Comparing actual and predicted diameter growth on the Mescalero Apache Reservation in New Mexico using Continuous Forest Inventory Data

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Abstract

We compared predicted diameter growth rates from the Forest Vegetation Simulator with actual diameter growth rates to see if an adjustment was necessary. Our results provided such adjustments, if needed, and will allow the Bureau of Indian Affairs (BIA) to more accurately model expected volume and produce reasonable allowable annual cut timber sale amounts in managed stands for commercial species {(*Abies concolor* (white fir), *Pinus strobiformis* (southwestern white pine), *Pseudotsuga menziesii* (Douglas-fir), and *Pinus ponderosa* (ponderosa pine)}. The diameter growth difference was calculated from Continuous Forest Inventory (CFI) data from the Mescalero Apache Reservation in south-central New Mexico. Using diameter growth calculated from the 2002 and 2012 re-measurements, we compared non-calibrated FVS runs with statistically calibrated runs. We found 3 out of the 4 species had positive or negative bias from actual growth. Using the growth comparison results, we applied modifications to the diameter growth multiplier values in FVS, allowing for more accurate growth and yield predictions for the Mescalero Apache Reservation.

Introduction

Growth and Yield Models

Growth and yield modeling of forests involving computers is a relatively new practice to the field of forestry and has become essential to its study and progress (Botkin et al. 1972, Wykoff et al. 1982, Peng 2000). Models help forest managers predict the growth of individual trees and stands (Botkin et al. 1972, Wykoff 1990, Teck et al. 1996, Canavan 2000). Using variables and the effects of treatments on a resource, these models predict the outcome of various management-proposed scenarios (Botkin et al. 1972, Teck et al. 1996, Canavan 2000, Peng 2000). Land management agencies often use growth and yield models, such as the Forest Vegetation Simulator (FVS), to evaluate the influence of management objectives or disturbances on a chosen resource, while maintaining sustainable forestry practices (Wykoff et al. 1982, Teck et al.1996, Canavan 2000, Peng 2000, Dixon 2002). Land managers can use modeling software applications to predict and plan for various objectives of a specific resource including the ability to take into consideration the allowable annual cut (AAC - the quantity of timber that can be removed annually, while maintaining the ratio of total growth equal to or greater than amount removed) (Roise 2007, Forrest 2009). While using these models is an essential tool for land managers, if there is bias in the model or inaccuracies in a proposed simulation scenario, the predicted outputs can be unreliable, unsustainable, and inappropriate for the intended resource (Botkin et al. 1972, DeRose et al. 2010, Ex and Smith 2014).

Validation

Growth and yield models are built using inventory records and mathematical and statistical equations for specific species and locations (Botkin et al. 1972, Wykoff et al. 1982, Keyser and Dixon 2008, DeRose et al. 2010). Accuracy of the models is assessed through validation; a process which compares predictions to inventory data, establishing statistical confidence levels and reducing inaccuracy (Botkin et al. 1972, Wykoff et al.1982, Vanclay and Skosgaard 1997,Trasobares et al. 2004, Cawrse et al. 2010, DeRose et al. 2010).

Validating the growth parameters of FVS against permanent plots allows for modifications to increase the accuracy of estimates of both short and long-term yield (Botkin et al. 1972, Goulding 1979, Rykiel 1996, Cawrse et al. 2010, DeRose et al. 2010). The use of prediction error analysis projected into figures is used to illustrate the interaction between the model and the data (Mayer and Butler 1993, Cawrse et al. 2010, Ex and Smith 2014). This process illustrates errors between predicted and actual data, quantified using statistics such as bias and root mean square error (Mayer and Butler 1993, Cawrse et al. 2010, Ex and Smith 2014). These growth and yield models require continual validation with inventory data, to ensure accuracy and bias are acceptable and ensure appropriate results as model use changes (Trasobares et al. 2004, Walther and Moore 2005, Peng and Wen 2006, Cawrse et al. 2010, Ex and Smith 2014).

Bureau of Indian Affairs

The Bureau of Indian Affairs (BIA) is the agency under the Department of Interior providing services to Native Americans, including administration and management of land on Native American reservations. The forest management plans developed by the BIA require certain elements for approval, including AAC for any removal of timber resources (Forrest 2009). The management policy of AAC originates from the BIA's Regional Director's policy directive and is calculated from the Indicated Annual Cut, "calculation of expected annual harvest under the constraints of current management during a conversion period from the present to a regulated forest condition" (Forrest 2009). Recently, the BIA on the Mescalero Apache Reservation (MAR) in south-central New Mexico expressed concern about the lack of current FVS validation for the MAR. Error in FVS growth and yield predictions will create inaccuracies in setting the AAC for updated management plans being developed by the BIA.

Specifically, our objectives, using Continuous Forest Inventory (CFI) data from the MAR, were 1.) to compare predicted and actual growth rates for commercial tree species using FVS and 2.) to adjust FVS growth parameters as necessary (Wykoff 1990, DeRose et al. 2010). Our results will enable the BIA to more accurately model expected volume as well as set AAC for commercial species in managed stands, on both a tree- and stand-level (Trasobares et al. 2004).

Methods:

Study location and data

The MAR is located in south-central New Mexico between the Smokey Bear and Sacramento Ranger Districts of the Lincoln National Forest. The managed forest area on the reservation covers approximately 192,000 acres, and the elevation of the forest ranges from 6500 ft to 9000 ft (Hornsby 2011). Soils of the MAR include a sub-soil of silty clay loam, which transitions into cobbly clay loam for 20 to 40 inches until reaching fractured limestone bedrock (Maker et al. 1972). The local climate ranges from an average maximum temperature of 65.9 ºF to an average minimum temperature of 32.1 ºF. Average annual precipitation varies from about 15 inches at lower elevations to more than 32 inches at higher elevations with a majority of the precipitation happening June-August (Hornsby 2011).

The MAR collects forest inventory data regularly on a series of plots within the Continuous Forest Inventory (CFI) network (Forrest 2009). The CFI plots are permanent, located on a systematic grid, and measured once every 10 years (Forrest 2009). The data recorded for each tree (>4.9" diameter at breast height (DBH, 4.5 ft from base)) falling within the plot area includes: species, DBH, height, tree condition (live or dead), and regeneration abundance (Forrest 2009, Hornsby 2011). Plot-level site index was calculated using Minor (1964) (ponderosa pine) and Edminster (1991) (Douglas-fir) site index curves with a base age of 100-yrs. Accuracy of the plots is estimated at 5% sampling error (+/-1 standard deviation), which includes a 10% plot verification to ensure quality control (Forrest 2009). We used the complete CFI data of understory and overstory trees to accurately incorporate growth competition on the different sites, but only included outputs on the following commercial tree species: *Abies concolor* (white fir), *Pinus strobiformis* (southwestern white pine), *Pseudotsuga menziesii* (Douglas-fir), and *Pinus ponderosa* (ponderosa pine), greater than 4.9 inches DBH in our growth analysis. The BIA provided data for 153 of the 525 plots on the MAR. These specific plots were treated between the 1992 and 2002 measurement. The remaining 372 plots were either treated before or after that time period or are located in a different management strata, and thus not included in our analysis (Hornsby 2011). The 153 plots represented 10 different habitat types (Table 1).

Data Analysis:

Obj 1: Growth Comparisons

The main growth and yield component of FVS uses a combination of small and large tree height growth models (Stage 1973, 1975), mortality models (Hamilton and Edwards 1976), small tree growth, and large-tree diameter increment models (Wykoff 1983, Dixon 2002). Data input into the growth and yield model is specified under certain regional growth conditions called a "variant", which is a choice of 19 different regional growth conditions in the United States (Dixon 2002, Keyser and Dixon 2008). The variant used for this growth and yield simulation validation was the Central Rockies (CR) variant (Keyser and Dixon 2008), which uses GENGYM developed by Edminster et al. (1991) as a model for ponderosa pine and mixed conifer variable density stand projection in the Southwest.

We used data from the 10-yr plot re-measurements to compare change in individual-tree diameter growth. The 1992 re-measurement CFI data was used to establish 10-yr actual growth and scale growth predictions using the built -in calibration function in FVS. Calibration statistics modify predicted growth and are used to correct bias over large geographic areas (Dixon 2002). The output of calibration statistics is a scale factor (scaled from 0 - 2.6) of the model's growth by species (Dixon 2002). We ran FVS with and without built-in calibration statistics. We turned off the default mortality rates generated by FVS to ensure the comparison between diameter growth data was not confounded by predicted mortality. In addition, we turned off FVS' tripling feature which increases the number of trees to focus on the individual tree diameter growth comparison. We accepted default values for all other parameters. We used three diameter growth datasets to compare diameter growth differences. First, we ran FVS from the CFI data collected in 2002, for 10 years without calibration statistics. Second, we ran FVS using the 2002 CFI re-measurement data for 10 years, and used the built-in calibration function to generate growth scale factors. Third, the observed CFI diameter growth data from 2002 to 2012 was calculated to use as comparison for FVS growth predictions.

Using the FVS model validation protocols, we analyzed individual tree diameter growth using standard numerical and graphical procedures for each of the three growth comparisons described above (Walther and Moore 2005, Cawrse et al. 2010). First, we used a common numerical method, including calculating prediction error. We calculated the difference between individual tree diameter growth and predicted growth on the two model estimates using equation 1 (Walther and Moore 2005, Cawrse et al. 2010).

Eqn. 1: $\text{Error} = \text{DBH}_{\text{Predicted (2012)}} - \text{DBH}_{\text{Actual (2012)}}$

Positive error in individual tree growth output by FVS indicates an over prediction while negative error indicates under prediction. The individual tree error was used in the bias equation; the average deviation of repeated estimates from the true value (Walther and Moore 2005, Cawrse et al. 2010, equation 2).

Eqn. 2: $$\text{Bias} = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n}$$

where n= number of observations, yi = observed diameter growth, $\hat{y}i$ = predicted diameter growth of yi

Second, we developed figures to illustrate the bias in the individual tree errors across each species. In these figures, we examined box and whisker plots by 5 inch diameter classes. We then calculated relative error (Equation 3) to investigate the relationship of error across diameter classes within a species and determine whether error was within acceptable limits (+/- 5% relative error).

Eqn. 3 : $(\text{DBH}_{\text{Predicted (2012)}} - \text{DBH}_{\text{Actual (2012)}}) / \text{DBH}_{\text{Actual (2012)}}$

Obj 2: Growth Modifications

We implemented a diameter growth multiplier that scales the growth after model calculations, using boxplots and figures to illustrate the bias. "These multipliers are designed to simulate the effects such as silvicultural treatments or environmental changes that might be expected to affect a given stand" (Dixon 2002). We modified diameter growth multiplier values within 5-inch diameter classes by species to scale growth positively (>1) or negatively (<1) with 1 being the unmodified growth value to ensure fit and reduce bias within each species (Dixon 2002). The diameter growth multiplier values can range from 0.0 - 999.0 (Hamilton 1994, Dixon 2002). This modification is applied after species growth equations (diameter, height) in FVS's processing sequence, thus only affecting mortality rates (Dixon 2002). An increase or decrease of 0.1 of the diameter growth multiplier value changes predicted diameter growth by 10% (Dixon 2002). These analyses and modifications were then applied to non-calibrated and calibrated FVS runs. We used root mean square error (standard deviation of error, Equation 4) from individual tree error to determine the magnitude and accuracy of the difference of the error (Vanclay and Skosgaard 1997, Walther and Moore 2005, Cawrse et al. 2010).

Eqn. 4: $$\text{Root mean square error} = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}}$$

where n= number of observations, yi = observed variable, $\hat{y}i$ = predicted value of yi

Once these modifications were refined, an input file as shown in Appendix A, Table 1 (key component file (.kcp)), was created to enable MAR land managers to easily utilize the modified growth parameters in FVS. In addition, Pearson's correlation coefficient was used to measure linear correlation between error (for both FVS runs and actual diameter growth) and habitat type and site index.

Results

A variety of vegetation types and site conditions were represented across the MAR CFI plots (Table 1). The most common habitat types were white fir/Gambel oak (*Quercus gambelii*), Douglas-fir/Gambel oak, and Douglas-fir/wavyleaf oak (*Quercus undulata*) (Table 1). The site index also ranged widely, suggesting highly variable growth conditions (Table 1). The highest site index was the ponderosa pine/Gambel oak habitat type while the lowest was the white fir/Gambel oak type (Table 1). The highest 10-yr diameter growth average was in the white fir/Rocky Mountain maple type while the lowest 10-yr diameter growth average was in the ponderosa pine/wavyleaf oak (Table 1).

Table 1. Stand attributes and growth differences on 153 Continuous Forest Inventory (CFI) plots, Mescalero Apache Reservation, NM between habitat types. Means and standard error (in parentheses) are shown for each attribute. Mean diameter growth represents 2001-2012 CFI plot data. Site index range was included where possible.

Habitat Type	# of Plots	# of Trees	Site Index (mean)	Site Index (range)	Diameter Growth
white fir/Rocky Mountain maple	1	1	87	-	3.20
white fir/Gambel oak	29	369	78 (0.65)	54-133	1.50 (0.05)
white fir/bigtooth maple	1	13	57	-	1.50 (0.18)
white fir/New Mexican locust	1	3	82	-	1.40 (0.23)
ponderosa pine/blue grama	1	8	84	-	2.05 (0.35)
ponderosa pine/Gambel oak	6	59	105 (1.95)	85-119	1.75 (0.16)
ponderosa pine/wavyleaf oak	15	240	85 (0.7)	57-113	0.77 (0.03)
Douglas-fir/Gambel oak	75	744	73 (0.37)	48-106	1.29 (0.03)
Douglas-fir/mountain muhly	1	2	109	-	1.55 (1.15)
Douglas-fir/wavyleaf oak	23	196	65 (1.07)	40-132	1.20 (0.05)

**Abies concolor* (white fir), *Acer glabrum* (Rocky Mountain maple), *Quercus gambelii* (Gambel oak), *Acer grandidentatum* (bigtooth maple), *Pinus ponderosa* (ponderosa pine), *Bouteloua gracilis* (blue grama), *Robinia neomexicana* (New Mexican locust), *Pseudotsuga menziesii* (Douglas-fir), *Quercus undulata* (wavyleaf oak), *Muhlenbergia montana* (mountain muhly)

The highest 10-yr diameter growth average was in the white fir/Rocky Mountain maple habitat type while the lowest 10-yr diameter growth average was in the ponderosa pine/wavyleaf oak (Table 1). The highest growth rate for white fir was in the ponderosa pine/blue grama habitat type while the lowest was in Douglas-fir/Gambel oak (Table 2). The highest growth rate for southwestern white pine was in the white fir/Gambel oak habitat type (Table 2). The lowest growth rate for ponderosa pine was in the ponderosa pine/wavyleaf oak (Table 2). The highest growth rate for Douglas-fir was in the white fir/Rocky mountain maple habitat type (Table 2). The lowest growth for southwestern white pine, ponderosa pine, and Douglas-fir was in the Dougals-fir/wavyleaf oak (Table 2). There were only three habitat types that included all four commercial tree species: white fir/Gambel oak, Douglas-fir/Gambel oak, and Douglas-fir/wavyleaf.

Table 2. Ten-year Continuous Forest Inventory CFI (2002-2012) actual growth increment (mean and standard error (SE)) by species within 153 CFI plots, Mescalero Apache Reservation, NM (WF - white fir, SW - southwestern white pine, PP - ponderosa pine, DF - Douglas-fir)

Habitat Type	white fir		southwestern white pine		ponderosa pine		Douglas-fir	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
white fir/Rocky Mountain maple	-	-	-	-	-	-	3.2	-
white fir/Gambel oak	1.51	0.05	1.5	0.05	1.48	0.04	1.51	0.05
white fir/bigtooth maple	1.5	0.18	-	-	-	-	1.53	0.14
white fir/New Mexican locust	-	-	-	-	1.4	0.23	-	-
ponderosa pine/blue grama	2.17	0.38	-	-	-	-	2.2	0.48
ponderosa pine/Gambel oak	-	-	-	-	1.73	0.16	3.1	-
ponderosa pine/wavyleaf oak	-	-	-	-	0.80	0.03	-	-
Douglas-fir/Gambel oak	1.09	0.04	1.28	0.03	1.29	0.03	1.28	0.03
Douglas-fir/mountain muhly	-	-	-	-	-	-	1.55	1.15
Douglas-fir/wavyleaf oak	1.7	0.19	1.09	0.05	1.18	0.05	1.20	0.05

We found relatively little bias overall in both calibrated and non-calibrated FVS model output (Table 3). The calibration statistics reduced the overall bias slightly (Table 3). The RSME shows the standard deviation of errors at 0.83 for non-calibrated and 0.88 for calibrated model results (Table 3). The overall bias for non-calibrated FVS and calibrated FVS is relatively low (Table 3). Most of the species are under-predicting the growth (positive value) while ponderosa pine is actually over-predicting (negative value). Calibrated FVS runs resulted in less bias for all species except southwestern white pine (Table 3).

Table 3. Comparison of error in non-calibrated FVS runs and calibrated FVS runs without modified growth showing bias (inches), root mean square error (RSME) (inches), standard error (STDERR) (inches), and bias by species (inches).

	FVS Non-Calibrated		FVS Calibrated
BIAS	0.03	BIAS	-0.01
RSME	0.88	RSME	0.83
STDERR	0.02	STDERR	0.02
Bias By Species			
WF	0.97	WF	0.85
SW	0.43	SW	0.50
PP	-0.49	PP	-0.21
DF	0.18	DF	-0.04

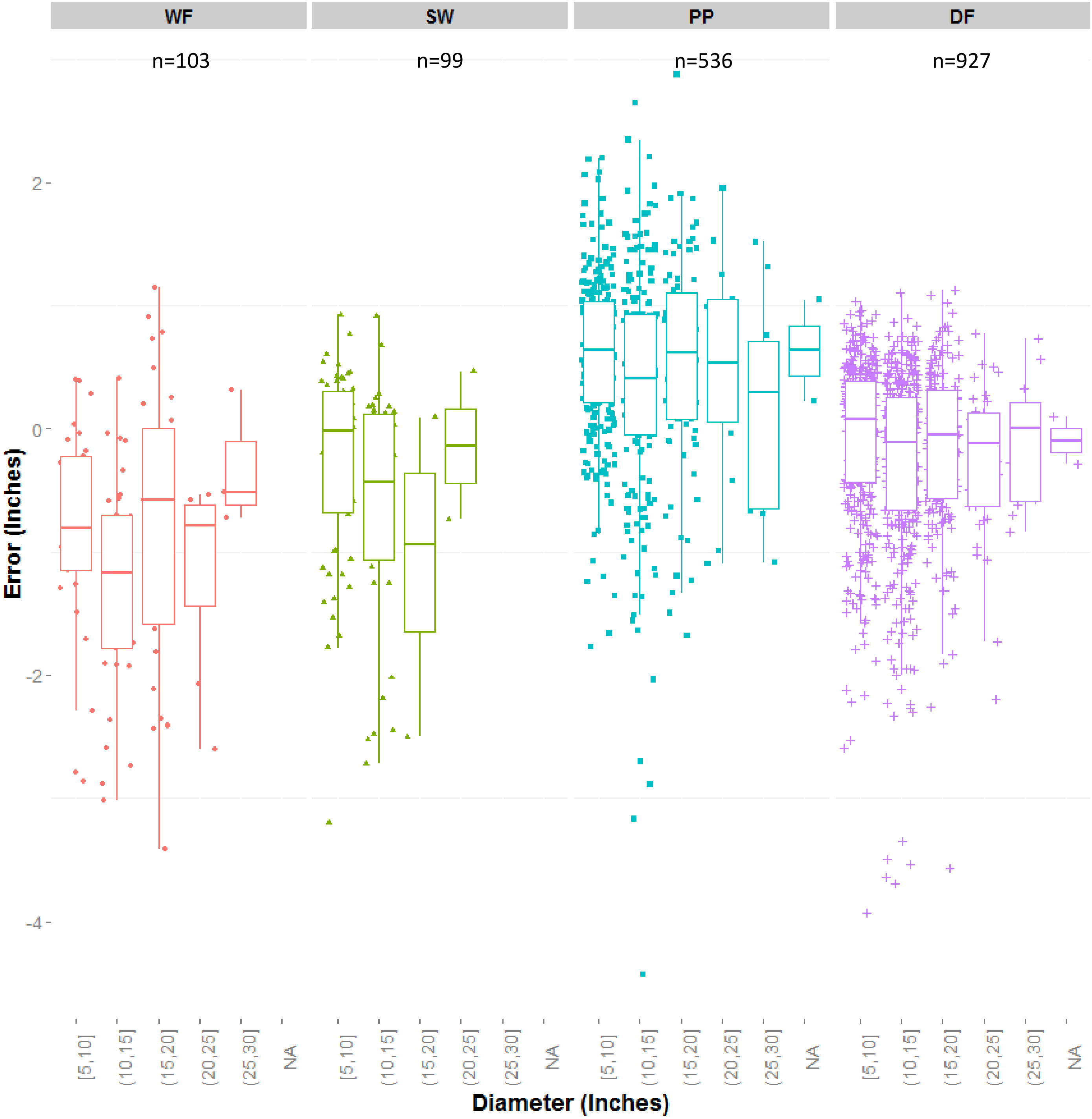

Figure 1. FVS non-calibrated diameter growth data error (inches) over diameter (5 inch diameter classes) without growth modifications. The center line on each boxplot describes median error (bias) while the boxplot breaks the data into quartiles indicating variability in each quartile (n=sample size). (WF - white fir, SW - southwestern white pine, PP - ponderosa pine, DF - Douglas-fir)

Figure 1 shows that both white fir and southwestern white pine error ranges between 1 and -3.5 error values with little to no grouping. In white fir and southwestern white pine, most of the error occurs in diameter values between 5-20" (Figure 1). Ponderosa pine and Douglas-fir both exhibit less variability and more symmetry of error compared to white fir and southwestern white pine. Most of the ponderosa pine error ranges between 2 and -2 inches of error, while a majority of error for Douglas-fir ranges between 1 and -2 inches of error.

Ponderosa pine diameter growth is over-predicted in non-calibrated and calibrated FVS runs (Table 3). In white fir and southwestern white pine the errors in calibrated runs are skewed toward negative bias but not as much as in the non-calibrated runs (Figure 1). Calibrated FVS output reduced bias in Douglas-fir and ponderosa pine while still over-predicted ponderosa pine growth (Figures 1 and 2)

There was a statistically significant correlation between error and habitat type (Pearson's correlation coefficient, $P < 0.05$) for FVS non-calibrated ($\rho = 0.22$), FVS calibrated ($\rho = 0.22$), and modified FVS calibrated ($\rho = 0.07$). Site index and growth error had no statistical siginificant correlation (Pearson's correlation coefficient, $P > 0.05$).

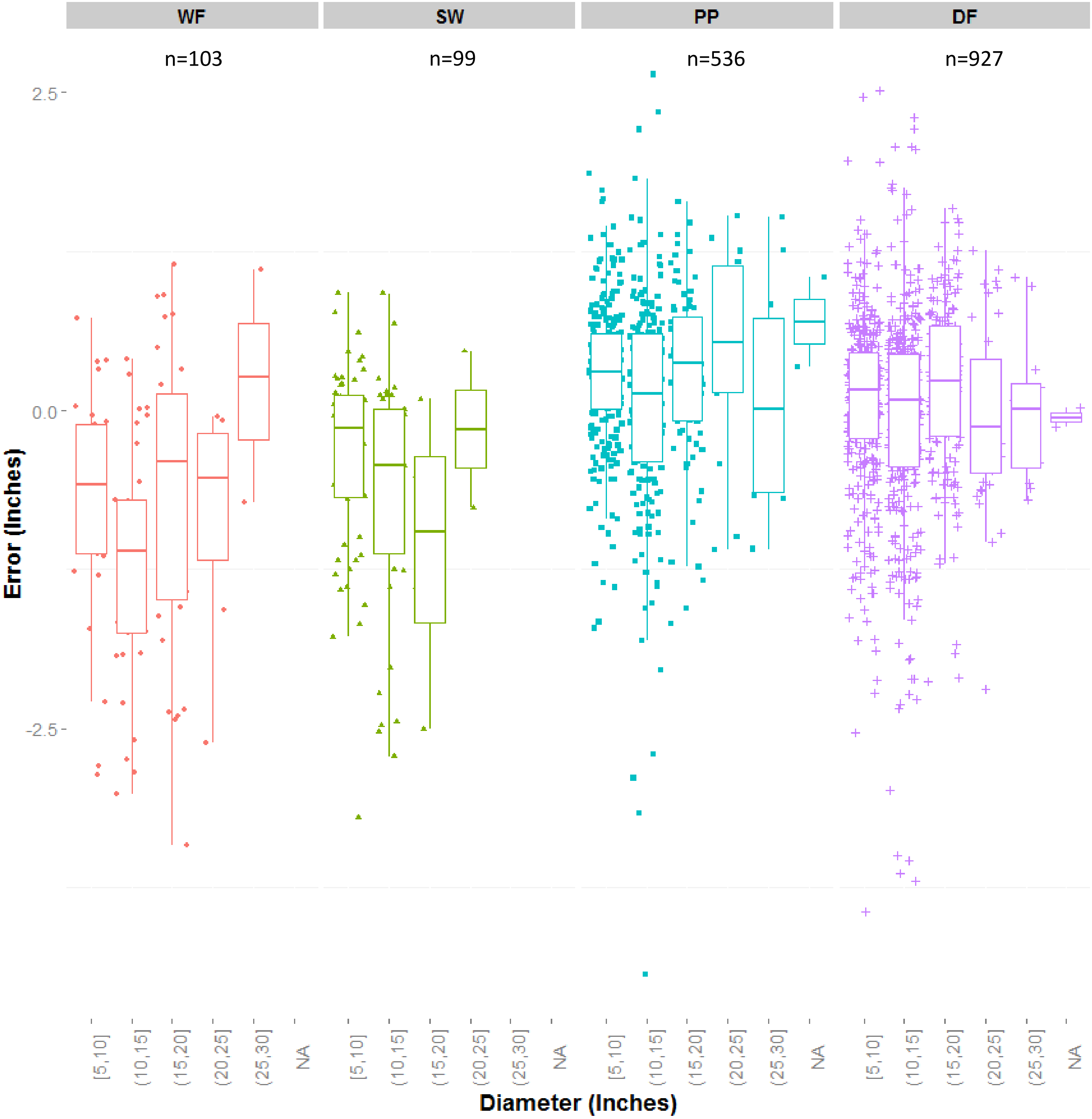

Figure 2. FVS calibrated diameter growth error (inches) over diameter (5-inch diameter classes) without growth modifications. The center line on each boxplot describes median error (bias) while the boxplot breaks the data into quartiles indicating variability in each quartile (n=sample size). (WF - white fir, SW - southwestern white pine, PP - ponderosa pine, DF - Douglas-fir)

Table 4. Mean relative error of non-calibrated FVS growth by 5 inch diameter class (D -Class) for all commercial timber species.

	white fir		southwestern white pine		ponderosa pine		Douglas-fir	
D - Class	Mean	SE	Mean	SE	Mean	SE	Mean	SE
5-10	-10%	2%	-3%	1%	8%	1%	0%	0%
10-15	-10%	1%	-5%	1%	3%	1%	-3%	0%
15-20	-5%	1%	-6%	3%	3%	1%	-1%	0%
20-25	-5%	2%	-1%	2%	2%	1%	-1%	0%
25-30	-2%	1%	-	-	1%	1%	0%	1%
30-35	-	-	-	-	2%	1%	0%	1%
Mean	-8%	1%	-4%	1%	5%	0%	-1%	0%

The relative percent error results showed similar trends of positive or negative skew away from zero in non- and calibrated FVS runs (Tables 4 and 5). We found most of the skew occured in the lower diameter classes (Figures 1 and 2), providing additional evidence that white fir and southwestern white pine are under-predicted, ponderosa pine is slightly over-predicted, and Douglas- fir is model accurately by FVS (Tables 4 and 5).The 5-inch diameter classes not within our acceptable range were white fir 5-15", southwestern white pine 15-20", and ponderosa pine 5-10" (Tables 4 and 5). FVS calibration stastistics actually increased the skew of the mean away from 0% in southwestern white pine for both the overall mean and within each diameter class (Table 5).

Table 5. Mean relative error of calibrated FVS growth by 5 inch diameter class (D -Class) for all commercial timber species.

	white fir		southwestern white pine		ponderosa pine		Douglas-fir	
D - Class	Mean	SE	Mean	SE	Mean	SE	Mean	SE
5-10	-9%	2%	-4%	1%	4%	0%	1%	0%
10-15	-10%	1%	-6%	1%	1%	1%	-1%	0%
15-20	-4%	1%	-6%	3%	2%	0%	1%	0%
20-25	-4%	2%	-1%	3%	2%	1%	0%	1%
25-30	0%	2%	-	-	0%	1%	0%	1%
30-35	-	-	-	-	2%	1%	0%	0%
Mean	-7%	1%	-5%	1%	2%	0%	0%	0%

Table 6. The diameter growth multiplier value (DGMV) by species and diameter class (D-class) (based on non-calibrated FVS growth data) (WF - white fir, SW - southwestern white pine, PP - ponderosa pine, DF - Douglas-fir).

	WF	**SW**	**PP**	**DF**
D-Class		**DGMV**		
5-10	1.80	1.00	0.58	0.9
10-15	2.65	1.83	0.80	1.19
15-20	1.35	2.1	0.50	1.0
20-25	5.20	1.12	0.6	1.18
25-30	0.60		1.08	0.98
30-35			0.1	1.05
Mean	2.32	1.51	0.61	1.05

We found the mean diameter growth multiplier values (DGMV) in non-calibrated FVS growth data were consistently higher values (0-5.2) to the calibrated FVS DGMV (Tables 6 and 7). Douglas-fir required almost no diameter growth multiplier adjustment (Table 6). Across all species the lower diameter classes had some of the highest variation in residual values while in the higher diameter classes the growth error was reduced in variation and bias (Table 6).

Table 7. The diameter growth multiplier value (DGMV) by species and diameter class (D-class) (based on calibrated FVS growth data) . (WF - white fir, SW - southwestern white pine, PP - ponderosa pine, DF - Douglas-fir).

	WF	**SW**	**PP**	**DF**
D-Class		**DGMV**		
5-10	1.67	1.2	0.7	0.85
10-15	2.6	1.95	0.98	0.95
15-20	1.08	2.23	0.65	0.75
20-25	1.27	1.18	0.48	1.25
25-30	0.85		1.25	1
30-35			1	1.05
Mean	1.49	1.64	0.84	0.98

Calibrated FVS runs required diameter growth modifiers closer to one (Table 7). However, the DGMV within ponderosa pine strays farther away from one as diameter class increases (Table 7).

Applying the DGMV corrected most bias across all species for both non-calibrated and calibrated FVS runs (Figures 3 and 4). Applying the DGMV to the calibrated FVS model resulted in unbiased growth predictions (Figure 4). The distribution of error within species was generally within 2 deviations (RSME) (Figures 3 and 4). We found the distribution of error patterns was similar between ponderosa pine and Douglas-fir while the pattern differed between but white fir and southwestern white pine (Figures 3 and 4). The 5-inch diameter classes in white fir (20-25, 25-30) had few data points leading to the large spread between few diameter growth error values (Figure 4).

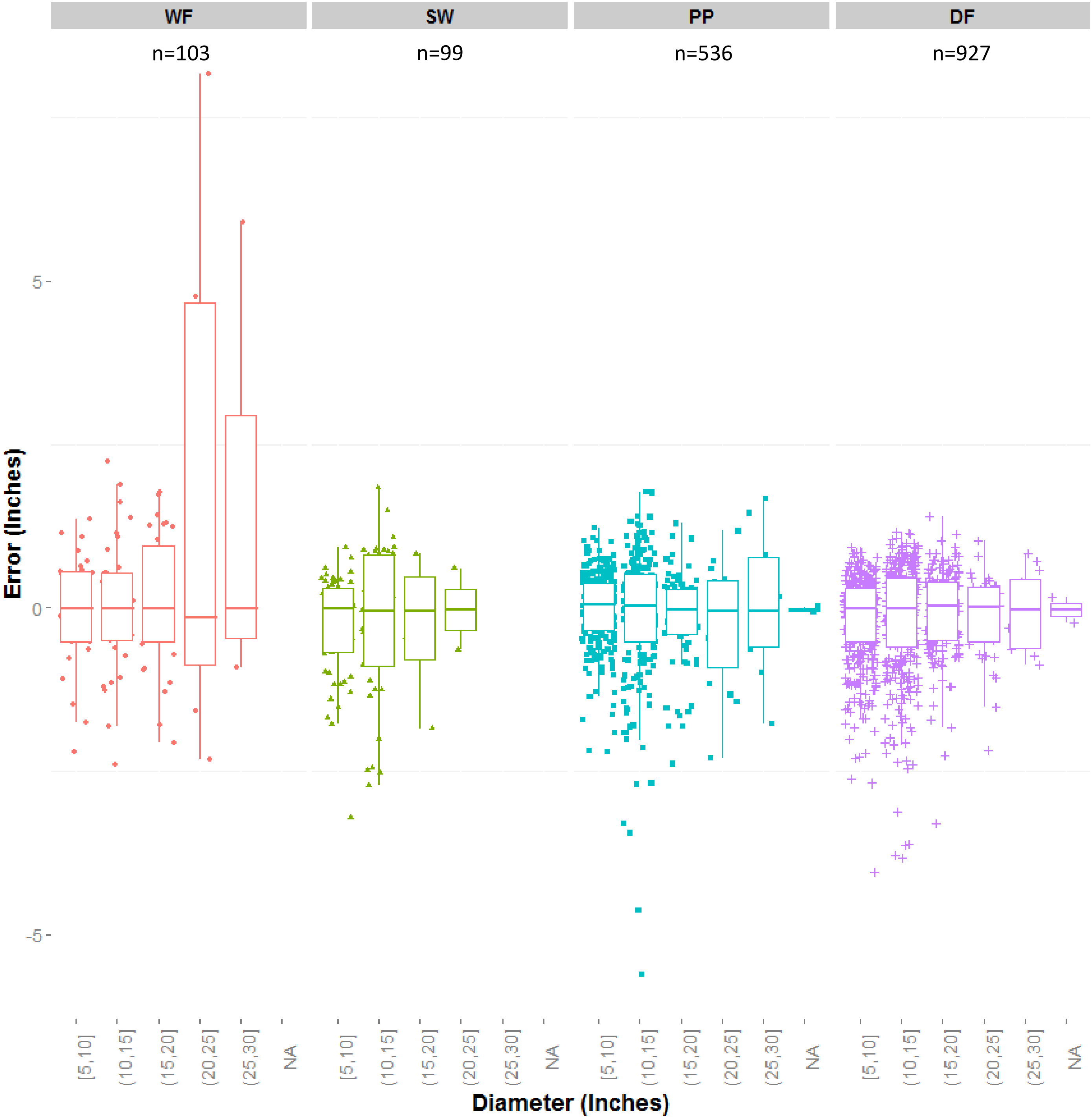

Figure 3. FVS non-calibrated diameter growth data error (inches) over diameter (5inch diameter classes) with growth modifications. The center line on each boxplot describes median error (bias) while the boxplot breaks the data into quartiles indicating variability in each quartile (n=sample size). (WF - white fir, SW - southwestern white pine, PP - ponderosa pine, DF - Douglas-fir)

The growth modifications completed for the FVS calibrated diameter growth created little to no bias within diameter classes and within species (Figure 4). The FVS calibrated growth was less biased than the non-calibrated results but both still required growth modifications (Figures 3 and 4).

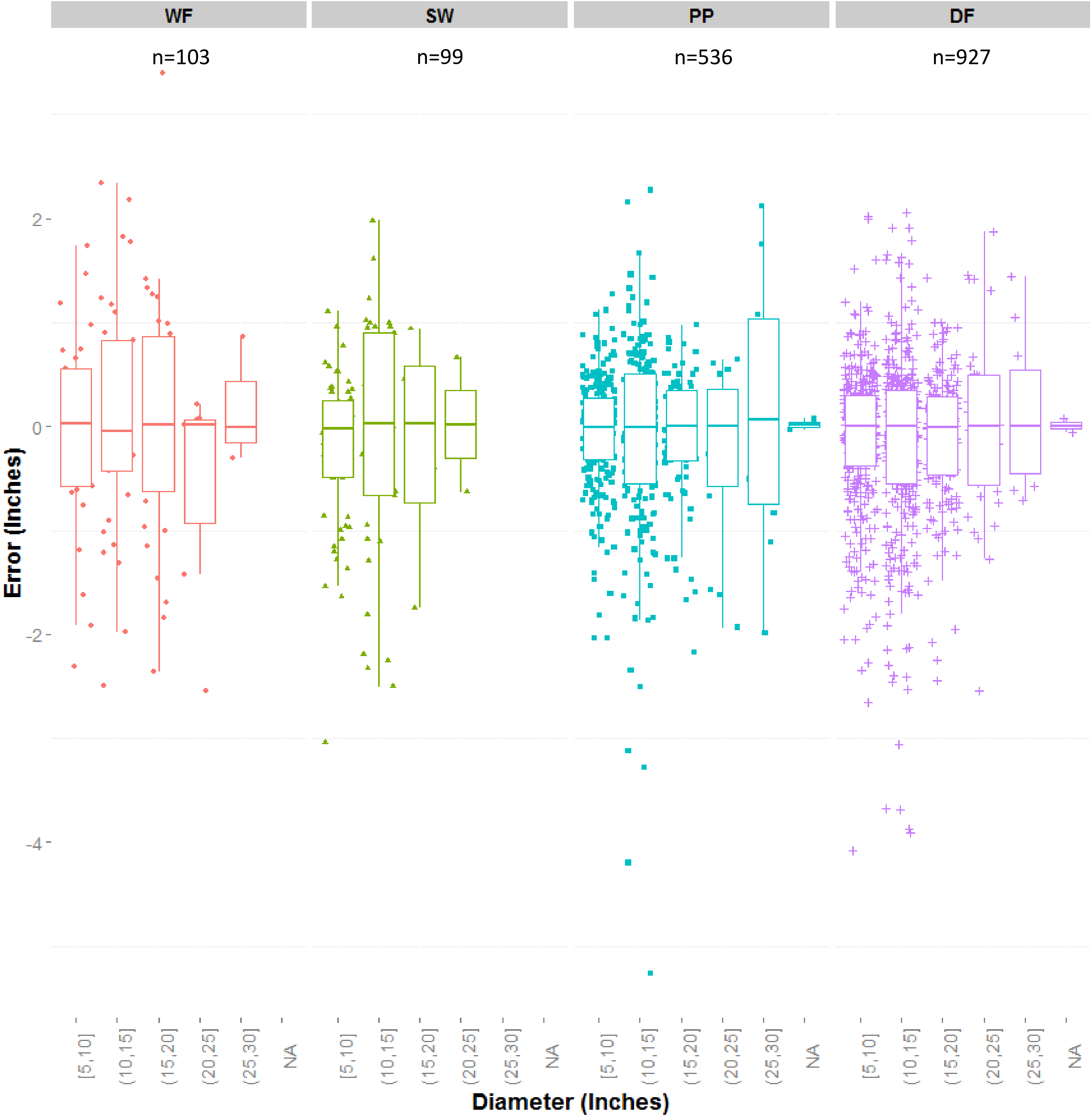

Figure 4. FVS calibrated diameter growth data error (inches) over diameter (5inch diameter classes) with growth modifications. The center line on each boxplot describes median error (bias) while the boxplot breaks

the data into quartiles indicating variability in each quartile (n=sample size). (WF - white fir, SW - southwestern white pine, PP - ponderosa pine, DF - Douglas-fir)

Table 6. Comparison of error in non-calibrated FVS runs and calibrated FVS runs with modified growth showing bias (inches), root mean square error (RSME) (inches), standard error (STDERR) (inches), and bias by species (inches).

	FVS Non-Calibrated		FVS Calibrated
BIAS	0.05	BIAS	0.06
RSME	1.24	RSME	1.24
STDERR	0.03	STDERR	0.03
BIAS by Species			
WF	0.05	WF	0.03
SW	-0.10	SW	-0.09
DF	0.07	DF	0.08
PP	0.04	PP	0.06

Bias was reduced in non-calibrated and calibrated values when using growth modifiers (Table 6). Using the calibrated FVS model with growth modifications reduced bias to very close to zero for all species (Table 6). The RSME for both modifications increased from the original RSME (from 0.83 non-calibrated and 0.88 calibrated to 1.24), while species' bias values ranged between -0.10 and 0.08 (Table 6). Overall, error was removed and evenly dispersed. Growth modifications by site index reduced the bias in each species (Figures 1-4 in Appendix A).

Discussion

We found little indication to support the hypothesis that FVS modeled growth was not accurate across all species; however, we did find variation within species. We achieved Objective 1 by analyzing the bias within species. The two species that had the highest bias were white fir and southwestern white pine. Previous literature from the Southwest suggests that ponderosa pine and Douglas-fir have been the focus of incremental diameter growth modeling, while the other species have been largely ignored (Edminster 1991, Dixon 2002, Williams et al. 2010). With time and additional growth data from species in the Southwest, managers should decide to recalibrate or use new species growth equations to more accurately predicted diameter growth. For Objective 2, we used a more simplistic solution, diameter growth multiplier values (DGMV) per 5 inch per species. The DGMV was used because of the number of Continuous Forest Inventory data collection periods (10 years) with complete data was not enough to calibrate the growth equations (Walther and Moore 2005). Based off of local land managers revising species growth equations, we estimate at least four periods depending on time scale would be required to make ensure variation in diameter growth was consistent (Petrova et al. 2014).

We found a typical amount of growth variation, as compared to that reported in the literature for the Southwest, across a large topographic range with several different habitat types and site indices (Wykoff 1990, Trasobares et al. 2004, Ex and Smith 2014). Understanding the site and how the species are responding is essential for any land manager (Stage 1973, Stage 1975, Wykoff 1990, Canavan 2000, Peng and Wen 2006, Ex and Smith 2014). While there was a significant relationship between error and habitat type, analyses of this relationship was limited by unequal sample sizes and further analysis is needed. However, it is likely that the many habitat types represented by a single plot affected the overall correlation. We suspect the uneven distribution of plot sample size within habitat types had a role in the correlation. With more data and equal sample sizes possibly habitat type could show statistically significance to determine which habitat type incurs the majority of the bias. We found no statistical significance between error and site index.

We found the highest amount of relative error within species in the smaller diameter classes was skewed positively or negatively from actual growth observation. This could be the growth and yield of smaller diameter classes has higher growth variation than larger diameter classes because of differing response to temporal variation of growing space (Lhotka and Loewenstein 2011, Petrova et al. 2014). Surprisingly, the percent error actually indicated calbration statistics helped each species except southwestern white pine. This could be from the lack of modeling or research of this species in the Southwest. It is also probably that there were an insufficient number of trees measured in both southwestern white pine and white fir to accurately model diameter growth in FVS. Originally, FVS was built with data from inventory data from the 1960's and 70's (Wykoff et al. 1982, Edminster et al. 1991 and Dixon 2002). The management objectives and sites' species composition, abundance, and density are quite different from current conditions (Wykoff et al. 1982, Edminster et al. 1991 and Dixon 2002). The use of growth equations from a different time period could have implications multiple species.

With time and additional CFI re-measurements, diameter growth multiplier values should be shifted into species growth equations (Wykoff 1990, Vanclay and Skosgaard 1997, Walther and Moore 2005, Peng and Wen 2006). We specifically looked at a ten-year time period, and without longer projections and more CFI data periods we cannot extrapolate growth rates (Walther and Moore 2005). With increased aridity and temperatures, equations might need revision across the Southwest (Seagar et al. 2007, Williams et al. 2010). We suggest continual monitoring will be essential for appropriate and sustainable land management into the future (Canavan 2000, DeRose et al. 2010, Williams et al. 2000, Ex and Smith 2014).

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Appendix A

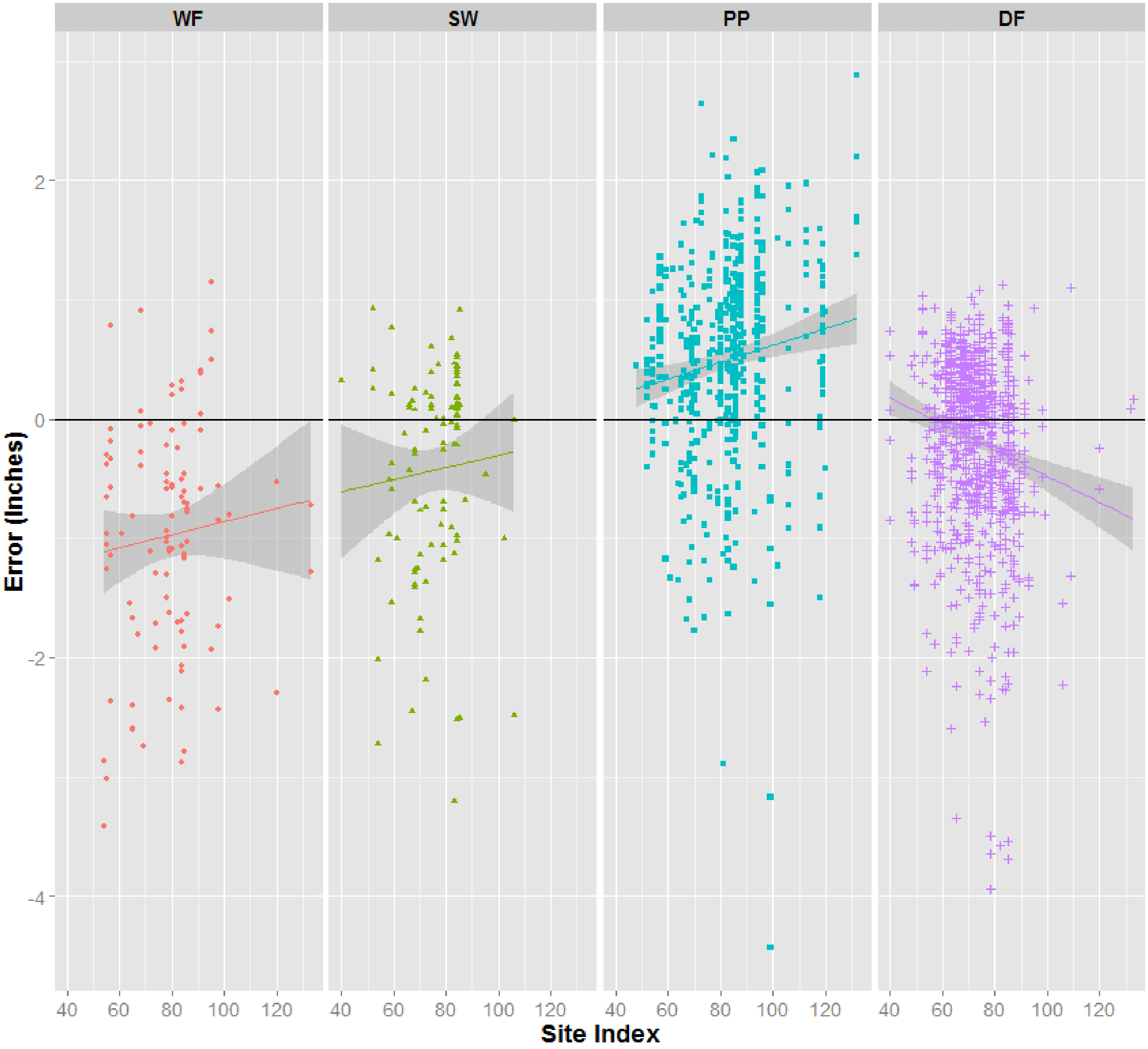


Figure 1. FVS non-calibrated growth data error (inches) over site index without growth modifications. The lines are lines of best fit; this line describes bias and the grey area around the line represent the 95% confidence interval. (WF - white fir, SW - southwestern white pine, PP - ponderosa pine, DF - Douglas-fir)

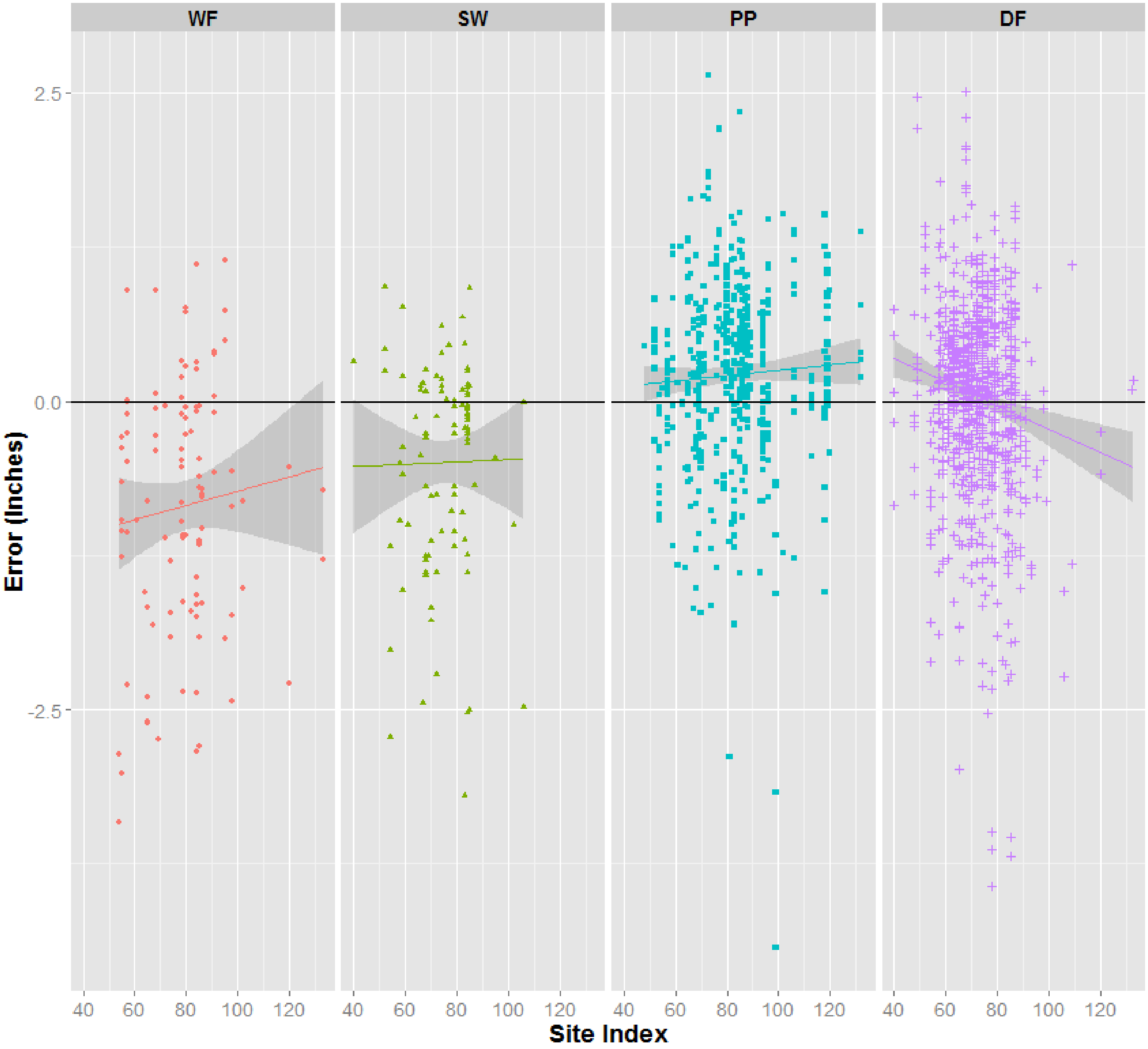


Figure 2. FVS calibrated growth data error (inches) over site index without growth modifications. The lines are lines of best fit; this line describes bias and the grey area around the line represent the 95% confidence interval. (WF - white fir, SW - southwestern white pine, PP - ponderosa pine, DF - Douglas-fir)

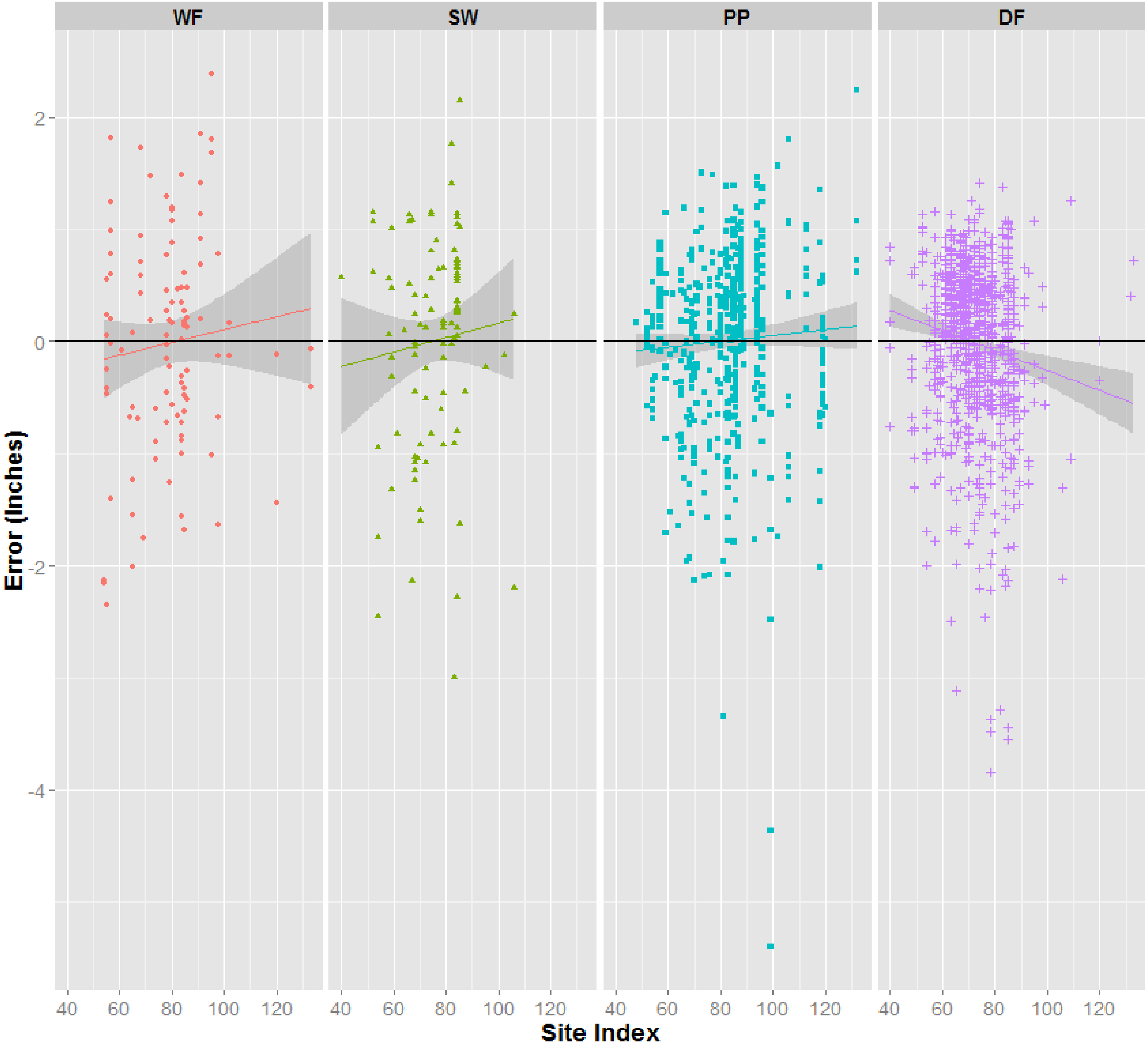


Figure 3. FVS non-calibrated growth data error (inches) over site index with growth modifications. The lines are lines of best fit; this line describes bias and the grey area around the line represent the 95% confidence interval. (WF - white fir, SW - southwestern white pine, PP - ponderosa pine, DF - Douglas-fir)

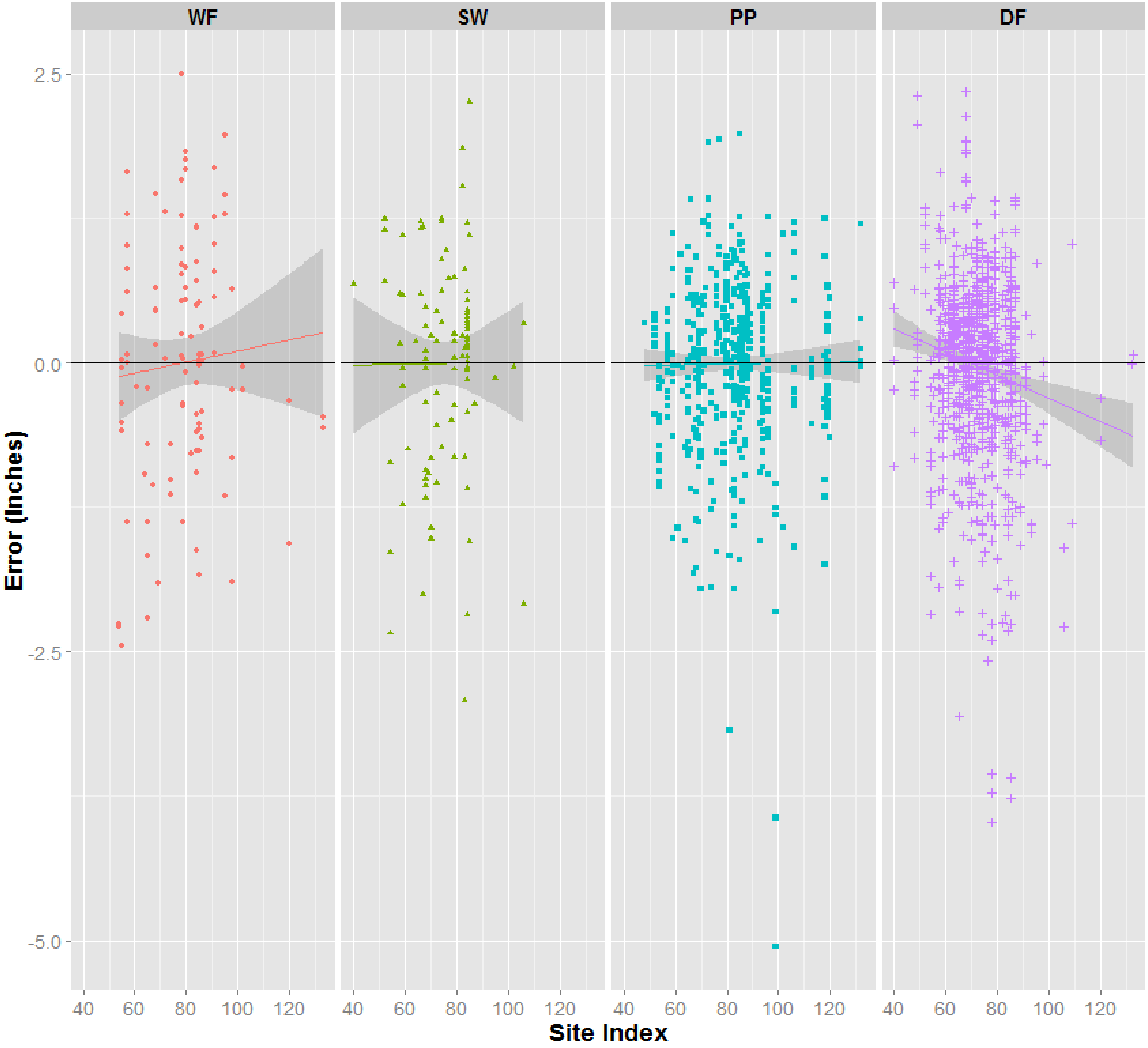
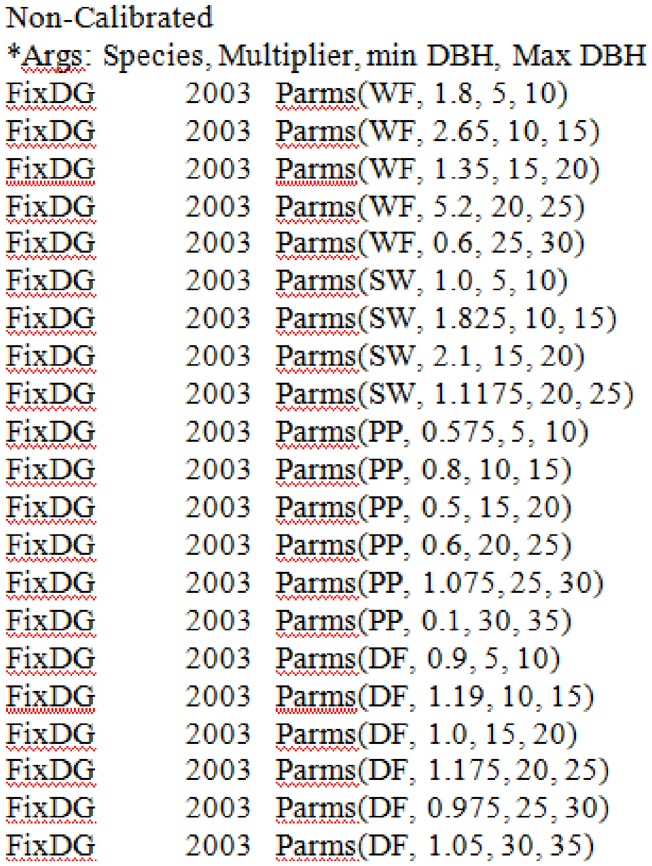


Figure 4. FVS calibrated growth data error (inches) over site index with growth modifications. The lines are lines of best fit; this line describes bias and the grey area around the line represent the 95% confidence interval. (WF - white fir, SW - southwestern white pine, PP - ponderosa pine, DF - Douglas-fir)

Table 1. Input file text (key component file (kcp)) for both non-calibrated runs (non-calibrated) and calibrated FVS runs (calibrated) using Diameter Growth Multiplier Value post processor (DGMV).



```
Non-Calibrated
*Args: Species, Multiplier, min DBH, Max DBH
FixDG        2003   Parms(WF, 1.8, 5, 10)
FixDG        2003   Parms(WF, 2.65, 10, 15)
FixDG        2003   Parms(WF, 1.35, 15, 20)
FixDG        2003   Parms(WF, 5.2, 20, 25)
FixDG        2003   Parms(WF, 0.6, 25, 30)
FixDG        2003   Parms(SW, 1.0, 5, 10)
FixDG        2003   Parms(SW, 1.825, 10, 15)
FixDG        2003   Parms(SW, 2.1, 15, 20)
FixDG        2003   Parms(SW, 1.1175, 20, 25)
FixDG        2003   Parms(PP, 0.575, 5, 10)
FixDG        2003   Parms(PP, 0.8, 10, 15)
FixDG        2003   Parms(PP, 0.5, 15, 20)
FixDG        2003   Parms(PP, 0.6, 20, 25)
FixDG        2003   Parms(PP, 1.075, 25, 30)
FixDG        2003   Parms(PP, 0.1, 30, 35)
FixDG        2003   Parms(DF, 0.9, 5, 10)
FixDG        2003   Parms(DF, 1.19, 10, 15)
FixDG        2003   Parms(DF, 1.0, 15, 20)
FixDG        2003   Parms(DF, 1.175, 20, 25)
FixDG        2003   Parms(DF, 0.975, 25, 30)
FixDG        2003   Parms(DF, 1.05, 30, 35)
```

Calibrated

```
*Args: Species, Multiplier, min DBH, Max DBH
FixDG         2003   Parms(WF, 1.665, 5, 10)
FixDG         2003   Parms(WF, 2.6, 10, 15)
FixDG         2003   Parms(WF, 1.075, 15, 20)
FixDG         2003   Parms(WF, 1.265, 20, 25)
FixDG         2003   Parms(WF, 0.85, 25, 30)
FixDG         2003   Parms(SW, 1.2, 5, 10)
FixDG         2003   Parms(SW, 1.95, 10, 15)
FixDG         2003   Parms(SW, 2.225, 15, 20)
FixDG         2003   Parms(SW, 1.175, 20, 25)
FixDG         2003   Parms(PP, 0.7, 5, 10)
FixDG         2003   Parms(PP, 0.975, 10, 15)
FixDG         2003   Parms(PP, 0.65, 15, 20)
FixDG         2003   Parms(PP, 0.475, 20, 25)
FixDG         2003   Parms(PP, 1.25, 25, 30)
FixDG         2003   Parms(PP, 0.15, 30, 35)
FixDG         2003   Parms(DF, 0.85, 5, 10)
FixDG         2003   Parms(DF, 0.95, 10, 15)
FixDG         2003   Parms(DF, 0.75, 15, 20)
FixDG         2003   Parms(DF, 1.25, 20, 25)
FixDG         2003   Parms(DF, 1.0, 25, 30)
FixDG         2003   Parms(DF, 1.05, 30, 35)
```