Modeling the effects of forest management on the carbon cycle in a loblolly pine (*Pinus taeda*) plantation.

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Abstract

Forests have the ability to alleviate the impact of global warming through carbon sequestration. Six forest management scenarios for a 27,000 acre study area are modeled to determine the impact of forest management on carbon sequestration. Forest management determines annual harvested volume and end-use disposition category of wood products, and inventory volume. Shorter rotations tend to produce short-lived wood products, while longer rotations produce long-lived wood products. Thinning removes pulpwood, which increases the average diameter of the stand and increases the proportion of sawtimber products. Changing forest management complicates accounting for changes in future C storage.

Understanding the distinction between pre- and post-regulation harvest volume and C storage is essential to understand the effects of forest regulation. Plotting harvested volume and C storage volume over time shows distinctive pre- and post-regulation characteristics. The pre-regulation curves exhibit irregularities and varying thinned volume due to the uneven area in the existing age classes. Post-regulation curves are level because a constant area is annually thinned and clearcut.

Carbon storage is the amount of C that is sequestered into a C pool, which for the purposes of this study is either inventory volume or residual wood product volume. Converting volume flows to C storage involves tracking the accumulation of wood products and standing volume over time then converting volume to a measure of C. Once the forest is regulated, C stored in the inventory pool remains constant from year to year, while the C stored in wood products continually increases. Longer rotations store more carbon than shorter rotations because they have larger inventory pools. Wood products are a substantial carbon pool: at the end of 50 years; the ratio of incremental C in the wood products carbon pool to incremental C in the inventory pool ranges from 6 to 122 for the modeled scenarios.

Three accounting periods are evaluated to examine the importance of C sequestration timing to determine if a market for C can influence forest management. Long rotations meet the objectives of maximizing C sequestration and NPV for the modeled regimes regardless of the accounting period considered, or if the forest is regulated or un-regulated.

Model sensitivity to decomposition rate, discount rate and timber prices is assessed to determine the effects of uncertainty (measurement error and future trends) on the results of the model. Short rotations are most sensitive to decomposition assumptions and stumpage prices because they produce a large amount of fast-decaying wood products. Long rotations are most affected by discount rate. Carbon storage of all scenarios increases substantially when the pulpwood decomposition rate equals the sawtimber decomposition rate to reflect a potential future increase in composite lumber production.

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Chapter 1. Introduction

Atmospheric levels of CO_2 have been increasing during the last several decades due mostly to anthropogenic inputs, but also from natural variability in the global carbon cycle. The effects of global warming may not be catastrophic, but there is common agreement of increased global temperature. Despite all the uncertainty surrounding the extent of the impact of global warming, it is known that forests have the ability to reduce the accumulation of atmospheric CO_2 through carbon sequestration. Forests have market and non-market value, and economic investment in management can be recovered. Forest-sequestered carbon is stored in biomass, whether it is living or harvested volume in wood products. Forest management controls the annual harvested volume and the end-use disposition category of wood products. Shorter rotations tend to produce short-lived wood products, while longer rotations produce long-lived wood products.

Potential markets for carbon credits have the ability to influence forest management. Income from the sale of carbon credit may motivate a change in loblolly pine (*Pinus taeda*) plantation management. The focus of this project will be to determine the effects of increasing timber revenue with income from marketable carbon credits on forest management. Timber volume and resultant wood products will be projected using a growth and yield model and tracked through time with a spreadsheet model. Carbon stored in wood products and standing biomass will be compared among modeled regimes.

The forest carbon cycle is an infinitely complex system. Creating a model of the carbon cycle is limited to only better-understood components. Each additional component compounds the uncertainty associated with the cycle. A sensitivity analysis of the spreadsheet model will indicate where future research is best focused to improve our understanding of the carbon cycle, thereby reducing uncertainty and increasing the accuracy of carbon estimates.

Through the spreadsheet model and sensitivity analysis, this project addresses the following questions:

1. How does forest management change affect harvested volume, revenue production and carbon sequestration? Do the timing and frequency of intermediate treatments (thinnings) influence C sequestration? Do long rotations sequester more carbon than short rotations due to production of more durable wood products?

2. Can the sale of carbon credits affect forest management in the form of supplemental revenue?

3. How sensitive are estimates of carbon storage to assumptions about wood product decay?

Chapter 2. Literature Review

Energy from the sun influences earth's climate. Solar energy is either absorbed by the earth's surface, or reflected back into space. Greenhouse gasses (GHG) absorb the energy of reflected radiation and warm the atmosphere, making life possible (EPA 2001 a). Natural GHG include water vapor, carbon dioxide (CO_2), methane (CH_4) and particulate matter, such as dust. Artificial GHG (nitrous oxide, hydrofluorocarbon, perfluorocarbon and hexafluoride) are much more powerful than natural GHG in absorbing energy (EPA 2001 b).

Recent anthropogenic input of GHG into the atmosphere has altered the carbon balance of the Earth, and enhanced the capacity of the atmosphere to absorb reflected solar radiation. Carbon dioxide is the most important GHG because it accounts for 80% of total GHG emissions (EPA 2001 b) and 61% of the enhanced absorption (Sarmiento and Bender 1994). Due to its primary role in anthropogenic forcing of Earth's radiative balance, CO_2 has become the focus of intense study and debate.

This literature review explores CO_2 and climate change, forests as carbon sinks and sources, predictions of global warming, forest carbon modeling, tradable C permit systems, possible carbon implications of silviculture and similar studies.

2.1 CO_2 and Climate Change

2.1.1 The Role of CO_2

Using methodologies consistent with the 1996 IPCC guidelines for national greenhouse gas inventories, EPA found an 11.6 % increase in total greenhouse gas emissions from 1990 levels in the United States, although the single year increase from 1998 to 1999 was the lowest annual change of the decade (EPA 2001 b). Fossil fuel combustion was the single largest source of CO_2 emissions and accounted for 80 % of total greenhouse gas emissions, in terms of global warming potential.

About half of the total CO_2 emissions are from electricity production, while about 30% is from transportation related consumption of fossil fuels. In the transportation end-use sector, 60% of emissions come from gasoline consumption in motor vehicles. This increase in total GHG emissions is due to short- and long- term trends. Short-term trends include population and economic growth, energy price fluctuations, technology changes and seasonal temperatures. Long-term trends are scale of consumption, energy utilization efficiency and consumer behavior (EPA 2001 b).

2.1.2 Current and Historic Levels

The Vostok glacial ice cores show an increase in CO_2 of 80-100 ppmv during each of the glacial cycles (Monnin et al. 2001). The approximate mean pre-industrial atmospheric CO_2 concentration was 278 ppmv, whereas the current level is about 350 ppmv (Sarmiento and LeQuere 1995). As a result of the increase, global temperatures have risen 0.6^0 C over the 20th century, and 0.4^0 C since 1980 (IPCC 2001). The initial anthropogenic input during the 20th century was mostly CO_2 from the combustion of fossil fuels. The enhanced effectiveness of artificial GHG to absorb solar radiation has contributed considerably to global warming.

2.1.3 Historical Patterns

It is difficult to differentiate between anthropogenic disturbances and natural variability in biogeochemical cycles. For example, the 1991 eruption of Mt. Pinatubo released 17 megatons of sulfur dioxide into the atmosphere, which oxidized into sulfate aerosols. The amount of solar radiation reaching earth’s surface was reduced, and contributed to subsequent global cooling (Keppler 1999).

Cycles between global temperature and potential causative factors are evident at temporal scales ranging from seasonal to 100,000 years. Shorter cycles enable prediction of at the short-term effects of GHG emission mitigation, whereas long cycles provide a comprehensive look into the past. Seasonal oscillation is a result of biological processes such as net biological production. Satellite data of climate forcings has been collected since 1979, and includes information such as stratospheric aerosols from volcanic eruptions, increasing greenhouse gasses, changes in solar irradiance and ozone depletion (Hansen et al. 1998). A 22-year climate cycle has been constructed from sediment depth of glacial lakes, where thickness indicates melt season temperature (Kerr 2000). The longest cycles are estimated from ice cores taken from ancient glaciers.

The Vostok glacial ice core data analysis shows that variations in atmospheric CO_2 and temperature have operated within a relatively constrained domain over the past 420,000 years (Petit et al. 1999). The effect of anthropogenic inputs of greenhouse gasses on this domain remains uncertain (Falkowski et al. 2000). Although scientists have yet to reach a consensus about detailed effects, they agree that anthropogenic inputs pose a serious challenge to predicting the behavior of the climate (IPCC 2001).

2.1.4 Climate Change

Vegetation patterns may shift due to changing climate. Modified precipitation and temperature patterns influence the species distributions and associations of an ecosystem. Therefore, old ecosystems are destroyed and new ones are formed by climate change. Altered precipitation patterns could cause an old growth ecosystem to decline, and increased temperatures would accelerate organic matter decomposition, which shifts the function of the ecosystem from sink to source.

Increased atmospheric CO_2 could increase terrestrial net primary productivity (NPP) because it is not saturated by current CO_2 concentrations, which increases the potential for terrestrial plants as a carbon sink. However, the saturation function reaches an upper limit as CO_2 increases, so increased CO_2 can promote NPP a finite amount (Falkowski et al. 2000). The increased temperatures associated with elevated atmospheric CO_2 may increase heterotrophic respiration, releasing more CO_2 into the atmosphere, detracting from NPP enhancement (Kirschbaum 1995).

2.2 Forests as carbon sinks and sources

2.2.1 Definition of sinks and sources

The terrestrial biosphere removes CO_2 from the atmosphere through photosynthesis and stores it as biomass. It is considered to be a sink because it absorbs CO_2 from the atmosphere and stores it in a carbon reservoir. The carbon is subsequently released to the atmosphere through autotrophic (maintenance respiration) and heterotrophic (decomposers) respiration, and disturbance such as fire (Falkowski et al. 2000). The release of CO_2 from a reservoir to the atmosphere defines a carbon source.

Generally, forest ecosystems are C sinks but could become C sources in several decades due to ecosystem change and the net primary productivity (NPP) saturation function (IPCC 2000). These factors consider only the effects of climate change on the current ecosystem, not changes in land-use or technological advances. The inherent uncertainty associated with modeling climate change makes it difficult to predict the effects beyond a few decades.

A newly established forest plantation is a C source until the carbon sequestered by juvenile tree growth exceeds the carbon emitted from decomposing coarse woody debris (CWD) and soil organic matter. As the plantation approaches canopy closure, it becomes a C sink and remains so until harvest when the merchantable portion of the tree is removed, and tree tops and limbs are left to decompose as CWD. Mineral soil is fully exposed to sunlight, and soil organic matter quickly decomposes.

2.2.2 Carbon storage in forests

Carbon storage proportions for components of an eastern forest in the United States are soil (60%), trees (30%) and forest floor/understory vegetation (10%). These estimates of carbon come from regional ecosystem studies, which are subject to statistical errors in measurement, estimation, and conversion (Birdsey et al. 1995). The standard error associated with forest floor/understory vegetation and soil is higher than timber inventories because there are no comprehensive, statistically valid methods to sample non-tree carbon (Birdsey et al. 1993).

The capacity for a forest to sequester C may be limited by nutrients or other biophysical factors. Enhanced nutrient availability through fertilization is limited by tree uptake. Nutrients that are not absorbed by plants may be transported by surface or subsurface runoff, which could lead to eutrophication of surface waters (Pritchett and Fisher 1987).

The magnitude of forest carbon storage of the United States varies by region. Southern forests have lower carbon storage than northern forests due to greater management intensity and harvest volumes. Carbon storage in the west has decreased because of conversion to second growth forest. Nationwide, industrial timberland area has been relatively constant. Restricted harvest levels in National Forests will increase carbon storage over time (Birdsey et al. 1995) assuming that harvest levels remain constant. Land in warm climates may have 50% of terrestrial carbon in soil while cold climates like Alaska may have 75% of carbon in soil due to temperature, precipitation and management intensity differences (Birdsey et al. 1995). Cooler temperatures decrease oxidation of the carbon compounds in the soil, so less carbon is lost. Increased precipitation implies greater root growth and slower decomposition, organic matter and carbon in the soil.

2.2.3 Storage in wood products

Forest management heavily influences forest carbon storage. The timing of harvest and intermediate treatments determine the timing and amount of carbon stored in wood products. Timber harvest and volume utilization reallocate carbon from forest biomass to wood products, which store carbon for long periods of time (Row 1996). After timber harvest and conversion to wood products, carbon is entombed in landfills or it decomposes with time and is released into the atmosphere as CO_2. The decomposition rate depends on the utilization of the harvested volume; sawtimber product decay is more gradual than pulpwood product decay (Row and Phelps 1996). Sawtimber wood products tend to be long-lived due to their use as construction material, because buildings have a lifespan of decades or centuries. Pulpwood products are short lived because the product life of paper is much shorter than sawtimber.

2.3 Predictions

Predicting future levels of GHG in the atmosphere and consequent climate change has been a difficult subject to approach. The myriad of components and uncertainty associated with the carbon cycle is debated at many different levels.

The Forest Service of the United States Department of Agriculture has been attempting to quantify the amount of carbon stored in forests in the US and to predict future trends of carbon storage and land use. Currently, private timberland in the US and Canada is a carbon sink (Birdsey et al. 1993). Base-run results of FORCARB (see description in section 2.4.3) indicate an increase in carbon sequestration until 2010, and then the carbon mimics a decreasing trend in growing stock resulting in increased harvest rates which are expected to surpass growth in 2020. Carbon stored in wood products and landfills will continue to decompose and more C will be added to the wood products pool with continued harvest. Timberland held for non-timber use, due either to management objectives or inaccessibility (Plantinga and Birdsey 1993), decreases the potential area for timber production and carbon sequestration in wood products. If demand were great enough, currently unproductive timberland could be made to be productive. However, increased stumpage demand may influence management of forests and carbon storage in biomass and wood products.

The International Panel on Climate Change (IPCC) is an international panel of scientists that are developing standards for assessing the extent of damage, environmental risks and developing solutions to global warming. The international nature of the IPCC raises the level of science to a global scale. Member scientists must discuss and defend their hypotheses, which strengthen the panel's conclusions. Resultant methods to account for GHG emissions will be internationally uniform. The IPCC produces reports about global warming, and each subsequent report becomes more definitive about the causes and extent of global warming. The evolution of IPCC reports has been drastic. In 1995, they were reluctant to confirm that global warming was reality. A stark contrast is the 2001 report, which concludes that global warming is caused by increased greenhouse gas concentrations from anthropogenic inputs (IPCC 2001). The focus of debate has shifted from if humans have influenced global warming to the extent of the anthropogenic disturbance.

2.4 Forest Carbon Modeling

2.4.1 Introduction

Individual components and processes of the carbon cycle are better understood than the interactions among them due to the disciplinary approach to modeling. There may be a specific sequence of interaction among marine and terrestrial ecosystems, changes in ocean circulation and salinity, radiative forcing and greenhouse gasses that results in natural atmospheric and climatic cycles (Kirschbaum 1995). Discovering such a sequence would strengthen understanding about global warming, and quantify the effects of anthropogenic inputs.

Reducing uncertainty of carbon models is paramount. Carbon is difficult to sample and model accurately due to variation across the components of the forest, notably in the soil. Accounting for all of the components and processes in the forest is virtually impossible due to the inherent complexity of the system. Only some of the more important components to the model's purpose are modeled. Each additional component adds uncertainty to the model, increasing the potential error.

Expanding the scope of the system to include other disciplines further exacerbates the uncertainty issue. However, scientists need to change the focus of climate modeling efforts from a disciplinary approach to a systems approach. It seems as though inter-disciplinary collaboration to link components of the carbon and biogeochemical cycles will result in an understanding of the relationships between components and the effect on global warming. International collaboration, such as the IPCC, raises the level of science of global warming through enhanced scientific review. A large international pool of scientists debating the causes of global warming will yield strong conclusions and ensuing actions, although it will take longer to reach decisions.

There are different approaches to model carbon in a forest. Two carbon models are reviewed that represent a range of scale from individual tree to regional. Pipestem is a physiological model to predict the production of carbon substrate in loblolly pine. The mathematical basis of model development is explicitly explained (Valentine et al. 1999). FORCARB is both physiological and economic and uses several sub models to explain the Forest Service's methodology to determine carbon sequestration (Birdsey et al. 1995). Tauyield is a loblolly pine growth and yield model that could be an integral component of a carbon model of any scale (Amateis et al. 1996).

2.4.2 Pipestem

In its current form, Pipestem can be used to determine the effects of elevated atmospheric CO_2 on loblolly pine tree growth (Valentine et al. 1999). Pipestem is a stand-level, physiologically detailed carbon allocation model for even-aged monocultures that permits an analysis of the impacts of climate change (elevated atmospheric CO_2 and temperature) on tree growth. The model has 25 parameters in 4 categories of differential equations: production of carbon substrate, dry matter production, constructive/preventative respiration of leaves, roots and live wood, turnover of foliage and roots, and loss of tissue due to crown rise and self thinning. Pipe-model theory is used to create trees by giving size and shape to the dry matter (Valentine et al. 1997).

The model stand consists of leaves, feeder roots and two types of pipes: active and disused. Active pipes connect leaves to feeder roots and represent the bole and branches. Disused pipes represent the bole and create taper but do not connect leaves to roots. Woody volume is produced by elongation of existing active pipes and the creation of new pipes. Loss of woody volume comes from turnover of leaves and feeder roots and the pipe that connects them, crown rise and self-thinning. The model compensates for crown rise through self-pruning by disconnecting disused pipes. After crown closure, the model removes basal area to match the rate of self-thinning of the stand. During active self-thinning, the rate of loss of disused pipes is a constant ratio of the rate of production of new active pipes. The model stand approaches crown closure as active pipe area reaches an upper bound. In fully closed situation, an old pipe deactivates when a new pipe is produced (Valentine et al. 1997).

As a stand matures, annual production and loss of woody dry matter and total dry matter become increasingly sensitive to annual weather variation. Maintenance respiration increases with pipe length, which reduces the amount of carbon substrate available for growth as the tree ages (Valentine et al. 1997). Good weather can increase the production of carbon substrate, which can be used for growth. If weather is not favorable for tree growth during the following year, the tree has less carbon substrate to allocate to growth because maintenance respiration is paramount.

2.4.3 FORCARB

The Forest Service developed this model to explore the options for strategies to either reduce CO_2 emissions or utilize timberland to offset emissions and to account for changes in C storage. It uses estimates from periodic inventories, which are very detailed except for age class distribution (Birdsey et al. 1995). FORCARB is used to project the effects of management practices on the ability of timberland to sequester carbon.

FORCARB does not include response to climatic conditions, and only models carbon changes in the merchantable portion of the stand. Carbon of the floor, soil and understory vegetation is determined by conversion equations developed in second growth forests. Carbon in the non-merchantable portion of the tree is assumed instantly lost at harvest. Soil carbon decreases after harvest due to increased heat and reduced moisture, then increases with litterfall, tree growth and root turnover. A condition in the model specifies that pre and post harvest soil carbon are equal to reflect that soil C recovers over the course of a rotation. The model assumes that any soil C accumulated during the rotation is converted to emissions by harvest and planting activities (Plantinga and Birdsey 1993). Wood used for fuel is considered to be a source, even though it is a substitute for fossil fuel (Plantinga and Birdsey 1993). Theoretically, a tree burned for fuel is not a C input into the atmosphere provided another tree is planted to grow in its place.

2.4.4 Tauyield

Tauyield is a stand level loblolly pine growth and yield model that was developed from a comprehensive data set of thinned and unthinned permanent remeasurement plots throughout most of the native range of Loblolly pine. Three critical stand parameters (height growth, survival and basal area) are the basis of projection, which satisfy the two main objectives of model development of high predictive capability (component equations function equally well individually and in unison) and biological accuracy (Amateis et al. 1996).

The user enters the initial stand parameters: site index, planting density and seedling mortality. A modeled stand can be grown from age 8 in annual increments to age 36 for unthinned stands, and to age 45 for thinned stands. A stand table of volume by one-inch dbh size class is displayed for each growth increment. A variety of thinnings (row thin, low thin, row/low thin, and thinomatic) can be performed at any age. Thinomatic thinning will be used in this study because it is based on patterns demonstrated by operational thinnings, where all dbh (diameter at breast height) classes are subject to removal. A user defined residual basal area (ft^2/ac) specifies the amount of basal area removed from each dbh class. Basal area is removed from each dbh class starting with the smallest and ending with the largest. If the desired residual basal area is not removed after the entire dbh distribution has been passed through, then all trees are removed in the smallest dbh class until the desired residual basal area is reached (Amateis et al. 1996). Tauyield produces the stand tables that are the initial inputs into the spreadsheet model. Predicting forest growth is a preliminary step to determine the amount of C a forest will sequester, coupled with assumptions about timber harvest and wood product decomposition.

2.5 Carbon trading

2.5.1 The Kyoto Protocol

2.5.1.1 Introduction

The Kyoto Protocol is an international treaty to stabilize the levels of GHG in the atmosphere to reduce the effects of global warming. Conceived in 1997, the political nature of the negotiations has prevented a majority decision and continued deliberation. Negotiators are dealing with the highly uncertain topic of global warming, so they are cautious to use definitive language simply because they lack certainty about the consequences of global warming and the mechanisms they should use to reduce GHG levels. Vague wording and ambiguity of the Protocol has provoked considerable debate about the “true” meaning of the articles (Murray et al. 2000).

Annex I (developed) countries are required to reduce GHG emissions in 4-year commitment periods beginning with 2008-2012. Currently, Annex II (undeveloped) countries are not required to reduce emissions in the first commitment period (UNFCCC 1997). This difference has caused some countries to shy away from ratifying the Protocol. While these countries have not ratified the Protocol, they still possess considerable scientific interest in understanding global warming and quantifying the amount of carbon storage in a country.

2.5.1.2 Mitigation mechanisms

Mechanisms to reduce GHG emissions using a least-cost mix of strategies are outlined in the Protocol. Article 4 defines joint implementation as member countries sharing the burden of achieving reductions, because the nature of global warming is not constricted to a national border. To meet emissions limits, Article 6 authorizes a developed country to invest in a climate change mitigation project in another developed country and then receive credit for the reductions as emissions avoided (UNFCCC 1997). This helps to equalize differences in costs of projects among countries.

Article 12 defines the Clean Development Mechanism (CDM), which permits a developed country to invest in a climate change mitigation project in an undeveloped country. The project must foster sustainable development. Reductions that would ordinarily occur are not eligible for credit because an additionality requirement states that the CDM projects must be an active reduction. An emission-trading scheme is developed in Article 17. Member countries agree on maximum emissions per country, and then try to reduce emissions both internally and using the mechanism of Article 6 and 12. Countries earn credit for being below their limit, and can then sell their credits to countries that cannot comply with their limit (UNFCCC 1997).

2.5.2 Tradeable permits

A general framework for trading emission permits has been established by the Kyoto Protocol. Following IPCC accounting guidelines, the forest is classified by a threshold of either canopy cover or carbon-density and then C is accounted using a land based or an activity-based system. Relevant C pools are above- and below- ground biomass, litter, woody debris, soil carbon and harvested materials. With market-based incentives, corporations are quick to find abatement solutions or establish mitigation strategies.

Economic models represent uncertainty of carbon estimates and potential damage from climate change with a damage function (van Kooten et al. 1997). Most literature considers forest-based sequestration as a single objective, in which carbon will be stored in tree biomass forever. Marginal benefits and costs are compared to determine if a forest-based mitigation plan is worthwhile. Benefits are typically defined as reduced damage costs from climate change, such as depressed agricultural crop productivity (van Kooten et al 1997). The marginal cost associated with sequestering an additional unit of atmospheric CO_2 in forest biomass equals the marginal cost of reducing CO2 emissions in the most expensive situation (Solberg 1997). Another approach to determining marginal cost of sequestering an additional unit of CO_2 is to divide lost NPV of timber revenue by the discounted value (tons) of the additional unit of CO_2 (Hoen and Solberg 1994).

Other methods to determine the marginal cost of C sequestration have been defined by Newell and Stavins (2000). Flow summation is the present value of costs divided by total carbon. Mean carbon storage is similar to flow summation, except that the present value of costs is divided by the mean annual C storage. Both methods fail to consider the time profile of sequestration and are extremely sensitive to the total time period. Levelization is defined as present value of costs divided by discounted present value of C stored. This method assumes constant marginal damages from atmospheric C, and that benefits and costs are discounted at the same rate.

2.6 Silviculture and possible carbon implications

Silviculture is the art of manipulating forest vegetation to achieve desired management goals. In general, the four basic steps of plantation management are successful establishment, crop tree growth that satisfies the management objective, timber harvest, and stand regeneration (Smith et al. 1997). Silviculture increases the quality of the stand and often the volume of timber, which increases the potential C sequestration for a forest. Forest management scenarios vary in the amount of C sequestered and the pattern of sequestration over time (Marland et al. 1997). The silvics of the plantation species dictate successful management actions. For example, coniferous species with serotinous cones must be periodically burned to ensure seed release. An identical fire may kill a thin barked hardwood species.

Loblolly pine plantations are predominant throughout the southeast United States. The main silvicultural tool for a loblolly pine plantation is the timing of thinning and harvest to achieve production goals. Rotation length depends on end-use of products and alternative uses (Solberg 1997). Additional activities may help achieve production goals sooner, or satisfy other management objectives. These activities may include site preparation, competing vegetation control, pre-commercial thinning, prescribed burning and fertilization (Shultz 1997).

In general, intermediate treatments increase the growth rate of residual stems and enhance the value of the plantation as a C sink. Commercial and pre-commercial thinning removes competitors or badly formed or suppressed crop trees. The resources of a site are freed for crop trees to utilize, which improves the quality of residual trees and increases the growth of merchantable volume. However, when a stand is thinned it loses productive capacity because the increased growth of residuals does not compensate for the volume production of removed boles for a period after the thinning (Amateis et al. 1996). Site-specific fertilization replaces nutrients that limit tree growth, which effectively increases site index, the potential productivity of the site (Smith et al. 1997).

Carbon is stored in soil, standing biomass and wood products from intermediate treatments. The treatments described above can be combined to achieve specific production goals, such as maximizing sawtimber production. To achieve this, a rotation length may be 40 years, with 2 thinnings. Competing vegetation control may be applied around seedlings at years 1, 3 and 5 and fertilization may occur immediately after each thinning. The wood products from the thinnings will mostly be pulpwood, and the final harvest will yield mostly sawtimber. Pulp products have a shorter product life than sawtimber products (Birdsey 1996).

Conversely, pulpwood production may be the management objective. A completely different management regime is necessary. Rotation length may be 20 years with competing vegetation control at years 1, 3 and 5 and no intermediate treatments. It would appear that this pulpwood management would store less carbon than the sawtimber management because the wood products are less durable. However, two pulpwood rotations could occur in the same timeframe as one sawtimber rotation.

The marginal benefit of silviculture to increase C sequestration must be considered in terms of management goals (Dixon 1997). Some forest management techniques are more effective than others to increase C sequestration in a forest. Fertilization may be the most effective method to increase sequestration, (Hoen and Solberg 1994, Huettl and Zoettl 1992, Nilsson 1993), but efficient use of harvested timber is more effective than increasing site productivity (Marland and Schlamadinger 1997). Hoen and Solberg (1994) conclude that thinning is not an effective method of C sequestration. However, thinning improves the stand and enhances the quantity and quality of future harvested volume. Thinning for pulpwood may reduce the total volume in a stand, but it increases the sawtimber proportion of final harvest, which could enhance the amount of C stored in the wood products pool (Sedjo et al. 1995).

A number of studies examine the potential forest management effects on forest C storage and sequestration. If stumpage prices of timber are lower than the value of wood for C sequestration (Solberg 1997), then forests should be grown solely to store C. Wood quality of these carbon “projects” doesn’t matter because the wood is never used for timber. Harmon et al. (1990) conclude that converting old growth forests to younger, managed forests releases carbon to the atmosphere. Old growth forests are a large store of C because they exist in a state of equilibrium between biomass production, and biomass mortality & decomposition. However, wood products delay the release of C back into the atmosphere (Hoen and Solberg 1994), so in the long run the additive effects of C storage in wood products over time can become substantial. Continually increasing demand for wood products (Adams 2002) requires a large area of managed forests.

Little work has been done to compare the effects of forest management change across a forest on C sequestration within the constraints of operational forestry. A study by Thornley and Cannell (1999) examines silvicultural methods to balance sustainable timber production and C storage; they conclude that removing 20-40% of the biomass through annual thinnings produces the most timber and stores the most C because continuous canopy cover is maintained. If this silvicultural system was implemented in a loblolly pine plantation, stand regeneration might prove to be difficult. Thompson et al. (1997) study changes in forest management of a real forest, but export all timber, so the model does not account for CO_2 emissions from wood product decay.

Chapter 3. Methods

3.1 Overview

Area regulation is applied to the study area for each of six forest management scenarios to determine the effects of changing forest management on harvested volume and C sequestration. Inventory volume (merchantable above ground biomass of overstory trees) and residual volume in wood products are tracked through time with a spreadsheet model. Annual timber harvest revenue and carbon stored in inventory volume and residual wood products are compared to determine tradeoffs between timber production and C storage.

3.2 Study Area

The Chesapeake forest is located on the lower eastern shore of Maryland. It is a 58,000-acre area managed for environmentally sound, sustainable loblolly pine timber production. A primary management goal is to make the Chesapeake Forest a model of certified sustainable forestry. Loblolly pine plantation covers 81 % of the forest area, and there is a hardwood component on the remaining 19% of the area that is mostly riparian management zones. The study area is a portion (22,733 acres) of the Chesapeake Forest (Figure 1). The age class distribution was utilized to represent a realistic forest estate and because management for C credits is being considered for this area. Most acres (84%) are less than 20 years old, with 9% between the ages of 21 and 35, and 1% from 36 to 50 years old (Figure 2). This skewness indicates recent heavy levels of harvest, perhaps in response to tight timber markets. The Chesapeake Forest has supplied 15-20% of the annual timber harvest in the region, yet it occupies 12% of the area. The baseline management for the Chesapeake forest is a 25 year rotation length with thinnings at ages 15 and 22, as determined by sampling the Chesapeake stand data for an average timing of harvest and thinnings. Although this sampling may not accurately represent all facets of former forest management, it provides a solid basis for comparison by establishing a consistent initial volume among all modeled management regimes.

Figure 1: Location of the Chesapeake Forest, MD.

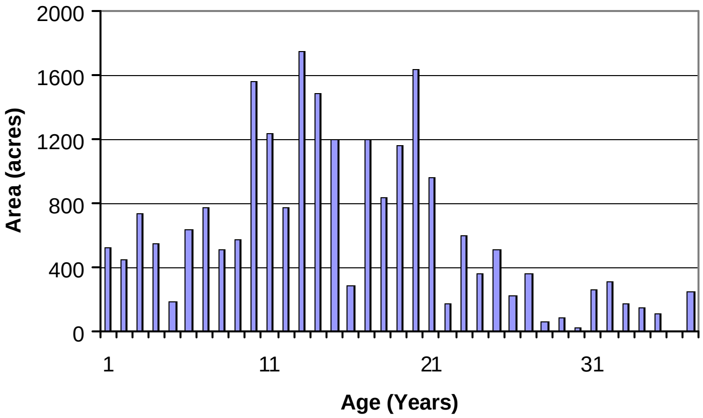

Figure 2: Area by age class of the Chesapeake forest, MD.

3.3 Spreadsheet Model

A spreadsheet model was developed to track inventory & harvested area and volume, and track the decomposition (residual volume) of wood products over the course of 50 years. The description here serves as a general overview of the model. Additional model documentation, including a model schematic, can be found in Appendix 1. The model accounts for the state variables by rows (age classes) and columns (time). Only merchantable biomass in the aboveground portion of the forest is modeled. A stand level growth and yield model (Tauyield) determines pulpwood and sawtimber volume in thousand cubic feet (MCF) per acre by age class.

Six management regimes varying in rotation length and thinning timing were defined to represent a full range of practical loblolly pine management. Nomenclature for the regimes begins with the rotation length and ends with the thinning regime (Table 1). For example, 30t15&22 is a 30-year rotation with thinning at years 15 and 22. Scenario 20nt is a pulpwood management regime with a 20-year rotation length and no thinnings, and 40t17&30 is a sawtimber management regime with two thinnings and a 40-year rotation length. The other scenarios achieve a range of timber volumes and wood products between 20nt and 40t17&30. For example, holding rotation length constant and changing the thinning regime (scenarios 25t17 and 25t15&22), and increasing rotation length by five years while holding the thinning regime constant (scenarios 25t15&22 and 30t15&22) were designed to reveal differences in inventory and harvested volume among the rotations. A spreadsheet model simulates a single management regime, so six spreadsheet models were used.

Table 1: Nomenclature of the six management regimes. Scenario “35t17&25” denotes a 35 year rotation thinned at ages 17 and 25.

Scenario	*Rotation Length*	*Thinning Regime (age)*
20nt	20 years	None
25t17	25 years	17
25t15&22	25 years	15&22
30t15&22	30 years	15&22
35t17&25	35 years	17&25
40t17&30	40 years	17&30

Tauyield is a widely used growth and yield model; here it generated yield tables for each of the six management regimes. The model was developed from a comprehensive data set of 192 thinned and unthinned permanent remeasurement plots throughout most of the native range of loblolly pine (Amateis et al. 1996). Initial stand parameters entered by the user are site index, planting density and seedling mortality.

Rotation length is constrained in Tauyield to age 36 for unthinned stands, and thinned stands to age 45. A variety of thinnings (row thin, low thin, row/low thin, and thinomatic) can be performed at any age. Thinomatic thinning is used in this study because it is based on patterns demonstrated by operational thinnings, where all dbh (diameter at breast height) classes are subject to removal. Basal area is removed from each diameter class starting with the smallest and ending with the largest. If the desired residual basal area is not removed after the entire diameter distribution has been passed through, then all trees are removed in the smallest diameter class until the desired residual basal area is reached (Amateis et al. 1996). The parameters we used in Tauyield are: site index of 60 feet (base age 25), 726 trees planted per acre, 90% seedling survival after the first year, and thin to a residual basal area of 70 ft^2 per acre.

The spreadsheet model assumes that the forest is subjected to area regulation (Clutter et al 1983), where the number of annual harvested acres equals total area (22,733 acres) divided by the rotation length plus one year for site preparation and planting. Inventory acres are tracked annually, with each age class growing into the next age class. Harvested and inventory acres are dynamically linked such that harvested acres are subtracted from the oldest inventory age classes and then added to the youngest inventory age class the following year. Harvested acres begin with the oldest age classes, and continue to younger age classes until the annual harvest area target is reached. Thinning is not performed by strict area regulation because all acres in the thinned age class are cut. Strict area regulation is imposed when the forest becomes regulated, and it involves harvesting the same area during thinning and clearcut.

For each harvested age class, clearcut and thinned volume by product class is determined by multiplying the area harvested by the corresponding volumes from the yield table. Volumes are summed for all harvested age classes to determine total annual harvested volume. Harvest volumes are divided into two classes, pulpwood and sawtimber, as determined by the merchantability breakdown of Tauyield (Burkhart and Bredenkamp 1989). Harvested volume is valued by multiplying total harvested volume by product prices. The stumpage value for pulpwood is assumed constant over all scenarios at \$220/MCF, while the value of sawtimber increases from \$473/MCF for the smallest diameter sawtimber to \$734/MCF for the largest diameter sawtimber due to an increasing average diameter from 8.5 to 11.4 inches. Clearcut and thinned harvest volumes are combined by product for each year. For each product, revenue is calculated annually by multiplying harvested volume by stumpage prices, assuming no real price increases. Site preparation and planting costs are assumed to be \$200/ac for shearing, burning and planting (Reynolds 2000). Net present value (NPV) is calculated on an annual basis using the following equation:

$$\frac{I_t - C_t}{(1 + r)^t}$$

Where I_t = income at time t
= clearcut volume * price + thinned volume * price
C_t = cost of site establishment
= acres in age class 0 at time t * \$200/ac
r = discount rate, set at 5%
t = time from present (number of years)

Residual harvested volume is converted to tons C assuming that there are 7.79 tons of carbon per MCF of volume. This conversion factor is based on the assumption that there are 15.57 pounds of carbon per cubic foot of loblolly volume. The fate of harvested volume lies in four categories: product (wood products in use), landfill (discarded wood products), energy (cofired for energy production), or emission (release of CO_2). The residual portion of harvested volume is the focus of this project, and it is calculated by adding the residual volume in products and in landfills (Tables 2 and 3). Other fates (energy and emissions) represent additions to atmospheric C. Volume stored in landfills decays slowly with time, but it never completely decays. Decomposition rate of wood products depends on the product life of the end-use category. Sawtimber wood products tend to be long-lived due to their use as construction material, because buildings have a lifespan of decades or centuries. Pulpwood products are short lived because the product life of paper is much shorter than sawtimber. The decomposition of pulpwood and sawtimber is illustrated in Figure 3. Both lines have a similar general linear trend, and decomposition is obviously slower in sawtimber products.

These decomposition assumptions are taken from the US forest carbon model (Birdsey 1996), and are linearly interpolated from a decadal to an annual scale. Harvested volume is multiplied by the residual volume factors and tracked though time.

Sequestered carbon is calculated as the sum of the annual change in C storage. Carbon credits are calculated by finding the difference in sequestered C between the end and beginning of a period.

Table 2: Residual proportion of initial loblolly pine pulpwood volume remaining in various pools. Residual is calculated as the sum of Products and Landfills, which are linearly interpolated from figures in Birdsey 1996.

	Year					
Category	0	10	20	30	40	50
Products	0.30	0.07	0.05	0.04	0.03	0.03
Landfills	0.00	0.16	0.16	0.16	0.15	0.14
Residual	0.30	0.23	0.21	0.20	0.18	0.17

Table 3: Residual proportion of initial loblolly pine sawtimber volume remaining in various pools. Residual is calculated as the sum of Products and Landfills, which are linearly interpolated from figures in Birdsey 1996.

	Year					
Category	0	10	20	30	40	50
Products	0.47	0.28	0.24	0.21	0.18	0.17
Landfills	0.00	0.13	0.16	0.17	0.18	0.19
Residual	0.47	0.42	0.40	0.38	0.36	0.35

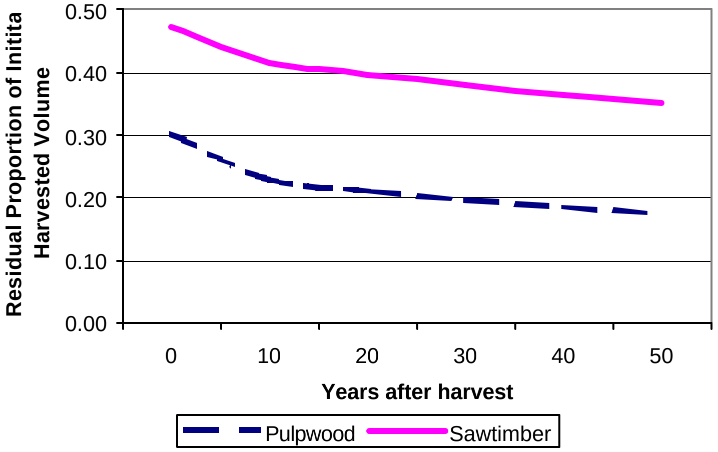

Figure 3: Comparison graph of pulpwood and sawtimber wood products decomposition.

Chapter 4. Forest Regulation

Forest regulation requires forest management change, which complicates accounting for changes in future C storage. Understanding the distinction between pre- and post-regulation harvest volume and C storage is essential to understand the effects of changing forest management. The use of an authentic initial age class distribution and evaluation of an entire forest estate sets this analysis apart from other studies of forest C sequestration.

4.1 Harvested Volume

Clearcut and thinned pulpwood and sawtimber harvested volume flows are summed over a 50-year period (Figure 4). Each harvested volume curve has two distinct parts: pre- and post-regulation. Understanding the distinction between the pre- and post-regulation harvest volume is essential to understand the effects of forest regulation. Pre-regulation volume harvest is a combination of new and old management. The pre-regulation curve exhibits irregularities and varying thinned volume due to the varying acreage in the existing age classes. Post-regulation harvest volume of a scenario results from the growing stock created (average diameter, stem spacing, etc) from management specific to that scenario. It is equivalent to beginning with bare soil and growing the forest from the ground up. Post-regulation curves are flat because a constant area is annually thinned and clearcut. Modeled scenarios have different rotation lengths and thinning regimes, both of which influence standing volume (growing stock), harvest volumes and patterns, and growth rate. Post-regulation harvest volume is shown by the post-regulation portion of the harvested volume curves (Figure 4).

Pre-regulation thinned volume flow can be characterized by spiked increases in harvested volume resulting from large areas in age classes being thinned. Age class area varies from 1755 to 30 acres (Figure 2). When the 1755-acre class (age 13, Figure 2) works its way through the regulation matrix, it has significant contribution to the thinned volume curve. The large spike in year 2017 of Panel F in Figure 4 is a result of thinning the current age 13 class. Scenario 25t17 (Panel B) shows a similar increase in harvested volume at regulation as 20nt (Figure 4 Panel A). The other scenarios demonstrate a more gradual transition into regulation.

Post-regulation harvest is the volume produced by the new management regime. Long rotations yield less pulpwood than short rotations because fewer acres are annually harvested and extended time for growth allocate more volume to sawtimber products (Table 4). Post-regulation harvest is a composite of harvested volume from a forest structure created by former management and yield resulting from new management. The numbers in Table 4 represent area and volumes for length of the rotation, i.e. two 20nt rotations occur in the same time span as one 40t17&30 rotation. Forest management change can be visualized as the difference between pre- and post-regulation harvest, where a greater difference indicates a more substantial management change (Figure 5).

Compared to the other scenarios, 20nt has a moderately smooth harvested volume curve (Figure 4 Panel A). The most notable feature is the large amount of pulpwood produced after regulation. Scenario 20nt has an initially large sawtimber harvest resulting from harvesting the older age classes that are mostly sawtimber-sized volume. The harvested volume curve decreases and remains relatively constant until the forest approaches regulation, when the harvested volume sharply increases. Scenario 20nt has higher pulpwood and lower sawtimber post-regulation harvested volume yield than baseline (25t15&22) because it is a change to pulpwood management. However, 20nt shows the largest discrepancy (75.5%) between pulpwood pre- and post-regulation volume harvest because it lacks the intermediate volume harvest of the thinned scenarios (Figure 4 Panel A and Figure 5). During regulation, the oldest age classes (those that are clearcut first) of the existing forest reflect baseline management, so a larger volume of sawtimber is harvested than the regime will yield after regulation (Table 4).

Table 4: Pre- and post-regulation annual harvest volumes for length of rotation by management regime of the Chesapeake Forest, MD. Scenario "35t17&25" denotes a 35 year rotation thinned at ages 17 and 25.

Scenario	Acres per Age Class (Regulated)	Average Annual Harvest (Million ft^3)		Sawtimber Proportion	
		Pre-Regulation	Post-Regulation	Pre-Regulation	Post-Regulation
20nt	1083	2.15	3.32	79.1%	45.1%
25t17	874	2.71	3.26	63.8%	61.7%
25t15&22	874	3.17	3.08	64.1%	61.9%
30t15&22	733	3.01	2.97	66.1%	68.0%
35t17&25	631	3.06	2.87	67.7%	70.4%
40t17&30	554	3.03	2.86	71.7%	74.6%

Scenario 25t17 exhibits a depressed pulpwood pre-regulation harvest similar to 20nt (Figure 5). However, post-regulation sawtimber harvest is 13.8% higher than pre-regulation sawtimber harvest because the two thinnings of baseline removed more volume than the single thinning of 25t17. Although the quality of residual trees and the growth of merchantable volume increase after thinning, a thinned stand loses productive capacity because the increased growth of residuals does not compensate for the volume production of removed boles. A less intense thinning regime results in higher levels of growing stock, which enhances pulpwood and sawtimber clearcut harvest.

Scenario 25t15&22 produces the largest volume of pulpwood because of its thinning frequency and its rotation length. This scenario produces more pulpwood than 20nt and 25t17 because every acre in both thinned age classes is harvested, which produces a relatively level harvested volume curve (Figure 4). Longer rotations clearcut fewer acres annually, so there is less clearcut volume. Pre- and post-regulation harvest of 25t15&22 should be the same (Figure 5) because it is the baseline scenario, and a 3% difference between pre-and post-regulation harvest shows that indeed a close baseline has been established (Table 4). Periods of varying harvest levels prevent a single area regulation scenario from precisely describing former management.

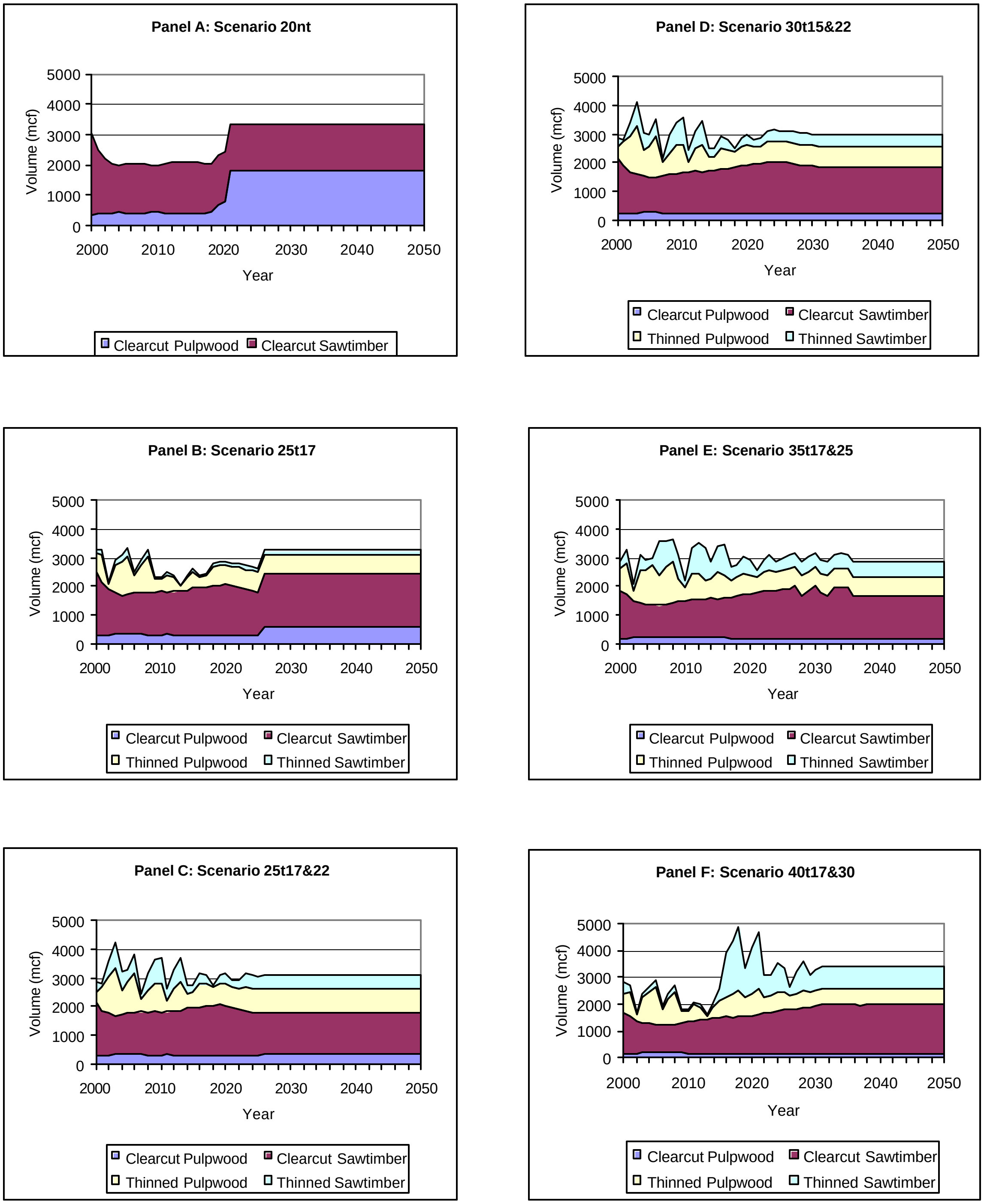

Figure 4: Harvested volume (MCF) by scenario for the Chesapeake forest, MD. Scenario "35t17&25" denotes a 35 year rotation thinned at ages 17 and 25.

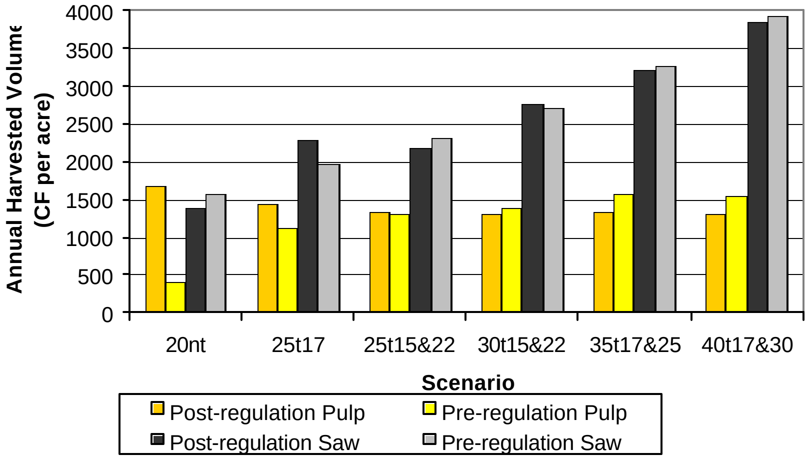

Figure 5: Pre- and post-regulation pulpwood and sawtimber harvest volume per harvested acre for the Chesapeake Forest, MD. Scenario "35t17&25" denotes a 35 year rotation thinned at ages 17 and 25.

The last three scenarios, 30t15&22, 35t17&25 and 40t17&30 have longer rotation lengths than baseline and the least variation between pre- and post-regulation harvest. 30t15&22 has a 7.4% higher sawtimber harvest after regulation. The timing of thinnings for 30t15&22 and baseline are identical, but five additional years of growth enhances sawtimber production. Thinning timing is unique to 35t17&25 and 40t17&30, but both scenarios demonstrate similar sawtimber harvest (≅2% greater after regulation) and pulpwood harvest is approximately 17% higher before regulation. These two scenarios harvest the least number of acres annually (Table 4), so it takes a longer time to regulate the forest.

Differences from baseline (25t15&22) are obvious from the harvested volume curves. More acres are annually harvested in 20nt than in the baseline, so there is an initial decrease in harvested volume and then a sudden increase as it approaches regulation. Scenario 40t17&30 displays an opposite trend, with a pre-regulation increase in harvested volume followed by a decrease as the forest is regulated. The other scenarios have more level curves, which illustrate that the difference from baseline is less pronounced. This reiterates the difficulty of determining baseline management based on stand management records. If the Chesapeake Forest were already regulated and any of the scenarios precisely described past management, then the harvested volume curves would be smooth. However, the uneven initial age class distribution shows that the

Chesapeake Forest was not strictly area regulated, so the total standing volume is not consistent from year to year.

4.2 Carbon Storage

Carbon storage is the amount of C that is sequestered into a C pool, which is either inventory volume or residual wood product volume. Converting volume flows to C storage involves tracking the decomposition of wood products and the accumulation of standing volume over time then converting volume to a measure of C. Carbon storage profiles (Figure 6) mimic the trends of the harvested volume curves. The spikes in the harvested volume curves (Figure 4) are smoothed out due to the decomposition of volume converted to wood products. Overall carbon storage and the carbon stored in sawtimber increases with rotation length, while the carbon stored in pulpwood decreases (Figure 6). Carbon storage prior to the year 2000 is ignored because it is the same for all scenarios (due to common past management) and therefore would not affect this comparative analysis, and it would be difficult to estimate. Carbon stored in standing volume generally increases with rotation length for the thinned regimes (Figure 6) because they annually harvest less volume than shorter rotations.

The shortest rotation, 20nt, sequesters the smallest amount of C overall (Figure 6 Panel A) because it has the least standing volume due to a small average diameter and it yields a large amount of fast-decaying pulpwood products (Table 4). Scenario 25t17 stores more carbon than 20nt because thinning increases the average diameter of the stand and harvests more volume, and an extra 5 years of growth increases the standing volume. Scenario 25t15&22 adds a second thinning that increases volume harvest, but the thinning reduces the growing stock so there is less carbon storage in standing timber than 20nt or 25t17 (Figure 6 Panels A,B,C). The remaining scenarios (30t15&22, 35t17&25 and 40t17&30) have similar carbon storage in wood products, but the effects of extending rotation length increases the carbon stored in standing volume (Figure 7, Panels D, E, F).

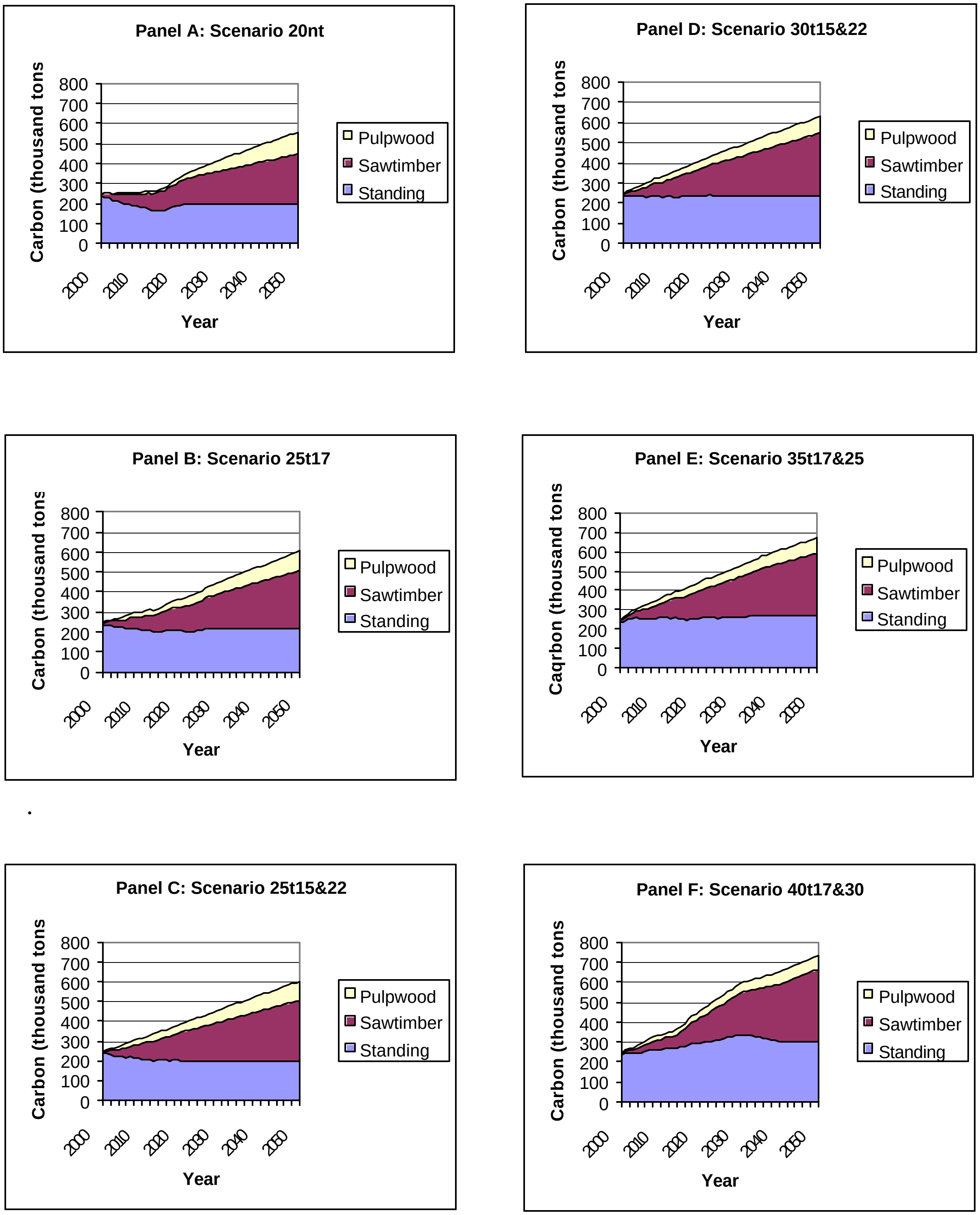

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Figure 6: Carbon storage over 50 years by component for the Chesapeake Forest, MD. Scenario "35t17&25" denotes a 35 year rotation thinned at ages 17 and 25.

Incremental carbon storage (Figure 7) is calculated by summing the annual increment of C storage in each of the three components from Figure 6. In the figure, "Pulpwood" and "Sawtimber" represent residual volume from these products. Over time, residual carbon from wood products accumulates because it never completely decomposes and more wood products are annually harvested. The wood product pool becomes a substantial carbon store, especially in sawtimber products (Figure 7). Standing C is carbon stored in inventory volume, and it is not an important storage component compared to the magnitude of wood products in the context of incremental storage. The ratio of incremental C in the wood products pool to the inventory pool ranges from 6 to 123 over 50 years. At the end of the initial rotation for each scenario, the ratio ranges from 4.9 to 21.5. Regimes in which the standing inventory at the end of the simulation was lower than the initial standing inventory (Figure 6, Panels A, B, C) corresponds to negative incremental C storage (Figure 7).

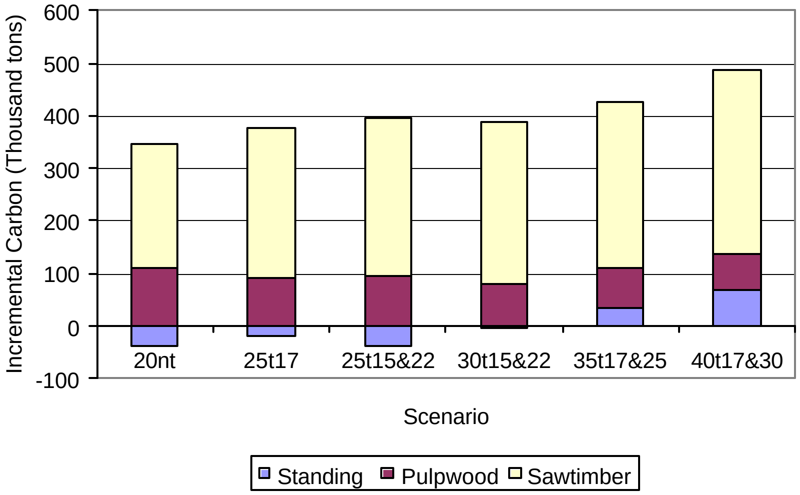

Figure 7: Incremental C storage summed over 50 years by component for the Chesapeake Forest, MD. Scenario "35t17&25" denotes a 35 year rotation thinned at ages 17 and 25.

4.3 Conclusions

Forest management influences forest C sequestration. Under area regulation, timing and intensity of thinning and rotation length determine the quantity of growing stock and harvested volume, and the merchantability classification of harvested volume. Short rotations annually harvest more area than long rotations, which converts more timber volume to wood products and decreases standing volume.

The use of an authentic initial age class distribution and evaluation of an entire forest estate sets this analysis apart from other studies of forest C sequestration. Rather than beginning each scenario from bare ground, forest management is altered to determine the consequence on C sequestration. Imposing area regulation on an unregulated forest complicates accounting for changes in future C storage. If the rotation length of the new management is less than the rotation length of the old management, there is a huge amount of harvested volume during the initial regulation period while volume in standing timber decreases. Conversely, rotations longer than previous management decrease harvest volume and increase volume in standing timber. Comparing scenarios over 50 years permits completion of at least one rotation of each scenario and provides a common timeframe for comparison, but blurs the distinction between regulating an existing forest and creating a hypothetical plantation.

Chapter 5. Economics

Management regime choice has substantial impact on NPV and the amount of C sequestered. Plotting NPV against average incremental C storage shows combinations of these outputs produced by the six regimes. The timing of C sequestration is paramount to determine if a market for C can influence forest management. To quantify the effects of forest regulation, three evaluation periods are evaluated; before and after regulation, and a combination of both.

5.1 Tradeoffs between timber production and C sequestration

Revenue from wood products production increases with the addition of thinnings but then levels off for the twice-thinned scenarios (Figure 8). Scenario 35t17&25 has the highest overall NPV and sawtimber NPV because it has the optimum combination of rotation length and thinning timing of the modeled scenarios. Harvested volume from thinning is mostly sawtimber that occurs throughout the rotation, rather than in large peaks like 40t17&30 (Figure 4). These peaks represent a large surge of income for 40t17&30, but are more heavily discounted than the relatively even flow from the thinnings of 35t17&25. If the regimes were analyzed in a bare-ground comparison, then 40t17&30 would produce the most sawtimber volume and have the largest NPV (Figure 5). Scenario 25t15&22 produces the most pulpwood NPV because it has the largest harvest volume, and the second lowest pre-regulation sawtimber proportion (Table 4).

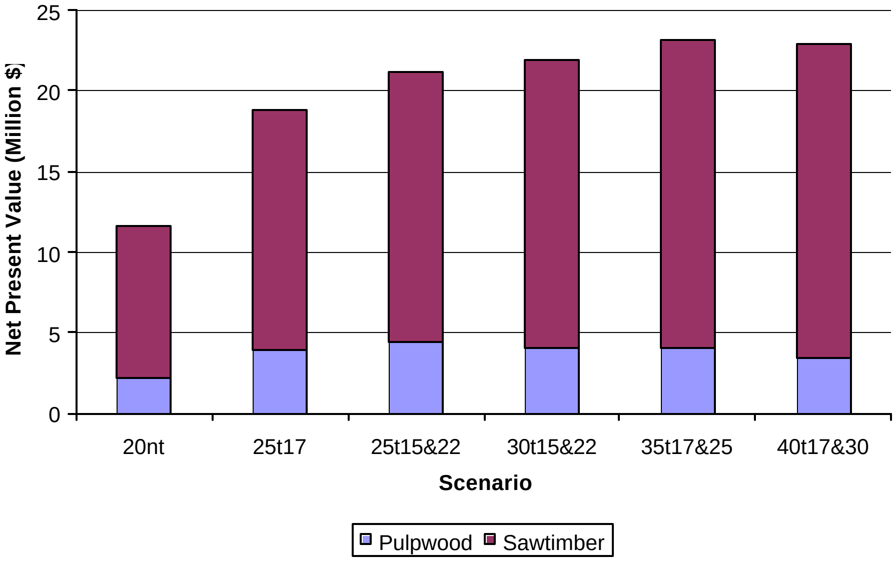

Figure 8: Net present value of wood products over 50 years for the Chesapeake Forest, MD. Scenario "35t17&25" denotes a 35 year rotation thinned at ages 17 and 25.

Management regime choice has substantial impact on NPV and the amount of C sequestered. Plotting NPV against average incremental C storage shows combinations of these outputs produced by the six regimes (Figure 9). Desirable scenarios that combine high NPV with high C storage are in the upper right corner, while undesirable scenarios are in the lower left corner (Figure 9). Scenarios 25t15&22, 30t15&22, 35t17&25 and 40t17&30 have NPVs within 9.4% of each other, but the amount of sequestered C varies by over 35% among these regimes. Scenario 20nt lies in the undesirable portion of Figure 9 because it stores less carbon (Figure 7) and provides the lowest NPV (Figure 8).

Discounted revenue flow illustrates the difference in revenue between the scenarios (Figure 10). As with the harvested volume figures (Figure 5), there are distinct pre- and post-regulation portions of the series. Pre-regulation is characterized by spikes representing the uneven age class area distribution of the existing forest while post-regulation exhibits a smoother behavior. Changing management from 20nt to 25t17 adds a thinning and increases rotation length. A single thinning creates intermediate volume harvest and revenue (Figure 10). Sawtimber harvest increases 10.4% because of the thin. Elevated NPV from the management change is illustrated in Figure 9.

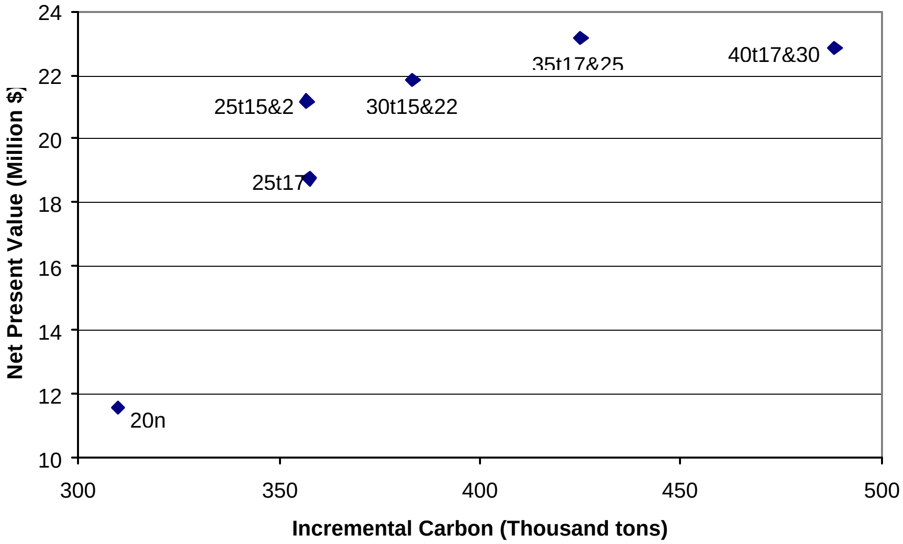

Figure 9: Incremental carbon storage and net present value over 50 years for the Chesapeake Forest, MD. Scenario “35t17&25” denotes a 35 year rotation thinned at ages 17 and 25.

Scenario 25t15&22 sequesters only 2.6% more C than 25t17, but the difference in discounted revenue is a more substantial 32.3% (Figure 9). Adding a second thinning to a 25-year rotation enhances the revenue of a scenario (Figure 10). Revenue from clearcut harvest is more heavily discounted than intermediate volume harvest from thinning because it occurs (later) at the end of the rotation. The flow of NPV for 25t15&22 is consistently higher than 25t17 until regulation, after which 25t17 produces slightly more NPV (Figure 10). The second thinning adds intermediate income, but it removes enough volume such that the enhanced growth of the residual trees dies not match the volume production of the removed stems.

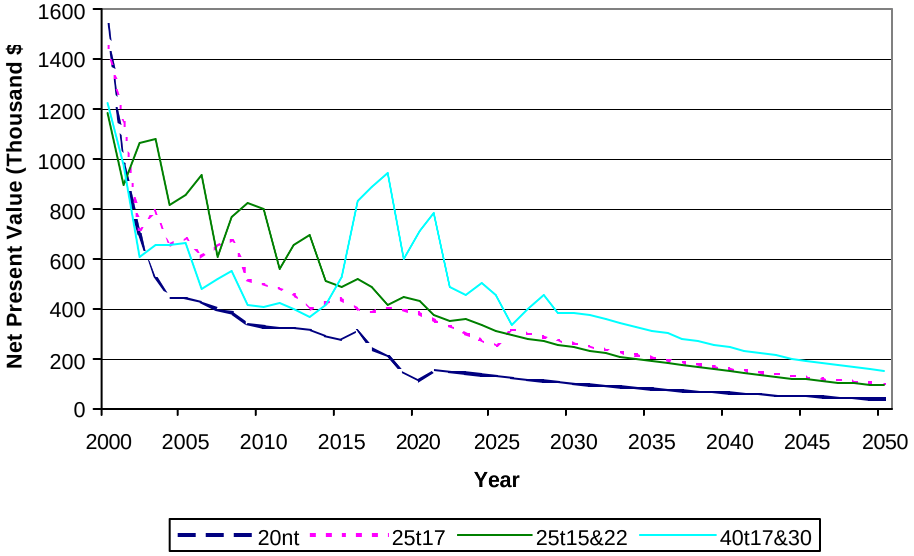

Figure 10: Discounted revenue flow over time for four management scenarios for the Chesapeake Forest, MD. Scenario "25t15&22" denotes a 25 year rotation thinned at ages 15 and 22.

Scenario 40t17&30 begins the modeled period with the lowest revenue flow, but once the large age classes reach thinning age (Figure 2) the revenue increases substantially and remains higher than the other scenarios (Figure 10). If the forest management goal is to maximize NPV, then the best management scenario is 40t17&30. Due to the high carbon storage in standing timber (Figure 7) and large sawtimber yield and harvest (Table 4), 40t17&30 maximizes C sequestration (Figure 9). If sequestered C had a market value, then 40t17&30 could have a larger NPV than 35t17&25.

5.2 Tradable C permits

Scenario 35t17&25 has the highest NPV, but 40t17&30 sequesters the most carbon over 50 years (Figure 9). Could a market for sequestered C influence the selection of management regimes? The timing of C sequestration is paramount to determine if a market for C can influence forest management. To address this issue, the period for comparison must be defined. To quantify the effects of forest regulation, three evaluation periods were chosen; before and after regulation, and a combination of both. The period 2008-2012 occurs during the initial rotation and the period 2044-2048 occurs after regulation. Both of these five-year periods are commitment periods of the Kyoto Protocol. A 50-year period beginning in the year 2000 permits completion of at least one rotation for each scenario. Incremental C storage and the difference in NPV from the maximum NPV for that period are calculated for each scenario during each accounting period.

Scenario 35t17&25 earns the most NPV for all periods considered. But in the 50-year period 40t17&30 sequesters the most carbon (Table 6). The management objectives of maximizing NPV and C storage are not compatible in this period. Supplemental income from selling C credits in the 50-year period could influence a forest management change from 35t17&25 to 40t17&30 if a ton of C had a market value of at least $173.

Table 6: Net present value (over 50 years) and the incremental C storage during the period indicated in the column heading. Scenario "35t17&25" denotes a 35 year rotation thinned at ages 17 and 25.

		Incremental Carbon Storage (tons)		
Scenario	**NPV**	**50 Years**	**2008-2012**	**2044-2048**
20nt	11564074	4026	-1386	13351
25t17	18759742	5562	1591	8392
25t15&22	21161912	5165	5450	9140
30t15&22	21846971	5507	6895	9998
35t17&25	23161327	5473	10023	10405
40t17&30	22843835	7323	5350	20204

The period 2008-2012 is during the forest regulation period of this analysis. Scenario 35t17&25 sequesters the most C in this period, so it is the best management choice. After the year 2040, all of the scenarios have been regulated, so harvest volume flows have been regulated (Figure 5), and carbon stored in inventory volume is constant from year to year (Figure 6). Scenario 40t17&30 maximizes NPV and carbon storage in the period 2044-2048, so it would be the best management regime choice.

5.3 Conclusions

If the Chesapeake Forest were managed to maximize NPV, then scenario 35t17&25 would be the best scenario of the six evaluated because it has the highest overall NPV. However, if a market for sequestered C provided an opportunity to sell C credits, 40t`7&30 would be profitable during the 50-year period if carbon was worth at least $173/ton. Of the six management regimes considered, longer rotations meet the objectives of maximizing C sequestration and NPV regardless of the accounting period considered, or if the forest is regulated or not regulated.

Chapter 6. Sensitivity Analysis

Model sensitivity to adjustment of decomposition rate, discount rate and timber prices is assessed to determine the effects of uncertainty (measurement error and future trends) on the model results. Adjusting the decomposition rate tests effects on C storage, and discount rate and timber prices assess the sensitivity of NPV. Percent change is calculated as the percent difference in stored C or NPV between default and adjusted parameter values.

Slower decomposition slides the decomposition curves in Figure 3 up the y-axis without changing the shape or relationship of the curves to each other. As the decomposition rate is decreased, residual volume in wood products increases, adding C to the wood product pool. When decomposition rate is increased, less C remains in the wood products pool (Table 8). The symmetric increase and decrease (Table 8) is due to the linear formulation of harvested volume multiplied by decomposition assumptions. Only the carbon stored in residual product volume is affected by the decomposition assumption.

Rotation length implies the amount and product proportions of harvest volume, both of which determine the magnitude of the effects of decomposition rate change. Scenario 20nt is most affected by decomposition rate adjustment (Table 8) because the short rotation length allows one pre-regulation rotation and 1.5 post-regulation rotations, resulting in the most volume harvest over 50 years (Table 4, Figure 5). The scenarios with a 25- year rotation length are highly affected because two rotations occur in 50 years. Scenario 25t15&22 is more sensitive than 25t17 because it is thinned sooner and more volume is removed. Thinned volume is more sensitive to decomposition rate than clearcut volume because it occurs sooner in the rotation, so it begins to decompose sooner than clearcut volume. Scenarios 30t27&30, 35t17&25 and 40t17&30 are less sensitive to the decomposition rate change (Table 8) because as rotation length increases, annual timber harvest volume decreases and the proportion of sawtimber volume increases (Table 4).

Table 8: Default annual incremental C storage over 50 years and percent change in C storage from default resulting from decomposition parameter adjustment for the Chesapeake Forest, MD. "Pulp=Saw" means that the decomposition rates for pulp and saw products are equal. Scenario "35t17&25" denotes a 35 year rotation thinned at ages 17 and 25.

		Decomposition Rate		
Scenario	Default C (tons)	10% Slower	10% Faster	Pulp = Saw
20nt	309900	11.19%	-11.19%	42.22%
25t17	357467	10.55%	-10.55%	34.35%
25t15&22	356865	11.07%	-11.07%	35.43%
30t15&22	383277	10.08%	-10.08%	30.33%
35t17&25	425085	9.18%	-9.18%	27.34%
40t17&30	488325	8.58%	-8.58%	23.41%

When the pulpwood decomposition rate equals the sawtimber decomposition rate, the C storage of all the scenarios increases substantially (Table 8). This differential shift of decomposition rate could be created by composite lumber production. Potential large-scale production of composite lumber may reduce the difference between pulpwood and sawtimber because smaller logs can be made into large beams, which reduces the demand for large timber. Pulpwood used in composite lumber would have a longer product lifecycle and face durable (long-term) storage in buildings rather than short-term storage as paper products in landfills.

The sensitivity of net present value was tested with changes to discount rate and stumpage price. Discount rate has a non-linear effect in NPV, so the effects of a positive adjustment do not mirror the effects of a negative adjustment. A higher discount rate decreases the current value of revenue generated later in the rotation, so the longer rotations experience a percent NPV decrease (Table 9). Conversely, a lower discount rate magnifies the current value of revenue at the end of the rotation, so longer rotations have a percent NPV increase (Table 9).

Table 9: Default NPV over 50 years and percent change from default induced by the parameter adjustment noted in the column heading for the Chesapeake Forest, MD. Discount rates are noted. Values for stumpage price represent the amount of change from the default values. The heading “20% (pulp only)” signifies a 20% increase in pulpwood stumpage price while holding sawtimber stumpage prices constant. Scenario “35t17&25” denotes a 35 year rotation thinned at ages 17 and 25.

		Discount Rate		Stumpage Price		
Scenario	NPV	5.50%	4.50%	-10%	10%	20% (pulp only)
20nt	$11,564,074	-5.92%	6.69%	14.29%	-14.29%	9.45%
25t17	$18,759,742	-7.55%	8.65%	12.14%	-12.14%	5.16%
25t15&22	$21,161,912	-7.19%	8.18%	11.89%	-11.89%	4.46%
30t15&22	$21,846,971	-7.32%	8.35%	11.54%	-11.54%	3.89%
35t17&25	$23,161,327	-7.64%	8.72%	11.25%	-11.25%	4.03%
40t17&30	$22,843,835	-8.93%	10.30%	11.11%	-11.11%	3.58%

When stumpage prices are adjusted by ± 10%, the effects on the scenarios are inversely proportional to rotation length (Table 9). If more revenue is generated by the harvested timber, then more of the establishment costs are offset. Site establishment costs are larger for shorter rotations because more acres are annually harvested. A price increase or decrease corresponds to an identical change in revenue from harvested timber. If the value of only pulpwood increases 20%, then the NPV for short rotations increases more than the NPV for long rotations (Table 9) because short rotations produce more pulpwood (Table 4). This one-sided price increases accompanies the differential shift of decay assumptions for pulpwood to sawtimber because of the potential for composite wood products.

Chapter 7. Conclusions

Long rotations sequester more carbon than short rotations. Approximately half of the carbon stored by a management regime resides in inventory volume and the other half accumulates in wood products. In general, the proportion of carbon stored in wood products decreases with rotation length because long rotations harvest fewer acres annually, so there is more inventory volume. Rotations that favor sawtimber production produce durable wood products, but the storage in inventory volume is a more substantial carbon store.

The sale of carbon credits can influence forest management, but defining an accounting system and period are critical. Forest management will be influenced only if the revenue from carbon credit sale supplements enough revenue to exceed other management options. It appears that longer rotations meet the objectives of maximizing C sequestration and NPV regardless of the accounting period considered, or if the forest is regulated or not regulated.

The timing and frequency of thinnings heavily influence carbon sequestration and harvest revenue. During regulation, when large age classes reach the thinning age, they create peaks in the carbon storage and NPV flow curves that correspond to a large surge of revenue. Thinnings that are more frequent add intermediate revenue and carbon storage, which improve the value of the scenario. However, if the increased volume growth of residuals fails to replace the volume removed by thinning, then clearcut harvest value may suffer.

Wood product decay rate assumptions were the most sensitive parameters tested, and the complex nature of assumption development leaves the most room for improvement. The decay assumptions I used were compiled prior to publication in 1996. Many factors could have changed since then, including mill utilization, category distribution and product end use fate. If technology advances allow mills to become more efficient, then more volume is converted to products because less volume is converted to slabs or sawdust. If more products are manufactured, then the category distribution will shift to reflect more residual volume in products. Technology advances could also improve landfill design, so there would be less product decomposition. Engineered composite lumber could reduce the difference between pulpwood and sawtimber because smaller diameter trees can be assembled into large pieces of lumber. Increasing the residual proportion of products (less decay) is a realistic assumption because more wood will become products, and smaller trees can be fabricated into larger, slow-decaying structural wood. Increased rates of recycling could prolong the period in which C is stored in products in use. More rapid adoption of modern landfill technology also increases C storage and decreases decomposition.

There are a number of limitations of this model. The model tracks the growth, harvest and fate of inventory volume and harvested volume converted to wood products of merchantable aboveground biomass of a loblolly pine plantation with specific initial site parameters. Other components can be added to the model to include other components of the forest carbon cycle, such as belowground biomass, understory vegetation, or soil CO_2 efflux. The results reported here are intended for comparison among the modeled scenarios. As is, the model is suitable only for the specified scenarios for a loblolly pine plantation. The stand table, decomposition assumptions and volume conversion factors can be easily modified to work for other management scenarios and tree species.

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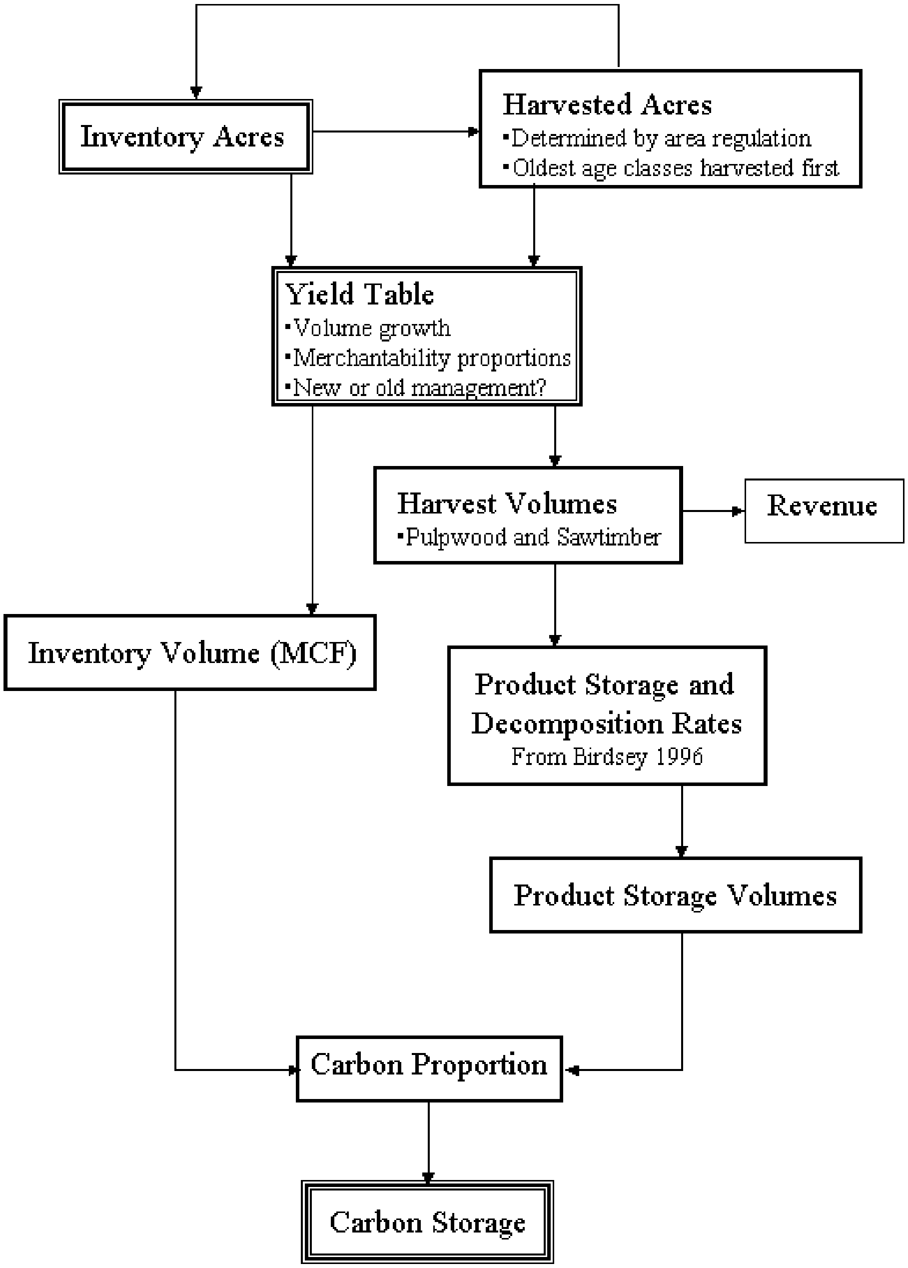
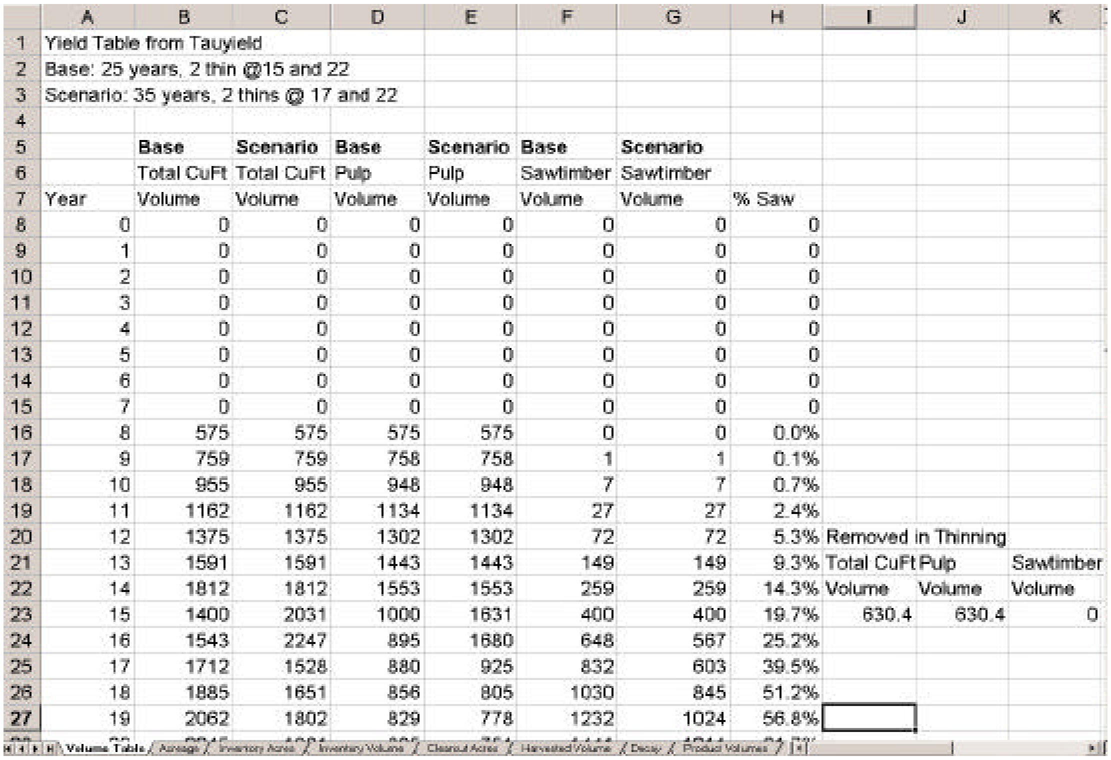
Appendix: Model Description

This flowchart illustrates the overall structure of the model, where Inventory Acres and Yield Table are inputs, and carbon storage is the output. The only feedback loop of the model is where Harvested Acres returns the clearcut acres to age class 0 in Inventory Acres. Each of the components, except for Carbon Proportion, represents a tab in the spreadsheet model. Each tab will be explained in detail.



Yield Table

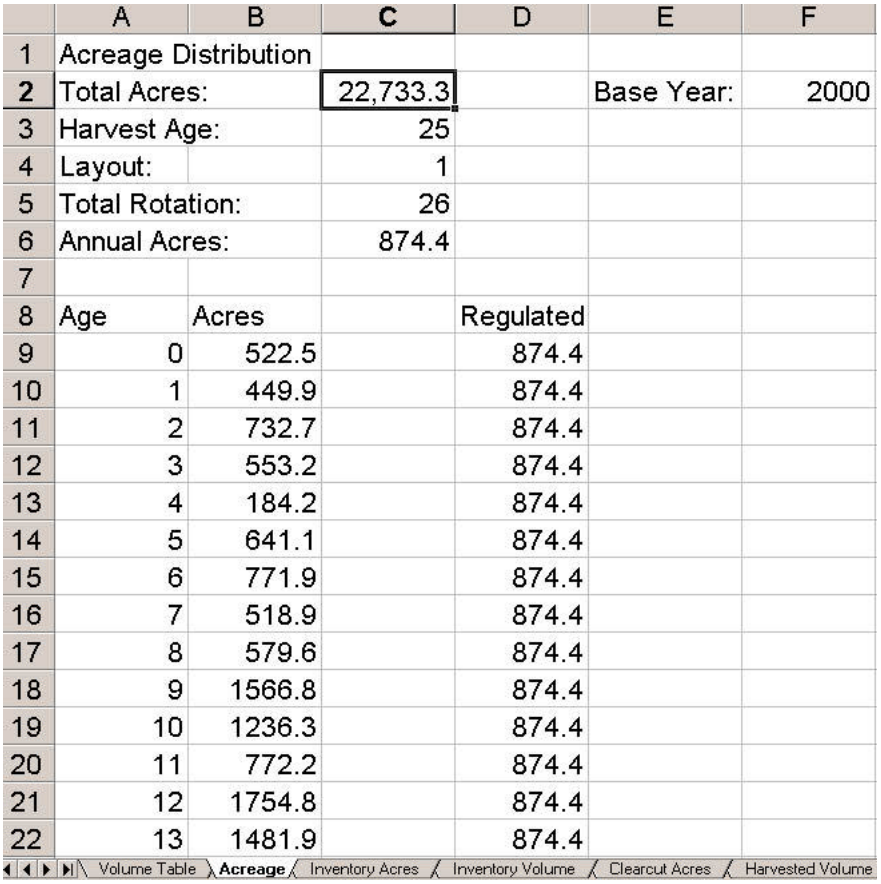
The first tab in the model is Yield Table. Here there are three categories of volume: total cuft, pulp and sawtimber. For each category, there is a base or scenario volume. Base volume is defined on the tab, and in this case, it is 25t15&22. The scenario volume is also defined on the tab; here it is 35t17&22. The volumes are identical until the first thinning, which is in year 15. Volume removed by thinning is shown in columns I,J and K.



	A	B	C	D	E	F	G	H	I	J	K
1	Yield Table from Tauyield										
2	Base: 25 years, 2 thin @15 and 22										
3	Scenario: 35 years, 2 thins @ 17 and 22										
4											
5		**Base**	**Scenario**	**Base**	**Scenario**	**Base**	**Scenario**				
6		Total CuFt	Total CuFt	Pulp	Pulp	Sawtimber	Sawtimber				
7	Year	Volume	Volume	Volume	Volume	Volume	Volume	% Saw			
8	0	0	0	0	0	0	0	0			
9	1	0	0	0	0	0	0	0			
10	2	0	0	0	0	0	0	0			
11	3	0	0	0	0	0	0	0			
12	4	0	0	0	0	0	0	0			
13	5	0	0	0	0	0	0	0			
14	6	0	0	0	0	0	0	0			
15	7	0	0	0	0	0	0	0			
16	8	575	575	575	575	0	0	0.0%			
17	9	759	759	758	758	1	1	0.1%			
18	10	955	955	948	948	7	7	0.7%			
19	11	1162	1162	1134	1134	27	27	2.4%			
20	12	1375	1375	1302	1302	72	72	5.3%	Removed in Thinning		
21	13	1591	1591	1443	1443	149	149	9.3%	Total CuFt	Pulp	Sawtimber
22	14	1812	1812	1553	1553	259	259	14.3%	Volume	Volume	Volume
23	15	1400	2031	1000	1631	400	400	19.7%	630.4	630.4	0
24	16	1543	2247	895	1680	648	567	25.2%			
25	17	1712	1528	880	925	832	603	39.5%			
26	18	1885	1651	856	805	1030	845	51.2%			
27	19	2062	1802	829	778	1232	1024	56.8%			

Acreage

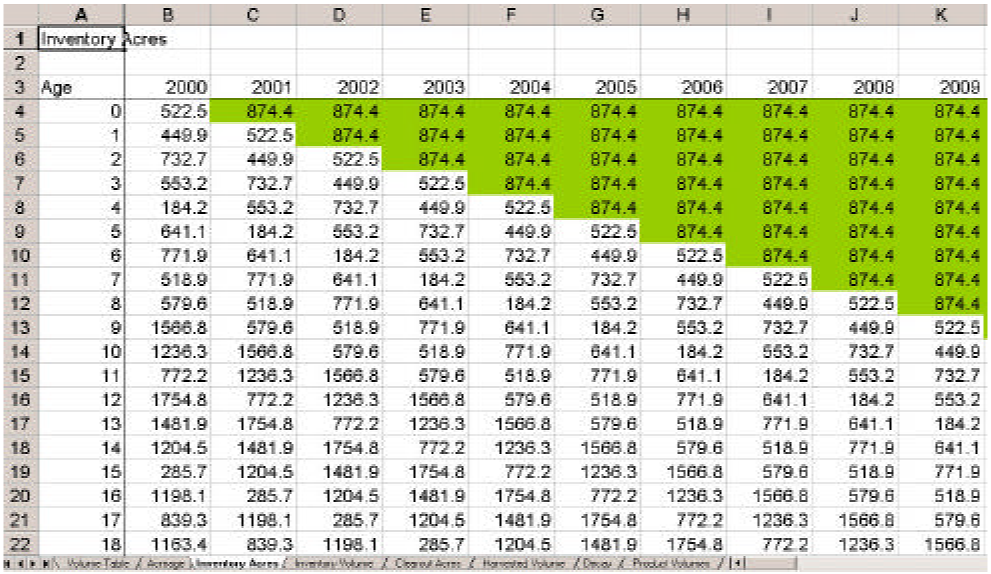
The second tab in the model is Acreage. The initial age class distribution of the Chesapeake Forest is in Column B, and the number of acres in each regulated age class is shown in column D. The top left corner shows the variables required for area regulation.



	A	B	C	D	E	F
1	Acreage Distribution					
2	Total Acres:		22,733.3		Base Year:	2000
3	Harvest Age:		25			
4	Layout:		1			
5	Total Rotation:		26			
6	Annual Acres:		874.4			
7						
8	Age	Acres		Regulated		
9	0	522.5		874.4		
10	1	449.9		874.4		
11	2	732.7		874.4		
12	3	553.2		874.4		
13	4	184.2		874.4		
14	5	641.1		874.4		
15	6	771.9		874.4		
16	7	518.9		874.4		
17	8	579.6		874.4		
18	9	1566.8		874.4		
19	10	1236.3		874.4		
20	11	772.2		874.4		
21	12	1754.8		874.4		
22	13	1481.9		874.4		

Inventory Acres

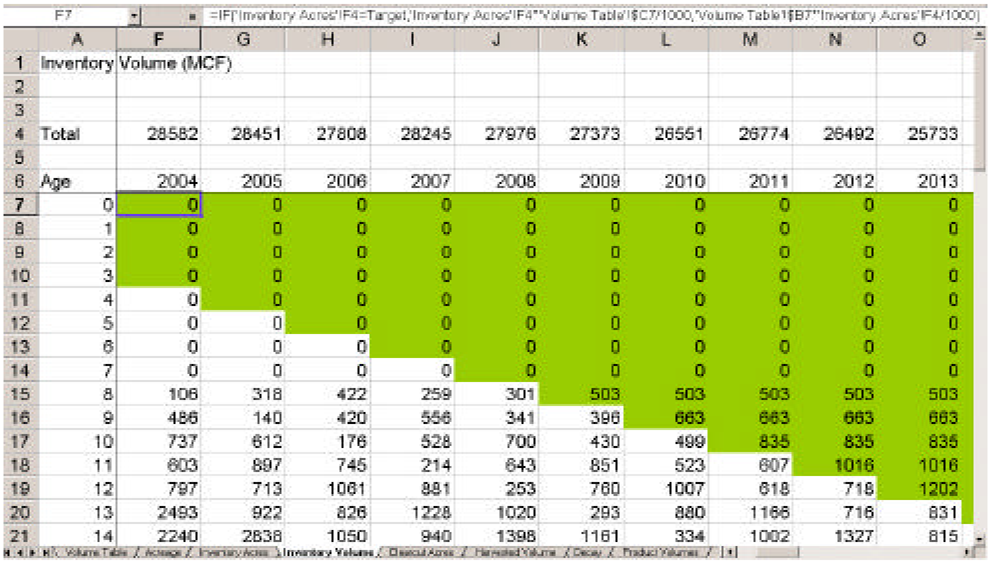
The third tab of the model is Inventory Acres. Column B repeats the initial age class distribution found in the Acreage tab. The highlighted cells represent age classes that have been regulated.



	A	B	C	D	E	F	G	H	I	J	K
1	Inventory Acres										
2											
3	Age	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
4	0	522.5	874.4	874.4	874.4	874.4	874.4	874.4	874.4	874.4	874.4
5	1	449.9	522.5	874.4	874.4	874.4	874.4	874.4	874.4	874.4	874.4
6	2	732.7	449.9	522.5	874.4	874.4	874.4	874.4	874.4	874.4	874.4
7	3	553.2	732.7	449.9	522.5	874.4	874.4	874.4	874.4	874.4	874.4
8	4	184.2	553.2	732.7	449.9	522.5	874.4	874.4	874.4	874.4	874.4
9	5	641.1	184.2	553.2	732.7	449.9	522.5	874.4	874.4	874.4	874.4
10	6	771.9	641.1	184.2	553.2	732.7	449.9	522.5	874.4	874.4	874.4
11	7	518.9	771.9	641.1	184.2	553.2	732.7	449.9	522.5	874.4	874.4
12	8	579.6	518.9	771.9	641.1	184.2	553.2	732.7	449.9	522.5	874.4
13	9	1566.8	579.6	518.9	771.9	641.1	184.2	553.2	732.7	449.9	522.5
14	10	1236.3	1566.8	579.6	518.9	771.9	641.1	184.2	553.2	732.7	449.9
15	11	772.2	1236.3	1566.8	579.6	518.9	771.9	641.1	184.2	553.2	732.7
16	12	1754.8	772.2	1236.3	1566.8	579.6	518.9	771.9	641.1	184.2	553.2
17	13	1481.9	1754.8	772.2	1236.3	1566.8	579.6	518.9	771.9	641.1	184.2
18	14	1204.5	1481.9	1754.8	772.2	1236.3	1566.8	579.6	518.9	771.9	641.1
19	15	285.7	1204.5	1481.9	1754.8	772.2	1236.3	1566.8	579.6	518.9	771.9
20	16	1198.1	285.7	1204.5	1481.9	1754.8	772.2	1236.3	1566.8	579.6	518.9
21	17	839.3	1198.1	285.7	1204.5	1481.9	1754.8	772.2	1236.3	1566.8	579.6
22	18	1163.4	839.3	1198.1	285.7	1204.5	1481.9	1754.8	772.2	1236.3	1566.8

Inventory Volume

The Inventory Volume tab is the fourth tab of the model. It shows the volume (MCF) in each age class by year, and is calculated by multiplying the number of acres in an age class by the corresponding total volume value in the Yield Table tab. A condition in the model determines whether to use the base or scenario volume. The highlighted cells show regulated age classes.

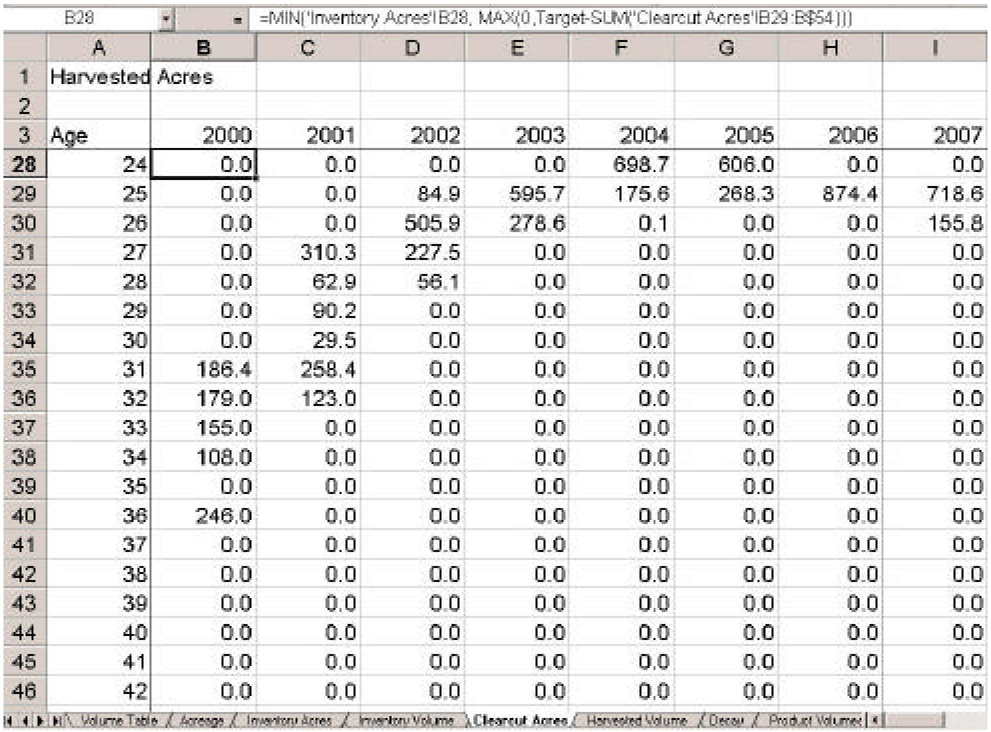


F7 =IF('Inventory Acres'!F4=Target,'Inventory Acres'!F4*'Volume Table'!$C7/1000,'Volume Table'!$B7*'Inventory Acres'!F4/1000)

	A	F	G	H	I	J	K	L	M	N	O
1	Inventory Volume (MCF)										
2											
3											
4	Total	28582	28451	27808	28245	27976	27373	26551	26774	26492	25733
5											
6	Age	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
7	0	0	0	0	0	0	0	0	0	0	0
8	1	0	0	0	0	0	0	0	0	0	0
9	2	0	0	0	0	0	0	0	0	0	0
10	3	0	0	0	0	0	0	0	0	0	0
11	4	0	0	0	0	0	0	0	0	0	0
12	5	0	0	0	0	0	0	0	0	0	0
13	6	0	0	0	0	0	0	0	0	0	0
14	7	0	0	0	0	0	0	0	0	0	0
15	8	106	318	422	259	301	503	503	503	503	503
16	9	486	140	420	556	341	396	663	663	663	663
17	10	737	612	176	528	700	430	499	835	835	835
18	11	603	897	745	214	643	851	523	607	1016	1016
19	12	797	713	1061	881	253	760	1007	618	718	1202
20	13	2493	922	826	1228	1020	293	880	1166	716	831
21	14	2240	2838	1050	940	1398	1161	334	1002	1327	815

Harvested Acres

The fifth tab of the model is Harvested Acres and it shows the number of clearcut acres. The oldest age classes are harvested first, then the next youngest age class until the harvest area target is met.

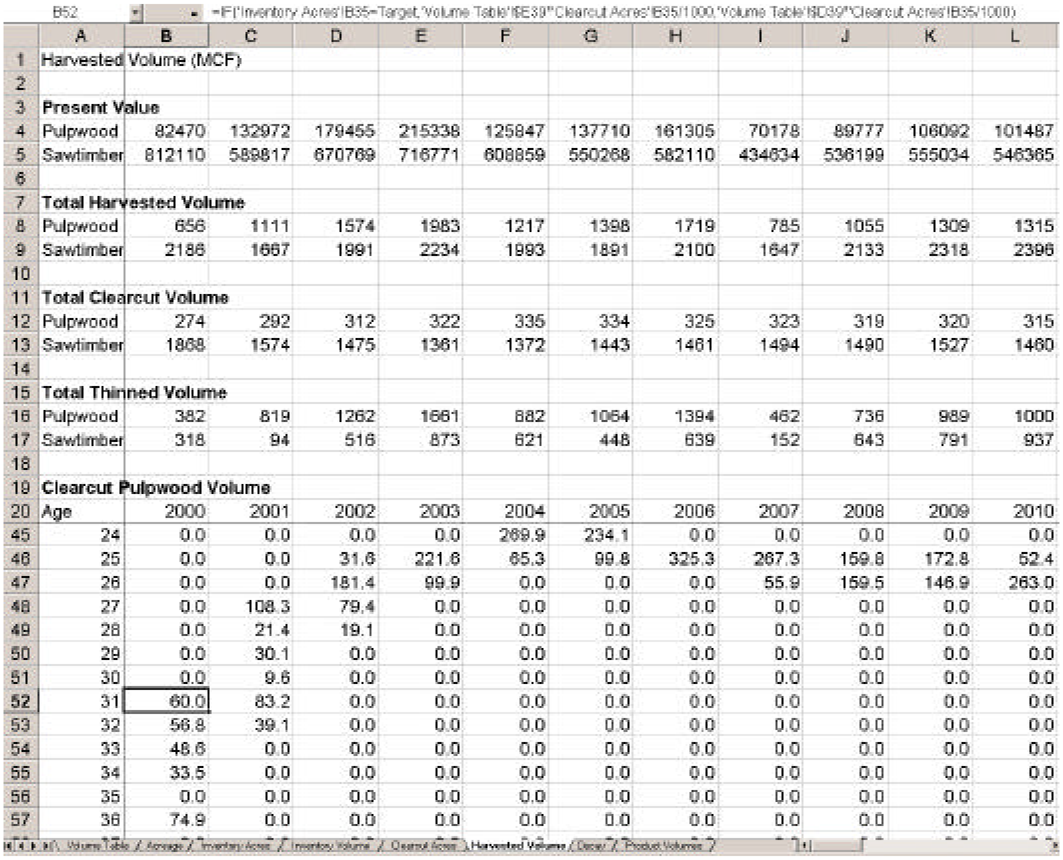


B28 =MIN('Inventory Acres'!B28, MAX(0,Target-SUM('Clearcut Acres'!B29:B$54)))

	A	B	C	D	E	F	G	H	I
1	Harvested Acres								
2									
3	Age	2000	2001	2002	2003	2004	2005	2006	2007
28	24	0.0	0.0	0.0	0.0	698.7	606.0	0.0	0.0
29	25	0.0	0.0	84.9	595.7	175.6	268.3	874.4	718.6
30	26	0.0	0.0	505.9	278.6	0.1	0.0	0.0	155.8
31	27	0.0	310.3	227.5	0.0	0.0	0.0	0.0	0.0
32	28	0.0	62.9	56.1	0.0	0.0	0.0	0.0	0.0
33	29	0.0	90.2	0.0	0.0	0.0	0.0	0.0	0.0
34	30	0.0	29.5	0.0	0.0	0.0	0.0	0.0	0.0
35	31	186.4	258.4	0.0	0.0	0.0	0.0	0.0	0.0
36	32	179.0	123.0	0.0	0.0	0.0	0.0	0.0	0.0
37	33	155.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
38	34	108.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
39	35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
40	36	246.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
41	37	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
42	38	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
43	39	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
44	40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
45	41	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
46	42	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Harvested Volume

Harvested Volume is the next tab in the model. Clearcut volume is divided into pulpwood and sawtimber wood products. Volume is calculated by multiplying the number of clearcut or thinned acres by the corresponding volume in the Volume Table tab. The matrix at the bottom of the screenshot shows the pulpwood volume from clearcut harvest; there is a similar matrix for clearcut sawtimber volume. Present value is calculated annually from the combined clearcut and thinned volumes.

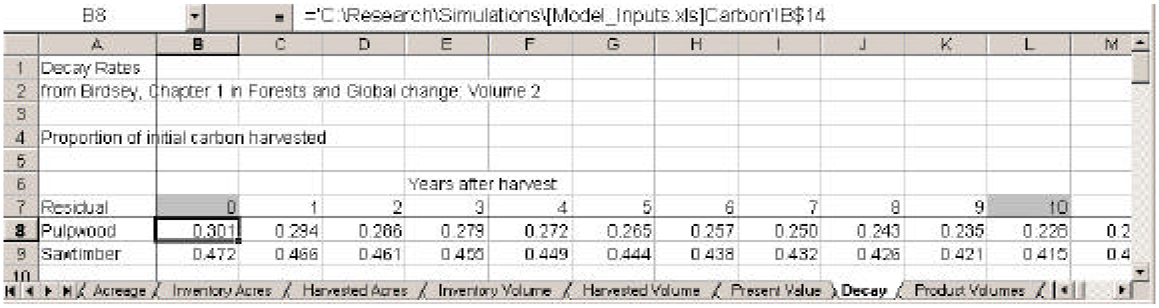


=IF('Inventory Acres'!B35=Target,'Volume Table'!$E39*'Clearcut Acres'!B35/1000,'Volume Table'!$D39*'Clearcut Acres'!B35/1000)

	A	B	C	D	E	F	G	H	I	J	K	L
1	Harvested Volume (MCF)											
2												
3	**Present Value**											
4	Pulpwood	82470	132972	179455	215338	125847	137710	161305	70178	89777	106092	101487
5	Sawtimber	812110	589817	670769	716771	608859	550268	582110	434634	536199	555034	546365
6												
7	**Total Harvested Volume**											
8	Pulpwood	656	1111	1574	1983	1217	1398	1719	785	1055	1309	1315
9	Sawtimber	2186	1667	1991	2234	1993	1891	2100	1647	2133	2318	2396
10												
11	**Total Clearcut Volume**											
12	Pulpwood	274	292	312	322	335	334	325	323	319	320	315
13	Sawtimber	1868	1574	1475	1361	1372	1443	1461	1494	1490	1527	1460
14												
15	**Total Thinned Volume**											
16	Pulpwood	382	819	1262	1661	882	1064	1394	462	736	989	1000
17	Sawtimber	318	94	516	873	621	448	639	152	643	791	937
18												
19	**Clearcut Pulpwood Volume**											
20	Age	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
45	24	0.0	0.0	0.0	0.0	269.9	234.1	0.0	0.0	0.0	0.0	0.0
46	25	0.0	0.0	31.6	221.6	65.3	99.8	325.3	267.3	159.8	172.8	52.4
47	26	0.0	0.0	181.4	99.9	0.0	0.0	0.0	55.9	159.5	146.9	263.0
48	27	0.0	108.3	79.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
49	28	0.0	21.4	19.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
50	29	0.0	30.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
51	30	0.0	9.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
52	31	60.0	83.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
53	32	56.8	39.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
54	33	48.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
55	34	33.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
56	35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
57	36	74.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Decay

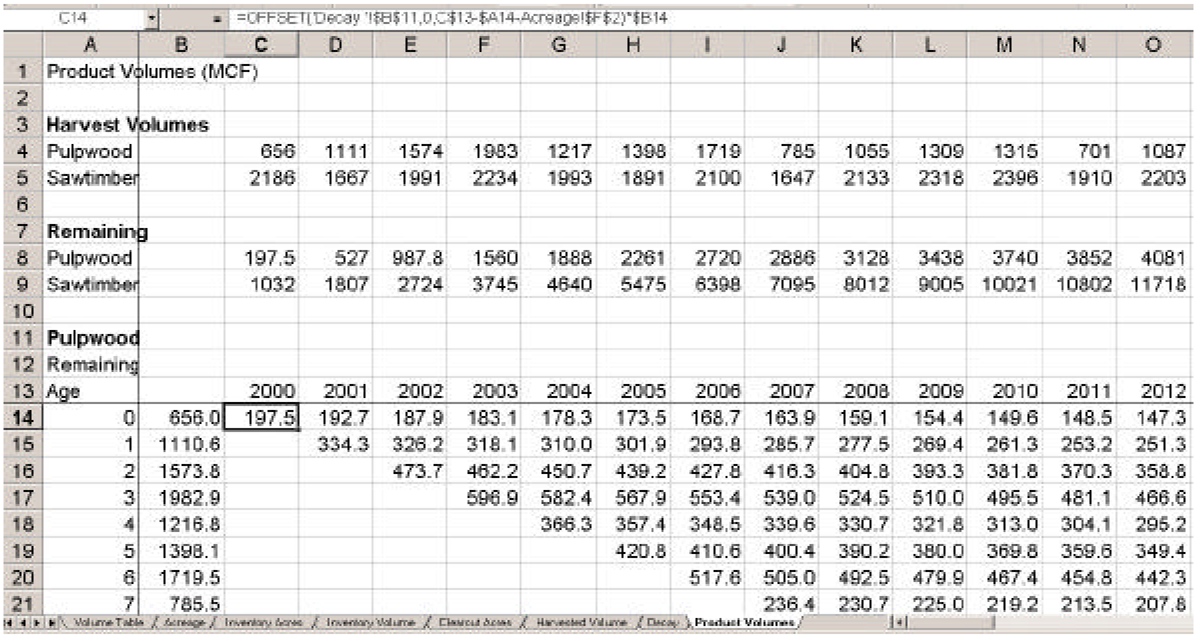
The seventh tab of the model is the Decay coefficients for pulpwood and sawtimber. The coefficients are identical to Tables 2 and 3, except they are on an annual scale.


B8 ='C:\Research\Simulations\[Model_Inputs.xls]Carbon'!B$14

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Decay Rates												
2	from Birdsey, Chapter 1 in Forests and Global change: Volume 2												
3													
4	Proportion of initial carbon harvested												
5													
6					Years after harvest								
7	Residual	0	1	2	3	4	5	6	7	8	9	10	
8	Pulpwood	0.301	0.294	0.286	0.279	0.272	0.265	0.257	0.250	0.243	0.235	0.228	0.2
9	Sawtimber	0.472	0.466	0.461	0.455	0.449	0.444	0.438	0.432	0.426	0.421	0.415	0.4
10													

Product Volumes

The Product Volume tab is the final tab of the model. The harvested volumes are shown in rows 3 and 4, and are transferred to column B. Similar to Harvested volume, there are separate matrices for pulpwood and sawtimber. This volume is multiplied by the decay coefficients, which tracks the decomposition of wood products harvested that year as time progresses across the row. Each column is summed into rows 8 and 9, which is the total residual volume for all volume harvested in or previous to that year.


C14 =OFFSET('Decay '!$B$11,0,C$13-$A14-Acreage!$F$2)*$B14

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	**Product Volumes (MCF)**														
2															
3	**Harvest Volumes**														
4	Pulpwood		656	1111	1574	1983	1217	1398	1719	785	1055	1309	1315	701	1087
5	Sawtimber		2186	1667	1991	2234	1993	1891	2100	1647	2133	2318	2396	1910	2203
6															
7	**Remaining**														
8	Pulpwood		197.5	527	987.8	1560	1888	2261	2720	2886	3128	3438	3740	3852	4081
9	Sawtimber		1032	1807	2724	3745	4640	5475	6398	7095	8012	9005	10021	10802	11718
10															
11	**Pulpwood**														
12	**Remaining**														
13	Age		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
14	0	656.0	197.5	192.7	187.9	183.1	178.3	173.5	168.7	163.9	159.1	154.4	149.6	148.5	147.3
15	1	1110.6		334.3	326.2	318.1	310.0	301.9	293.8	285.7	277.5	269.4	261.3	253.2	251.3
16	2	1573.8			473.7	462.2	450.7	439.2	427.8	416.3	404.8	393.3	381.8	370.3	358.8
17	3	1982.9				596.9	582.4	567.9	553.4	539.0	524.5	510.0	495.5	481.1	466.6
18	4	1216.8					366.3	357.4	348.5	339.6	330.7	321.8	313.0	304.1	295.2
19	5	1398.1						420.8	410.6	400.4	390.2	380.0	369.8	359.6	349.4
20	6	1719.5							517.6	505.0	492.5	479.9	467.4	454.8	442.3
21	7	785.5								236.4	230.7	225.0	219.2	213.5	207.8

Vita

The author was born in Weymouth, Massachusetts on April 7, 1978. He received a Bachelor of Science degree in Forestry from Virginia Tech with an emphasis on Environmental Resource Management in May of 2000. While enrolled there as an undergraduate, he spent time gaining experience in Urban and Industrial Forestry internships. He began his graduate work at Virginia Tech in August of 2000 and expects completion in April of 2002. Upon completion, the author hopes to begin a career.