarios

Natural tree death results in cycling most of the carbon stored in the tree back into the atmosphere within a few decades. The wood from trees that are harvested, on the other hand, may be preserved intact for very long periods. GORCAM tracks the fate of carbon in wood products based on their longevity. In the present analysis, wood from harvested trees may be left in the forest to decay, lost during processing to transient materials like sawdust or wood chips, or end up as lumber that lasts for relatively long periods.

The information available from forestry experts about the types and amounts of wood products from harvesting operations in Maryland's state forests is reliable, but not based on quantitative measurements. Department of Natural Resources foresters have

⁵ By only considering the proportion of the carbon that is immobilized in the soil, we have not explicitly accounted for litter material that is incorporated into the soil organic matter and then used and released back to the atmosphere by soil microbes and other elements of the soil community. The effects of these short-term soil processes on carbon fluxes are included instead in the litter decay totals. Thus, the soil storage pool does not represent total soil organic matter, only the portion actually sequestered against atmospheric release. Any substantial long-term accumulation of carbon in the soil occurs in this portion.

told us that roughly half of the tree biomass is left behind in the forest as unusable.⁶ Of the half that is removed from the forest, only about 50% is actually turned into lumber. Another 25% is rendered into sawdust during processing, and the remaining 25% ends up as wood chips. These proportions are in general agreement with the estimates for the Northeast region presented in tables D6 and D9 of DOE 2006, although there isn't a direct correspondence with the product categories that we are using.

In addition to the distribution of harvested material among the litter and wood product pools, the rates at which the products are created, recycled, or discarded must be specified. Given the difficulty of obtaining, or even of estimating these rates, we have simplified the accounting somewhat, as follows:

- (1) We assume that the material left in the forest adds directly to the existing litter pools and shares their fate.
- (2) The entire soil carbon pool is assumed to be released to the atmosphere as a result of disturbance by harvesting operations. This potentially underestimates total carbon sequestration, providing a conservative bias with respect to the natural death scenario, in which all soil carbon is assumed to stay sequestered.
- (3) The sawdust is assumed to decay and release its carbon back to the atmosphere immediately.
- (4) The wood chips are typically collected and processed into composite products that are marketed for use as solid wood substitutes. The chipwood products are treated as an intermediate term carbon storage pool (10-20 years sequestration), although we do not carry out further analysis of the size and decay of this pool.
- (5) We assume that the lumber products themselves form a long-term carbon storage reservoir, without accounting for their functional longevity or ultimate disposition.

The net result is an estimate of carbon sequestered in the lumber and chipwood at the time that it leaves the mill. Carbon accounting at this point is suitable for comparing different forest management approaches, since the downstream carbon fates will be similar for all approaches. The treatment of harvested products is summarized in Table 5.

Table 5. Distribution of harvested biomass.

Product:	Litter	Lumber	Wood Chips	Sawdust
Biomass Fraction:	1/2	1/4	1/8	1/8
Disposition:	Decays in 10-20 years	Long term carbon storage	10-20 year carbon storage	Carbon released to atmosphere

With these assumptions in place, simulations for a given harvest schedule can provide order-of-magnitude estimates for both wood product yields and carbon

⁶ There is increasing recognition that this residual material could be used for biofuels, e.g. Westbrook and Greene, 2007. We have not accounted for either fossil fuel use in harvesting or energy recovery from biofuels. These elements are highly specific to each harvesting operation and have opposing effects on carbon storage. We assume that the net impact is the same for all rotation scenarios in the same plot, and thus does not affect comparisons between scenarios.

sequestration amounts. The simplest scenario is a fixed-length rotation in which trees grow without management between clearcut harvesting events. This is the fundamental scheme built into GORCAM. Commercial forestry in Maryland, however, also employs one or two "thinning" harvests⁷ that alter the production and distribution of biomass. GORCAM must be modified to run in a piecewise fashion to account for these harvests and the growth of the forest plot between them.

The nature of thinning harvests differs depending on the type of trees in the forest. State foresters have told us that hardwood forests are usually thinned once during a rotation, to a basal area of about 70 sq. ft./acre. It appears from the Frieswyk and DiGiovanni (1988) inventory data that this thinning occurs when the trees are about 12-14" dbh. Final harvest then seems to take place, for the most part, when the remaining trees have reached 18-20" dbh. To deal with this thinning scenario, MD-GORCAM must allow the thinned stand to grow without crowding deaths until the basal area again reaches A_b (100 sq. ft./acre in our simulations). The thinning harvest also adds an instantaneous increase to the amount of litter, and a slug of carbon moves into the pool of products created from the removed wood. These effects can be seen as discontinuous changes in the curves in Figure 4.

Softwood management is more complex. Plots of young trees (about 15-20 years old) are thinned to 70 sq. ft./acre. We estimate from the Loblolly Pine growth curve that most trees are about 6" dbh at this thinning. Approximately 10 years later, when the trees are about 8" dbh, the plot is thinned a second time, leaving the best 100 trees per acre. The final harvest may occur when the trees are only about 40 years old and 12" dbh. This fast growth cycle with multiple interruptions and changing thinning criteria further complicates tracking the biomass, litter, and wood product carbon pools. In principle, however, it is handled in the same way as the hardwood case: the plot growth is broken into intervals during which crowding deaths occur and litter accumulates and others during which they do not. A summary of the thinning regimes is given in Table 6.

Table 6. Thinning Criteria for the Plot Simulations

	Hardwood	Softwood
Starting Basal Area	100 sq. ft./acre	100 sq. ft./acre*
Number of Trees at 6" dbh	509	509
Early Thinning	Not Applicable	To 70 sq. ft./acre at 6" dbh
Regular Thinning	To 70 sq. ft./acre at 12" dbh	To 100 trees/acre at 8" dbh
Harvest	Clearcut at 18" dbh or larger	Clearcut at 12" dbh or larger

* *Plantations may be artificially maintained at basal areas of 150-200 sq. ft./acre*

⁷ Thinning harvests selectively remove trees from the plot with the dual goals of obtaining usable wood and optimizing the growth of the remaining trees to the final clearcut harvest. This management approach is not the same as the "selective harvest" mode of GORCAM defined by Schlamadinger and Marland (1996), in which trees are selectively removed every time the plot reaches a threshold biomass, without ever harvesting the whole plot. We use the term "thinning harvest" to distinguish the Maryland management approach that we are adding to MD-GORCAM from the predefined selective harvest mode.

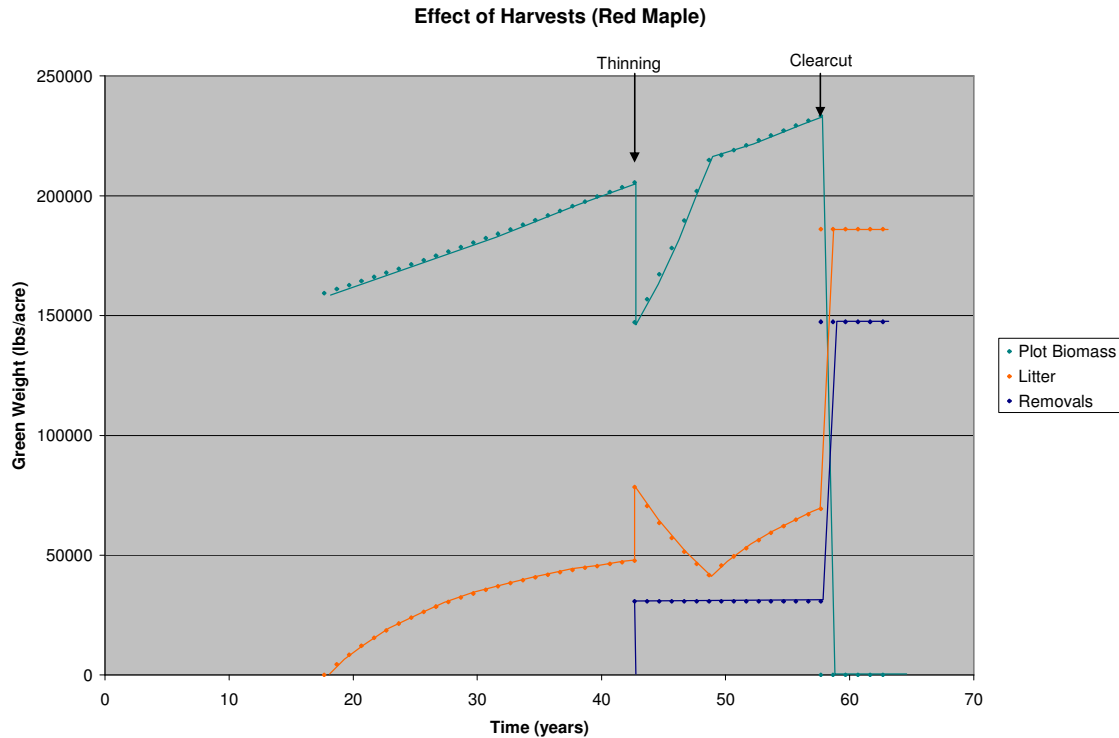


Figure 4. *Simulated Changes in Biomass, Litter, and Wood Products for a One-Acre Plot*

The full scenarios for the three species we have analyzed are built upon the parameters and assumptions given in Tables 1-6. Biomass accumulation, decay, and removal are computed for each growth stage for natural (unmanaged) forests and for managed (thinned) forests using several different rotation cycles (see Table 7). These simulations are carried out on a per acre basis for each species. While Loblolly Pine is typically grown as a monoculture, hardwood forests in Maryland are more often a mix of several species. To obtain more accurate estimates of the yield and carbon sequestration for hardwood stands, the results for each species in the stand should be weighted by the proportion of the area that species occupies. The detailed inventory data available for the DNR Forests may allow this refinement in a future study, particularly if the data are available to derive calibrated growth curves for the other important species in these forests. It should be recalled, though, that Red Maple and White Oak were chosen to reflect the range of growth rates and biomass to diameter ratios found in Maryland's hardwood forests. Therefore, we expect that carbon sequestration rates for most of the state's hardwood forests will fall between the results obtained for these two species.

Results and Recommendations

The results of the simulations are given in Table 1 of Part II of this report. Validating the simulations is difficult without detailed information on the trees in a plot that has been monitored over a full rotation cycle. However, the harvest amounts can be

Table 7. DNR Forest Simulation Scenarios

	Red Maple	White Oak	Loblolly Pine
Stage 1. Establishment	6" dbh trees are obtained about 18 years after a clearcut.	6" dbh trees are obtained about 24 years after a clearcut	6" dbh trees are obtained about 20 years after a clearcut.
Stage 1A. Early Thinning	NOT APPLICABLE	NOT APPLICABLE	Thinning harvest to 70 sq. ft./acre when trees are 6" dbh (20 years).
Stage 2. Growth Phase	Natural growth from 6" to 12" dbh.	Natural growth from 6" to 12" dbh.	Natural growth from 6" to 8" dbh.
Stage 3. Regular Thinning	Thinning harvest to 70 sq. ft./acre when trees are 12" dbh (43 years).	Thinning harvest to 70 sq. ft./acre when trees are 12" dbh (55 years).	Thinning harvest to 100 trees/acre when trees are 8" dbh (29 years).
Stage 4. Second Growth Phase	Natural growth to a basal area of 100 sq. ft./acre (14.4" dbh, 49 years); to 18" dbh at 58 years; to 25" dbh at 73 years; to 34" dbh at 100 years.	Natural growth to a basal area of 100 sq. ft./acre (14.4" dbh, 63 years); to 18" dbh at 74 years; to 25" dbh at 93 years; to 35" dbh at 140 years.	Natural growth to 12" dbh (43 years); to a basal area of 100 sq. ft./acre (13.6" dbh, 48 years); to 18" dbh at 60 years; to 25" dbh at 85 years.
Stage 5. Harvest/Death	(a) Clearcut at 58 years. (b) Clearcut at 73 years. (c) Natural death at 100 years.	(a) Clearcut at 74 years. (b) Clearcut at 93 years. (c) Natural death at 140 years.	(a) Clearcut at 43 years. (b) Clearcut at 60 years. (c) Natural death at 85 years.

converted to predictions of the lumber production of the plot. In Table 2 of Part II the predicted yields are compared to historical averages for the state forests. The degree of agreement is acceptable, given the approximations in parameterizing the model and the uncertainties in the management regimes represented by the historical yields. The most important sources of the differences between predicted and observed values are likely to be the conversion between biomass and board feet of lumber (which is dependent on wood density and milling practices, and hence on the species mix in the plot); the available harvest biomass in an actual mixed-species, multi-aged hardwood forest stand; and the efficiency of biomass removal in softwood forests (which can be much higher in managed plantations than in open woodland). Further discussion is in Part II.

The simulation scenarios were implemented as ad hoc spreadsheet calculations to introduce and test the variations from the standard GORCAM model that were necessary to describe tree growth and harvesting practices in Maryland. On the basis of the understanding this experimentation has produced, several changes to the MD-GORCAM software are recommended to allow it to simulate more realistic scenarios and increase its usefulness in tracking carbon sequestration projects.

- (1) The default GORCAM growth models should be augmented with a logistic + crowding model. The basal area parameter introduces an important concept to the model using a number that can be (and frequently is) directly estimated in the field.

- (2) The MD-GORCAM harvest rotation scheme should be revised to allow the user to specify up to two thinning harvests, with a choice of criteria (basal area, number of trees) for those thinnings. The current "selective harvest" option appears to be of little practical use in this regard.
- (3) The capability to grow multiple species simultaneously on a single plot should be incorporated into MD-GORCAM.
- (4) The dynamic soil model included in GORCAM uses a fixed (average) decay rate for all conditions. Soil disturbance during harvesting that mixes soil organic matter from surface and deeper layers may change the average rate and result in accelerated carbon release. The magnitude and duration of this effect should be evaluated and consideration given to temporarily modifying the decay rate in response to a harvesting event.

In addition to these modifications, carbon sequestration planning and tracking for offset credits (e.g. under the Regional Greenhouse Gas Initiative) would require follow up studies that fill in more details of species growth rates, litter and soil organic matter decomposition rates, and the amount and type of wood products that are (or will be) created after harvest. Carbon sequestration verification protocols should also be revised to include related measurements, so that delayed or avoided carbon emissions provided by wood products can be properly valued.

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Part II.
**Valuing Timber and Carbon Sequestration in Maryland's
State-owned Forestlands**

Robert C. Wieland

I. Introduction

Considerable effort has been extended to improve the measurement and accounting of carbon sequestration by forests⁸. On the international stage, carbon sequestration accounting protocols have been put forward so that benefits of carbon sequestering projects can be measured under standard definitions⁹. The European Union has supported the development of a carbon sequestration computational model that allows users to input data concerning specific forestry conditions and practices and to estimate their expected carbon sequestration effects¹⁰. While the latter provides a detailed accounting of the flow of carbon through a forest under a range of management and environmental conditions, it is not clear that it can be easily calibrated to measure changes in carbon sequestration under different management (i.e., length of harvest rotation) policies.

In Maryland, the Power Plant Research Program (PPRP) has supported research aimed at simulating the accumulation of carbon on forests in the state. Part I of this paper outlines the effort to adapt a more complete carbon model (MD-GORCAM) to better account Maryland-specific forestry applications. As discussed in Part I, these refinements to the MD-GORCAM model are calibrated with growth and volume predictions based on empirical data from all of Maryland's forests. In this part of the paper, we apply those modeled expectations to a subset of Maryland's forests – State-owned forestland. This focus on State-owned forestland allows us to compare the biomass estimates generated under the MD-GORCAM forestry module with a reasonably well-documented history of forest management and harvest outcomes.

The creation of carbon sequestration value in a forest is very similar to its creation of timber value. Both are dependent on the accumulation of biomass, which is, in turn, a function of species type, stocking rates, environmental factors, and time. Foresters have addressed the timber optimization problem by focusing on the land on which timber grows and the length of time any given stand of trees might be allowed to grow before its final harvest¹¹. Given the long-term nature of the atmospheric carbon problem, it is appropriate to take a similar view toward forests' carbon sequestration services.

⁸ See Lubowski and others 2006 and Sedjo 1999

⁹ See WRI/GHG, 2007. "Land Use, Land Use Change and Forestry Guidance for GHG Project Accounting".

¹⁰ See CASFORII/CO2FIX V 3.1 - A modeling framework for quantifying carbon sequestration in forest ecosystems at: <http://www.efi.fi/projects/casfor/>

¹¹ Henceforth this length of time between the start of a stand's growth and its "final" harvest will be referred to as a "rotation". This terminology makes clear that any stand's "final" harvest is part of an on-going cycle.

A standard forestry model for timber production accounts the growth characteristics of the species growing on the site, the value of the mix of wood products that can be generated from its timber and the value of future stands that can be grown there. At a zero discount rate, the maximum value is obtained for a site when its average annual net yield in timber value is highest¹². Within this general model, foresters are also concerned about the costs of managing the site and, in some instances, discount rates that are higher than zero.

If we wish to address the carbon storage impacts of a change in forest management in conjunction with its impacts on timber production, it is necessary to have consistent measures of change in both of these factors with respect to rotation length. The model described in Part I provides a convenient way to estimate per acre average annual rates of carbon sequestration and timber growth across a range of rotation lengths. The following section reports these per acre estimates for the State Forests' general management areas and then compares them with historical harvest volumes under current policies. As order-of-magnitude estimates, timber volumes predicted by the biomass model are shown to be near to historical harvest volumes on relevant general management areas. The next section describes harvest management on general management areas and uses historical harvest rates as a means of comparing carbon sequestration under several different harvest rotations. In a final section, average annual sequestration and timber values are reported for several rotation scenarios.

II. Estimating Biomass Accumulation on Maryland State-owned Forestland

Using the growth predictions of the biomass model and rules of thumb about the relations between tree biomass and carbon storage and processing, the number of pounds of carbon sequestered per acre of forest can be estimated. This carbon sequestration estimate accounts carbon returned to the soil, returned to the atmosphere and sequestered for varying lengths of time as wood products. Most importantly, this estimate of pounds of carbon sequestered per acre can be used to generate an average annual rate of carbon sequestration, so that different management scenarios using different timber rotations can be compared with respect to this important variable. **Table 1** reports the estimated average annual rates of carbon sequestration for several different rotation scenarios for White Oak, Red Maple and Loblolly Pine.

Under the four White Oak scenarios, the greatest difference in average annual sequestration rates is between scenarios 3 and 4. Scenario 4 is a 'no harvest option' which unfolds over 140 years. Scenario 3 is a 93 year rotation which has carbon coming off as timber in both a thinning and a regeneration harvest and which restarts the vigorous uptake of a growing forest more rapidly than scenario 4. If we use the estimated carbon sequestration rates for these two scenarios and account the difference between the two at

¹² In the discussion that follows, timber value is treated as a constant function of biomass. This greatly simplifies the discussion. In a more precise estimation, timber value might be more accurately described as an increasing function of biomass over some portion of its growth.

140 years, scenario 3 would have sequestered 147 tons/acre and scenario 4 only 120 tons per acre carbon over the period. Thus, the model predicts a 22 percent increase in carbon sequestration, depending upon whether one harvests the trees (at 93 years) or merely lets them grow old and be replaced in a natural succession of the forest.

Table 1: Expected Pounds of Carbon Sequestration Under Various Timber Management Scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Units
White Oak					
Returned to atmosphere	156,177	167,357	243,315	382,178	lbs/acre
Sequestered	152,690	148,849	194,952	240,586	lbs/acre
Sequestration Rate	2,063	2,011	2,096	1,718	lbs/acre/yr
Red Maple					
Returned to atmosphere	137,825	144,490	199,449	271,641	lbs/acre
Sequestered	118,640	115,564	135,305	148,065	lbs/acre
Sequestration Rate	2,046	1,992	1,853	1,481	lbs/acre/yr
Loblolly Pine					
Returned to atmosphere	47,855	76,806	80,185	184,186	lbs/acre
Sequestered	76,825	80,578	117,857	117,356	lbs/acre
Sequestration Rate	1,787	1,874	1,964	1,381	lbs/acre/yr
White Oak Scenarios					
Scenario 1	Grow to 12", Thinning at 12" Final harvest @18" (74 yrs)				
Scenario 2	Grow to 18", Final harvest @ 18" (74 yrs)				
Scenario 3	Thinning at 12" Final harvest @25" (93 yrs)				
Scenario 4	No thinning, no harvest to natural mortality (140 yrs)				
Red Maple Scenarios					
Scenario 1	Grow to 12", Thinning @ 12" Final harvest @18" (58 yrs)				
Scenario 2	Grow to 18", Final harvest @ 18" (58 yrs)				
Scenario 3	Thinning @ 12" Final harvest @25" (73 yrs)				
Scenario 4	No thinning, no harvest to natural mortality (100 yrs)				
Loblolly Pine Scenarios					
Scenario 1	Thinnings @ 6"dbh and 8"dbh, and clearcut @ 12"dbh (43 yrs)				
Scenario 2	Grow trees to 12" and clearcut (43 yrs)				
Scenario 3	Thinnings @ 6"dbh and 8"dbh, and clearcut @ 18"dbh (60 yrs)				
Scenario 4	No thinning, no harvest, to natural death at 85 years				

The differences between the maximum and minimum Red Maple scenarios with respect to rates of carbon sequestration are 2,046 lbs/acre for scenario 1, which has the shortest rotation and 1,481 lbs/acre for the ‘grow to 100 years and do nothing’ scenario 4. This

amounts to a 38 percent difference between scenario 1 and scenario 4. This means that on an average site, growing (almost) two crops of trees would sequester 38 percent more carbon as growing a single crop for 100 years on the site. These are more striking differences than the White Oak results. Yet White Oak grown under scenario 3 is predicted to sequester more carbon than Red Maple, under its most productive rotation.

Over the four modeled Pine scenarios, it can be seen that annual sequestration rates increase over the lengthening harvest rotations and fall considerably if the stand is left to die a natural death. Pine is a fast growing species that is sensitive to management treatments such as planting, pre-commercial thinning, fertilizing and competition control. The model correlates biomass accumulation to the general case found in Maryland forests that, for the most part, have not had intensive management. Moreover, our standard rule of thumb that only one half of the total biomass available comes off in a harvest, may be more appropriate for hardwoods, which have more biomass in limbs, than for Pine, which has a larger share of its biomass in its trunk. In these two ways, these estimates are likely very conservative with respect to Pine's carbon sequestration potential.

Reconciling the Production of Timber and Carbon Storage

As described in Part I, these varying carbon sequestration outcomes are based on biomass accumulation models and presumed relationships between carbon stored as tree biomass and natural processes that either release carbon back into the atmosphere or store it in the soil or in lumber. Each of the three species addressed is predicted to have different rates of biomass accumulation. On any given acre in a stand, individual trees increase in both biomass and diameter at different rates and cause mortality as they crowd one another out. As some trees continue to grow and others die and rot, the model accounts the implied accumulation of carbon and its continuous release back into the atmosphere from litter and dying trees.

Carbon storage from timber coming off in a harvest is estimated by the model as follows. Of the large woody biomass accounted as available for harvest, one half is left in the forest as litter, and one half comes off in the harvest. The fate of the biomass taken away in a harvest is broken out into lumber (50%), sawdust (25%) and chips (25%). Carbon in lumber and a fraction of the chips are accounted as being "stored" while sawdust and bark is assumed to rapidly decompose back to the atmosphere. Under these assumptions, the amount of carbon sequestered through wood products utilization is only 3/8 of the total carbon taken up into biomass on any given acre. In addition to affecting the carbon balance by removing timber biomass from a site, timber harvests affect the rate at which carbon is processed from the atmosphere and stored in either biomass or soil.

Focusing on the timber product portion of the biomass generated under any of the various management scenarios, **Table 2** reports how well the model's predicted harvested portions compare with actual timber harvests on state-owned forestland. This is done by using standard conversion factors used by foresters to estimate volume on the basis of scale weight. Those conversion factors are 14 pounds per board foot for hardwood trees and 12.5 pounds per board foot for pine. These conversion factors include wastage as in

sawdust, slabs and bark which, as noted above, are presumed to be one half of the biomass that comes off a site in a harvest. So, while the board feet estimates are generated from a measure that includes all of the biomass coming off of a site, sawdust and chips are still estimated at the ¼ and ¼ levels outlined previously.

Historical harvest data for this table were developed from MD DNR harvest records from the four largest State Forests – Green Ridge, Savage River, Potomac-Garrett, and Pocomoke State Forests. Average board foot per acre measures are a simple average of board feet per acre across the forests that are relevant to each species (e.g., the western forests are used for red maple and white oak and Pocomoke is the comparator for loblolly pine). This harvest data only provides a measure of regeneration harvests, as the history of harvested acres with respect to both commercial thinning and regeneration harvests is not generally available.

Table 2: Predicted Production* and Historical Regeneration Harvest Averages

Species & Treatment	Rotation Years	Sawdust & Chips (Tons)	Predicted Bdft/acre	Historical (State Forests) Bdft/acre**
Red Maple				
Scenario 1	58	36	10,528	6,793
Scenario 2	58	30	8,450	
Scenario 3	74	40	11,623	
White Oak				
Scenario 1	74	49	13,980	
Scenario 2	74	40	11,530	
Scenario 3	93	60	17,177	
Loblolly Pine				17,821
Scenario 1	43	35	11,287	
Scenario 2	43	23	7,239	
Scenario 3	60	44	14,185	

* Board feet from both thinning and regeneration harvests

** Red Maple and White Oak harvest volumes are compared against average harvests volumes from Green Ridge, Savage River and Potomac-Garrett State Forests. Loblolly Pine is compared with average harvests from Pocomoke State Forest.

Our assumption is that most harvested stands of mixed hardwood in the western forests (the forests that generate the hardwood historical averages in Table 2) are between 90 and 110 year old. Thus, the closest comparator to this among the scenarios is scenario 3 for white oaks. That scenario has a thinning operation which increases the yield, but if we net that thinning harvest out, the expected yield is 14,763 board feet per acre. This is over twice the historical average, which requires some explaining.

First, the historical yields are calculated by dividing harvested area by tally (board feet) volume. This approach underestimates true yield per acre, to the extent that acres marked

as harvested include non-harvested acreage (buffers – see below). Secondly, our model assumes a forest of a single species that grows in the manner of white oaks (growing in mixed hardwood stands). Given that most other species do not produce the volume after growing 93 years that white oaks do, we expect our estimate to be somewhat high. A third consideration is that our model was calibrated with growth data from Savage River State Forest where conditions for growth are somewhat better than either Green Ridge or Potomac-Garrett. When we look at annual board feet per acre measures for Savage River, 2003's harvest was more than 17,000 board feet per acre and the most recent two years were more than 10,000 board feet per acre. The average over nine years is brought down by several years of low-yielding harvests. And, fourth, the board foot harvest figures do not account cordwood, which amounts to 8 cords per acre across the sample of harvests.

Whereas the model's predicted productivity for White Oak as a proxy for mixed hardwood appears high, predicted values for Loblolly Pine are lower than historical yields. If most of the stands harvested in Pocomoke State Forest are 70 years old, they generate an average yield of 17,821 board feet per acre. The model predicts that at 70 years, with no thinning harvests, the yield should be around 8,940 board feet per acre.

The model's underestimate has two likely sources. First, we maintained the rate of removals to standing biomass (50 percent) that was assumed for hardwoods. Because so much of Pine's biomass is in its trunk, it is possible that a larger percentage of the standing biomass is removed in harvests. Maryland straddles the border between southern forests where removals average 91 percent of softwood standing biomass and the northeastern forests where harvest removals average 53 percent of softwood standing biomass. Clearly, more accurate data specific to the State would help to refine this measure. Secondly, the model uses a basal area of 100 square feet per acre, and it is possible that the State Forests have a higher stocking rate than implied by that measure.

Given the very general rules that were used to estimate harvest volumes in the model these estimates track reasonably well with actual harvest volumes. Doubtlessly, refinements in both the biomass accumulation models that underlie volume estimates and in the rules of thumb used to partition harvest volumes and wastage could improve the accuracy of those estimates. But, this effort to correlate the accumulation of biomass (and, consequently, carbon) with timber harvest volumes provides estimates that appear promisingly indicative of what is happening in the forest.

As a means of evaluating the potential usefulness of these estimates for carbon sequestration with respect to timber production and length of rotation, we consider in the following section what our estimates might imply for harvests of timber on state-owned forests. This will entail a description of those forests and their productivity and current management practices. Current implied rotations are then compared with modeled biomass accumulation under the scenarios discussed above and with particular regard to their different rates of carbon sequestration. It should be noted that harvest practices employed on private forest land are not a part of this analysis.

III. Timber Harvests on State-Owned Forestland

Our geographic area of interest is limited to general management areas of Maryland's State Forests¹³, wherein timbering is generally allowed. There are other state-owned forestlands where timbering takes place, but these are small, relative to general management acres in the State Forests and the Chesapeake Forest.

With respect to forested land held by the state as State Forests, State Parks and Chesapeake Forestlands, general management acres account for about 31.6 percent of the total¹⁴. In the overall market for forest products in Maryland, general management areas of state forests account a much smaller portion of the total "timberland" resource base. Using Frieswyk's (2001) figures for timberland¹⁵, state forests' general management acres account for about 4 percent of the total.

With respect to their importance to the annual state harvests, timber harvests from state lands¹⁶ formed, on average, 3.4 percent of average annual harvested acres over the years 1998 to 2001 (Irland, 2004). This estimate somewhat overstates the importance of harvests from general management areas in the targeted state forests, because the numerator includes harvests from other state lands. On the other hand, it understates the importance of harvests from those areas because it uses acres harvested as a proxy for volumes harvested. Timber on state forest lands tends to be better managed and, therefore, of greater volume and value, than harvests from private timberland.

While timber harvests from state-owned forestland are a small fraction of state-wide timber sales, they compose a more significant portion of harvests in specific regions, particularly in the western part of the state. In addition, as will be shown below, timber harvests from state-owned forestland might supply a larger share of the state total if harvest rotations were shortened. And, with respect to long-term timber supply, an unknown but likely significant portion of timber harvests from private forestland in Maryland is accompanied with a change in land use. As the base of private forestland available for timber production shrinks through this process, timber on state-owned forestland will come to hold an increasing share of total harvestable timber.

¹³ These include: Green Ridge, Savage River, Pocomoke, and Potomac-Garrett State Forests, and Chesapeake Forest. Although Chesapeake Forest is not a State Forest, a significant portion of its land is managed for timber production so it will also be considered in the analysis.

¹⁴ Chesapeake Forest general management acres are estimated using the Sustainable Forest Management Plan for Chesapeake Forest Lands, (2005) reporting of acres not impacted by priority habitat considerations (29.4 percent of the total acres). As some harvests will likely occur on other parts of those forests, this is a minimum estimate.

¹⁵ Forestland that is potentially in the resource base for timber – i.e., is not excluded from harvest by regulation or contract.

¹⁶ A larger set than just harvests from general management areas

A. *Harvest Management on State Owned Forestland*

Timber management plans

Timber harvests in State Forests are generally part of a forest's annual work plan, which is, in turn, based on a ten year resource management plan. Both the longer term resource management plans and the annual plans use information about the forest and its standing stock of timber derived, in part, from a recurrent forest inventory. Annual work plans are vetted with an inter-disciplinary team, a state advisory committee and the public. The inter-disciplinary team is composed of the state foresters, the director for the lands involved, fresh-water fisheries and water resources staff, heritage, wildlife and environmental staff, and representatives from the Maryland Department of the Environment, among others. State advisory committees are made up of stakeholders and citizens representing: the forest industry, Forest Conservancy District Boards, and recreational and environmental interests. Harvest proposals that pass both the inter-disciplinary and advisory committees are also vetted with the general public, and sales larger than \$50,000 must be approved by the state Board of Public Works.

Considering the annual management plans for 2007, out of a total of 988 acres proposed for harvest over the four forests, 845¹⁷ acres were accepted, for an overall approval rate of 85.5 percent. However, approval rates for specific forests ranged from 99 percent to 72 percent. The harvests considered in this calculation include both thinnings and regeneration harvests, but exclude pre-commercial thinnings. It is also noteworthy that the acres recorded for these harvests include non-harvestable areas such as buffers. It would appear that the approval process for timber harvests, while widely inclusive, works on a practical level to control harvests at a level that is only slightly (15 percent) reduced from resident foresters' proposed optimum. In the following section, we consider the outcome of this process with respect to harvests over the nine years 1998 to 2006.

Harvest rates

Harvest rates are discussed here in terms of acres harvested (in regeneration harvests only) annually¹⁸ and total acres available for harvest. The ratio of annual harvested acres divided into the total available acres provides an approximation of the length of rotation in each of the state forests' general management areas. The reported harvest figures are based on a nine year average of annual regeneration harvests from each State Forest. Thinnings and selective harvests (other than deferment) are not accounted in these figures. The number of general management acres in each state forest used in the numerator of this ratio are reduced by 30 percent as an approximation for acres that are in general management areas, but which will likely never be harvested, for either environmental or aesthetic reasons.

¹⁷ In the record keeping for this process, revisions of management plans are accounted in acres when given and, when not given, calculated as 90 percent of the original proposal.

¹⁸ It is noted in the Annual Work Plan for Green Ridge, 2007, that acres included in a proposed harvest include acres that will remain un-harvested either as buffers or as wildlife refuges. Therefore, these acreage figures can be thought of as the maximum harvest acreage.

Table 3: Annual Harvests and Implied Rotations by State Forests

	70% of GM Acres	Av. Annual Harvest (acres)	Implied Rotation
Savage River	21,284	102	209
Potomac-Garrett	7,328	48	153
Green Ridge	17,520	146	120
Pocomoke	5,598	92	61
Chesapeake Forests*	12,019	209	58

* Harvest acres are 2006 proposed. There is not a time series for current management.

The implied rotations reported in **Table 3** for the three western forests are surprisingly long. With the exception of the forests on the Eastern Shore, most of the general management acres accounted above have been managed for more than 75 years. Unless the period used to generate average annual harvests (1998 to 2006) was anomalously low, two plausible explanations for these low exploitation rates are that either the amount of land that is actually harvestable in general management areas is less than the calculation used (total general management acres minus 30 percent), or foresters are waiting for the forests to mature, at which point harvests will increase. It is also possible, of course, that the rotations in those western forests are significantly longer than the generally suggested 100 years.

The numbers reported in **Table 3** do not tell the whole story for timber productivity from these forests as they exclude harvests generated in thinning operations. To give a sense of the relative importance of thinning activity in each forest over the period, we divide total regeneration acres harvested by those harvested by thinning. A number larger than one implies that regeneration harvests account for more acres than thinning harvests and a number less than one implies the reverse. This generates the following ratios: Savage River = 0.35; Potomac-Garrett = 0.5; Green Ridge = 11; and Pocomoke = 3.

Harvest Volumes

Each of the four targeted forests has different environmental conditions and, consequently, different timber management. These differences lead to different harvest results which are captured in **Table 4** as varying board feet per acre (bdft/ac) yields by forest. The averages reported in that table represent nine years of regeneration harvests in each of the four forests¹⁹.

Table 4: Regeneration Harvest Productivity across Forests (Board feet/acre)

	Savage River	Potomac Garrett	Green Ridge	Pocomoke	Chesapeake
Bdft/ac	8,392	6,856	5,131	17,868	na

¹⁹Also included in this category are salvage and deferment harvests

B. Carbon Sequestration Implications of Current versus Modeled Rotations

It is possible to use the estimated carbon sequestration rates described above to compare the volumes of carbon sequestered on state forests under their existing rotations and under the scenarios outlined in Section II, above. We should note in this exercise that we do not expect that rotation lengths on the various forests will remain at the level implied by recent harvests. It seems likely that as the forests mature, rates of harvest on general management acres will rise. We use those rotation lengths here because they provide useful reference points for comparing the carbon sequestration implications of rotations of varying lengths.

Table 5 reports predicted annual sequestration rates for White Oak across the three western forests under their implied rotation lengths. These per acre rates are factored by the number of acres relevant to that rotation length and reported as sequestered volumes in tons per year. The 93 year scenario is measured with respect to the entire area of interest so that the difference between it and the implied rotations of each forest can be compared. The sum of the three forests’ annual carbon sequestration under their implied rotation lengths is 28,426 tons. This is 18,098 tons less than the 93 year rotation with no thinning. While these estimates are crude, if they are at all indicative of trends in carbon sequestration across different rotations, a difference of this magnitude encourages us to think that it is important to consider the rotation length in assessments of forest carbon sequestration. In this respect, it would be useful to refine the estimates of sequestration rates under different harvest management policies and, perhaps, to provide forest-specific estimates.

Table 5: White Oak Carbon Sequestration by Forest and Rotation Length

Forest/Rotation	Sequestration Rate per acre per year (lbs)	Harvestable GM Acres	Carbon Sequestered @ 1 Year (tons)
S.R. (years=209)	918	21,284	9,769
P-G (years=153)	1,207	7,328	4,422
G. R (years=120)	1,625	17,520	14,235
93 Year Scenario*	2,017	46,132	46,524

*This scenario has no thinning harvest as per the single harvest rotations with which it is being compared.

While it is clear that the carbon sequestration value for Red Maple would be greater at shorter rotations, it is trickier to apply the same procedure used above because at 209 years of age most Red Maples would be dead. However, as a means of testing the sensitivity of the Pine biomass/carbon sequestration estimates, we consider in **Table 6** the difference at Pocomoke State Forest between the implied 60 year rotation and a reported²⁰ rotation of 70 years. Both rotations are estimated without any intermediate thinning. It should be born in mind that, because of pine’s responsiveness to different management treatments, these estimates are merely illustrative. With more aggressive

²⁰ Private communication with Sam Bennett, MD DNR Forester at Pocomoke.

management such as planting, fertilizing, thinning, and treatments to control hardwoods, these rates of sequestration will vary considerably.

Table 6: Loblolly Pine Carbon Sequestration at Pocomoke State Forest

Rotation	Annual Sequestration Rate (lbs)	Harvestable GM Acres	Carbon Sequestered @ 1 Year (tons)
60 years	1,691	5,598	4,733
70 years	1,501	5,598	4,201

By these estimates, a 60 year rotation at Pocomoke would generate an additional 532 tons of carbon sequestration each year compared to the 70 year rotation. Or, an additional 31,909 tons over 60 years. While this is a small portion of the total carbon sequestered, it is not an insignificant amount of carbon sequestration. Below, we consider these differences with respect to hypothetical values for carbon sequestration.

Timber and Carbon Values

A goal of this study was to compare the relative values of timber production and carbon sequestration on Maryland’s state-owned forestland. So far, the focus has been on annualized rates of carbon sequestration with respect to different management scenarios. Of course, biomass accrual is also fundamental to growth in timber value. Pine forests, as on the coastal plain, have fairly well-developed growth models that allow managers to predict rates of return based on rotation lengths, among other factors. The mixed hardwoods of the central and western Maryland forests are less well understood with respect to this relationship between biomass accrual and timber value. Timber values are somewhat discontinuous in biomass accumulation because of the different products that can be generated from trees of different sizes. However, because we are considering rotations that generate a similar potential product mix, we use changes in biomass to estimate changes in value.

In keeping with the more intuitive approach that has been used to calculate carbon sequestration values in this study, we forego a full-blown estimation of the Faustmann equation for comparing timber values across scenarios. Instead, we consider changes in timber values as changes in undiscounted average annual increments under the White Oak and Pine scenarios described above. To do this, we assume that the total biomass²¹ of a Pine stand at year 70 (the assumed actual) is to total biomass at year 60 as the per acre value of pine at year 70 is to its value at year 60²². The same relationship is assumed for mixed hardwood forests of Central and Western Maryland, with the biomass accumulation of White Oak serving as a proxy for stand biomass increase. Historical per acre value yields for Pine at Pocomoke are assumed to be 70 year rotation values. Historical per acre yields for mixed hardwoods in the other forests are assumed to be 93 year rotation values. In **Table 7**, in which these estimates are reported, all values presume a rotation with just one, final harvest.

²¹ We use standing biomass at the end of the period for this measure.

²² Note that, while value is assumed to be a constant function of biomass in this estimation, the growth curve for biomass is not linear, but increases at a decreasing rate at these ranges of the rotation.

Table 7: Imputed Periodic Mixed Hardwood & Pine Scenario Values

Scenario	Timber \$/acre/year	C@\$14.68 /ton \$/acre/year	C@\$25.69 /ton in \$/acre/year	C@\$37.60 /ton \$/acre/year
WO (209)	17.98	6.74	11.79	17.26
WO (153)	24.30	8.86	15.50	22.69
WO (120)	28.99	11.93	20.87	30.55
WO (93)	30.55	14.80	25.91	37.92
Pine (70)	77.89	11.02	19.28	28.22
Pine (60)	85.33	12.41	21.72	31.79

Carbon values are introduced into **Table 7** as a range of possible per ton carbon prices. Because there is not yet a binding constraint on carbon emissions in the United States²³, current prices for carbon reductions are set according to independent factors such as Public Relations budgets, rather than factor prices and market demand. Still, market institutions are being created in the United States that will be useful when costs or caps are imposed on carbon emitters and there is competitive trading in carbon offsets. Under the Regional Greenhouse Gas Initiative (RGGI) a “trigger price” of \$7.00 per ton of carbon dioxide is envisaged. Above, we consider that price plus or minus \$3.00 per ton of carbon dioxide. Because our measure for carbon sequestration is carbon, we have to factor those carbon dioxide prices by 3.67 to obtain a comparable price estimate. **Table 7** factors the carbon sequestration for each rotation/forest type by these hypothetical prices per ton of carbon.

Because both timber values and carbon sequestration rates are based on the same biomass accumulation rates, they track in parallel, so that the rotations that generate the highest annual timber increment also generate the highest carbon sequestration value at any given price for sequestration. What is of interest in this is that the value of an acre of forestland for storing carbon is shown to be sensitive to the length of rotation, as is the value of the timber produced. Moreover, carbon sequestration forms a much larger share of the total value generated in the mixed hardwood forests than in the pine forest.

IV. Conclusions

We developed a deterministic model to estimate the rate of biomass accumulation in forests, based on growth functions derived from Maryland stand data and species-specific volume equations. Using expectations for the carbon portion of forest biomass and transparent rules for allocating forest biomass across such fates as continued growth, extraction, death and decomposition, we have estimated different rates for carbon sequestration under different forest management practices. Our modeled annual average rates of carbon storage show that, among the scenarios considered, rates of carbon sequestration vary considerably. In a final application of the modeled rates of biomass accumulation, we estimated the differences in both average annual timber value

²³ See Convery and Redmond 2007

increments and average annual carbon sequestration under several management scenarios, using several hypothetical carbon sequestration values.

The analysis did not account for the monetary value of time, and used a simple expectation that timber value increases as a constant factor of biomass. The objective was to use available data and a single biomass growth model to compare changes in carbon sequestration and timber values, so scenarios were calibrated to model practices that are applied on state-owned forestland. Care must be taken, therefore, in transferring these results to private forestland in Maryland.

The study did not attempt to identify an optimal rotation for timber growth and carbon sequestration. Such a step requires: 1) refinements in the biomass growth estimates, 2) relaxing the simplifying assumption of a zero discount rate, and 3) adopting a more realistic model for the relationship between biomass and timber value. In addition, in a market for forest-sequestered carbon, risk will doubtless be an important factor and any attempt to maximize the net present value of carbon sequestration and optimization analyses should account this risk.

It is apparent under this model that changes in the length of harvest rotations generate considerably different annual average carbon sequestration rates. These results suggest that it would be useful to further refine the estimates for biomass accumulation and the fate of that biomass under different management conditions and on a forest-specific basis. MD DNR Forest Service does not have a mandate to maximize financial returns from timber production in its state forests but, to the extent that maximizing forest biomass accumulation tracks closely with maximum carbon sequestration, such information could be useful to them in determining harvest policies.

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