# PRODUCING GROWTH ESTIMATES OF DUKE FOREST PINE STANDS USING USDA'S FOREST VEGETATION SIMULATOR

Master's project submitted in partial fulfillment of the requirements for the Master of Forestry degree in the Nicholas School of the Environment of Duke University

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## Executive Summary

Duke Forest manages its loblolly pine stands for timber revenues. Duke Forest seeks construct a management plan informed by an optimized harvest schedule. This project aims to produce a reliable growth and yield model in order to produce the volume yield estimates necessary to compute the optimized harvest schedule. This was accomplished by testing and calibrating USDA's Forest Vegetation Simulator (FVS) using Duke Forest Continuous Forest Inventory data. FVS was tested by using different site index inputs, and the diameter growth modifiers of FVS were then applied to reproduce current loblolly pine stand characteristics. It was found that the observed site index of a Duke Forest loblolly pine stand produces a better estimate of Duke Forest basal areas than do the Natural Resource Conservation Service's Web Soil Survey site indices. Despite the use of the more accurate site index numbers, FVS needed further calibration in order to produce statistically significant estimates of Duke Forest basal areas. Diameter growth modifiers of 1.25, 2.6, and 2.6 were applied to stands with low, average, and high site indices respectively, which calibrated the model. FVS, when calibrated, can provide Duke Forest with a workable growth and yield model. In the future, even more precise calibrations will be possible as the continuous Forest Inventory process continues, and plots sampled for this project are re-sampled. This will inform the diameter and height growth increments FVS uses to grow the inputted trees into the future.

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## Introduction

Duke Forest, as part of a research institution and as an integral part of the Durham community, is managed for more than just timber value. It is also managed for habitat, aesthetics, and for research purposes. The goal of the Duke Forest (DF) is to sustainably manage its even-aged loblolly pine (*Pinus taeda* L.) stands for timber, while targeting an uniform distribution of age classes within its 'loblolly pine core'. As part of its effort to maximize the yields from the pine core, Duke Forest wants to create a long-term management plan that includes a forecasted harvest schedule. Harvest schedules require estimates of future yields, which can be produced using a growth and yield model. Empirical growth and yield models use biometric equations and complex relationships (accounting for, e.g., the effects of tree size/age, stand density, and site quality on tree diameter and height growth) to predict the volume growth of forests into the future (Kershaw, Ducey, Beers, & Husch, 2016). The US Department of Agriculture's US Forest Service produces a free growth and yield model called the Forest Vegetation Simulator (FVS, https://www.fs.fed.us/fvs/software/complete.php, 2021). As inputs, FVS uses tree-level measurements (tree height and diameter at breast height), i.e. data that are typically collected in forest inventories (Kershaw, Ducey, Beers, & Husch, 2016). Forest inventories are typically conducted by measuring sample plots in the stands of interest. Sampling usually consists of cruising the timber, or measuring the trees and recording the demographics of the plot, and collecting data on the non-timber attributes as well. DF conducted a spatially-referenced, forest-wide inventory, as a part of its Continuous Forest Inventory (CFI) effort in 2019. The purpose of this Master's Project is to use the data collected in the CFI to calibrate the FVS growth and yield model to the growing conditions of the Duke Forest pine core in order to accurately forecast yields into the future.

## Duke Forest Continuous Forest Inventory

Duke Forest’s CFI was conceptualized and put into action in 2018. The stated purpose of the CFI was to generate “Volume, monetary value, and growth estimates”, and to “Develop an estimate of the live standing stock of trees and their growth over time.” (Childs, 2018). The initial inventory was conducted in 2019. The permanent plots are oriented on a 1000 ft x 1000 ft grid and DF’s intent is to resample 20% of the plots every other year to complete a full inventory cycle every 10 years (Craven, 2020). After the initial pass, it was determined that not enough plots had been cruised in the Duke Forest pine core stands, and that more data was needed to achieve a ratio of 1 plot per 25 acres of pine stand. In order to address this shortcoming, temporary plots were placed in those stands, which were cruised in the manner of the permanent CFI plots.

The plots all share an identical design. Each plot consists of a 5th acre circle with a 10th acre, 100th acre, and 1000th acre circle nested inside of it (Craven, 2020). The three larger plots all share a center, but the 1000th acre plot’s center is 16 feet north of the main plot center. Within each part of the plot there was a different sampling criterion. In the 5th acre plot, trees above 18” at breast heigh were measured, in the 10th acre plot trees above 6” but below 18” at breast height were measured, and in the 100th acre plot trees above 4.5’ tall (breast height) and below 6” in diameter at breast height were measured. In the 1000th acre plot, ground cover description and information on plants shorter than 4.5’ were recorded. Regardless of the part of the plot, each tree found within the plot is recorded with species, diameter at breast height, and height. The height to live crown is also recorded for the 5th and 10th acres plots. Data collected in the CFI subsequently became an input to the growth and yield model used in this project.

## Description of FVS

FVS is a “semi-distant-independent individual tree growth and yield model” (Dixon, 2002). FVS is only “semi-distant-independent”, because it uses some plot-level information (such as distribution of tree sizes) to simulate, e.g., effects of competition on the growth of individual trees. FVS also uses regional growth rates which are unique to the variant of FVS, which in the context of the current study is the Southern variant (https://www.fs.fed.us/fvs/documents/guides.shtml). FVS requires two input files. The first is a keyword record file. This file tells FVS all about where the stand is located and how the plots were measured, e.g., the inventory year, the USFS region number, the age of the stands, the sampling design, and the site index. The second file that FVS needs to operate is the tree lists. The information in this file includes, e.g., the number of trees represented by the individual tree record, the species, the diameter at breast height, the total height of the tree, and the height to live crown for certain trees. Various management activities can be included in the simulation using FVS’s user interface. When FVS runs, it goes through the sequence shown in Figure 1 in order to grow the stand.

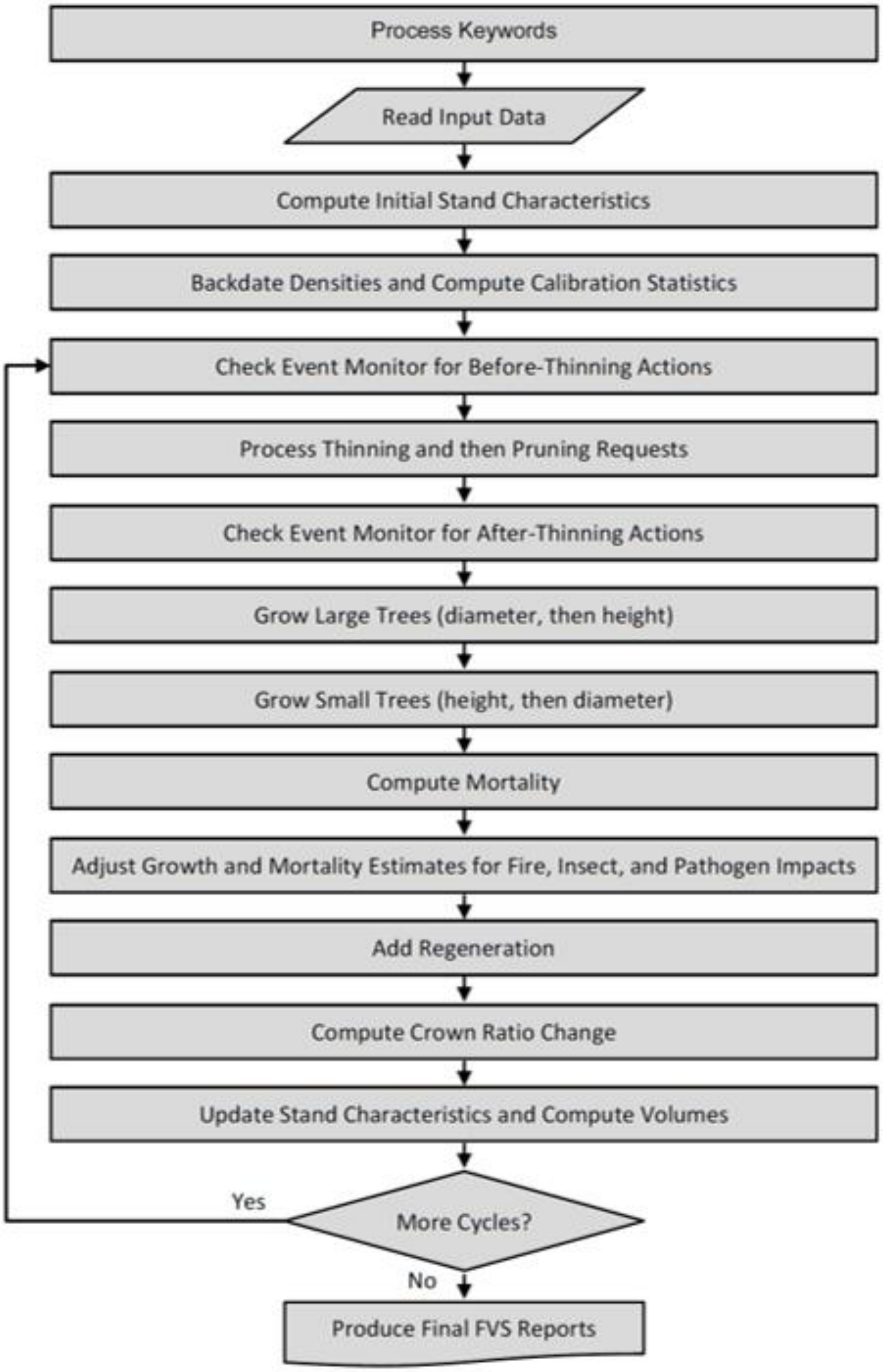


**Figure 1.** Forest Vegetation Simulator run sequence (Dixon, 2002).

In short, FVS determines what the stand looks like at the beginning of the cycle (the default cycle length in the Southern variant is 5 years (Keyser 2008)), computes stand statistics, applies the management activities (prescriptions) laid out in the keywords, grows the trees, applies either mortality or regeneration, then recomputes the stand statistics. The growth of a particular tree is calculated using regional and species-specific diameter and height growth increment functions. The diameter growth increment is determined by the following variables: the diameter at breast height, the crown ratio, the relative height of a tree compared to the trees in the same stand, the site index of the stand (a proxy for site quality and thus potential growth), the stand basal area, the proportion of basal area made up of large trees, as well as certain geographic variables that do not vary plot to plot (Keyser, 2008). The height growth increment is determined by these additional variables: the bark ratio and the plot basal area. Thus, both the diameter and height growth increment depend on site index. This makes the choice of site index important to overall accuracy of the model.

FVS is capable of very fine calibration of diameter and height growth increments to the particular forest being modeled by modifying those increments. This is possible through measurements of height growth and/or diameter growth (e.g., through repeated measurements or from increment cores). Diameter increment calibration directly affects the growth calculations for individual trees in each FVS cycle, so both height and diameter growth will be affected (Dixon, 2002). Another way to calibrate FVS is to use a ‘diameter growth modifier’ that is applied at the tail end of the cycle, after all growth in height and diameter has occurred. It affects mortality and other density dependent processes, but not height growth or parts of the sequence that precede individual tree growth (Van Dyck & Smith-Mateja, 2000). The default diameter growth modifier in FVS is "1". Raising it will increase the growth rate, lowering it will decrease the growth rate.

## Previous Work on FVS Calibration

Based on the many studies done on the recalibration of FVS to local growth increment, it is clear that FVS variants represent regional average growth patterns, and do not always make accurate predictions at a finer scale. For example, Lacerte et al. 2004 noted that the basal areas predicted by the Lake States variant of FVS did not match the basal areas observed in northern Ontario. Lacerte et al. 2006 attempted to remedy this shortcoming by producing new models to use in FVS, by studying the growth of trees in permanent plots. This paper, and others like it, lead Russell et al. (2012) to undertake a recalibration of several sub-models of the FVS Northeast variant for the purposes of better predicting the height, 5-year diameter, and height increment of 20 of the most frequently encountered species in the region. This paper relied on recalibration using Forest Inventory and Analysis (FIA) data from 13 states, collected over the course of 13 years. It is notable that in Russel et al. (2012), one of the methods used to calibrate this variant was to re-estimate site index for the FIA plots. Taken together, while the recalibration of FVS frequently relies on large data sets, usually permanent plots, that are resampled over the course of many years, model outputs can also be adjusted by fine-tuning inputs such as site index.

## Project Objectives and Scope

The overarching goal of this Master's Project is to test and calibrate the basal area estimates of FVS for the Duke Forest pine stand through the choice of site index and diameter growth modifier. The DF has taken the first step towards repeated growth measurements by initiating their CFI effort, however, in the present study, the FVS calibration to the conditions of the DF relies on inventory data from the first year only, without directly adjusting any sub-model within the Southern variant. Specifically, the basal areas produced with FVS are compared with the current basal areas of Duke Forest stands (both the FVS grown stands and Duke Forest stands were managed the same way). If the basal areas of FVS grown stands do not match the basal areas of actual Duke forest stand, then FVS must be calibrated to return the correct basal area statistics. The first step to testing and calibrating FVS is providing FVS with the most accurate site index measure available. Second, if there is still a difference in the basal areas of FVS grown stands and the basal areas of the actual Duke Forest stands, the simulated growth rates are further adjusted using a diameter growth modifier.

### Methods

In order to first test to see if FVS approximates Duke Forest basal areas before determining if further calibration is necessary, the following procedures were followed:

1. The plots from the CFI first were aggregated into stands that could be grown in FVS
2. The site index of each plot was determined for two separate measures of site index, and they were divvied up into three site index buckets (low, average, and high) for each measure. The tree data from each plot was then put into different input files for each bucket, and for each measure. This resulted in a total of six FVS input files.
3. The input files were loaded into FVS, and the stands received the "average prescription". FVS was run, and the stand statistics were downloaded into excel, for a total of 6 output files.

## CFI Data Aggregated into Stands

The data from the CFI, which consists of 89 sample plots from the pine core, was divvied up into stands. There are two possible ways to divide the plots so as to ensure the resulting stands contain a single age class. The first is to treat each plot as its own stand. The drawback inherent to this method is that there can only be a single sample for each stand, which limits the use of statistical analyses of the outputs. The second way is to separate the plots by age-class. Although DF does not always have a record of the exact age of a stand, it is possible to place a stand within a 10-year span. Stands were pre-sorted in a DF shapefile into age-classes, which DF refers to as "strata". In excel and ArcGIS, each plot was linked to the stand it occurred in, then assigned a stratum. The average age of each age-class (stratum) is the middle of the 10-year increment. The summary of the seven age-class stands, including their average age and acreage within the pine core is shown in Table 1.

**Table 1.** Summary of Duke Forest Age Class Strata as Stands.

| Stand | Age | Acres |
|---|---|---|
| L_0 | 5 | 530 |
| L_1 | 15 | 471 |
| L_2 | 25 | 370 |
| L_3 | 35 | 552 |
| L_4 | 45 | 93 |
| L_5 | 55 | 147 |
| L_M | 75 | 384 |
| **TOTAL** | | **2546** |

## Assigning Site Index

After assigning the plots into stands, the next step is to assign site index. The two measures of site index available are the Natural Resource Conservation Service's Web Soil Survey (WSS) (https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm) site indices and the calculated site indices obtained from the observed heights and ages of CFI plot site trees. To find the WSS site index for each plot, the plot center shapefile was converted from a point into a polygon shapefile by buffering the point by the radius of a 5th acre plot. That plot shapefile was loaded into the WSS database. The database returned the corresponding soil type for each plot. Those soil types were then recorded in Microsoft Excel, and then connected with the corresponding site index.

To calculate the observed site index from the site trees, the heights of all loblolly pines were ranked for each plot, and the tallest half were averaged for each plot to obtain an estimate of site tree height. The top 50% were used to include both dominant and co-dominant heights. This averaged "Site Tree" height was then entered, along with the age, into the USDA's 1929 loblolly pine Site index formula where H= height (in feet) and A = total age (years) (Carmean, Hahn, & Jacobs, 1989):

$$S = 0.8765 * H^{0.9902} * (1 - e^{-0.0447*A})^{-1.2443*H^{0.0502}} \text{ (Equation 1)}$$

This returned each plot's observed site index (in feet). The plots were then divvied up into three buckets for each measure: Low, Average, and High. Low and High were picked by excluding extreme observations, where only a handful of plots had extremely low or high site indices. The average was the arithmetic mean site index. The buckets were defined by the midpoint between the low and average, and the average and high value. Below, in Table 2, are the site index and buckets chosen for each measure.

**Table 2**: Site Index (in feet) for each run, and the accompanying buckets used to divide plots:

| | WSS SI | WSS Buckets | Site Tree SI | Site Tree Buckets |
|---|---|---|---|---|
| Low | 67 | 67-73 | 86 | 86-94 |
| Avg | 80 | 74-83 | 103 | 95-109 |
| High | 87 | 84-95 | 116 | 110-128 |

An FVS input file was created from the plot data from each of the three buckets, for both measures of site index, for a total of six FVS input files. Although the process is to transfer CFI data into the FVS tree list format, the way the plot was sampled created complications for one variable: tree count. The large-tree plot size was a 1/5th acre, and was recorded as such in the keyword input file. However, if the tree count were not altered, the trees sampled in the smaller nested plots would be underrepresented. Therefore, the tree count needed to be multiplied by 2 for any tree sampled in the 1/10th acre plot, by 20 for any tree in the 1/100th acre plot, and 200 for any tree in the 1/1000th acre plot. This process transforms the data into a standardized 1/5th acre plot.

It is important to note that not every stand was represented in each of the six runs. Because of varying site index compositions, some stands are absent from one of the buckets, or almost entirely composed of plots from one site index bucket. This is summarized by the Figure 2.

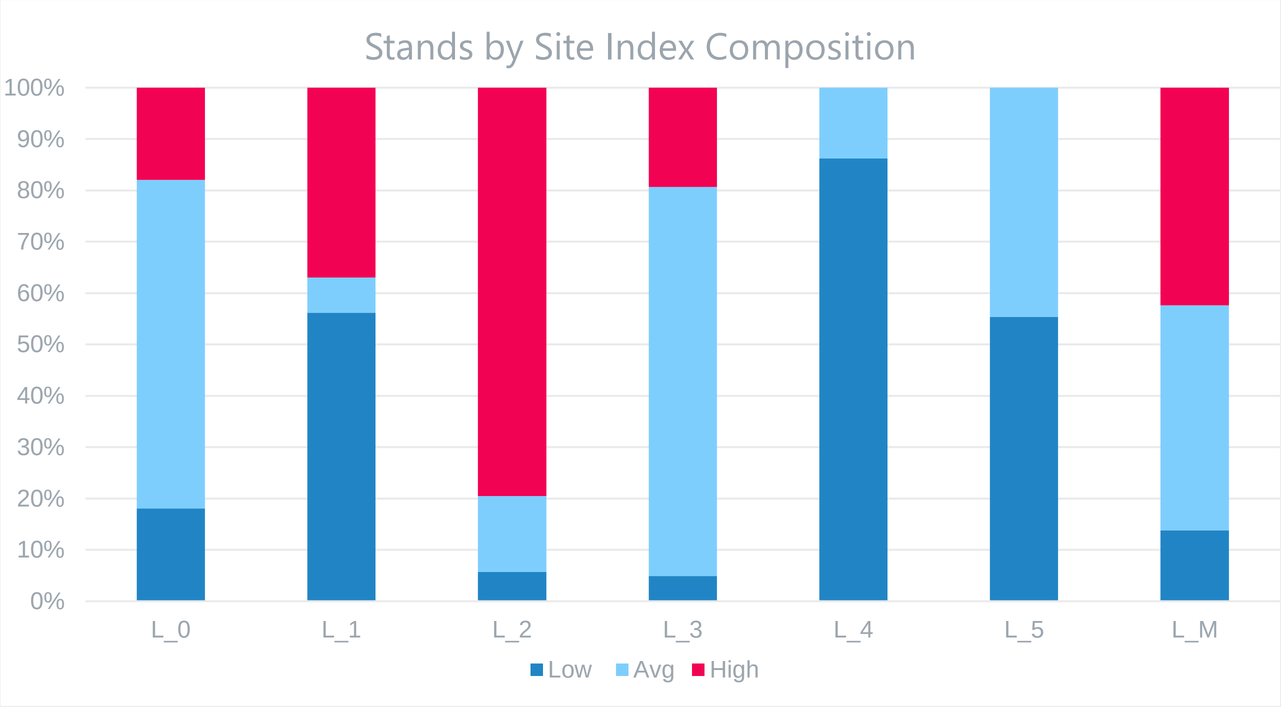


**Figure 2**: Relative site index composition by stand.

To compare the two measures of site index, the values of the observed Site Tree site index were placed on the x-axis, and the WSS values were placed on the y-axis. The result, shown in Figure 3, appears below.

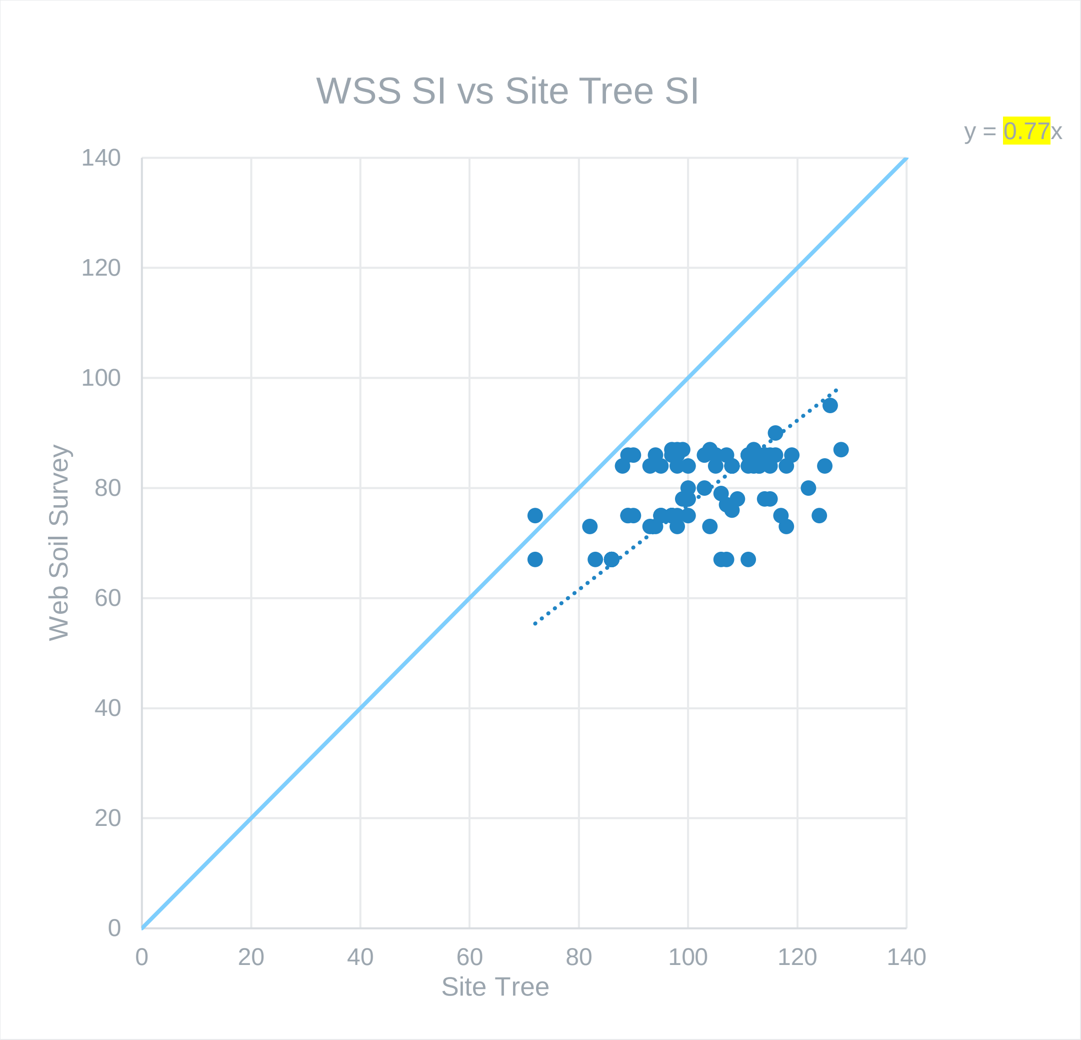


**Figure 3**: Web Soil Survey Site Index (in feet) vs. Site Tree Site Index (in feet) for each plot. The light blue colored line has a slope of "1". The Site Tree measure is 23% greater than the WSS measure on average.

Every plot, with the exception of one, falls below the light blue line with the slope of "1", which shows that the Site Tree site index is almost always larger than the WSS site index. The slope of the line of best fit shows that the Site Tree site index is 23% greater than the WSS site index on average. The variance of the Site Tree data is also considerably larger than the variance of the data from the WSS, indicating that the WSS measure of site index does not explain the variability that is empirically observed in the DF.

**Average Prescription**

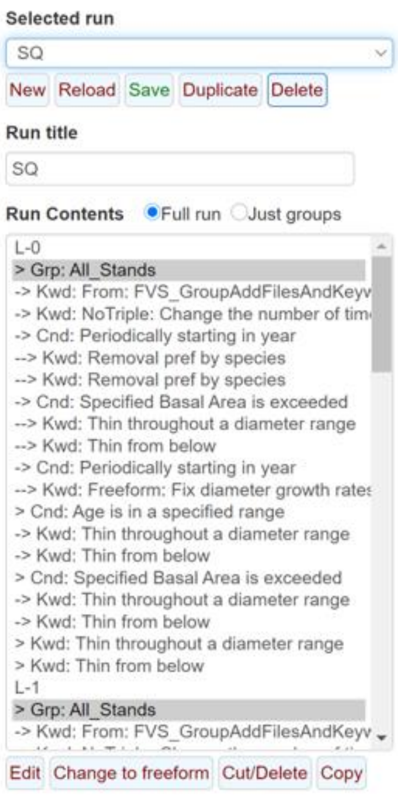
With the six FVS input files in hand, the DF “average prescription’ was then applied to all six of the runs. The FVS input files were loaded into the “Local Configuration” version of FVS. The “average prescription” is a suite of management activities that broadly represents what most loblolly pine stands have received over the last 50 years. The management activities are as follows:

Precommercial Thinning (PCT): While the stand is between the ages of 0 and 10 years of age it can be pre-commercially thinned. Because Duke Forest establishes loblolly stands through natural regeneration (seeding), there can be thousands of recruits per acre prior to the PCT. The PCT treatment reduces the number of trees per acre to 436, at a spacing of 10x10 feet. Only trees that are under 4 inches DBH are eligible to be PCTed, because the brush cutting head used to fell the saplings cannot get through larger trees in a timely manner. Individuals of species other than loblolly pine are removed along with the smaller loblolly pines. Because the plots are aggregated into stands by age class, only L-0 is eligible for this treatment.

1st Commercial Thin: When the stand reached 140 sqft of basal area, the stand is eligible for a 1st commercial thin. The thin reduced the basal area down to 75 sqft of basal area, and preferentially cuts non-loblolly pine species, then the smaller loblolly pines. After removing Individuals of species other than loblolly pine and small loblolly pines, the model then removes merchantable trees.  This is considered a commercial thin because it is the first thin that removes wood that is eligible for sale in local markets (the minimum DBH is 6’’). Again, because the stands are composed of a single age class, only L-1 and L-0 are eligible for this treatment.

2nd Commercial thin: When the stand reached 150 sqft of basal area, the stand is eligible for a 2nd commercial thinning. The thin reduces the basal area down to 80 sqft of basal area, and preferentially cuts non-loblolly pine species, then the smaller loblolly pines. All stands are eligible for this treatment.

Once the treatments have been applied, FVS is ready to be run, and the results may be analyzed in order to test and calibrate the efficacy of the model in growing DF lolblolly pine stands. Below, in Figure 4, is a picture of the contents of the Site Tree- Site Index, Low Bucket run. After these management activities are implemented in FVS, the result is the graph of the merchantable volume of a single stand, L-0, over the 50 year growing period, pictured in Figure 5. Each dip in merchantable volume represents one of the 3 management activities from the average prescription. In chronological order, the activities are the PCT, the 1st commercial thinning, then the 2nd commercial thinning.



Selected run: SQ

Run title: SQ

Run Contents: ● Full run ○ Just groups

```
L-0
> Grp: All_Stands
-> Kwd: From: FVS_GroupAddFilesAndKeyv
-> Kwd: NoTriple: Change the number of tim
-> Cnd: Periodically starting in year
--> Kwd: Removal pref by species
--> Kwd: Removal pref by species
-> Cnd: Specified Basal Area is exceeded
--> Kwd: Thin throughout a diameter range
--> Kwd: Thin from below
-> Cnd: Periodically starting in year
--> Kwd: Freeform: Fix diameter growth rates
> Cnd: Age is in a specified range
-> Kwd: Thin throughout a diameter range
-> Kwd: Thin from below
> Cnd: Specified Basal Area is exceeded
-> Kwd: Thin throughout a diameter range
-> Kwd: Thin from below
> Kwd: Thin throughout a diameter range
> Kwd: Thin from below
L-1
> Grp: All_Stands
-> Kwd: From: FVS_GroupAddFilesAndKeyv
```

**Figure 4:** FVS run contents for the “Average Prescription”, for the L-0 stand. The contents consist of the PCT, 1st commercial thin, and 2nd commercial thin

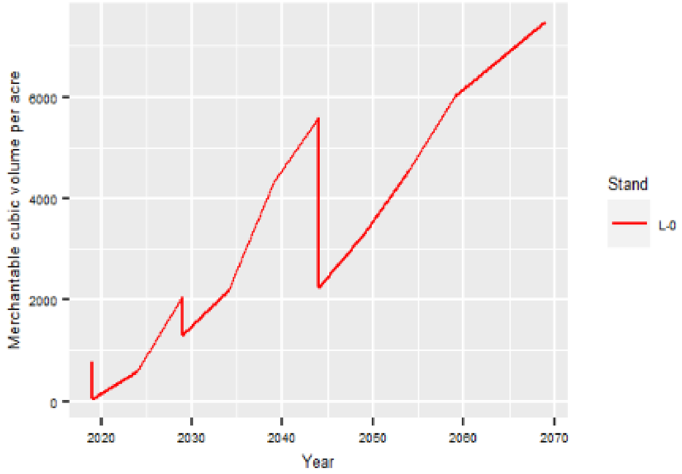


**Figure 5:** Merchantable cubic volume per acre for L-0 stand resulting from the “average prescription” (laid out in Figure 4) over the 50-year modeled time horizon.

For this project, the time horizon of the run is 50 years. Each cycle is 5 years long, so there are a total of 10 cycles. The inventory year was 2019, so the end of the model time horizon is 2069. After FVS is run, the outputs are downloaded into excel. The necessary output is the basal area of each stand for each cycle, for each run. At this point, the basal areas are ready for analysis, to see if further calibration is necessary.

**Results**

Using the FVS outputs from the six runs (WSS: Low, Avg, High, Site Tree: Low, Avg, High) are in excel, the following steps are taken:

1. The basal areas from stands grown in FVS are compared a real-life Duke Forest stand of a comparable age. Because all stands have received the same prescription, stands of the same age and site index should have the same basal area.
2. The two site index measures are compared against one another. If one does a superior job of estimating DF basal areas, then that measure will be selected.
3. The best measure of site index may still not do an adequate job of predicting Duke Forest basal areas. If that is the case, a diameter growth rate modifier must be applied to the runs with the superior measure of site index. Those runs are then compared to the runs without the diameter growth rate modifier. If the basal areas of the runs with the diameter growth rate modifier match real-life Duke Forest stand basal areas, the model is calibrated.

## Basal Area Plots

The basal areas of each stand grown in FVS were then compared to the basal areas of the DF loblolly pine stand that the FVS model was attempting to mimic. Each of the FVS attempts were averaged, and the average was plotted on the x-axis. The observed DF basal area was plotted on the y-axis. If FVS was doing a perfect job of growing DF stands, then the slope of the line of best fit would have been equal to “1”, as the basal areas of FVS would equal the basal areas observed in the DF. However, each of the six runs had a slope greater than “1” (Figure 6).

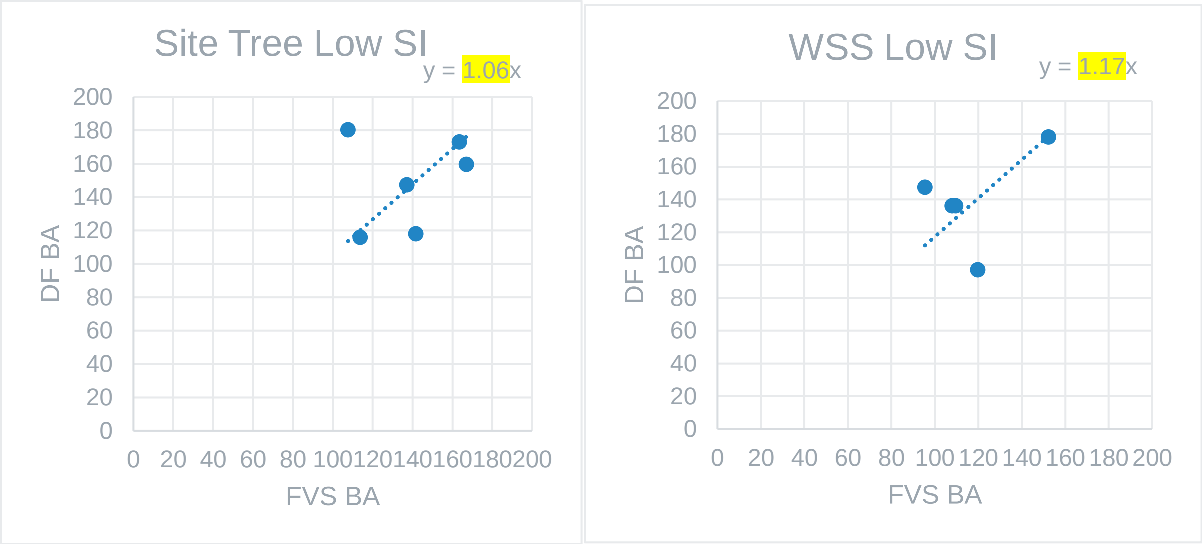


**Figure 6**: Right is the Site Tree site index “low” run, and left is the WSS site index “low” run. Both have a slope greater than “1”, indicating that the model is not yet calibrated, although the Site Tree measure of site index does a better job of approximating DF basal areas.

## Site Index Comparison

The superior site index measure was tested to see if it did an adequate job of producing DF basal areas. On average, the WSS site index runs had a slope of 1.3, and the Site Tree site index runs had an average slope of 1.14. This is depicted below, in Figure 7, with the WSS survey runs in dark blue, and the Site Tree runs in light blue. Both lines of best fit still had a higher slope than "1".

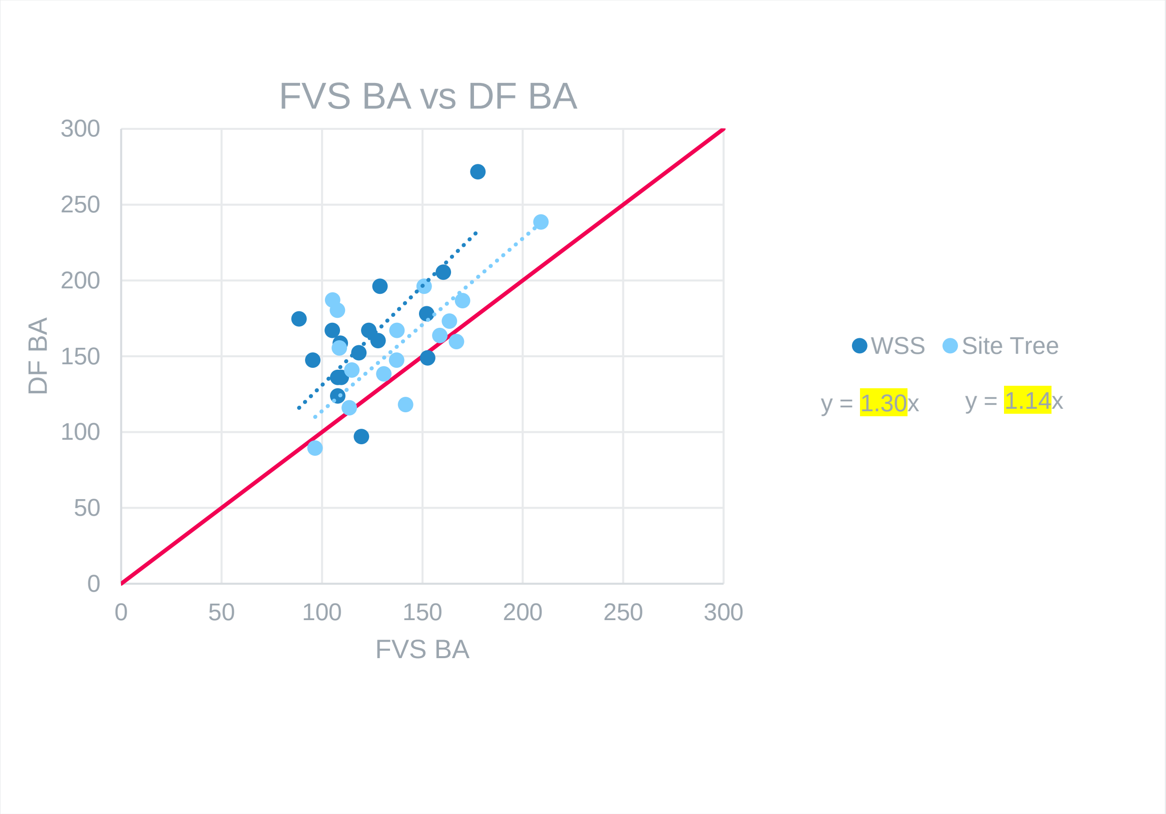


**Figure 7**: Duke Forest measured basal area (DF BA) plotted against FVS simulated basal area (FVS BA), with the runs based on Web Soil Survey site index in dark blue, and the runs based on Site Tree site index in light blue. The red line has a slope of "1".

Because the Site Tree measure of site index did a better job of approximating the basal areas of the DF stands, it is the better choice of site index to be used in the subsequent model simulations. This manner of comparing site index measures would not have ben statistically valid if the intercept of the line of best fit were not zero. The regression statistics for the Site Tree runs are shown in Table 4.

**Table 4**: Regression statistics from the Site Tree FVS runs. The dependent variable is the Duke Forest basal area.

| **Variable** | **Coeff** | **P-Value** |
|---|---|---|
| Intercept | 56.849 | 0.121 |
| BA_FVS | 0.746 | 0.008 |

The p-value of the intercept was higher than the alpha of 0.05. Thus, we could not reject the null hypothesis, that the intercept did not explain the patterns in the data. The slope of the ratio of FVS basal area to DF basal area was statistically significant, however, with the p-value less than the alpha of 0.05. We were able to reject the null hypothesis, and accept the alternative hypothesis, that the slope of the line explained the trends of the data. Therefore, comparing only the slopes of two regressions was a statistically valid way of determining if FVS is mimicking DF basal areas.

Next, the ratio of FVS-grown basal areas to Duke Forest-grown basal areas were compared to the hypothetically calibrated ratio of “1”. The ratio without an intercept was 0.88.

When a two-tailed 1-sample T-test was run on this ratio, against the ratio of a properly calibrated model- “1”, the p-value was 0.008. This means that the null hypothesis, that there is no difference between the two ratios, could be rejected, and that the ratio is different from “1”. The model needed further calibration to achieve that ratio.

### Applying a Diameter Growth Modifier to Calibrate the Model

To further adjust the simulation outputs, a Diameter Growth Modifier (DGM) was applied in FVS. As discussed previously, the default DGM in FVS is a value of “1”. A DGM greater than “1” increases the diameter growth rate, without affecting the core FVS diameter and height growth increments. Such a DGM was applied to each of the three site index buckets using the Site Tree measure of site index. From the default value of “1”, the DGM was gradually increased, until the slopes of the resulting FVS basal area vs Duke Forest basal area comparison graphs were equal, or very close, to “1” (Figure 8). This was accomplished using the exact same methods as described in the section on building the Basal Area Plots.

**Figure 8**: The Site Tree "High" site index bucket FVS run left, with the FVS-generated basal areas on the x-axis, and the observed DF basal areas on the y-axis. On the right is the same run but with a DGM of 2.6, which increased the basal areas of the FVS grown stands. Note that the slope is lower with the DGM.

Each site index bucket required a different DGM. In Figure 9, a bar chart summarizes the value of DGM necessary to force the slope of the that site index bucket to be equal, or nearly equal, to "1".

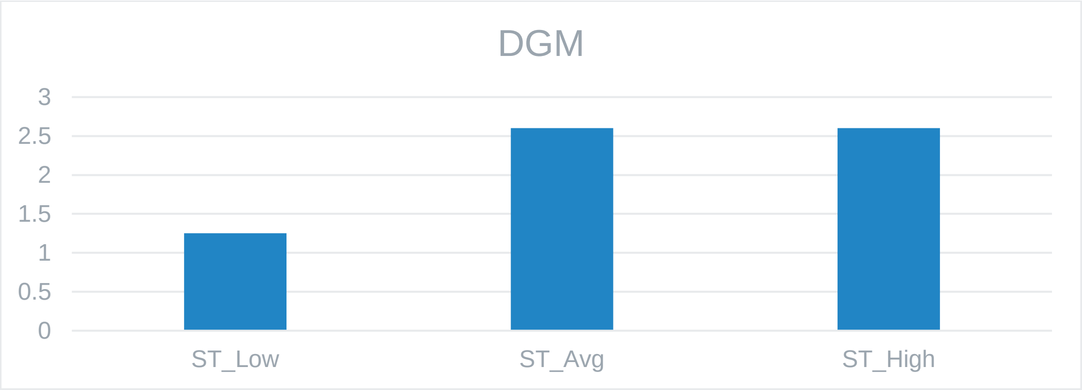


**Figure 9**: The diameter growth modifiers (DGM) used to adjust the basal area of stands grown in FVS until they matched the observed basal areas of Duke Forest stands.

These final DGMs (Low =1.25, Avg =2.6, High =2.6) were applied to their appropriate site index buckets and run. The same procedure was followed as before, with no DGM, the result of which is shown in Figure 10.

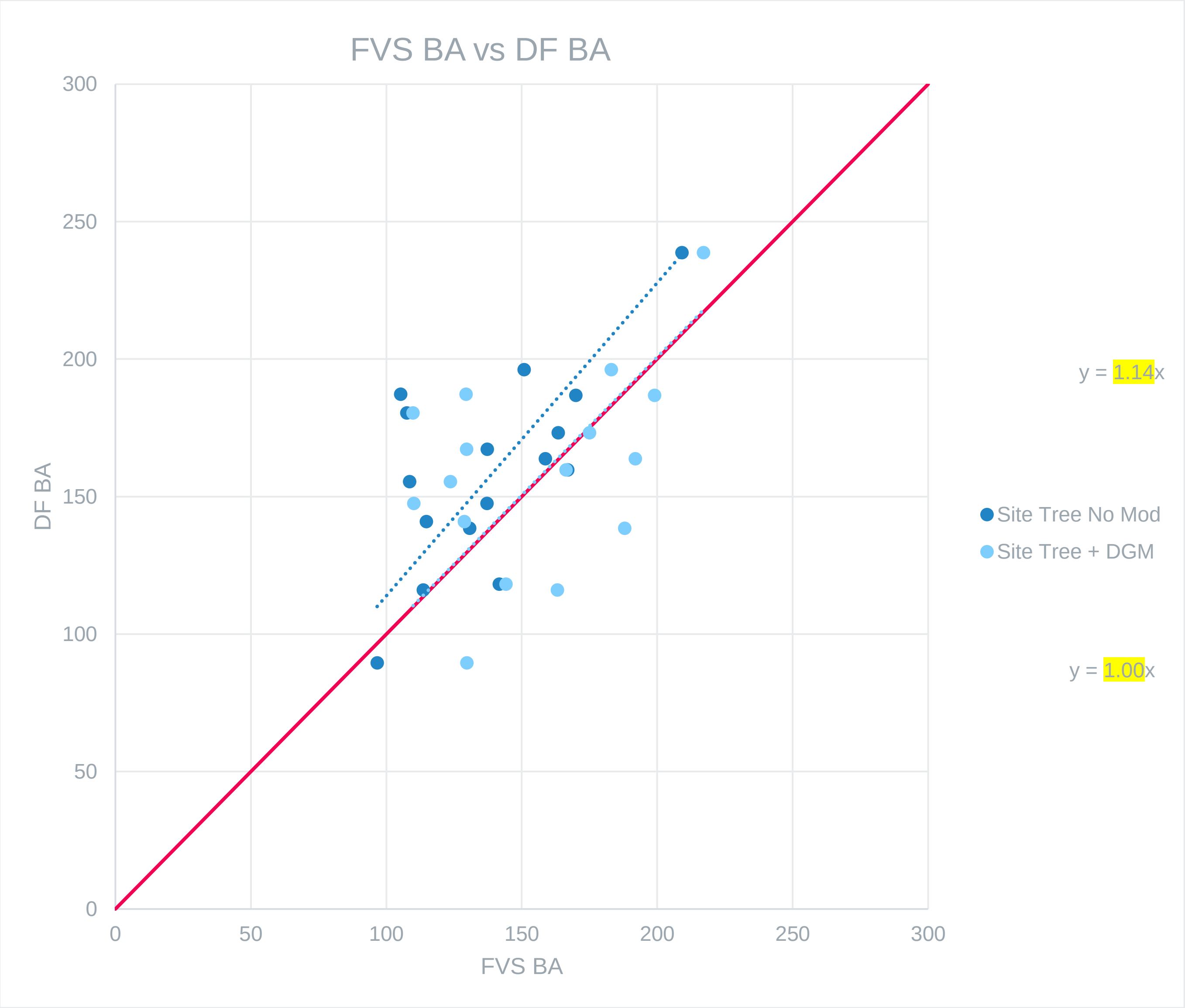


**Figure 10**: All unmodified Site Tree site index runs in dark blue, and all runs but with a DGM customized to each site index bucket in light blue. The red line has a slope of “1”.

Unsurprisingly, the slope of the line of best fit for the runs with a DGM was then “1”, as it was calibrated to be, while the unmodified runs still had a higher slope, at 1.14. Because the basal areas grown in FVS matched the observed basal areas from the Duke Forest, the model was then calibrated, using the Site Tree site index, and a diameter growth modifier.

## Discussion

The purpose of this project was to calibrate FVS to the conditions on the Duke Forest, to enable the production of yield tables. This was done by testing two measures of site index, and finding that the better measure in producing realistic basal area estimates was the observed, Site Sree measure of site index, rather than the more readily available Web Soil Survey numbers. However, the model still did not accurately predict Duke Forest basal area estimates, despite the improved measure of site index. To remedy this shortcoming, a diameter growth modifier was applied to the site tree site index runs, and a DGM was customized to each bucket (each plot was assigned to one of three buckets depending on its site index: Low, Average, High). The resulting DGM, when applied, allowed FVS to predict basal areas that were the same as those grown on Duke Forest, on average. If the site index range of the buckets were smaller, then even more precise DGMs could be calculated.

## Assessment of Methodology

As discussed in the introduction, the calibration approach used in this study does not take the form of calibrations done in some other projects (Shaw, Vacchiano, DeRose, Brough, Kusbach, & Long, 2006). Instead of manipulating or recalibrating the FVS Southern variant’s internal sub-models, as Lacerte et al. (2006) did to the Lake States variant and as Russell et al. (2012) did to the Northeastern variant, this project used a site-specific estimate of site index and keyword modifiers to calibrate the Southern variant. Future resampling of the CFI plots will provide valuable data on the height and diameter growth increments of the Duke Forest. As that dataset expands, new methods of calibration will be possible. This project is a stop-gap measure to providing DF with a workable growth and yield model in the interim.

The FVS outputs for this project were individual tree basal areas, which were converted to volumes outside of FVS. Although FVS outputs stand volumes, in board feet or cubic feet, it has default merchantability specifications (e.g., minimum diameter determining merchantable height) and stem defect parameters. These parameters could be customized to the Duke Forest, but they would only be approximations of the actual merchantability of the stand. For this reason, the individual tree basal area outputs from FVS are converted to merchantable volumes in post-model processing with a Duke Forest-specific volume-to-basal-area coefficient (also known as a VBAR). *Forest Mensuration*, by Kershaw, Ducey, Beers, and Husch, states that as far back as 1897 VBAR was used to estimate stand volume, "Flury (1897) observed a correlation between average stand height and VBAR and developed a series of VBAR tables that could be used to estimate volume from estimates of stand basal area." VBAR is calculated as the ratio of observed merchantable volume in the Duke Forest to the observed basal area. Because observation of defect and how the stem of a given pine is merchandized can be so particular to the market, the logging crew, and to the buyer of the timber, the VBAR has an edge over FVS merchantability specifications or stem defect parameters in capturing the variance inherent to loblolly pine.

Despite the model that was calibrated in this project working well for use with a VBAR, there could be large distortions if the volumes were taken alone from FVS. A byproduct of the methods used in this project is that when a DGM value >1 is applied to a run, the Quadratic Mean Diameter (QMD) of the stand could be skewed very high, resulting in larger trees than would otherwise be the case. As long as the VBAR is in use, this effect is dampened, as the basal area informs the volume, not the QMD. In general, the methods used in this study depended on averaging and aggregating diverse stands and stand management histories. If there were more precise estimates of some parameters, the calibration effort could have been more finely tuned to realities of DF. One such parameter is stand age. Without precise ages for the plots, site index cannot be accurate, as age is a variable in the equation used to calculate site index. The site index was of particular importance for both the diameter and height growth increment calculations in FVS. If this project were repeated, it would make sense to aggregate the plots by their exact age, rather than 10-year strata. The aggregate stands also suffer from a lack of a true "average prescription". The timing of the management activities each plot actually received were highly variable and did not always occur when the stand reached the basal areas that triggered a thin in this project. Of the papers on calibration of FVS mentioned earlier, all of them had the benefit of studying undisturbed, unmanaged forest. Unfortunately, the pine core is managed by design, making calibration more difficult. Pinning down those prescriptions is of prime importance to a re-calibration effort.

## Next Steps

Despite the shortcomings of this calibration effort, it is still a simple and user-friendly way of producing realistic basal areas for the Duke Forest loblolly pine stands grown in FVS. Used in conjunction with an accurate volume to basal area coefficient, this method can be used to produce reasonably accurate yields for the DF pine core. Those yields can then be used as inputs in a yield optimizer that uses linear programing to produce a harvest schedule for the Duke Forest Management plan. Linear programing has been used to optimize forest management since the 1960s (McDill et al, 2016). Linear programming uses a computer to mathematically optimize a linear objective function that is bound by a series of constraints. Using a yield optimizer, it is possible to maximize variables such as the monetary value of the forest or harvest volumes all by manipulating treatments, and the timing of harvests. One such commercially available yield optimizer software is called Woodstock (Remsoft, https://remsoft.com/, Walters et al, 1999). Woodstock reduces the amount of manual data entry that would be necessary to solve a linear optimization problem using a spreadsheet program, and drastically reduces computation time. In practice, this allows more variables, constraints, and stands to be entered into the program, while achieving a more accurate and usable solution (McDill et al, 2016). My recommendation to the Duke Forest is that they consider using the yield tables produced in this study to run Woodstock to find an optimal harvesting schedule for their loblolly pine stands. This harvest schedule can then become a part of DF's management plan, and can be edited or re-run as their needs change over the years.

Moving forward, I recommend that the Duke Forest consolidate its records of each stand, to more precisely determine age and past management activities. If possible, stands may also be combined, if age, management history, and site index are sufficiently close. This will reduce administrative effort, and allow for less modeling effort. Additionally, adding more plots per stand reduces error in the model, and increase the accuracy of the estimated site tree height. This, in turn, will increase the accuracy of the site index, and therefore the accuracy of the diameter and height growth increments calculated in FVS. To improve the VBAR coefficients, I recommend that DF sell more of its stands in the “Pay-as-Cut” manner, rather than lump-sum. Observing the way the buyer merchandizes the stand, and receiving the load-tickets back from the logger, will provide DF with invaluable information of the true value of their timber, and how the logger ultimately sorts the stems as they are cut. This will provide DF with a more realistic value of their standing timber.

In conclusion, the CFI is vital to the improvement of the data used to feed FVS. As methods improve, plots are resampled, and records cohere, the CFI will represent a wealth of information that can be employed to re-calibrate FVS to the growing conditions inherent to the Duke Forest. Small tweaks to the site index and age estimates will result in even more accurate yields. In the meantime, these simple calibration methods, when produced in conjunction with VBAR eistimates, can provide Duke Forest managers with reasonably accurate yields. These volume yields can be used to produce a harvest schedule that can guide management actions until another set of yield tables can be produced using resampled CFI plots.

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