Changing the Paradigm: Inventory Review and Scenario Modeling for the Duke Forest

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1. INTRODUCTION

Forest management in the 21st century is faced with the challenge of being economically viable in the short-term while taking into account long-term considerations brought about by a changing environment and economy. Throughout the 21st century, market forces and social trends have moved at rates faster than the growth of forestland, making long-term strategic planning essential for sustainable forest management. However, in the absence of technology that allows us to look into the future, forest managers are stuck making decisions based upon patterns of the past and their best educated guesses about what the future will yield. This discussion around future risk, uncertainty, and adaptation is at the core of resource management and maintaining the ability to respond flexibly in the face of this uncertainty is arguably the most important task in sustainable forest management.

Our client, the Office of the Duke Forest, is faced with these exact challenges of generating timber revenue to offset cost of forest operations in the present amidst planning for an uncertain future. Specifically, a combination of changing land-use patterns across the piedmont of North Carolina, low post-recession prices for wood products (particularly sawtimber), new emerging markets for wood products, and uncertainties around the impacts of climate change and invasive species will all have future implications for the forest's management (Wear 2013).

2. PROJECT OBJECTIVES AND SCOPE

An important component of understanding future management challenges is having the ability to estimate growth and yield of stands in light of different management practices. The purpose of the this project is to show how alternative growth and yield modeling could be used by the Duke Forest to address its need for long-term planning to create an even age class distribution, while still generating revenue for the operating budget. This has been identified by the Duke Forest staff as a priority so that it can promote sustainable harvest schedules based on realistic expectations of the productivity of the forest. To accomplish this, the project has the following objectives and questions:

1. **Comparing Methods of Volume Estimation**
    a. *Questions:* How does the current (2010) Duke Forest inventory method compare with an alternative method that estimates tree volume for the entire forest? How similar are these results between models?
    b. *Analysis:* We compared the Duke Forest equations used to estimate tree volume with the equations used by the US Forest Service's Forest Vegetation Simulator (FVS). The volumes obtained by these two methods were compared at tree and acre level and were assigned monetary value.
2. **Comparing Silvicultural Scenarios**
    a. *Questions:* How do different rotation lengths and planting of improved stock change volume and harvest estimates for the Dailey Division of the Duke Forest over 100 years?
    b. *Analysis:* We modeled five different rotation lengths, each with and without planting improved stock and compared harvest volumes over time.
3. **Financial Analysis between Silvicultural Scenarios**
    a. *Questions:* Which of the above management scenarios maximizes the net revenue and NPV?
    b. *Analysis:* We modeled cash-flow comparisons for management scenarios using updated prices for product classes and treatment operations estimating the NPV for the next 100 years.

To conclude the project, we report the implications of these findings within a forest-wide context. This summary informs the Forest of annual revenue expectations based off of alternative silvicultural scenarios. These can be used to inform management and budget planning.

3. BACKGROUND

3.1 Forest Management in the Southeast: A look into the future.

In order to understand future timber management opportunities and challenges for the Duke Forest, we must first acknowledge the greater context of forestry in the Southeast. The *Southern Forest Futures Project* (SFFP) authored by David Wear and John Greis of the US Forest Service provides one of the most comprehensive and authoritative sources that examines the future of forests in this region (Wear 2013).

Markets for wood products enjoyed steady increases throughout the later part of the 20th century, making forestry (particularly pine plantations) profitable across South, which has become known colloquially as the "timber basket of the world." However, since the Great Recession of 2007-2008 and the burst of the housing bubble, demand for many wood products has declined significantly, bringing down market prices for pine sawtimber by nearly a third (Wear 2013; TimberMart-South 4Q 2016). Economic modeling by the SFFP predicts a slow recovery of pre-recession prices for sawtimber over the next decade coupled with slightly declining or stabilizing prices for softwood-pulp compared to 2006 levels. An important implication for the latter are future biomass markets and the demand for alternative energy sources (Wear 2013).

3.2. Urbanization and Land Use Change

The conversion of forestland and agricultural land is projected to grow rapidly in the South over the next fifty years. The SFFP estimates that between 30 and 43 million acres of land will be developed across the region by 2060, depending on the amount of economic growth. This is more than double the amount of developed area in 1997, which was approximately 30 million acres (Wear 2013). Development rates are projected to be the highest across the Piedmont, from Georgia through North Carolina in counties surrounding major urban centers, such as Atlanta, Charlotte, the Triad, and the Research Triangle (Wear 2013 and 2010). Although timber products will be needed in the construction of this development, the overall effect of increased land values will likely have adverse effects on forestry across this region. Accordingly, future forest losses in the South are projected to be between 11-23 million acres, approximately 7-13 percent of the region's forestland, by 2060. (Wear 2013).

3.3. The Duke Forest

The Duke Forest comprises of 7,052 acres of land in Durham, Orange, and Alamance counties located in the North Carolina Piedmont. The Forest has been managed for teaching and research purposes since it was established by Duke University in 1931 (Duke Forest Staff 2015). The Forest is broken into six divisions ranging in size from 422 acres to 2,450 acres. The divisions of the Duke Forest are scattered around the western side of the Research Triangle area and vary in accessibility and proximity to surrounding developed areas.

The Duke Forest is charged with balancing multiple uses in its management and is accountable to a diverse group of stakeholders in the area. This responsibility is clearly stated in its mission statement: the Duke Forest strives "to facilitate research that addresses fundamental and applied questions about forested and aquatic ecosystems, and to aid in the instruction of students so they will become informed citizens and effective stewards of our natural resources" (Duke Forest Staff 2015). From this mission statement, Duke Forest defines the following management objectives:

1. Promote the Teaching and Research Mission
2. Sustainably Manage Natural Resources (Including Timber Production)
3. Protect Unique Biodiversity and Historical Elements
4. Provide Education and Outreach
5. Offer Recreational and Aesthetic Amenities

In addition to supporting education at local universities and schools, the Forest plays a fundamentally important role in the community by providing access to recreation, educational tours, and a wide variety of ecosystem services in an area of increased urbanization (Duke Forest

Management Plan 2015). Given the importance of the Forest to the University and greater Durham community, the primary management objectives of the Forest extend well beyond timber production (Duke Forest Management Plan 2015). For this reason, the University provides financial support to offset Forest operating expenses (Timber Revenue Analysis Presentation 2015).

3.3.1 Duke Forest Timber Management Practices

Of the 7,052 acres of the Duke Forest approximately 6,500 acres are included in the 2010 forest inventory and are eligible for harvest operations.[1] Four general forest types are found across this inventoried area including: upland hardwood, bottomland hardwood, pine, and mixed pine-hardwood forest types. These classes are broken out in greater detail to indicate age class and species type for management purposes. Historically, the Forest has been managed for loblolly pine (*Pinus taeda*) on a 50 year rotation period, with approximately 2,560 acres reported as pine in the current 2010 inventory; 2,034 of these acres are between ages 1 and 50, and constitute the majority of the core loblolly acreage for the forest.[2] Loblolly acres beyond fifty years are still harvested by the Duke Forest, but generally these stands are reserved for teaching, education, and cultural value. Revenues from pine harvests provide most of the timber related revenue for the forest (Duke Forest Management Plan 2010). Almost all of the remaining hardwood and mixed pine-hardwood types are second-growth forests following natural reforestation that continued after the property was acquired by the University. All timber management in the Forest is held to the Forest Stewardship Council (FSC) certification guidelines and is subject to an annual audit. Internally, the timber management practices for the Forest are guided by the following objectives (Duke Forest Management Plan 2015):

1. The preparation and maintenance of teaching and research areas.
2. The promotion of a wide variety of stand types and conditions.
3. The demonstration of various silvicultural techniques and practices.

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1 This difference accounts for areas being used by other University entities.

2 “Core” refers to loblolly stands ages 1 - 79 (Timber Revenue Analysis Presentation 2015)

4. The promotion of healthy, vigorously growing timber stands.
5. The prevention and control of insect and disease problems.

3.3.2 Forest Management Challenges for the Duke Forest

A significant management challenge that the Duke Forest faces in long term planning is the current age class distribution of pine. The age class distribution of the Forest's loblolly pine is disproportionately skewed towards younger age classes. Approximately 77% of the core loblolly pine stands (L0-L7) in the Forest is less than thirty years old, with half of that being less than ten years old (L0) (Figure 1). This limits the amount of sawtimber that will be available for harvest over the next several decades, especially when managing on a fifty year rotation (Timber Revenue Analysis Presentation 2015).

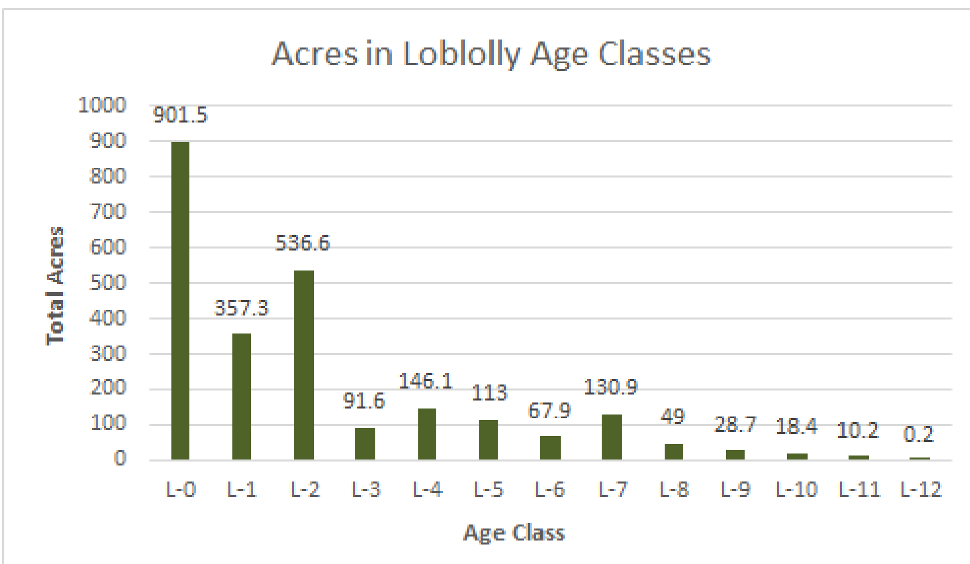

Figure 1: The number of acres in loblolly pine across different age classes. Note the increased acreage in younger age classes, L0, L1, and L2. This discrepancy poses a challenge for pine-sawtimber sales for the next 20 years for the Duke Forest if it continues to manage on a 50 year rotation. The Duke Forest prefers not to harvest pine stands over 80 years old because of their educational and ecological value. [3]

[3] See Appendix for additional age classification information.

Magnifying this problem, the Forest has been harvesting more than its self-imposed fifty acres per year harvest goal that was established in 2009.[4] Figure 2 below shows the acres sold for regeneration harvest between 2009 and 2016.

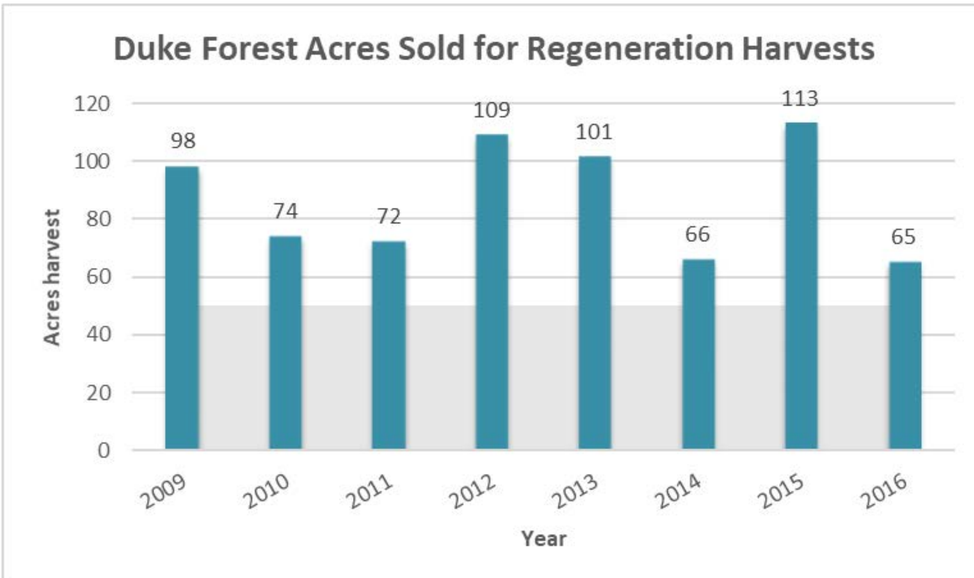

Figure 2: Shows the number of acres sold for regeneration harvests between 2009 and 2016. The annual target (grey) is 50 acres/year (Duke Forest Harvest Sheet, 2016).

In addition to the planning challenges posed by the Forest's age class distribution for pine, the Duke Forest has been faced with a series of challenges related to changing sawtimber prices since the 2007-2008 recession and housing market crash dropped prices for wood products across the South (Timber Revenue Analysis Presentation 2015; TimberMart-South 4Q2016; Wear 2013). Sawtimber value across the South dropped from approximately $36/ton in 2006 to $24/ton in 2016, a decline of approximately 33% (TimberMart-South 4Q2014).

The impacts of the recession have negatively impacted the Forest's revenue generation on pine sawtimber, the product class that has historically been the most important for the Forest's revenue. Figure 3 shows how the prices for timber sales in the Duke Forest between 2003 and

4 50 acres was chosen as the allowable cut based on an estimated 2,500 acres in loblolly pine operating on a 50 year rotation length (pers. comm. Sara Childs).
allowable cut = total acres/rotation length = 2,500 acres/50 years = 50 acres/year

2016 show a downward decline starting in 2008 in the price per thousand board feet (MBF). Although the prices for 2016 suggest a possible upward trend beginning in 2015-2016, the average price that the Duke Forest has received over the last ten years has declined.

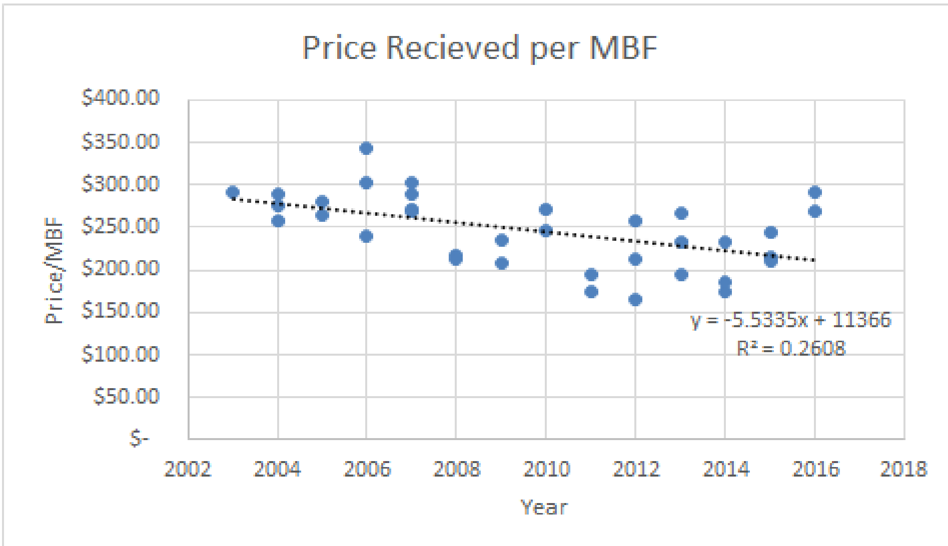

Figure 3: Duke Forest Sale Price per MBF 2003 - 2016.

Development in many of the areas surrounding the Duke Forest poses multiple challenges for the future of Duke Forest. One of these is the increase in logging costs; contractors have been pushed further away as forest area has declined across the region. This poses an operational challenge for the Forest in that it must figure out ways to bundle forest operations together or find ways to increase the size of the harvest units to justify the transportation, time, and fuel cost to harvest. This cost comes amidst a backdrop of increasing logging costs following the increase in diesel prices for the entire region, approximately 14% between 2006 and 2013 (pers. comm. Jenna Schreiber, TimberMart-South 2Q2016). The increase in the cost of logging could also be explained by a decrease in the number of people employed in the logging industry, calculated as a 15% decrease over the past 10 to 15 years in the Southeast (TimberMart-South 2Q2016). Another potential explanation is the recent closing and consolidation of many mills within the market local to Duke Forest. Limited demand from mills impacts price point, lowering the stumpage value for the Duke Forest (pers. comm. Tom Craven).

Another challenge related to development in the region is how the Forest balances its management priorities of recreation, research, and timber management with a growing number of community users seeking recreation and green space. Seen from this perspective the Forest is an incredible resource to the community -- unfortunately, the values of timber management and recreation are not always in agreement. Increasing populations and development around the Forest will likely mean that continuing the current tradition of pine management will be more difficult operationally and socially, especially over the next 20 years as pine areas yet to be harvested are located near forest boundaries.

Finally, in recent years, the Duke Forest has realized that revenue expectations exceeded the productive capacity of the current timber management program. To remedy this misalignment, the Duke Forest performed a timber revenue analysis in 2015. As a result the timber revenue expectation was adjusted downward, which meant that the proportion of the operating budget that could be offset by timber also declined. The offset went from nearly 69% of actual operating expenses in 2015 to 38% of actual operating expenses in 2016. Additional support from the University made up for the difference. [5] Given this background context, addressing the different challenges the Forest will face over the next century will require a new look into how it can use different modeling techniques to help make future management decisions. Our analysis seeks to identify whether alternative production scenarios could enhance the forest's future timber revenue potential and decrease the support needed from the University. Through this analysis, we also hope to demonstrate the value of growth and yield modeling software as a tool for evaluating the long-term impacts of any shift in the timber paradigm (Timber Revenue Analysis Presentation 2015).

4. METHODS

There were two main parts to our analysis: 1) forest-wide projections estimating growth and value and 2) stand-level scenario modeling the effects of more intensive pine management. Both

5 The Duke Forest does not need to be financially independent from the University.

parts of this analysis adhered to the principle of even-flow forestry.[6] The Forest-wide approach of this analysis allowed us to generalize our results to the entire Forest and provide an average expectation of growth and value for our client. The second approach utilized stand-level modeling to incorporate site specific environmental conditions, and capture the variation between proposed treatments.

The even-flow forestry approach to calculations was chosen because of its existence in the current Duke Forest management regime. The Forest outlines future management in accordance with these cycles, and we chose to continue this approach to facilitate incorporation of recommendations into their goals. Duke Forest believes this even-flow regime is well-suited for the annual cash-flow needs of the Forest and we made the assumption that this budget structuring will continue into the future.

Estimating volume in a forest is paramount for forest managers to understand what exists on their land, and what products they may be able to harvest. Their estimations inform them of the integrity and vitality of their forest, and speak to the financial stability of the forestry operations. Volume is typically estimated through the use of allometric equations, which are created through destructive sampling, the process of dissecting, measuring, and weighing trees. These allometric equations are specific to the species, region, and diameter or age class of the trees from which they are built; this is because growth rates and the allometric relationships change throughout a tree's lifetime. These equations are ultimately used to relate measurable qualities of trees, typically DBH and height, to volume.

The dataset for this project is from the most recent Duke Forest Inventory which occurred in 2010 (Duke Forest Staff 2010). The Duke Forest Inventory Report states 6,500 acres were divided into nine strata based on the dominant cover type (Duke Forest Staff 2010).[7] Table 1 identifies and describes these strata for the Forest.

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6 Even-flow forestry refers to even volumes and/or areas of harvested timber each cutting cycle.

7 "Dominant" cover type is defined by the duke forest as at least 1/3 of the canopy composition.

Table 1: Description of strata within the Duke Forest 2010 Inventory Report.

Strata	Description
L0L1	Loblolly 0-20 years
L2L3	Loblolly 21-40 years
L4+	Loblolly 41+ years
Mixed Conifer	Miscellaneous conifer species
Hardwood A/B	Poplar-Sweetgum | River Birch-Sycamore
Hardwood A/C	Poplar-Sweetgum | Oak (White, Black, Red)
Hardwood C/D	Oak (White, Black, Red) | Oak (Post, Blackjack)
Hardwood E/F	Mixed hardwood spp. (multiple hardwood genera with no individual > ⅓ basal area) and miscellaneous hardwood sp. (single species of hardwood not described in A, B, C, or D).
Mixed Conifer/Hardwood	Any combination of above conifer and hardwood types.

Sampling protocol within these stratum followed the double sample method from Oderwald 1991 with a total of 1,525 variable radius plots sampled, divided among each of the stratum according to its percent area cover in the Forest. One quarter of the plots (400 in total) within each strata were designated measurement points, meaning DBH, height, species, and merchantable height were measured for all "in" trees. Non-measurement points (1,125 in total) were also taken, and constituted tree tally and species for all "in" trees.

4.1 Division Selection

In order to model the full range of environmental data at a reasonable scope, we decided to choose single division of the Forest. Modeling is most powerful at the stand level since this is the scale at which forest operations occur.[8]

We wanted to capture the variability of the different stand types across the Duke Forest by choosing a division that was sufficiently representative of this distribution. Our main qualifiers for measuring this similarity were cover type and stand age. We decided to reclassify the existing

8 Time restrictions prevented forest-wide modeling at this scale.

cover types based on a broader naming scheme, which mainly relied on the distinction between hardwood and coniferous forest. The chosen cover type classifications were:

Classification Number	Cover Type Classification
0	Not Forested
1	Loblolly Pine
2	Mixed Pine
3	Mixed Hardwood
4	Mixed Pine/Hardwood

We also wanted to capture the age distribution similarities between the chosen division and the Duke Forest. The current Duke Forest age class system was maintained for this comparison.
We then identified the best choice by considering the following:

- Areas with little research and obstacles for forest management.
- Locations that could potentially be intensively harvested (i.e. sharing fewer borders with homeowners, less frequented for recreation purposes, etc.).
- The size of the division (smaller areas more manageable for data entry requirements).
- Registered natural heritage areas and other harvesting constraints that could interfere with our projected management scenarios.

After considering these criteria, we chose the Dailey Division as the best-suited candidate for our modeling purposes.

4.2. Stand Delineation

The Dailey Division had previously been divided into 72 stands. We chose to combine management units into larger, more cohesive stands capable of being implemented at an operational scale. We consolidated stands according to similar cover types, age classes, and site indices. Our justification for this approach was that timber stands will require similar silvicultural prescriptions if they share these attributes. Some of these consolidated stands did not have inventory points and were not compatible with adjacent stands for combination.[9] The original mean stand size was 5.8 acres; following reclassification the mean stand size was 21.8 acres.[10]

4.3. Forest Vegetation Simulator

For this project we used the Forest Vegetation Simulator (FVS), a modeling software developed by the US Forest Service. This software is used for stand level growth and yield modeling to assist forest managers in long term planning. FVS uses a graphical interface, called Suppose, as well as Microsoft Access to run through forest and treatment simulations (Crookston 1997). It was first developed in 1973 in Idaho and has since expanded to include the entire United States (Stage 1973; Dixon 2002). In order to expand to the rest of the nation, variants for 20 different regions across the country were assembled through sampling on forestlands, mostly in national forests (Dixon 2002).

For this project, we used the Southern Variant of FVS, a regional package designed for the Southeastern United States (Keyser 2016). The FVS Southern Variant includes mortality as trees age, but does not model regeneration, except for hardwood sprouting. Merchantable limits for softwood pulp begin at a DBH of 6 inches and end at a top inner-bark diameter of 4 inches; for sawtimber these values are 10 inches and 7 inches, respectively (Keyser 2016). FVS employs International ¼-inch log rules to convert from merchantable cubic feet of sawtimber into board feet (Keyser 2016).

4.4. Importing Data into Forest Vegetation Simulator

We first consolidated and organized the sample data by plot sample ID. We identified which of these sample plots were taken in the Dailey division by comparing Excel IDs to the Duke Forest's GIS sampling shapefile and the listed point attributes. The corresponding sample trees were

[9] Of the 420 acres in the Dailey Division, the stands that did not have inventory points totaled 70 acres and were excluded from our analysis.

[10] Original stand-size distributions: min-0.26 acres, max-60 acres, mean-5.8 acres
Following stand reclassification: min-4.8 acres, max-60 acres, mean-21.8 acres

hand selected from the Forest inventory according to their plot ID. The data of interest for each tree was species, DBH, total height, and age (if present). The species codes are listed in the Southern Variant Overview distributed by USFS (Keyser 2016). We identified the site index for each Plot ID using soil classifications from Web Soil Survey for Loblolly Pine at 50 years of age (United States Geological Survey 2016). We entered the site index as an attribute in the Duke Forest Soils GIS layer for each soil type.

The FVS Suppose modeling package requires data formatted in a Microsoft Access Database issued by the USFS. The database contains three separate tables: FVS_TreeInit, FVS_StandInit, and FVS_PlotInit which describe stand conditions at inventory. The database has an entry worksheet, but this method requires manual entry of each tree, plot, and stand. We instead exported the FVS_TreeInit table to Excel, and transferred our raw data into the appropriate columns. We imported this populated workbook back into Access, and repeated this method for Plot_Init. We opted to enter stand information using the Access Database worksheets. Constant variables for our analysis included:

Variant	Southern (SN)
Forest Service Region	8
National Forest	Uwharrie (81110)[11]
Ecoregion	231Ie[12]
Basal Area Factor	10
Breakpoint DBH	4.9 in

11 Location/Forest Code is used to alter the region-specific coefficients of volume equations used for growth modeling (Dixon 2002).

12 The Ecoregion affects species site index transformation, large tree diameter growth, and the initialization of live surface fuels (Keyser 2016).

4.5. Different Approaches to Forest-Wide Inventory Modeling

4.5.1 Volume Estimation Comparison

We compared the merchantable volume output from the Duke Forest equation to that of the output from FVS (Equation 1). In order to assess the merchantable volume in cubic feet of its loblolly pine, the Duke Forest utilizes an equation derived from Burkhart 1977. This base equation and its coefficients were built using data from loblolly pines found in the Virginia Piedmont and North Carolina Coastal Plain. Trees used in the construction of the allometric equation ranged from 2 to 12 inches in diameter. The input requirements for this equation are diameter at breast height and total height of the tree.

$$ft^3 = -0.538357 + 0.0026030*DBH^2*H \quad (1)$$

FVS has an extensive library of equations for assessing tree volume. For the Southern Variant, tree data was collected from US National Forests in the Southeast, and allometric equations were built for each species and each sub-region of the Southeast. The user supplies the model with species, DBH, and height, as well as the nearest National Forest in order to calibrate the equation to the specific sub-region in question. For this project, we selected the Uwharrie National Forest, which is situated in the North Carolina Piedmont, approximately 100 miles southwest of Duke Forest. The loblolly pines used to create this allometric equation ranged from 5 to 30 inches in DBH. This equation relies on a high number of variables and is thus provided by the USFS through an Excel Add-In.[13]

Volume calculations for both equations were done in Microsoft Excel. Rather than using measured DBH and height data for this comparison, we created a range of DBHs from 3 to 30 inches, in 0.1 inch increments. Total heights (ft) for these DBHs were calculated using a diameter-

13 The equation and all associated coefficients are written in Clark et al. 1991. USFS has created an Excel Add-In for FVS that calculates volume as a function of the necessary inputs, such as DBH, height, and location.

height relationship equation specific to loblolly pine provided by FVS, shown below (Keyser 2016):

$$H = 4.5 + 243.860648 * e^{(-4.28460566*DBH^{(-0.47130185)})} \qquad (2)$$

The DBH range of 3 to 30 inches was selected because the diameter-height equation's coefficients are calibrated for trees below three inches, and again for trees above three inches. Excluding DBHs below three inches allowed us to use only one diameter-height equation. Merchantable volume in cubic feet was then calculated using both the Duke Forest equation and the equation used in FVS.

In addition to using this set of dummy variables to assess the difference in volume yielded from these equations, we also applied these two equations to the Forest-wide Inventory. This analysis utilized only the loblolly strata: L0L1, L2L3, and L4+. By way of natural regeneration and succession, these strata also include a number of hardwood individuals, notably in the L4+ strata. For the purposes of this analysis, only loblolly pines were used, and so the hardwoods were excluded. For the 2010 inventory, the L0L1 strata encompassed 886 acres and contained 237 individuals in 24 plots. The L2L3 strata encompassed 664 acres and contained 370 individuals in 36 plots. The L4+ strata encompassed 1010 acres and contained 561 individuals in 57 plots. Once tree volume was calculated using the two equations, merchantable volume in cubic feet per acre was extrapolated following the method employed by the Duke Forest (Oderwald 1991).

We then used FVS to find an approximate percentage of sawtimber in the total volume for each of the strata based on the age classes contained within them. These percentages were 0%, 15%, and 86%, for L0L1, L2L3, and L4+, respectively. Conversion of sawtimber cubic feet to sawtimber board feet was achieved using a factor of 5.5 board feet to cubic foot. This ratio was found to be consistent with both Duke Forest Inventory calculations and FVS output, although it should be noted that the ratio will change with varying DBHs and heights. After these conversions were complete, monetary value of the standing volume in each strata was assessed by following the conversions and prices outlined in TimberMart-South 4Q 2016 (Appendix Table A1).

4.5.2 Forest-wide Implications

A weighted average site index for loblolly acreage ages 0 to 50 was calculated using the USGS soils map data and corresponding outputs from FVS.[14] We then increased this weighted site index by 7% in order to simulate using improved stock (Talbert 1985). Then we found the allowable cut acreages for 30, 35, 40, 45, and 50 year rotations (Equation 3). We calculated the volumes of timber that the Duke Forest can expect to sustainably harvest annually in the future, and what the net revenues of these harvests would be with current prices.

$$\textit{Allowable cut} = \textit{total harvestable acres} / \textit{rotation length} \qquad (3)$$

4.6 Growth and Yield Scenario Analysis of the Dailey Division

We compared the variation in rotation lengths and the impact of planting improved stock by comparing modeled harvest volume. We consulted the Duke Forest for its harvest schedule in order to establish a baseline for stands that will be managed in the future (pers. comm. Sara Childs). The Forest plans operations on 50 year cycles, with the current cycle ending in 2059. We identified eleven stands within the Dailey Division with proposed management, and used these stands for all modeling scenarios. Of the eleven stands nine were pine, one was a hardwood corridor and one was pine-adjacent (both of which appeared to be a good candidates for stand consolidation and pine conversion). A map of these stands can be found in the Appendix.

For the model, all harvests were assumed to be clearcuts followed by planted pine to allow for consistency in later comparisons. We chose a plantation pine strategy to avoid the costs of pre-

[14] The majority of Duke Forest pine management takes place in these age classes, totaling 2,034 acres.

commercial thinnings in the model.[15] Additionally, we included an herbicide treatment to minimize hardwood competition and a conditional thinning of pine species to a basal area of 80 sq.ft/acre once the basal area exceeded 120 sq.ft/acre, both of which are standard procedure for the Duke Forest.

4.6.1. Standard Stock with Changing Rotation Ages Scenario

We modeled the impact of shorter rotation lengths for planted loblolly pine at the Dailey Division in order to determine which length optimizes harvested volume from the site. We tested rotation lengths of 30, 35, 40, 45, and 50 years.[16] The Duke Forest proposed shorter rotation lengths as a means of addressing the issue of the uneven age class distribution. Rotation lengths were selected in five year intervals, beginning with the minimum industry standard of 30 years. This scenario was run over a 100 year time frame, from 2010 to 2110, to allow for two complete cycles of the 50 year rotation.

4.6.2 Improved Stock with Changing Rotation Ages Scenario

We modeled the impact of planting loblolly pine with improved genetic stock at the Dailey Division. We followed the exact procedure outlined above, with the exception of the stock improvement. We increased the site index for each stand by 7% as a proxy for improved genetic stock (Talbert 1985). Improved genetic stock is associated with increased growth rate, higher total volumes, straighter stems, and disease resistance, all of which contribute to a higher grade and value products that are of interest to the Duke Forest.

4.7 Financial Analysis of the Dailey Division

We used Microsoft Excel to analyze the financial implications of the modeled rotation lengths. This used standard conversion factors, regional prices for wood products using the TimberMart-South 2016 4th Quarter Report, and operational costs provided by Duke Forest to calculate the

[15] In practice, some planted stands may require pre-commercial thinnings as a result of natural regeneration from seed sources in adjacent loblolly stands. These potential costs should be considered in management decisions.
[16] As previously states, the Duke Forest currently utilizes a 50 year rotation

value of the wood products produced on the 240 acres of the Dailey Division modeled. Two different models were built to compare standard and improved stock scenarios. The only difference in the establishment cost between the two scenarios was the cost associated with planting improved stock. This was modeled at $22.5 dollars per acre for first generation seedlings, which approximated the $50 per thousand seedling premium for planting first generation improved stock (Barry 2011). Table A1 shows the default values chosen for the financial analysis for improved stock. Sensitivity analyses were conducted on important values such as the discount rate, establishment costs, and prices for different wood products, and provided to the Duke Forest as an Excel model.

5. RESULTS

5.1. Inventory Comparison Results

The results of our inventory volume comparisons between FVS and the Duke Forest show that Duke Forest volume equation predicts higher estimates of merchantable volume than FVS (Figure 4). The gross difference between the volumes increases with increasing DBH, equating to essentially 0-1 cubic feet at lower DBHs, and maximizing at 41.7 cubic feet when DBH equals thirty. Proportionally, the difference between the Duke Forest estimation and FVS estimation saturates at 17% when DBH is equal to 12 inches. Prior to this DBH, the Duke Forest equation predicts higher volume as compared to FVS. At a DBH of five inches this difference is nearly 50% and decreases rapidly to 25% at DBH 6.5 in.

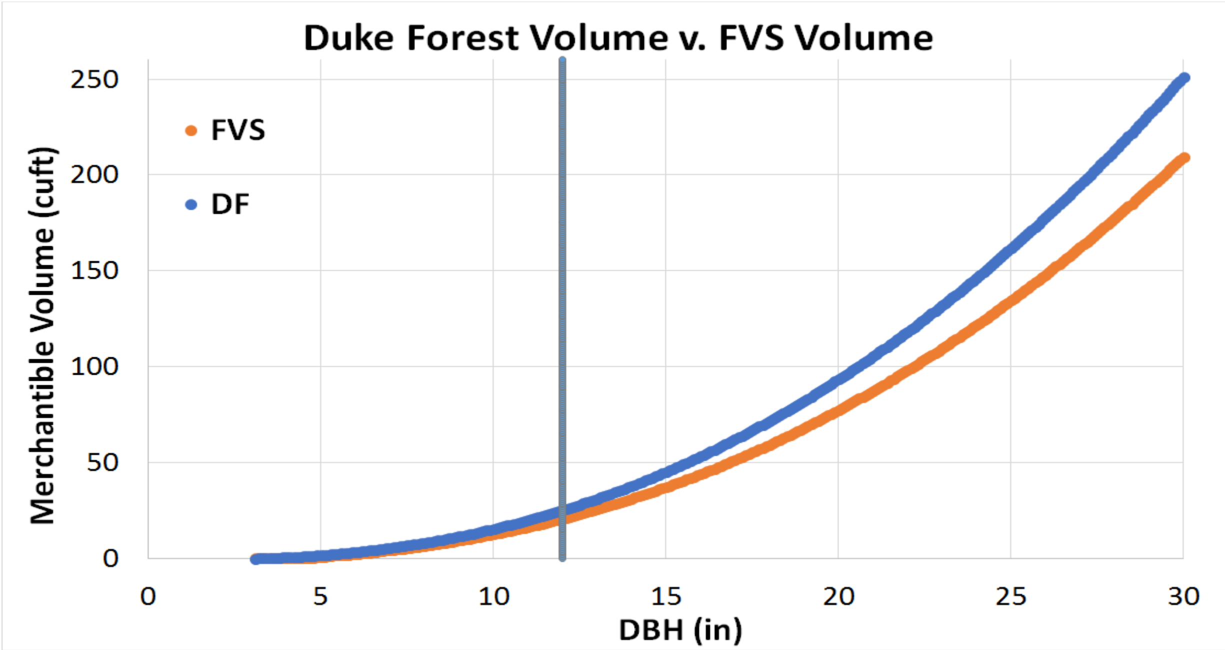

Figure 4. Difference in volume estimation methods between the Duke Forest and FVS equations.[17]

We next scaled up the volume from a per tree basis up to a per acre basis following the Duke Forest Inventory method for both the Duke Forest volume equation and the FVS volume equation. Results in cubic feet per acre per strata are given below in Table 2. The monetary value for these standing volume amounts, and the corresponding differences according to FVS, are also presented below in Table 2.

Table 2. Volume estimations and associated monetary value.

Merchantable Volume (cubic feet per acre)				Cash Value (per acre)				Cash Value (Forestwide)		
Strata	DF Method	FVS Method	Difference	DF Method	FVS Method	Difference	Acreage	DF Method	FVS Method	Difference
L0L1	2,004	1,609	395	$759	$609	$150	886	$672,000	$540,000	$132,000
L2L3	2,966	2,430	536	$1,336	$1,095	$241	664	$887,000	$727,000	$160,000
L4+	3,970	3,303	667	$3,202	$2,664	$538	1,010	$3,234,000	$2,691,000	$543,000
							Total	$4,793,000	$3,958,000	**$835,000**

17 Although not apparent in the graph, differences between estimations are proportionally highest at lower DBHs.

Harvestable volumes and the associated gross revenues were calculated for the five different rotation lengths. The results are shown below in Table 3.

Table 3. Sustainable annual harvests based on even-aged rotation, their value per acre, and gross revenue.

Rotation Length	Annual Harvest (acres)	Value per Acre	Annual Gross Revenue
30	67.8	$1,040	$71,000
35	58.1	$1,510	$88,000
40	50.9	$2,184	$111,000
45	45.2	$2,874	$130,000
50	40.7	$3,540	$144,000

5.2. Growth and Yield Modeling Scenario Analysis

5.2.1 Standard Stock with Changing Rotation Ages Scenario

Incrementally decreasing the rotation length by five years from 50 to 30 resulted in lower harvest volumes throughout the 100 year period (Figure 5).[18] There were also differences among the proportions of products that were harvested within each rotation. Shorter rotations had higher proportions of pulp volumes than sawtimber, and total sawtimber volumes increased over time. The longer rotations experienced more thinning operations throughout the 100 year period.[19]

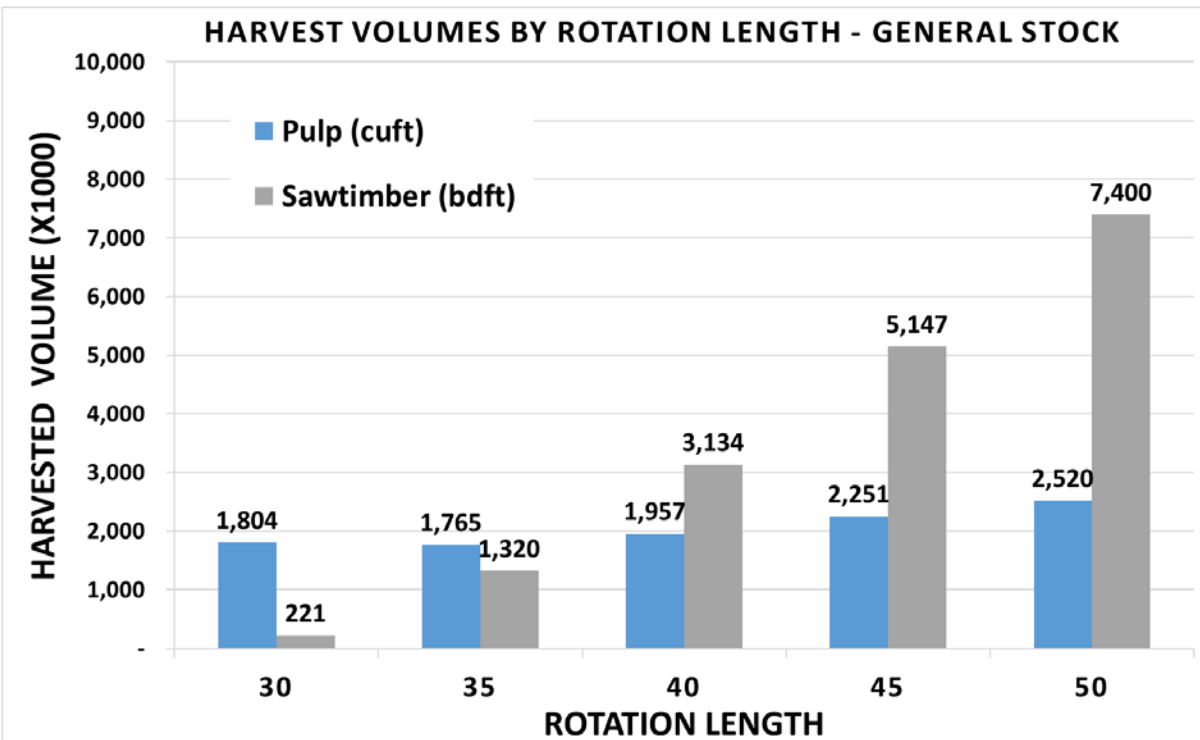

Figure 5: Total harvested sawtimber and pulp volumes (including thinnings) by rotation length over the 100 year simulation.

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18 Although more rotations of shorter age classes could fit in the 100 time horizon, a higher proportion of the volumes of these younger trees was not captured as merchantable in the FVS outputs. Another limitation of this comparison is the time horizon itself which disadvantages the shorter rotations against the 50 year rotation that divides neatly into two rotation within the 100 years. An alternative way of comparing these rotation ages that removed this bias is suggested in the section Additional Analysis.

19 On average, the 30 year rotation had no thinnings, 35 and 40 had one thinning, and the 45 and 50 year rotations had two thinnings. The number of thinnings varied by site index, with more productive sites requiring more frequent thinnings.

5.2.2. Improved Stock with Changing Rotation Ages Scenario

Improved stock increased volume yields of earlier harvest operations, with decreasing impact as the stand ages. The 30 year rotations realized a 70% increase in sawtimber, declining to ~30% increase in volume harvests of the 40 year rotations, and settling around ~10% by the 50 year rotation (Figure 6).

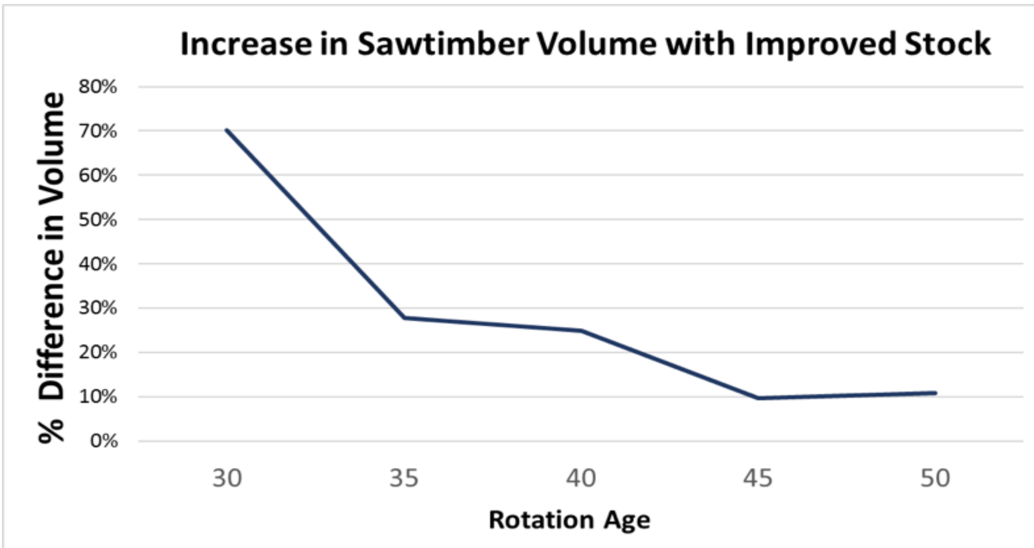

Figure 6: Volume increases associated with planting improved stock seedlings compared to standard stock seedlings across the first cycle of a 50 year rotation.

The total harvest volumes with improved stock followed the same trend as the standard stock seedlings; there was a slight decline in the total amount of pulp combined with a consistent increase in sawtimber with increasing rotation length (Figure 7).

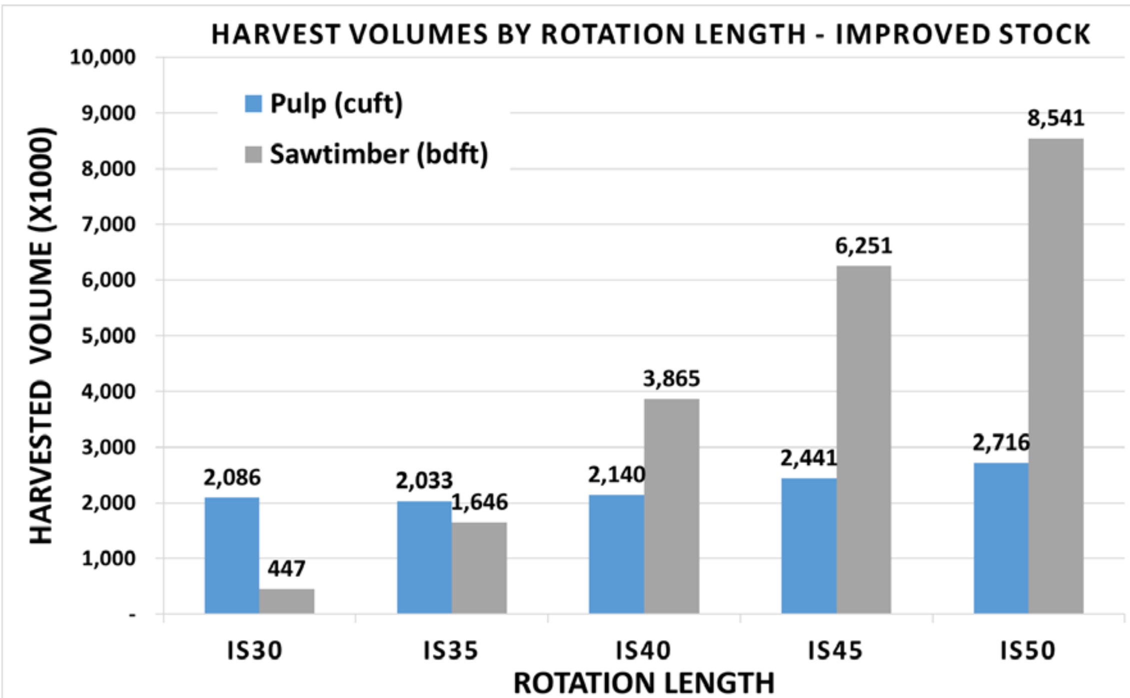

Figure 7: Total harvested sawtimber and pulp volumes (including thinnings) by rotation length over 100 years when planting genetically improved stock.

5.3. Financial Analysis

5.3.1. Standard Stock with Changing Rotation Ages

The net revenue from the Dailey Division was also modeled over 100 years for each of the rotations ages assuming 2016 prices for pulp, Duke Forest operations costs, and stand establishment cost. Values for these parameters can be seen in Table 4. The results of this model find that net revenue increases as the rotation length increases reflecting the accumulation of more volume growth over time and a greater percentage sawtimber in the later harvests. The net present value (NPV) of the harvests for each rotation length at a 5% discount rate is also shown in Figure 8. NPV increases through time at a decreasing rate and is highest in the 50 year rotation.

Table 4: Standard Stock Net Revenue and NPV over 100 years for the Dailey Division

Standard Stock Summary for 100 Years		
Rotation Length	Net Revenue 100 years	NPV 100 Years @ 5%
30 Year	$ 486,000	$ 1,000
35 Year	$ 623,000	$ 17,000
40 Year	$ 858,000	$ 29,000
45 Year	$ 1,152,000	$ 38,000
50 Year	$ 1,462,000	$ 41,000

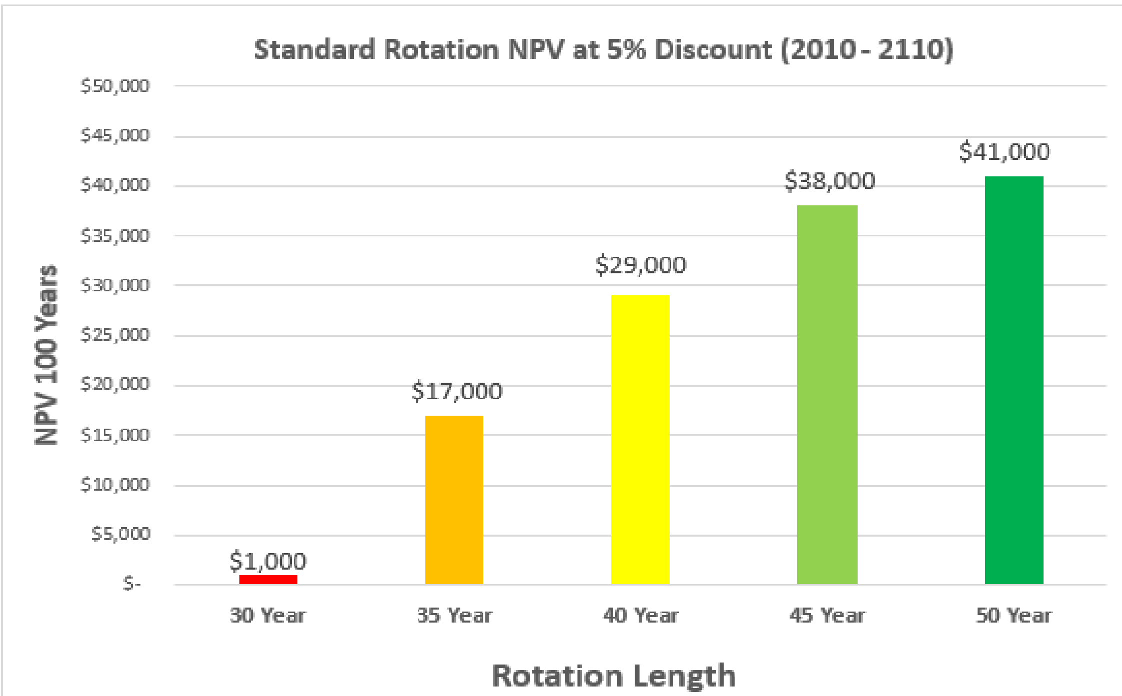

Figure 8: Standard Stock Net Present Value over 100 Years for Dailey Division

5.3.2. Improved Stock with Changing Rotation Ages

Similar to standard stock, the net revenue from the Dailey Division was modeled over 100 years for each of the rotations ages. Table 5 shows that the net revenue increases as rotation length increases. NPV increases at a decreasing rate and peaks around the 50 year rotation length. Across all rotation lengths, the NPV of improved stock was higher than the standard stock, justifying the cost for purchasing improved stock. However, above a cost of $47 per acre for improved stock, the NPV was lower across all rotations than the corresponding rotation lengths of standard stock.

Table 5: Improved Stock Net Revenue and NPV over 100 years for the Dailey Division

Improved Stock Summary for 100 Years		
Rotation Length	Net Revenue 100 years	NPV 100 Years @ 5%
30 Year	$ 591,000	$ 5,000
35 Year	$ 735,000	$ 21,000
40 Year	$ 972,000	$ 36,000
45 Year	$ 1,304,000	$ 45,000
50 Year	$ 1,619,000	$ 48,000

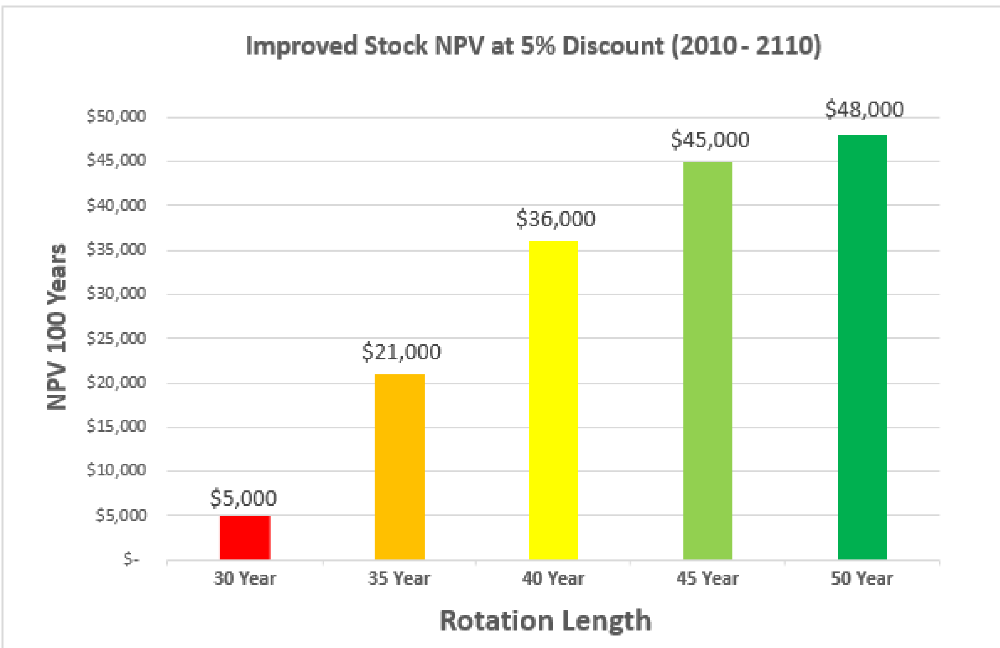

Figure 9: Improved Stock Net Present Value over 100 Years for Dailey Division

5.3.3. Sensitivity Analysis

The NPV of future harvest depends significantly the discount rate used in the model. Figure 10 shows the results of different discount rates and their impact on the NPV for each rotation length. At a discount of 0% NPV is equal to the Net Revenues from each rotation length. Beyond a discount rate of 6%, the NPV was negative for all rotations. Our financial calculations assume a

5% discount rate which reflects approximately what the Duke Forest or Duke University could expect over time on alternative investments.

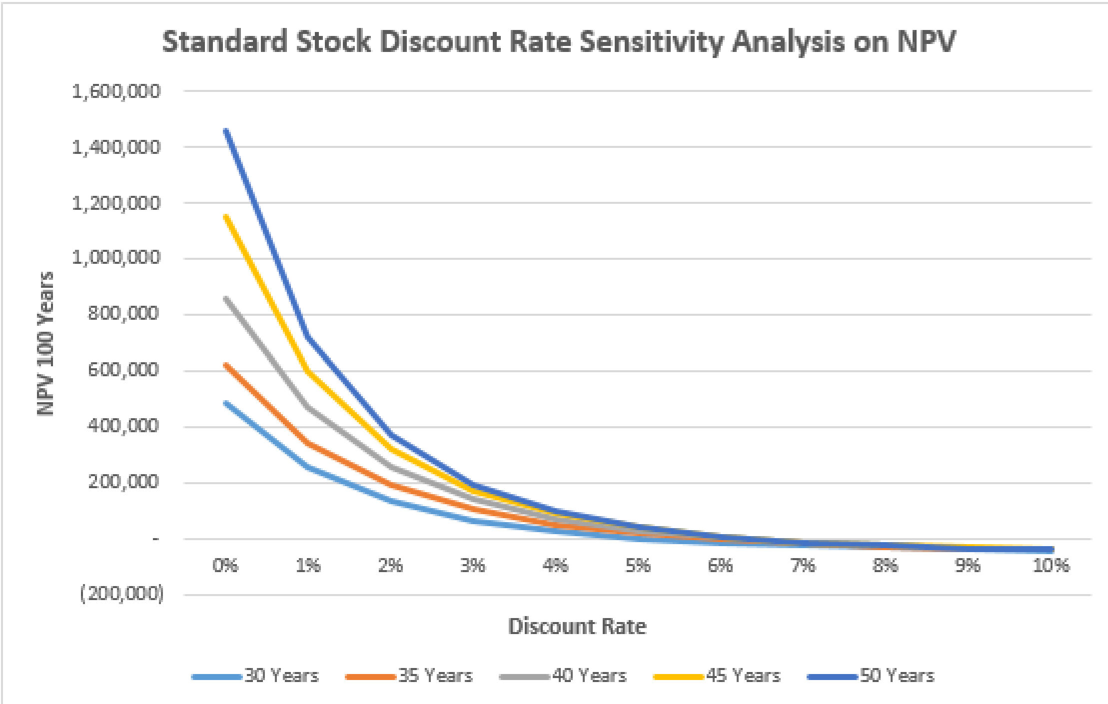

Figure 10: Sensitivity Analysis of Discount Rates on Standard Stock NPV. Tables with associated values for improved stock can be seen in Appendix Tables A2 and A3.

6. DISCUSSION

6.1 Inventory Comparison

As compared to the FVS model, the Duke Forest equation predicts higher volumes of loblolly pine (Figure 4). Typically more robust models are generated from larger datasets and are better at predicting actual volume. Additionally, the best models for forest volumes are built using the most locally available tree data to build the equations (pers. comm. Dr. Ram Oren). As this is a very expensive and time-consuming practice that might be outside the scope of the Duke Forest operation, the next best situation would be to use equations built from forests in the surrounding area. In our case, this meant using allometric equations built using loblolly pines growing in the central Piedmont of North Carolina.

The equation the Duke Forest uses combines loblolly pine from both the Virginia Piedmont and North Carolina Coastal Plain. Additionally, this equation was built using loblolly pine within a range of 2 to 12 inches DBH. This means that the Duke Forest's equation is only able to accurately capture the variation in volume output for trees within this range that it was built from. The reason for this is because as trees grow, the allometric relationships between DBH, height, and volume change. As a result, the equation becomes unsuitable for estimating the volume of larger, sawtimber sized trees (pers. comm. Dr. Ram Oren).

FVS utilizes an equation built with loblolly pine data within a DBH range of 5 to 30 inches. A caveat to the use of FVS, however, is that these loblolly trees were taken mostly from national forestlands all over the Southeast (Clark et al. 1991). To combat this averaging effect stemming from grouping together trees from such a vast and varied region, FVS calibrates its volume equation to a user-specified national forest. The user is advised to select the national forest nearest their own forest, and so we selected Uwharrie National Forest. While the Uwharrie is close to Duke Forest in the broader geographical perspective of the southeastern US, (approximately 100 miles southwest) the climate, terrain, species composition, and other factors affecting growth will be slightly different than in Durham, NC.[20] However, Uwharrie was the closest approximation we were able to model for this comparison.

Inaccurate volume estimates can have big implications for long term planning for harvest scheduling and revenue expectations. Table 2 indicates how this per tree overestimation, when aggregated, can have significant implications of long term planning. To examine this further, we used FVS to estimate the volume per acre of loblolly pine the Duke Forest would be able sustainably harvest on average given an even age class distribution and valued this monetarily.

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20 One way to validate this assumption would be to ground check the FVS values with measurements from trees planted at a known points in time in the Duke Forest. This would effectively allow the Duke Forest to see what differences in volume can be attributed to differences in the region selection.

Table 3 indicates that based on using improved stock and a fifty year rotation that includes thinning the Duke Forest would make approximately $144,000 in net revenue annually off of 41 acres of loblolly harvests.[21]

This estimate is important because in its 2016 financial report, the Duke Forest predicts an annual contribution to its budget of $190,000 based on historic sales. The difference between FVS's and Duke Forest's financial estimation could come from the volume difference explained earlier. Using the Duke Forest volume estimation method would increase the $144,000 to $168,000. The remaining $22,000 may come from hardwoods opportunistically harvested in older loblolly stands, or from combining small hardwood stands with a larger loblolly unit at the time of harvest. Additionally, the Duke Forest often receives a premium for its higher quality timber, which could also help make up this difference (pers. comm. Sara Childs).

It should also be noted that our numbers assume harvesting 41 acres of loblolly pine - which would be a sustainable annual harvest assuming an even age class distribution, running 50 year rotations with 2,034 total acres of loblolly pine. Decreasing the rotation length would increase the allowable cut in acreage, but would have an adverse effect on the revenues gained from such a harvest. Harvestable acreage may also increase if smaller hardwood stands that connect, or are adjacent to, larger pine stands are converted to loblolly, therefore increasing the total amount of loblolly acreage in the forest. And while this 41 acres is a sustainable, yearly harvest for 2,034 evenly-distributed acres of loblolly pine grown on fifty year rotations, the Duke Forest does not currently have an even-age class distribution. Therefore, these sustainable harvests of 41 acres will not be occurring for several decades, meaning the Duke Forest should expect to contribute much less money from harvests to their budget in the very near future, and for likely the next two decades, given the gap in the L4 and L5 age classes coming through during that time (Figure 1).

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[21] This value includes expected thinnings throughout the lower age classes in addition to any final harvests. The idea is that in any given year in an even age class distribution you would have thinnings on other acres in the younger age classes that would contribute to this final harvest value.

6.2 Scenario Analysis

Rotation length has the largest impact on total harvest volumes throughout the rotation period. Volume increases with rotation length, with the most significant changes occurring in the proportions of sawtimber. Shorter rotations are predominantly pulp volume -- a total which decreases over time. In the standard stock scenario, sawtimber volumes are very low in the 30 year rotation, significantly rising until the 50 year rotation which has 33 times as much sawtimber volume. Notably, the total harvest volumes are not significantly different between the 45 and 50 year rotations, which could indicate shortening the rotation length by 5 years when necessary will not significantly impact overall harvest amounts.

Volume increases with improved stock are consistently higher than standard stock volumes. The greatest benefit in terms of volume increase are realized in the shortest rotations that have double the amount of sawtimber volume in the first 30 years. However, this bump in total volume is not sustained throughout the longer rotations, tapering off to an average of 30% around 40 years, and declining at the 50 year rotation. These declines are expected because while improved genetics correspond with larger trees, growth rates occur along a saturation curve. Once the physical limitations of both the tree and the resource availability at the site are met, the tree cannot continue to grow. Our results show improved stock simply increases the rate at which this growth saturation is achieved, supporting shorter rotations on certain sites.

The average site index (SI) of 80 at the Dailey site may have been a limiting factor in the productivity of the improved seedlings. The 7% change in SI as a proxy for improved stock would have been a higher total increase at more productive sites (7.0 at SI 100, versus 5.6 at SI 80). This relationship can be interpreted in a variety of management contexts. Improved stock seedlings could be used on lower site indexes in order to more evenly distribute growth across a variety of sites, but it should be noted that poor quality sites may not realize the full potential of improved stock. Conversely, improved stock could be used exclusively at the best sites in order to maximize the volume potential of the premium seedlings.

Ultimately, volume maximization occurs on 50 year rotations with improved stock seedlings in the Dailey Division, suggesting current management practices are in line with best practices for planted loblolly pine.[22] When considering the context of age class redistribution, it is important to note the similarity between the 45 and 50 year rotations. As the younger pine cohort at Dailey begins to age, the Forest should realize that these projected volumes in shorter rotations are not trivial, and present a viable option for harvestable sawtimber volume. Additionally, the accelerated growth of improved stock seedlings can help achieve greater sawtimber volumes earlier than with the standard stock alone.

6.3 Financial Analysis

Under the current price, operational, and discount assumptions, we see that financial returns increase with rotation length. For both standard and improved stock, this is driven by the higher volumes of sawtimber produced in the older age classes that are associated with a higher value than pulp ($25.57/ton sawtimber versus $10.60/ton pulp). Additionally, the increased frequency of having to regenerate stands with the shorter rotations lowered the net revenue values obtained in these scenarios. Because a greater percentage of the volume of these shorter rotations was pulpwood, the increases harvest frequency did not generate higher NPV over the 100 year period.

The cost of purchasing genetically improved stock at $22.50/acre was outweighed in the long run by the associated increase in volume production. Figure 11 below shows the NPV per acre of the Dailey Division comparing both standard and improved stock to each other. We see that the increases in value (as a percentage) are larger for the younger rotations than the older ones. Based upon this model, there is value in continuing to plant improved stock up until a value of about $47.00 per acre (for the 50 year rotation). Beyond this point, the establishment cost outweigh the long term benefits from increases volume. Importantly, there might be other

22 The weighted average SI of 80 at Dailey was found to be closely representative of the forest-wide weighted average SI of 80, meaning trends in volume projections could have implications for forest-wide management decisions.

reasons to continue planting improved stock, for example, to achieve a better form class, disease resistance, or lower mortality in seedlings. Although they are important, these factors were not able to be modeled using FVS.

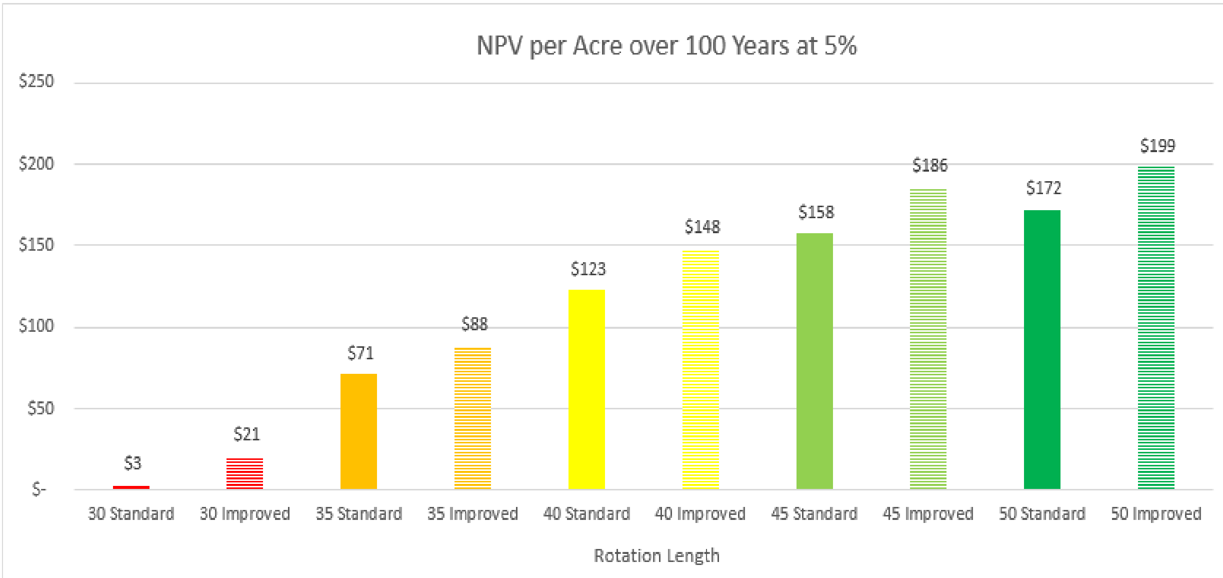

Figure 11: NPV per Acre over 100 Years at 5% for the Dailey Division.[23]

As Tables A2 and A3 demonstrate, the discount rate used in economic calculations is very important to comparing different scenarios. We assumed based on economic convention that the Duke Forest would have a discount rate around 5%, however, this could be more accurately modeled by looking at the opportunity cost of other investments by the Forest or Duke University. In general, as the discount rate increases the present value of future harvest becomes smaller, all things equal. Conversely, as the discount rate decreases, there is less "cost" for delaying harvest and the rotation length decreases. Other factors besides the discount rate will influence the optimum rotation age. For example, increasing the establishment costs of regenerating a stand will lengthen the rotation age. This is because deferring these cost into the future is advantageous from an NPV perspective. The relative value of sawtimber to pulp also has an impact the on the rotation length. At current prices this ratio is approximately 2.5. If this

23 These values have been calculated using a weighted site index.

were to decrease (pulp value goes up relative to sawtimber) it would favor a shorter rotation. The opposite would be true if the ratio between the two products increased.

The financial analysis that looks at pulp and sawtimber produced on the Duke Forest verifies that the current paradigm of planting improved stock on a longer rotation produces the most future value of the forest given current prices, assumptions, and limitation of the model.

6.4 Further Analysis

It is important to note that pulp and sawtimber are not the only two product classes that the Duke Forest produces in its timber operations. Another product, chip-and-saw, is also produced that can be thought of as a hybrid between both pulp and sawtimber that produces both products between an average DBH between 8 and 10 inches. This is important because this blended product increases the value per ton of timber that would have normally been considered pulp in FVS. This effectively increases the value of harvests at a shorter rotation length, increasing the value of shorter rotations relative to longer ones. With improved stock, we would expect this gain in volume at an early age to help the Forest realize higher values from chip-and-saw in the shorter rotations. Tables 6 and 7 compare the gross value per acre of the different rotation ages.

Tables 6 and 7: Per acre values with and without chip-and-saw included in the model. Note that chip-and-saw increases the value of the younger rotations more than the older rotations.

Orginal Calculations without CNS						
Age	**Total Cuft**	**Saw Cuft**	**Value Saw**	**Pulp Cuft**	**Pulp Value**	**Total Value**
30	2610	102	$ 89	2508	$ 950	**$ 1,039**
35	3378	457	$ 400	2921	$ 1,107	**$ 1,507**
40	4158	1226	$ 1,073	2933	$ 1,111	**$ 2,184**
45	4750	2164	$ 1,895	2586	$ 979	**$ 2,874**
50	5325	3067	$ 2,685	2259	$ 856	**$ 3,540**

Per Acre Values with CNS (8 - 10in dbh)								
Age	**Total Cuft**	**Saw Cuft**	**Value Saw**	**CNS Cuft**	**CNS Value**	**Pulp Cuft**	**Pulp Value**	**Total Value**
30	2610	0	$ -	2049	$ 1,264	561	$ 212	**$ 1,477**
35	3378	134	$ 117	2966	$ 1,830	278	$ 105	**$ 2,053**
40	4158	648	$ 567	3238	$ 1,998	273	$ 103	**$ 2,669**
45	4750	1421	$ 1,244	2997	$ 1,850	331	$ 126	**$ 3,220**
50	5325	2338	$ 2,046	2597	$ 1,602	391	$ 148	**$ 3,797**

At 2016 prices, the results of including chip-and-saw still favor the 50 year rotation. However, using the blended price premium of $21/ton between sawtimber and chip-and-saw that the Duke Forest has historically received (pers. comm. Sara Childs), the NPV analysis shifts to favor the 45 year rotation (Figure 12). Another factor making chip-and-saw more attractive financially is that the Duke Forest is close to a chip-and-saw mill which decreased transportation costs.

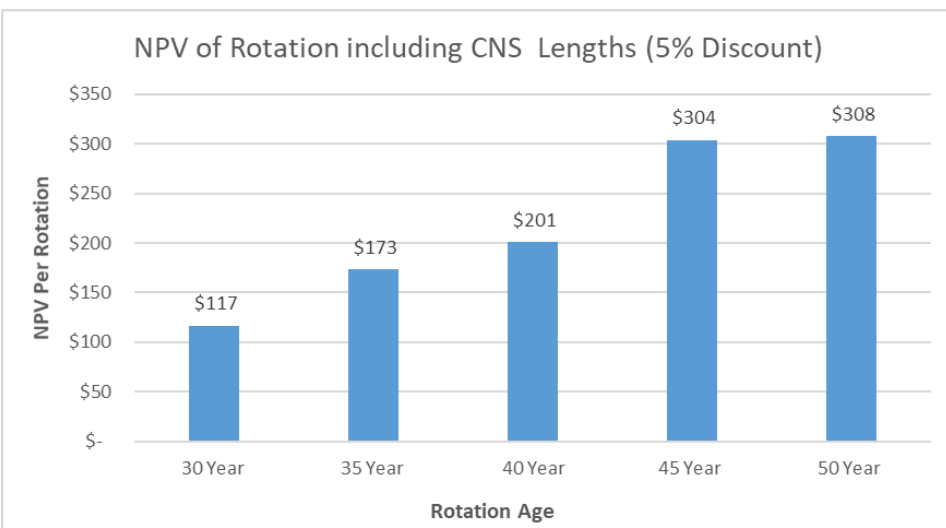

Figure 12: NPV of rotations ages when chip-and-saw value is included. Note that the optimal rotation becomes 45 years when a blended price of $21/ton is given for both sawtimber and chip-and-saw.

Forest-wide Impacts of Including Chip-and-Saw

If we include chip-and-saw into the FVS analysis, the value of an annual harvest of 41 acres of 50 year old loblolly pine almost exactly approximates the Duke Forest predicted value of $190,000. Including the value of chip-and-saw, FVS estimates approximately $3,800/acre on this rotation (Table 7). Scaling this $3,800 to the 41 acres, yields an annual revenue of $156,000. Accounting for the difference in volume estimation increases this value to approximately $183,000. This is easily within natural variation of the predicted value of $190,000. While the Duke Forest does not calculate chip-and-saw in the inventory, it does sell into this product class at the mill. The projections that the Duke Forest makes for how much its annual timber harvest can contribute to its budget are not based on the growth it expects out of the forest—but rather the value it has received at the mill for similar, recent transactions (pers. comm. Sara Childs).

Faustmann Formula

In order to avoid biasing the longer rotations, we did a similar rotation optimization analysis in Excel. We utilized the Faustmann Formula (4) for calculating Land Expectation Value (LEV) for infinite rotations with establishment costs.[24]

$$\pi = \frac{(p * Q(t) - c) * e^{-\delta t}}{(1 - e^{-\delta t})} \quad (4)$$

Using FVS standing volumes over the 100 year period, we calculated mean annual increment and utilized price values from the financial analysis to determine LEV. The optimal rotation length is defined as the rotation that maximizes LEV, in this case the 45 year rotation (Table 8). We would expect these results as economic theory states that planning for infinite harvests incentivizes the landowner to manage on shorter rotations, due to the opportunity costs associated with prolonging the start of the next rotation.

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24 Parameters for the Faustmann formula are: p = price, Q(t) = volume (tons), c = establishment cost, t = time (years), δ = discount rate (5%).

Table 8: Land Expectation Value per acre of the Duke Forest using the Faustmann Formula. This does not include thinnings, site index 80, t = rotation age. LEV is maximized at 45 years.[25]

t	p*Q	LEV
30	974	$ 215
35	1515	$ 271
40	2089	$ 292
45	2979	$ 324
50	3682	$ 309

It is important to note that these results are not directly comparable to our FVS models, since this software allowed us to capture the value and growth increases associated with thinnings. However, the Faustmann Formula is an optimization formula based on unthinned growth patterns alone. There is currently debate in the literature as to the best way to incorporate thinnings for more practical applications to forest management, which could be useful to explore in order to make a more informed decision about the best rotation length for the Duke Forest (Coordes 2014). Ultimately these results support the narrative of longer rotations being more profitable for the Duke Forest, with a potential for a paradigm shift towards a 45 year rotation.[26]

6.5 Discussion of Limitations

A major limitation for this analysis was the 2010 Duke Forest Inventory dataset. FVS modeling could only make use of the measured plots within the inventory, which excluded all of the non-measurement points. Large areas were excluded that lacked measurement points, limiting the total area we were able to model. Additionally, the stands that contained measurement points were still largely under-sampled, and may not adequately represent the landscape. Increased sampling intensity of measurement plots could avoid limiting similar analyses in the future.

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25 An expanded table is included in the Appendix and includes MAI (Tables A4, A5 and A6).

26 The Faustmann calculation also allowed us to explore the optimal "forester" rotation, which is defined as the point where Mean Annual Increment (MAI) is maximized. According to this analysis these conditions are obtained on a 75 year rotation, and indicate the point at which loblolly forest growth is at its peak (Appendix Figure A2)

FVS software is limited, like all growth and yield models, by its ability to accurately project volumes with increasing stand age. Data collection for allometric equations typically focuses on trees within managed age classes, meaning younger stands. Relationships to height will change with forest age, not just DBH, limiting the accuracy of equations for older trees.

Furthermore, default growth simulations are tied to the averages of collected datasets with variations around the mean that could manifest in each stand in different ways. Confidence intervals and standard error should always be considered when applying standard model equations. Calibration of equations to local conditions can limit this error in modeling, and would be a crucial step for adopting this approach to growth and yield modeling.

The FVS modeling software is limited in its ability to account for defect in standing trees from the inventory. FVS assumes all trees are uniform in shape and have perfect form class, unless otherwise indicated in the dataset. Since the DF inventory data only reports DBH and height, we were unable to incorporate defect specifications into the model. This impacts volume estimates by incorporating a positive structure bias, leading to an overestimation in our calculations. Incorporating the FVS defect categories into the timber cruise protocol would prevent this overestimation in the model.

Additional modeling limitations were in the availability of information for simulating improved stock seedlings. Our method is specific to volume increases of approximately 30% in 40 year rotations, values typically associated with first generation seedlings. However, the change in volume yields are widely variable and subject to change based on source of seedlings, generation, and the purposes for which they were bred. In order to more accurately model the specific benefits of improved stock, the forest would need to ask the supplier for the family-specific volume equations for the improved stock seedlings and update these equations in the FVS model. We can also expect technologies in improved stock to continue to improve into the future, meaning there is potential for increasing volume trends over time. Any advances in technology could alter the financial analysis by either making improved stock more affordable, or increasing the volumes in the earlier rotations. Each of these scenarios could favor a shift towards shorter rotations.

The conditional thinning treatment is limited by its independence of rational time frames for management. This means that thinnings in our model occurred according to the site condition alone. In order to more accurately model removals from thinnings, the model would need to account for consolidation of thinning prescriptions wherever possible. In practice the Duke Forest will schedule thinnings for multiple stands at the same time, rather than according to the needs and conditions of each individual stand.

A limitation of FVS modeling that is not addressed at this point is the ability to fully model standard practices of intensive pine management. For example, we were unable to incorporate bedding of seedlings, a common practice in many areas across the South that has been shown to improve the viability and growth of seedlings.[27] Additionally, although FVS does include a fertilizer application, we chose to exclude this from the model because simulations seemed overly simplistic and difficult to account for financially over time.[28]

We also do not compare the practice of intensive pine management with lower impact pine management strategies. This model exclusively simulates planted pine with clear-cut treatments, with no comparison to seed-tree cuts and natural regeneration. These practices present no upfront planting costs, but require payment for a pre-commercial thinning (PCT). Natural regeneration could be incorporated into future models by "planting" a higher seedling density into the FVS model and adding cost of PCT to financial scenarios.[29]

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27 Bedding is not as common in this part of the Piedmont (pers. comm. Tom Craven).

28 We modeled the impacts of fertilizer application on a sample stand at site index 80. FVS calculated a blanket volume increase of 20%, independent of other variables.

29 For the purposes of this natural regeneration scenario, there would be no associated planting costs.

Another source of bias in the model is the result of how the rotation cycles fit into 100 year window of analysis. Since each rotation does not evenly fit into our 100 year time frame, some rotations have standing volumes in 2110 that have not been accounted for in this analysis. As discussed in our further analysis, we used the Faustmann Formula as a validity check for our valuations. This method values infinite rotations, and is therefore able to avoid this timing bias. However, excluding the time bias comes at a tradeoff for capturing the impact of thinnings on the optimal rotation length.

This analysis did not model chip-and-saw products in our analysis of the Dailey Division, which would have added value to our shorter rotations. One reason for this was to keep our results compatible with the products classes that the Duke Forest reports in its inventory. In further analysis we addressed the value of chip and saw in comparison with our current values, which did shift results slightly in favor of shorter rotation lengths. However, the TimberMart-South values for the financial analysis were state-wide averages. The Duke Forest typically expects premiums for its sawtimber and chip-and-saw products (pers. comm. Sara Childs) over the state average, which were not accounted for in this model.

7. RECOMMENDATIONS

There is a need for robust, stand-level growth and yield modeling to inform long-term planning in the Duke Forest. FVS can be tailored to accommodate the needs of the Forest, and make reasonable projections to aid in management decisions. However, in order to realize the full potential of the software, the Duke Forest will need to address the following:

1) **Inventory Methods:**
   a) **Cover type** should be simplified to allow for consolidation into management-scale forest compartments. Instead of continuing the current strata classification, we recommend following the cover type procedure outlined in this analysis.

b) **Sampling methodology** should include fixed-area, measured plots. Sampling should be designed such that the inventory error is minimized at the most relevant planning unit scale to allow for more accurate modeling in FVS.

2) **Validate FVS Volume Equations and FVS Growth Models**

   a) **Cross-referencing** FVS stand projections with collected stand data can help the Duke Forest understand the suitability of the standard volume equations in the model. We identify the steps below for local validation. After validation, equations within FVS software should be updated to ensure the most accurate volume data and modeling.

   b) **Planting Simulations:** Simulate planted pine in FVS for a chosen stand in the Duke Forest with a known age. Run the simulation to the current age, and compare the FVS diameter distribution to actual stand conditions on the ground.

   c) **Comparison with Timber Buyer and Mill Receipts:** Following the 100% cruise at time of sale, input collected data into FVS and generate a "Cruise Summary Statistics Report." Compare these volumes with the timber buyer's cruise, and the volumes reported at the mill.

   d) **Comparing Growth:** Collect growth measurements in the field (increment cores, changing DBH through time, height, etc.), and compare with FVS growth estimates for DBH and height.

We also recommend the Duke Forest make further considerations for choosing the discount rate for any of its future financial analyses. As demonstrated in this analysis NPV results are heavily influenced by the chosen rate, which can have serious implications for long term management decisions. One way to inform this discount-rate decision is to utilize the interest rate on investments made into the Duke Forest endowment to demonstrate how quickly money grows "in the bank" as compared to value accumulation in the Forest.

We recommend that the Duke Forest use the results of this analysis when considering future management decisions. As we have discussed, the young pine cohort will have heavy management burdens that need to be considered. The Duke Forest should expect a large need for pre-commercial thinnings, which will be a high cost in its annual budget. Without management intervention the financial burden of managing the uneven age class distribution will continue as the young pines grow. It may be in the Forest's best interest to harvest on earlier rotations, forsaking the higher future value of sawtimber in favor of attaining even age classes. If the younger age classes are able to reach chip-and-saw sizes they will receive a significant bump in value over the value of pulp. In any case, as the Forest begins to redistribute its age classes, there will inevitably be trade-offs between this goal and revenue generation.

8. CONCLUSION

Our analysis sought to identify whether alternative practices could enhance the Forest's timber revenue potential and decrease the support from the University. This analysis showed that the current paradigm for pine management has the highest revenue and net present value given current market conditions, modeling assumptions, and FVS limitations discussed in this paper. Specifically, the favorability of the longer rotations is driven by the higher value of the sawtimber relative to pulp. At a discount rate of five percent, this rationalizes waiting longer to harvest. Additionally the establishment costs of planting improved stock is justified by the higher values associated with increased merchantable volumes. This holds true for all rotation lengths, assuming the price is below $47 per acre for first generation seedlings. This analysis changes with the introduction of chip-and-saw as a product class by adding value to younger timber, potentially reducing the optimal rotation length. These trends are all subject to change given price fluctuations and market demand. Changes in prices within each product class, blended prices for chip-and-saw and sawtimber, and any price premiums for the Duke Forest within the local market will influence the optimal rotation length.

This analysis provided a new approach for addressing these potential fluctuations using FVS modeling. Although there are challenges in updating the current inventory for FVS compatibility, calibrating the model for local conditions, and committing resources to learning and implementing software, FVS can be a powerful tool for long-term planning in the Duke Forest. This software provides a robust suite of functions and includes the potential for modeling future conditions that are outside the scope of the current Duke Forest models. Having the ability to experiment with different scenarios allows for flexibility in responses to the management challenges of forestry in the 21st century.

While this project has emphasized potential strategies to enhance future timber revenue by shifting the current management paradigm, the authors of this paper want to stress that our analysis is only a guide for making management decisions. Although this guide is important in considering future challenges of forest management, we feel our most important recommendation is for the Duke Forest to continue emphasizing the non-timber values of the Forest. The true value of the Duke Forest far exceeds the value of its timber and can be found in its contributions to education, research, community engagement, and dedication to improving the ecosystem health of an increasingly urban landscape.

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10. APPENDIX

Duke Forest Inventory Age Classification for Loblolly Pine:

L0: Loblolly, 0-9 years old
L1: Loblolly, 10-19 years old
L2: Loblolly, 10-29 years old
L3: Loblolly, 30-39 years old
L4: Loblolly, 40-49 years old
L5: Loblolly, 50- 59 years old
L6: Loblolly, 60-69 years old
L7: Loblolly, 70-79 years old
L8: Loblolly, 80-89 years old
L9: Loblolly, 90-99 years old
L10: Loblolly, 100-109 years old
L11: Loblolly, 110-119 years old
L12: Loblolly, 120+ years old
U: Uneven-aged

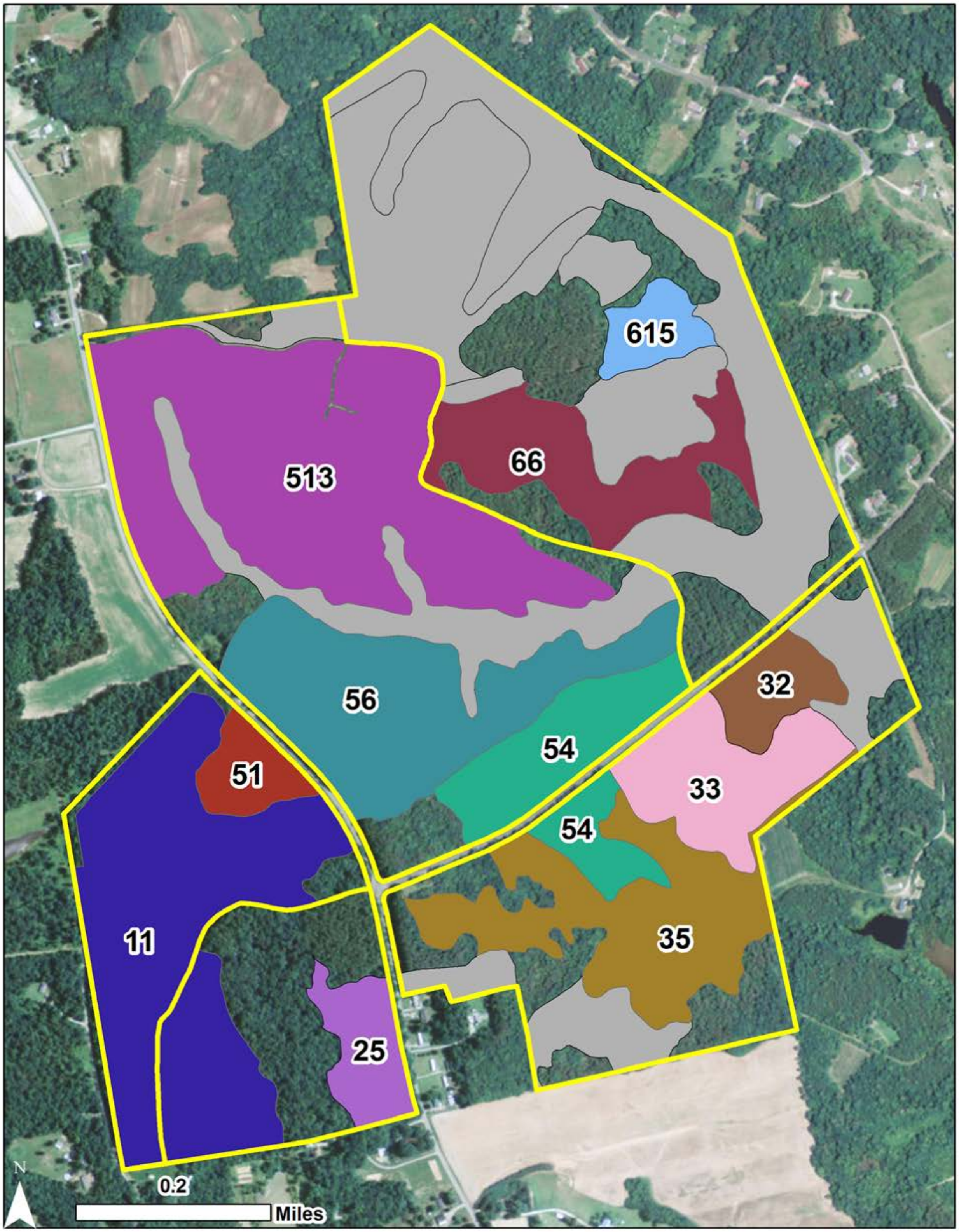

Figure A1: The Dailey Division divided into the 11 stands used in the modeling.

Table A1: Financial Modeling Default Parameter Values for Improved Stock

Model Parameters	
(Yellow Values Adjustable)	
Total Acreage	
239.89	Acres
Sawtimber	
6.225	Ton/MBF Pine (International 1/4 in)
5.425	Ton/MBF Mixed Hardwood (International 1/4 in)
$ 25.57	$/Ton Pine
$ 25.78	$/Ton Mixed Hardwood
Pulp	
75	cuft/Cord
2.68	Tons/Cord Pine
2.9	Tons/Cord Mixed hardwood
$ 10.60	$/Ton Pine
$ 4.88	$/Ton Mixed Hardwood
Operations Cost	
$ 145.00	$/acre herbicide
$ 80.00	$/acre planting
$ 22.50	$/acre improved stock @ 450 seedlings/acre
Discount Rate	
0.05	Assumed Discount
Sources	
TimberMart South 4Q2016	
Duke Forest Opertations Estimation Sheet	
Berry J.E. Making Sense of Loblolly Pine Varieties. USDA	

Tables A2 and A3: Discount Rate Sensitivity Analysis on NPV

Standard Stock Discount Sensitivity											
Rotation	0%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
30 Years	486,000	253,000	132,000	65,000	25,000	1,000	(15,000)	(26,000)	(33,000)	(39,000)	(43,000)
35 Years	623,000	344,000	191,000	103,000	50,000	17,000	(5,000)	(19,000)	(29,000)	(36,000)	(41,000)
40 Years	858,000	468,000	259,000	141,000	72,000	29,000	3,000	(15,000)	(27,000)	(35,000)	(40,000)
45 Years	1,152,000	600,000	322,000	172,000	88,000	38,000	7,000	(13,000)	(26,000)	(34,000)	(40,000)
50 Years	1,462,000	722,000	372,000	194,000	97,000	41,000	8,000	(13,000)	(26,000)	(35,000)	(41,000)

Improved Stock Discount Sensitivity											
Rotation	0%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
30 Years	$ 591,000	$ 310,000	$ 163,000	$ 82,000	$ 34,000	$ 5,000	$ (14,000)	$ (27,000)	$ (36,000)	$ (42,000)	$ (46,000)
35 Years	$ 735,000	$ 400,000	$ 221,000	$ 120,000	$ 59,000	$ 21,000	$ (3,000)	$ (20,000)	$ (31,000)	$ (39,000)	$ (44,000)
40 Years	$ 972,000	$ 533,000	$ 296,000	$ 163,000	$ 84,000	$ 36,000	$ 5,000	$ (15,000)	$ (28,000)	$ (38,000)	$ (44,000)
45 Years	$ 1,304,000	$ 681,000	$ 366,000	$ 197,000	$ 101,000	$ 45,000	$ 10,000	$ (13,000)	$ (27,000)	$ (37,000)	$ (44,000)
50 Years	$ 1,619,000	$ 803,000	$ 415,000	$ 217,000	$ 110,000	$ 48,000	$ 10,000	$ (13,000)	$ (28,000)	$ (38,000)	$ (45,000)

Table A4: Calculated Land Expectation Value. Parameters for the Faustmann formula are: p = price, Q(t) = volume (tons), c = establishment cost, t = time (years), δ = discount rate (5%). Volume has been converted to tons using Timber Mart South conversion factors to allow for inclusion of both sawtimber and pulp values (p*Q). Trees were grown on SI 80. No thinnings occurred. Green represents rotation lengths tested in this analysis.

Year	Time	Pulp (Q)	Pulp (p)	Saw (Q)	Saw (p)	p*Q	LEV
2010	0	0.0	10.6	0.0	25.57	0	
2015	5	0.0	10.6	0.0	25.57	0	-792
2020	10	0.0	10.6	0.0	25.57	0	-347
2025	15	0.0	10.6	0.0	25.57	0	-201
2030	20	11.0	10.6	0.0	25.57	116	-63
2035	25	48.4	10.6	0.0	25.57	513	116
2040	30	84.0	10.6	3.3	25.57	974	215
2045	35	99.4	10.6	18.1	25.57	1515	271
2050	40	104.8	10.6	38.3	25.57	2089	292
2055	45	82.1	10.6	82.5	25.57	2979	324
2060	50	72.4	10.6	114.0	25.57	3682	309
2065	55	61.4	10.6	146.7	25.57	4403	285
2070	60	47.3	10.6	182.8	25.57	5176	259
2075	65	40.2	10.6	211.1	25.57	5824	226
2080	70	30.9	10.6	230.4	25.57	6217	187
21.27	75	22.9	10.6	247.5	25.57	6570	153
2090	80	17.4	10.6	261.4	25.57	6868	124
2095	85	14.4	10.6	272.2	25.57	7114	100
2100	90	11.8	10.6	283.0	25.57	7361	80
2105	95	10.2	10.6	292.4	25.57	7585	64
2110	100	8.4	10.6	302.0	25.57	7812	51

Table A5 and A6: MAI maximizes at 75 years for sawtimber and 35 years for pulp (green). Values were calculated under the same assumptions as Table A4.

MAI for Sawtimber per Acre			
Year	**Time**	**Q (bdft)**	**MAI**
2010	0	0	0
2015	5	0	0
2020	10	0	0
2025	15	0	0
2030	20	0	0
2035	25	0	0
2040	30	524	17
2045	35	2901	83
2050	40	6149	154
2055	45	13246	294
2060	50	18309	366
2065	55	23570	429
2070	60	29366	489
2075	65	33909	522
2080	70	37006	529
21.27	75	39752	530
2090	80	41992	525
2095	85	43731	514
2100	90	45460	505
2105	95	46975	494
2110	100	48521	485

MAI for Pulp per Acre			
Year	**Time**	**Q (cft)**	**MAI**
2010	0	0	0
2015	5	0	0
2020	10	0	0
2025	15	0	0
2030	20	327	16
2035	25	1445	58
2040	30	2508	84
2045	35	2966	85
2050	40	3127	78
2055	45	2451	54
2060	50	2162	43
2065	55	1833	33
2070	60	1412	24
2075	65	1201	18
2080	70	921	13
21.27	75	683	9
2090	80	518	6
2095	85	431	5
2100	90	353	4
2105	95	304	3
2110	100	250	3

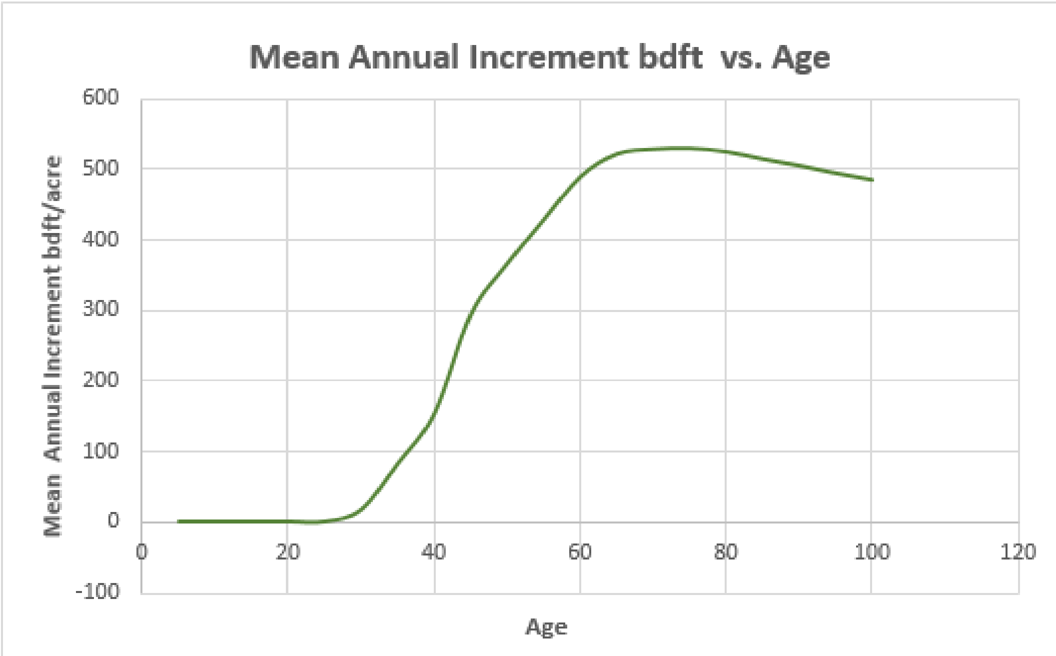

Figure A2: MAI is maximized for unthinned stands at age 75 for the Duke Forest. Site index 80.[30]

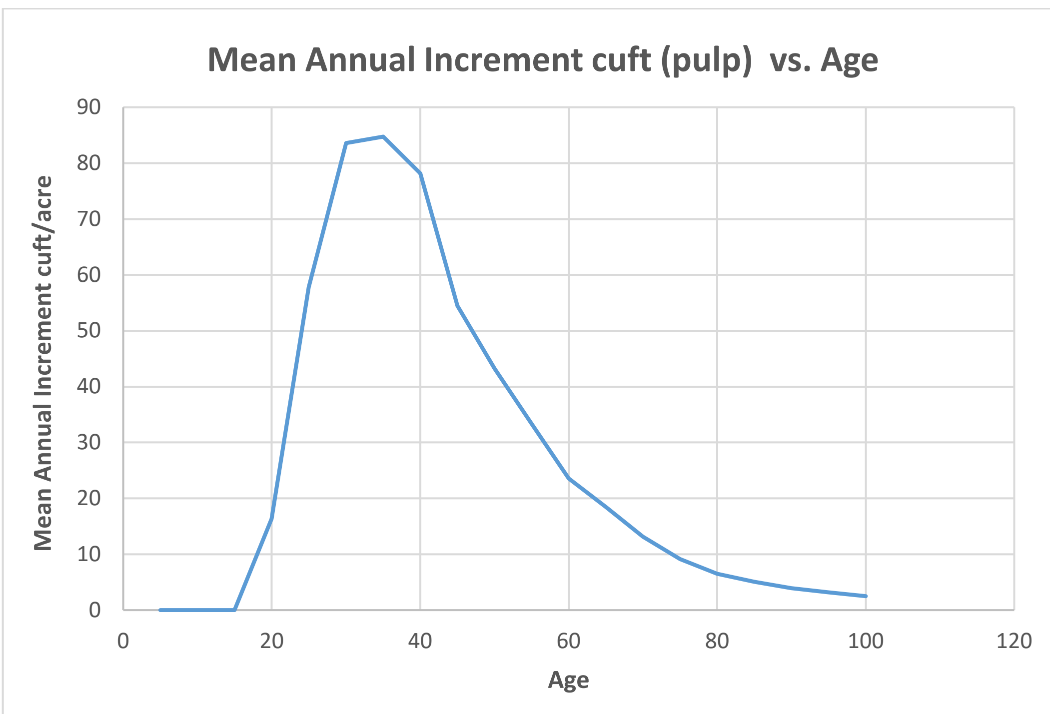

Figure A3: MAI is maximized for unthinned stands at age 35 for the Duke forest. Site index 80.

30 Note that maximizing board feet volume may not maximize biological growth. FVS does not output merchantable timber (sawtimber and pulpwood) until the minimum DBH has been reached.