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This is the author's manuscript

Original Citation:

Availability:

This version is available http://hdl.handle.net/2318/1614159 since 2018-03-27T13:10:11Z

Published version:

DOI:10.5849/forsci.16-048

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19 April 2024

Projecting non-native Douglas fir plantations in Southern Europe with the Forest Vegetation Simulator

Abstract

In Italy, Douglas fir has a high potential in terms of wood production and drought tolerance. However, a growth reference for mature stands is lacking. We calibrated and validated the Pacific Northwest variant of FVS to Douglas fir plantations, and ran the calibrated model to test management alternatives. We calibrated the height-diameter, crown width, crown ratio, and diameter increment submodels of FVS using multipliers fitted against tree measurements (n =704) and increment cores (180) from 20 plots. Validation was carried out on tree-level variables sampled in 1996 and 2015 in two independent permanent plots (275 trees). Multiplier calibration improved the error of crown submodels by 7-19%; self-calibration of the diameter growth submodel produced scale factors of 1.0 – 5.2 for each site. Validation of 20-years simulations was more satisfactory for tree diameter (-6% to +1% mean percent error) than for height (-10% – +8%). Calibration reduced the error of predicted basal area and yield after 50 years relative to yield tables. Simulated response to thinning diverged depending on site index and competition intensity. FVS is a viable option to model the yield of Douglas fir plantations in Italy, reflecting current understanding of forest ecosystem dynamics and how they respond to management interventions.

Keywords: Empirical forest models; growth and yield; calibration; plantation management; *Pseudotsuga menziesii* (Mirb.) Franco

1 Introduction

Plantations are a resource with global importance for wood and pulp production (Forest Europe 2015). In Europe, Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) has been planted on a large scale and is now the most economically important exotic tree species (Schmid et al. 2014; Ducci 2015). Douglas fir has usually a high growth rate in comparison with other forest tree species in Europe, has a higher resistance to drought (Eilmann and Rigling 2012), and may provide high added-value timber (especially after the first thinning) (Monty et al. 2008). In Southern Europe, no indigenous conifer has similar characteristics of productivity and timber quality (Corona et al. 1998).

In Italy, Douglas fir was introduced in 1882 (Pucci 1882) using seeds from the Pacific Northwest Coast of the United States (Pavari and De Philippis 1941). Between 1922 and 1938, the "Stazione Sperimentale di Selvicoltura" established 98 experimental plantations (Pavari 1916; Pavari and De Philippis 1941; Nocentini 2010). These trials demonstrated that a variety of sites in central and northern Italy was suitable for the species (Pavari 1958). Nowadays, Douglas fir plantations cover an area of about 0,8 million ha in Europe (Forest Europe 2015). In Tuscany (Central Italy), Douglas fir covers 3,360 hectares in pure stands and 2,112 hectares in mixed stands (Regional Forest Inventory of Tuscany 1998).

The key to successful management of productive Douglas fir plantations is a proper understanding of growth dynamics in relation to tree characteristics, stand structure, and environmental variables. The productivity of Douglas fir stands in Italy was studied by Pavari and De Philippis (1941) and, distinctly, by Cantiani (1965) who established a yield table for stands up to 50 years old, based on 115 plots of different ages.

Growth and yield models simulate forest dynamics through time (i.e., growth, mortality, regeneration). They are widely used in forest management because of their ability to support the updating of inventories, predict future yield, and support the assessment of management alternatives and silvicultural options, thus providing information for decision-making (Vanclay 1994). Much research has been carried out to model the growth of Douglas fir throughout its home range (Newnham and Smith 1964; Arney 1972; Mitchell 1975; Curtis et al. 1981; Wykoff et al. 1982; Wykoff 1986; Ottorini 1991; Wimberly and Bare 1996; Hann and Hanus 2002; Hann et al. 2003). In Italy, a growth reference for Douglas fir stands older than 50 years is currently lacking. Here, we propose the use of Forest Vegetation Simulator (FVS) to simulate the growth of such stands.

FVS is an empirical, individual tree, distance-independent growth and yield model originally developed in the Inland Empire area of Idaho and Montana (Stage 1973). FVS can simulate many forest types and stand structures ranging from even-aged to uneven-aged, and single to mixed species in single to multi-story canopies. There are more than 20 geographical variants of FVS, each with its own parameterization of tree growth and mortality equations for a particular geographic area of the United States. In addition, FVS incorporates extensions that can simulate pest and disease impacts, fire effects, fuel loading and regeneration (Crookston 2005).

FVS has been rarely used in Italy (Vacchiano et al. 2014). The aims of this work are: (1) calibrating and validating the Pacific Northwest Coast variant of FVS to Douglas fir plantations in Italy, (2) comparing predictions from the calibrated model against available yield tables for Douglas fir in Italy, and (3) using the calibrated model to test silvicultural alternatives for Douglas fir plantation management.

2 Materials

Data for this work were measured in 20 stands of Douglas fir planted between 1927 and 1942 over a 2000 km^2 wide area in the northern Apennines, mostly within and nearby Tuscany region (Figure 1), at elevations ranging between 770 and 1260 m a.s.l. For each stand, Table 1 reports climatic data derived from ClimateEU (Hamann et al. 2013) and Ecopedological Units (EU) from the

Ecopedological Map of Italy (Costantini et al. 2012). For each stand Table 2 reports aspect, slope, and site index, i.e. the top height at 50 years assessed according to Maetzke and Nocentini (1994).

Tree measurements were carried out in a 20-m radius circular plot located at the center of each sampled stand, except Pietracamela that had a radius of 10 m. For each living tree (for a total of 704 trees) we measured: stem diameter at 130 cm height (DBH), total height (HT), crown length (CL), and crown width (CW) as the average of two orthogonal crown diameters. From a sub-sample of 8-10 trees per plot, we extracted an increment core at 130 cm above the ground. Tree cores were prepared for measurement in the lab and analyzed with LINTAB and TSAP-WIN software; from each core (for a total of 180 cores) we measured the radial increment from the last 10 annual rings to the nearest 0.01 mm.

3 Calibration

In order to adjust FVS to local growing conditions, the model components (hereafter "submodels") need to undergo calibration against observed data. FVS submodels include height-diameter equations, crown width equations, crown ratio equations, tree diameter growth equations, tree height growth equations, mortality equations, and bark ratio equations. Due to the lack of repeated field measurements, this paper focuses on the first four submodels, leaving the others unchanged.
Since the considered populations of Douglas fir come from the Pacific Northwest coast of the United States (Pavari and De Philippis 1941), the Pacific Northwest (PN) variant of FVS (Keyser 2014) was used as a basis for model calibration and runs. The original range considered by this variant covers from a line between Coos Bay and Roseburg, Oregon in the south to the northern shore of the Olympic Peninsula in Washington, and from the Pacific coast to the eastern slope of the Coast Range and Olympic Mountains (Keyser 2014).

FVS includes two options to calibrate model performance to local growing conditions (Dixon 2002): (i) automatic scaling by the model, and (ii) user-defined multipliers of model output entered by the user by specific input scripts or “keywords” (Van Dyck and Smith-Mateja 2000). For the height-diameter and large tree diameter growth submodels we analyzed the performance of automatic calibration, while for crown width and crown ratio submodels we fitted user-defined multipliers. The following paragraphs illustrate, for each of the four submodels, the adopted calibration strategy and its results.

All the variables in the FVS equations are expressed in imperial units; conversion to and from the metric system was carried out outside the calibration algorithms. The simulation cycle is 10 years.

To check whether each submodel needed calibration, we fitted FVS submodels to the observed data and computed 95% confidence intervals for all regression coefficients. If default FVS coefficients were outside of locally-calibrated confidence intervals, model adjustment was deemed necessary. Additionally, we compared the fit of non-calibrated versus calibrated submodels against observed data, using coefficient of determination (R^2), root mean square error (RMSE), mean bias (MBE), mean absolute bias (MABE) and mean percent bias (MPE) as goodness-of-fit metrics (Rehman 1999).

3.1 Height-Diameter submodel

Height-Diameter relationships in FVS are used to estimate missing tree heights in the input data. By default, the PN variant uses the Curtis-Arney functional form as shown in Equation [1] (Arney 1985; Curtis 1967). Height-Diameter submodel (HT) uses an internal self-calibration method; if users don’t provide all stem heights, but more than three, the height-diameter equation is calibrated.

$$HT = 4.5 + p2 * \exp(-p3 * DBH^{p4}) \quad [1]$$

where p_2-p_4 are species-specific parameters (default values for the PN variant: p_2=407.1595; p_3=7.2885; p_4=-0.5908).
When fitted against observed tree heights from all the plots here considered, Equation (1) had two parameters whose confidence intervals did not include the FVS default values (Table 3): submodel adjustment was therefore needed.

The fit of the uncalibrated submodel against observations (Figure 2) produced a R^2 of 0.6 and MPE equal to 1.18%, corresponding to MBE equal to 33 cm and RMSE of 4.86 m. The new coefficients (p_2-p_4) were calculated by nonlinear regression: p_2 =199.4300348, p_3 =8.9860045, p_4 =-0.9680623. The calibrated HT submodel produced an MBE equal to -0.3 cm and an RMSE of 4.16 m.

3.2 Crown width submodel

In PN-FVS, crown width (CW) is computed as a function of tree and stand characteristics (Equation 2: Crookston 2005) and bound to <=24 m:

$$CW = (a1 * BF) * DBH^{a2} * HT^{a3} * CL^{a4} * (BA + 1.0)^{a5} * (\exp(EL))^{a6} \text{ []}$$

where BF is a species- and location-based coefficient (default *BF* for Douglas fir= 0.977), BA is stand basal area, EL is stand elevation in hundreds of feet, and a1–a6 are species-specific parameters (a_1=6.02270; a_2= 0.54361; a_3= -0.20669; a_4= 0.20395; a_5=-0.00644; a_6=-0.00378). When Equation [2] was fitted against observed data, only two parameters were inside the 95% confidence intervals of the uncalibrated equation (Table 3): submodel adjustment was therefore needed.
To this end, we used the CWEQN keyword that allows to enter user-defined coefficients for a new species-specific crown width model (Equation 3):

$$CW = s0 + (s1 * DBH) + (s2 * DBH^{s3}) \ [3]$$

where the coefficients s_0 - s_3 were determined by nonlinear regression: s_0=6.701, s_1=0, s_2=0.111, s_3=1.502. Calibration improved model fit: MPE decreased from 31% to 12%, MBE from 83 cm to 0.2 cm and RMSE from 2.12 m to 1.87 m.

3.3 Crown ratio submodel

Crown ratio (CR), i.e. the ratio of crown length to total tree height, is a commonly used predictor of diameter increment both in United States (Wykoff 1990) and Europe (Monserud and Sterba 1996). It is an indicator of the joint effects of stand density, tree size and vigor, and social position of each tree in the stand. Crown ratio equations are used for three purposes by FVS: (i) to estimate tree crown ratios missing from the input data for both live and dead trees; (ii) to estimate change in crown ratio for each simulated cycle for live trees; and (iii) to estimate initial crown ratios for regenerating trees established during a simulation (Keyser 2014).

PN-FVS uses a Weibull-based model to predict crown ratio for all live trees with DBH >2.5 cm (Dixon 1985). First, the average stand crown ratio (ACR) on a 1-100 scale is estimated as a function of stand density (Equation 4: Johnson and Kotz 1995):

$$ACR = d0 + d1 * RELSDI * 100 \ [4]$$

where d_0 - d_1 are species-specific coefficients (d_0 =5.666442; d_1=-0.025199) and RELSDI = relative Stand Density Index, i.e., the ratio between measured (SDI) and species-specific maximum SDI (SDImax). SDI is a measure of relative density based on the self-thinning rule (Yoda et al. 1963) i.e., the inverse relationship between the number of plants per unit of area and the mean size of the individuals (Comeau et al. 2010; Pretzsch and Biber 2005; Shaw 2006; Vacchiano et al. 2005). SDI (Reineke 1933) is calculated according to Equation (5):

$$SDI = TPA\left(\frac{Qmd}{25}\right)^{1.605} [5]$$

where TPA is the number of trees per acre. Maximum SDI is provided as species-specific default (SDImax for Douglas fir = 950). Maximum SDI also controls FVS mortality equations; by default, density related mortality begins at RELSDI =55% (Dixon 1986).

ACR is then used to estimate the parameters A, B, and C of the Weibull distribution of individual CRs (Equations 6-10):

$$A = A0\ [6]$$

$$B = B0 + B1 * ACR\ (bound\ to\ B > 3)\ [7]$$

$$C = C0 + C1 * ACR\ (bound\ to\ C > 2)\ [8]$$

$$SCALE = 1 - \big(0.00167 + (CCF - 100)\big)\ [9]$$

$$CR = A + B * \left(\left(-\log\left(1 - \left(SCALE * \frac{RANK}{N}\right)\right)\right)^{1/C}\right)\ [10]$$

where a_0, b_0 - b_1, c_0 - c_1 are species-specific coefficients (Keyser 2014) (a_0=0; b_0=-0.012061; b_1=1.119712; c_0=3.2126; c_1=0), N is the number of trees in the stand, RANK is a tree's rank in the stand DBH distribution (1 = the smallest; N = the largest), SCALE is a density-dependent scaling factor (Siipilehto et al. 2007) bound to 0.3 < SCALE < 1.0, and CCF is stand crown competition factor (Krajicek et al. 1961), computed as the summation of individual CCF (CCF_t) from trees with DBH > 2.5 cm (Equation 11: Paine and Hann 1982).

$$CCFt = r1 + (r2 * DBH) + (r3 * DBH^2) \ [11]$$

where $r_1 - r_3$ are species-specific coefficients (r_1=0.0387616; r_2=0.0268821; r_3=0.00466086).

When fitted against observed data, confidence interval of Equation [10] included the PN-FVS default values only in one case (Table 3), therefore calibration was needed.

The fit of the uncalibrated crown ratio model against observed data was very poor (R^2 = 0.08, MPE = 14%, MBE = -2.64 m, RSME = 4.47 m).

Crown ratio calibration was attained by a keyword (CRNMULT) that multiplies simulated crown ratios by a specified proportion (Hamilton 1994). The value of CRNMULT (=1.22) was determined by nonlinear regression using observed CR as dependent variable and the independent variables from Equations [4]-[10].

CRNMULT improved the fit of the CR submodel: R^2 from 0.08 to 0.91, MPE from -14.02% to 5.13%, MBE from -2.64 to -0.49 m and RMSE from 4.47 to 3.89 m.

3.4 Large Tree Diameter Growth submodel

The large (DBH > 7.62 cm) tree diameter growth model used in most FVS variants predicts the natural logarithm of the periodic change in squared inside-bark diameter (ln(*DDS*)) (Equation 12: Stage 1973) as a function of tree, stand and site characteristics:

$$\ln(DDS) = b1 + (b2 * EL) + (b3 * EL^2) + (b4 * \ln(SI)) + (b5 * \sin(ASP) * SL) + (b6 * \cos(ASP) * SL) + (b7 * SL) + (b8 * SL^2) + (b9 * \ln(DBH)) + (b10 * CR) + (b11 * CR^2) + (b12 * DBH^2) + \left(b13 * \frac{BAL}{\ln(DBH + 1.0)}\right) + (b14 * CCF) + (b15 * RELHT) + (b16 * \ln(BA)) + (b17 * BAL) + (b18 * BA) \quad [12]$$

where BAL is total basal area in trees larger than the subject tree, RELHT is tree height divided by the average height of the 40 largest diameter trees in the stand, b1 is a location-specific coefficient that defaults to -0.1992, and b2-b18 are species-specific coefficients (b_2=-0.009845; b_3=0; b_4=0.495162; b_5=0.003263; b_6=0.014165; b_7=-0.340401; b_8=0; b_9=0.802905; b_{10}=1.936912; b_{11}=0; b_{12}=-0.0000641; b_{13}=-0.001827; b_{14}=0; b_{15}=0; b_{16}=-0.129474; b_{17}=-0.001689; b_{18}=0) (Keyser 2014).

When fitted against the observations, confidence interval analysis showed that only two parameters of Equation [12] were inside the 95% confidence intervals of the uncalibrated equation (Table 3), therefore the model needed calibration. This was attained by enabling self-adjustment of growth predictions by scale factor calculation.

When five or more observations of periodic increment for a species are provided for a plot, FVS can adjust the increment models to reflect local conditions (Stage 1981). This automatic calibration computes a species-specific scale factor that is used as a multiplier to the base growth equations, bound to a range of 0.08-12.18, and applied at the plot level. The scale factors are attenuated over time. The attenuation is asymptotic to one-half the difference between the initial scale factor value and one. The rate of attenuation is dependent only on time, and has a half-life of 25 year (Dixon 2002).

In order to check for bias, we disabled the self-calibration and randomization algorithms of the large tree diameter growth model using the NOCALIB and NOTRIPLE keywords, and scrutinized scale factors for ln(*DDS*) automatically calculated against observed periodic increments.

These scale factors ranged from 1 to over 5, showing a large variety of growing conditions unaccounted for by the default growth equation (Table 4). The high heterogeneity of growth is also shown by the ratio of the standard deviation of the residuals for the growth sample to the model standard error, which is consistently higher than 1.0. Bayes weights (Krutchkoff 1972) are an expression of confidence that the growth sample represents a different population than does the original data used to fit the model (in this case, PN-FVS data). In other words, a value of 0.90 would indicate a 90% certainty that the growth sample represents a different population than the database used to fit the model (Dixon 2002).

4 Model validation

We used independent datasets from two of the oldest permanent plots in Italy (Mercurella: 85 years, 39,336°N, 16,081°E; Vallombrosa: 90 years, 43,749°N, 11,577°E) to validate the calibrated PN-FVS for a total of 275 trees. Using the the TIMEINT keyword, we ran a simulation from 1996 to 2015 with a cycle length of 5 years. We compared predicted vs. observed DBH and height (Mercurella: year 2012, Vallombrosa: year 2015). Initial stem heights in Mercurella (1996) were calculated with Curtis-Arney function (Curtis 1967). The value of R^2 between predicted and observed data for DBH was high in both sites (Table 5), especially for Vallombrosa (0.96), while R^2 for height was lower (0.54 in Mercurella and 0.72 in Vallombrosa).

5 Comparison with yield tables

We ran the locally-calibrated PN variant of FVS 50 years into the future using site characteristics referred to the measured 20 plots and starting from bare ground. Initial plantation density was set at 2745 trees per hectare, i.e. similar to the initial density of the yield table by Cantiani (1965), using the PLANT keyword. We instructed FVS to reproduce the same treatments prescribed by the Cantiani yield table, by using the THINBTA keyword (Thinning from below to trees per acre target); thinnings were scheduled after 20 years (20% basal area removal), 30 years (30% removal), 40 years (25% removal), and 50 years (25% removal). We compared basal area simulated by the uncalibrated and calibrated PN-FVS (mean across all stands) against the Cantiani yield table.

In all stands, simulated basal area was higher than the one predicted by the yield table with a MBE 9.23 m^2 ha^{-1}, RMSE 13.05 m^2 ha^{-1}, and MPE 26%.

Calibration reduced the difference between the Cantiani yield table established for Douglas fir plantations in Tuscany and simulated mean basal area (Figure 3) and volume (Figure 4) across all stands.

6 Model runs and management options

Finally, in order to evaluate management alternatives for mature Douglas fir plantations in Italy, we used the calibrated PN-FVS to simulate the results of thinning in two plots with comparable site index but different competition intensity. SDI controls FVS mortality model, and density related mortality begins when the stand SDI is above 55% of SDImax (Dixon 1986). We chose plots Acquerino58 (relative SDI 60.94%, Site index 31m) and Campamoli (relative SDI 48.15%, Site index 37 m) as test sites with similar fertility but different competition intensity. Data from both stands were run for 50 years into the future, starting from year 2013, and prescribing a thinning from below at the beginning of the simulation using the THINBTA keyword with three different management choices (type A 10%, type B 30%, type C control = no thinning).

Simulation results diverged depending on site index and current competition intensity. For all thinning regimes, both basal area and volume increased linearly in the low-competition stand (Campamoli: relative SDI =48%). In the high competition stand (Acquerino58: relative SDI = 60%) basal area decreased under the no thinning and 10% thinning regimes because of high competition mortality (Figure 5).

7 Discussion

FVS can be calibrated by self-calibration (e.g., the height-diameter and large tree diameter growth) or growth multipliers (e.g., crown width and crown ratio submodels). These multipliers allow the user to simulate growth patterns outside the region of first model calibration, i.e., in the presence of growth bias for any given species, geographic area, site, or forest type (Dixon 2002).

Height-Diameter self-calibration reduced from of 0.328 to -0.003 m, indicating that the functional form of this allometric equation is adequate to represent dimensional relationships of Douglas fir outside of its native range. A slightly different approach was followed to calibrate the crown width submodel, i.e., fitting a simplified equation with a different functional form. The analysis of maximum CW by Paine and Hann (1982) shows crowns larger than observed in Italy, probably because of the different thinning regimes and growing conditions in the two countries. Nevertheless, the new equation of crown width (Equation [3]) reduced MBE by 80 cm and MPE by 20 %, showing a satisfactory adjustment for this submodel.

Crown ratio is generally the second most important predictor of tree growth, after DBH. The uncalibrated CR submodel underestimated crown ratio in our plots. Observed crowns were 22% deeper than those predicted by default PN-FVS, possibly as a result of different forest management in these plots than in geographic range of origin (e.g., more intense thinning), altered competitive relationships (no inter-specific competitors in plantations), or improved growing conditions and soil fertility (site index in the upper part of the range provided by, e.g., McArdle et al. 1949). After calibration, the CR submodel improved considerably, although MBE remained negative: (-2.64 m default and -0.49 m calibrated).

Tree diameter growth or basal area growth equations have traditionally been used as one of the primary types of growth equations for individual tree growth models (Holdaway 1984; Ritchie and Hann 1985; Wykoff 1986; Wensel et al. 1987; Dolph 1988). A variety of equation forms and covariates have been used in diameter increment models. Wykoff (1990) indicated that three types of covariates need to be considered in a diameter increment model: tree size, competition and site. FVS includes them all: tree (DBH, height), stand (crown competition factor, basal area, basal area in larger tree) and site (aspect, slope, elevation, site index) characteristics are incorporated in a single equation (Equation [12]). Self-calibration of the large-tree diameter increment model occurs if, for a given species, there are at least five large (DBH >7.62 cm) tree records with measured diameter increments. Correction scale factors relating measured to predicted increment are then added to the simulations as multipliers. Scale factors higher than one, like the one computed by this calibration study, imply that the default model is underpredicting diameter growth. The amount of underprediction was major (up to 5-fold), but we could find no apparent relationship between scale factor and topographic or site variables in our sample plots. Actual growth performance might be related to unknown provenance differences, local soil water deficit (Sergent et al. 2014a), or soil nitrogen content, which was found important in tree growth recovery after drought spells (Sergent et al. 2014b). Previous calibrations of the FVS empirical diameter growth submodels found the a 18-parameter functional form too complicated to calibrate reliably and to discern ecological effects of individual predictors, suggesting replacement by much simpler model forms (Shaw et al. 2006) following sensitivity analysis of the most influential parameters (Vacchiano et al. 2008).

In this study it was not possible to calibrate other dynamic submodels of FVS, namely the height increment and mortality components, due to the lack of repeated measures as a calibration dataset. We acknowledge that mortality is an especially important component, as FVS has been previously found to be highly sensitive to small differences in the self-thinning algorithm (De Rose et al.

2008). More research and monitoring are needed to understand both density-dependent and density-independent mortality in the non-native range of Douglas fir, especially regarding tree susceptibility to drought stress (Ruiz Diaz Britez et al. 2014) or extreme weather events.

The validation against independent data from Mercurella and Vallombrosa stands showed that the DBH was predicted with a higher accuracy than height, probably due to the lack of measured heights and, consequently, the absence of height-diameter self-calibration for Mercurella in the initial simulation year (1996), and possibly to the lack of calibration of the height growth submodel.

The validation against these independent dataset showed that the calibrated model generally had a much lower prediction error than the original PN-FVS models, in particular for predicting DBH at Vallombrosa.

Even after calibration, PN-FVS overpredicted stand basal area at 50 years by 26% to a local yield table (Cantiani 1965). With only one direct measurement in time, it is impossible to ascertain whether this might be related to differences in species-specific carrying capacity (maximum SDI), or altered growing conditions as a consequence of e.g., climate change and/or higher nitrogen deposition relative to when the original yield table was fitted. However, biological validation of model behavior was successful, as simulated stands responded to different thinning (type A 10%, type B 30%) in a manner that was highly sensitive to their current site index and competition intensity. Where competition was higher, the benefit of thinning was greater.

In this work, our goal was to illustrate a model calibration procedure that could be replicated by forest managers starting from one-time tree size measurements compounded by an increment sampling. Calibration by multipliers is rigid in the sense that it does not allow for changing or simplifying model forms, e.g., dropping unused predictors or altering the shape of allometric curves (e.g., Russell et al. 2013), which could be attained only by rewriting the simulator code. However, our work was successful in providing a statistically validated decision support tool to project growth and yield of mature non-native Douglas fir plantations some decades into the future. Notwithstanding the inherent limitation of an empirical approach to forest modeling (Pretzsch

2009), the wealth of management options, model extensions, open access, and continuity of support by the developers make FVS an attractive option to managers and forest owners wishing to implement their management plans with scientifically based decision support tools.

8 Conclusion

This work has calibrated an age-independent, individual-tree, distance-independent growth and yield simulator for Douglas fir for Central Italy. A tree level simulator could be an effective tool for planning forest management. Calibrating this model to other areas and for other species in Italian forests may be a useful management support instead of traditional yield tables.

Other FVS submodels and extensions can be calibrated besides those here considered (Russell et al. 2015): regeneration, climate-FVS and especially mortality, which is an important growth submodel to be considered in future evaluations because it is one most sensitive to changes in future climate regimes, such as increases in drought severity and duration (Crookston et al. 2010). Simple modifications to the tree mortality model within PN-FVS could result in improved precision for estimating future number of trees (e.g., Radtke et al. 2012).

The self-calibration feature of FVS extends the geographic range over which the model can be exploited, assuming that the factors affecting growth in a given area also affect growth in the same way elsewhere. If this assumption cannot be accepted, the only other option is to refit the relationships using data from the geographic area of interest. If this procedure can be accepted, then the model equations can be calibrated rather easily.

Here, we have proved a relevant improvement for the application of FVS in Italy over the original model. The results also highlight the importance of using long-term historical growth data for the calibration and validation of the model. Permanent plots are generally well suited for tracking long-term model reliability and for evaluating model performance relative to specific treatments distinctively. Maintaining existing local networks of permanent plots, especially those with long histories of measurement, to predict forest growth in the climate change, is suggested (Crookston et al. 2010).

In conclusion, FVS has been proven to be a suitable type of yield modeling for Douglas fir forest growth in Italy: (i) it suitably represents current understanding of the dynamic forest ecosystem and how it responds over time to management interventions; (ii) it provides a monitoring target to test our assumptions with (for example, stand yield following different silvicultural treatments and successional pathways when no treatments are applied); (iii) it provides a modeling framework to integrate existing modeling components such as crown equations, site index curves and ecological land classification; (iv) it provides tools to develop and compare various silvicultural treatments; (v) it simulates a stand through time to inform and instruct forest managers; (vi) it can be effectively adopted to update inventory data.

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Table captions

Table 1: Main climatic and geographic parameters of the sampled stands: MAT=mean annual temperature, MWMT=mean warmest month temperature, MCMT=mean coldest month temperature, MAP=mean annual precipitation, MSP=mean summer precipitation, EU= ecopedological units.

Table 2: Main site and dendrometric characteristics of the study areas: SDI=stand density index, CCF=crown competition factor, PCC=percent of canopy cover, QMD=quadratic mean diameter, TH=top height, SI=site index.

Table 3: Confidence intervals of *HT* - *CW* - *CR* - ln(*DDS*) submodel parameters (bold: default PN-FVS value within 95% c.i. of the uncalibrated submodel).

Table 4: Scale factors computed by self-calibration of the ln(*DDS*) submodel.

Table 5: Results of calibrated PN-FVS model validation at Mercurella and Vallombrosa sites.

Table 1

Stand	Latitude	Longitude	Elevation	MAT	MWMT	MCMT	MAP	MSP	EU
	degrees		m asl		°C		mm		code
acquerino44	44.009	11.002	950	9.5	19.2	0.9	1485	463	8.07
acquerino58	44.005	11.009	900	9.8	19.5	1.2	1458	455	8.07
amiata	42.872	11.581	1100	10	19.7	2	622	246	16.01
berceto	44.498	9.978	950	9	18.9	-0.2	1301	444	8.08
camaldoli152	43.807	11.812	1030	9.3	18.9	0.9	1148	394	8.07
camaldoli209	43.805	11.819	1020	9.3	18.9	0.9	1142	393	8.07
campalbo	44.129	11.301	950	9.1	18.9	0.2	1365	415	10.01
campamoli	43.836	11.75	920	9.8	19.4	1.2	1134	390	10.04
cavallaro	43.959	11.748	880	9.8	19.7	0.8	986	362	10.03
cottede	44.105	11.175	1100	8.4	18.3	-0.6	1268	392	10.01
frugnolo	43.395	11.916	770	11	20.6	2.5	734	275	10.04
gemelli	43.968	11.728	1000	9.2	18.9	0.4	1211	424	10.03
lagdei	44.415	10.018	1250	7.5	17	-1	1780	578	8.07
lama	43.838	11.869	860	10.2	19.9	1.6	1103	384	8.07
lizzano	44.155	10.831	1120	8.5	18.1	0	1128	428	8.07
montelungo	44.024	10.962	1090	8.8	18.4	0.2	1464	456	8.07
orecchiella	44.206	10.364	1260	7.7	17.2	-0.6	1671	527	8.05
ortodicorso	44.04	10.988	1074	8.8	18.5	0.2	1482	459	8.07
pietracamela	42.515	13.548	1120	9.8	19.4	1	806	319	11.07
porretta	44.135	10.922	1057	8.8	18.5	0.2	1179	407	8.07

Table 2

Stand	Age	Aspect	Slope	Trees	SDI	CCF	PCC	QMD	TH	SI
	years	degrees		n	-	-	%	cm	m	m
acquerino44	75	135	30	49	517.5	417	87	53.2	41.1	31.1
acquerino58	85	180	60	31	578.9	499	76	75.9	47.4	31.1
amiata	75	225	10	34	512.1	428	53	66.5	46.8	34.1
berceto	82	355	50	44	488.6	420	69	54.9	35.8	28
camaldoli152	75	90	30	53	553.1	442	52	52.9	45.7	31.1
camaldoli209	75	135	30	39	550.5	456	41	63.8	48.9	34.1
campalbo	79	90	10	24	434.2	373	41	74.4	47.0	31.1
campamoli	72	270	40	36	457.4	375	64	59.8	49.2	36.9
cavallaro	80	45	55	35	485.7	402	64	63.2	47.2	31.1
cottede	87	180	20	37	481.1	405	48	60.6	40.7	28
frugnolo	86	355	20	43	466.4	375	45	54.2	46.5	31.1
gemelli	81	135	30	32	472.3	394	62	65.6	47.6	31.1
lagdei	87	357	10	35	509.7	425	72	65.1	40.2	28
lama	73	90	60	31	375.0	315	56	57.9	43.3	31.1
lizzano	80	90	30	39	568.8	474	78	65.1	48.0	34.1
montelungo	75	135	45	38	475.0	389	62	59.2	42.4	31.1
orecchiella	72	225	15	36	447.4	368	33	59	42.0	31.1
ortodicorso	80	45	40	34	411.5	335	66	58	42.6	28
pietracamela	80	315	85	21	783.5	619	76	49.2	43.1	28
porretta	85	40	25	46	556.0	453	58	57.9	40.6	28

Table 3

Submodel	Statistical parameters	Confidence interval		PN-FVS default
		2.5%	*97.5%*	
HT	p2	177.051041	244.5944047	407.1595
	p3	5.439085	16.9760288	**7.2885**
	p4	-1.274372	-0.6851091	-0.5908
CW	a1	3.59114045	23.884341979	**5.884**
	a2	0.80599868	1.311925335	0.544
	a3	-0.74220643	-0.308624119	-0.207
	a4	-0.02696175	0.142872953	0.204
	a5	-0.0869313	0.156519271	**-0.006**
	a6	-0.01535613	-0.003457285	**-0.004**
CR	A	20.029	41.385	0
	B	10.162	26.481	4.5
	C	-0.105	1.092	**0.311**
ln(DDS)	b1	95.403020	513.117783	-0.1992
	b2	0.248486	2.749077	-0.009845
	b3	-0.040339	-0.002925	0
	b4	7.360673	17.855091	0.495162
	b5	0.097451	3.735880	0.003263
	b6	-1.197667	1.942963	**0.014165**
	b7	-13.818310	7.291880	**-0.340401**
	b8	-14.522460	14.427475	**0**
	b9	2.005133	24.924225	0.802905
	b10	-10.721810	20.635366	**1.936912**
	b11	-25.792430	16.887971	**0**
	b12	-0.007620	0.007434	**-0.0000641**
	b13	-0.037989	0.302196	**-0.001827**
	b14	0.034499	0.126296	0
	b15	0.220498	9.916505	0
	b16	-125.8779	-42.562184	-0.129474
	b17	-0.100059	0.006533	**-0.001689**
	b18	-0.002082	0.229584	**0**

Table 4

Stand	Number of tree records	Fvs scale factor	Ratio std. Error	Bayes weight	Scale factor
acquerino44	7	1.019	3.642	0.451	1.043
acquerino58	9	1.555	2.663	0.85	1.681
amiata	8	2.869	1.543	0.999	2.872
berceto	9	1.988	3.549	0.947	2.066
camaldoli152	9	2.14	2.509	0.975	2.182
camaldoli209	8	2.447	1.56	0.995	2.458
campalbo	6	2.42	1.076	0.995	2.431
campamoli	10	3.388	2.029	1	3.388
cavallaro	6	1.882	3.061	0.924	1.982
cottede	8	3.181	1.288	1	3.181
frugnolo	8	1.656	2.143	0.896	1.756
gemelli	6	1.847	3.576	0.907	1.967
lagdei	7	1.072	2.333	0.579	1.128
lama	10	5.19	1.589	1	5.19
lizzano	9	3.299	2.5	1	3.299
montelungo	9	2.952	2.105	0.999	2.955
orecchiella	10	2.371	2.565	0.99	2.392
ortodicorso	9	2.372	1.992	0.991	2.391
pietracamela	9	2.282	2.151	0.987	2.307
porretta	13	1.363	3.241	0.759	1.504

Table 5

Statistical parameter	Mercurella		Vallombrosa	
	DBH	Height	DBH	Height
R^2	0.89	0.54	0.96	0.72
MBE	-4.36 cm	3.17 m	0.03 cm	-5.32 m
RMSE	6.15 cm	4.44 m	3.67 cm	7.07 m
MPE	-6.76%	8.85%	1.55%	-10.13%
MABE	4.79 cm	3.53 m	3.32 cm	6.31 m

Figure captions

Figure 1 – Location of the study areas

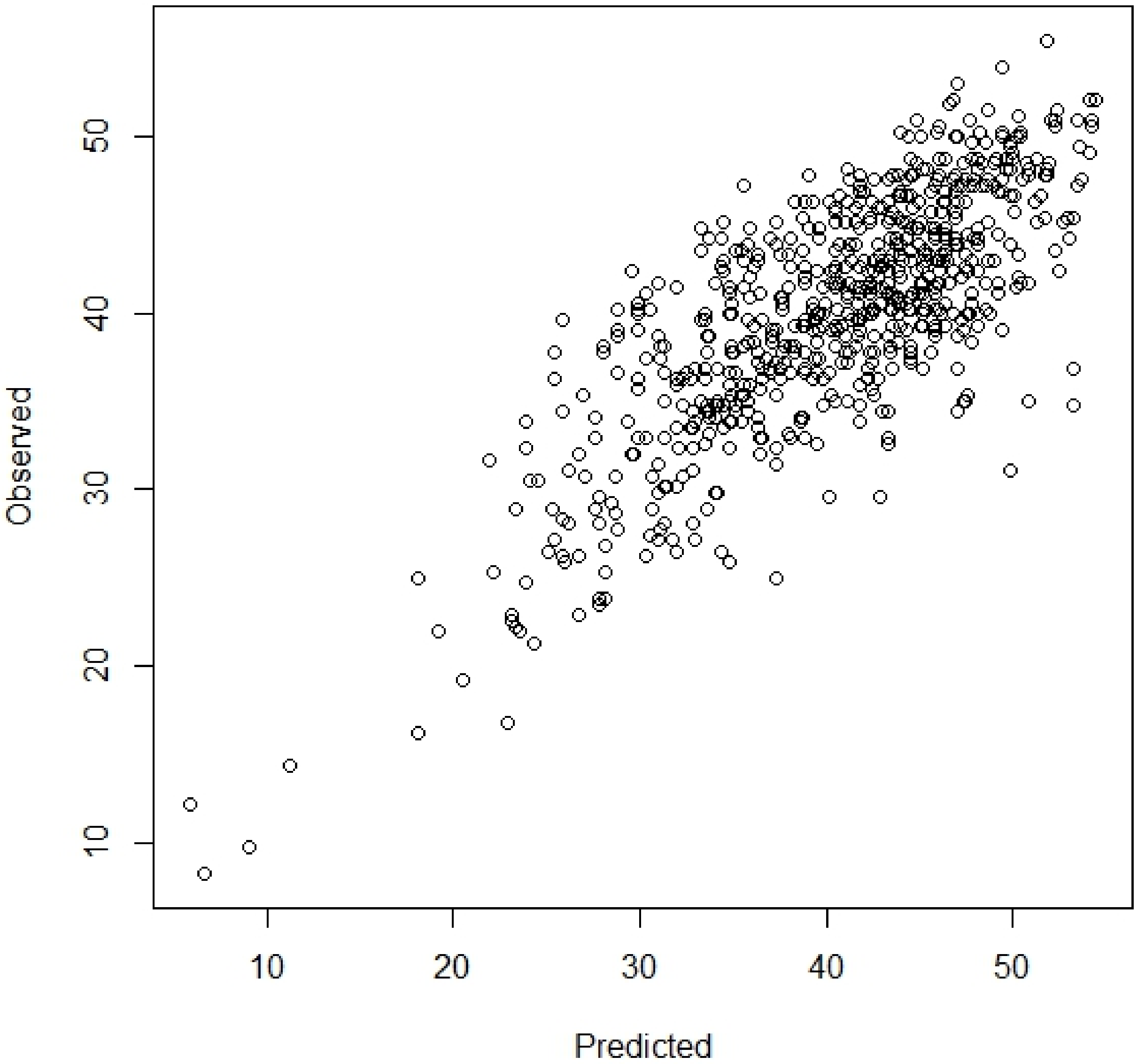
Figure 2 - Observed versus predicted tree heights by default PN-FVS Height-Diameter submodel

Figure 3 - Basal area predicted by PN-FVS default, by calibrated PN-FVS and by Cantiani yield table (1965)

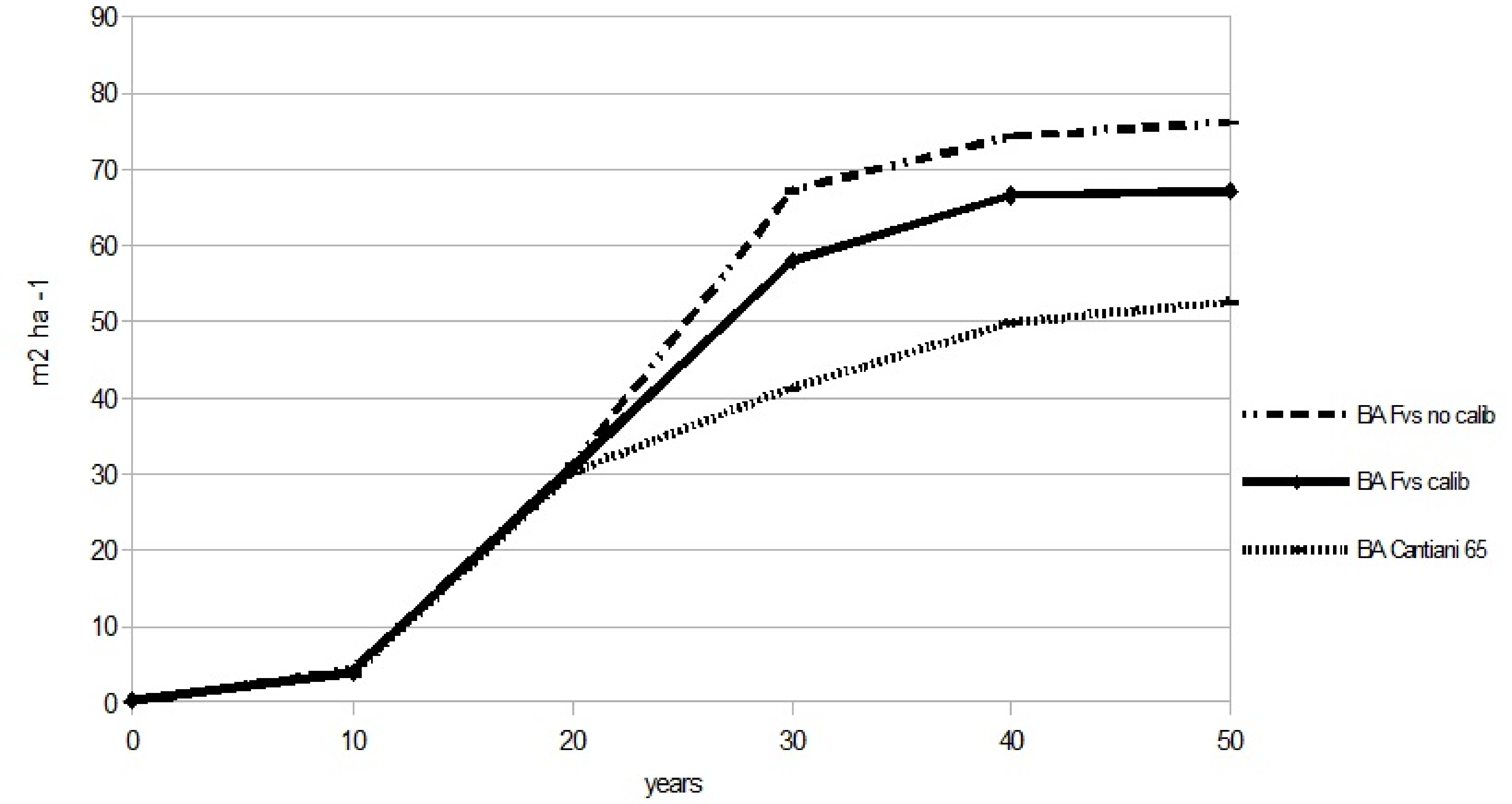
Figure 4 - Volume predicted by PN-FVS default, by calibrated PN-FVS and by Cantiani yield table

Figure 5 - Simulation of the response of stand basal area (above) and volume (below) to thinning from below in the Campamoli (left) and Acquerino58 (right) stands.


10°E
12°E
14°E
44°N
10°E
12°E
14°E
44°N



Observed
10
20
30
40
50
10
20
30
40
50
Predicted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80
70
60
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0
m2 ha -1
0
10
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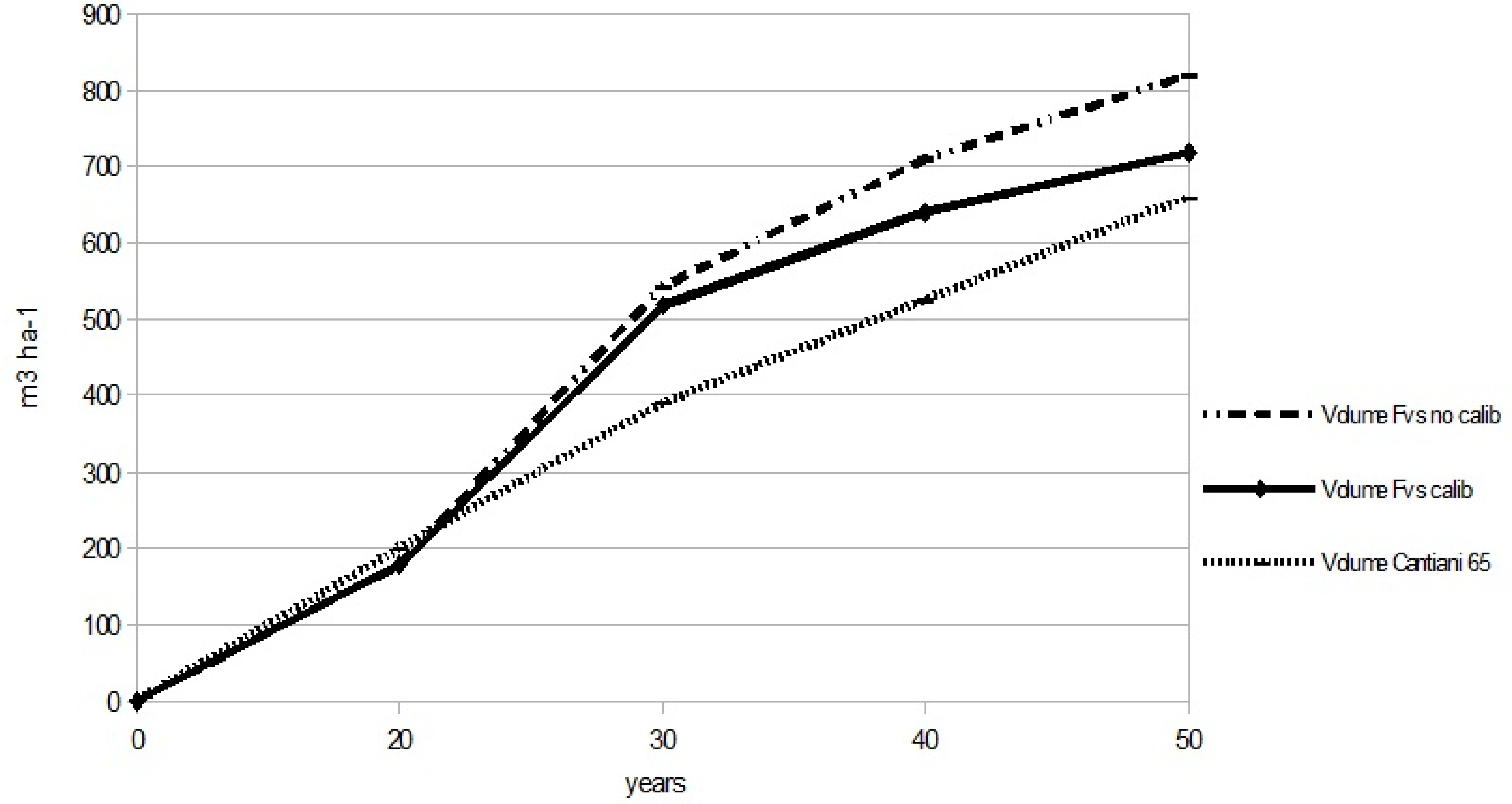
years
BA Fvs no calib
BA Fvs calib
BA Cantiani 65



900
800
700
600
500
400
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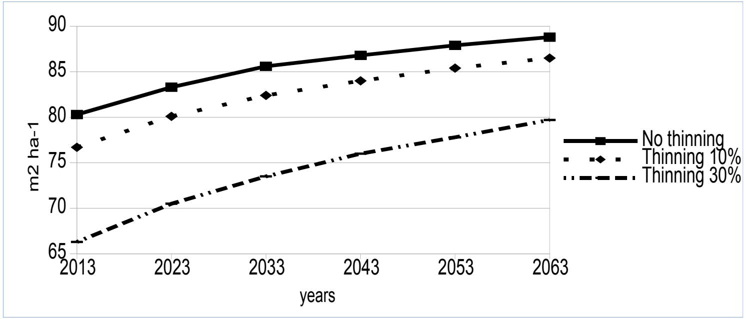
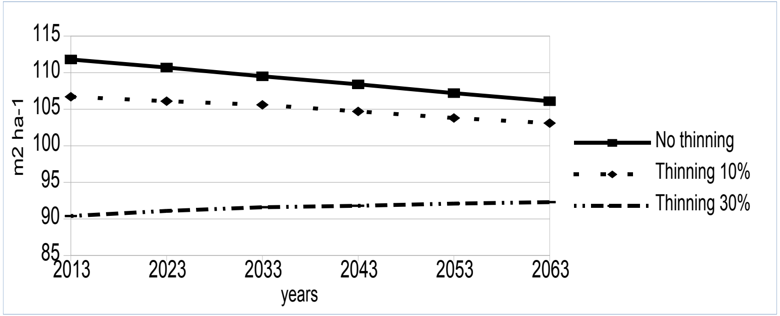
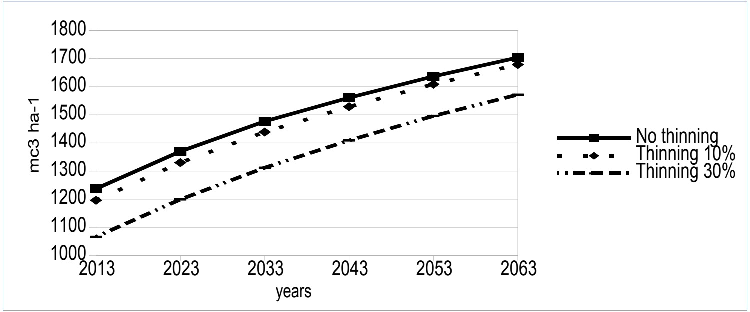
200
100
0
m3 ha-1
0
20
30
40
50
years
Volume Fvs no calib
Volume Fvs calib
Volume Cantiani 65



90
85
80
75
70
65
m2 ha-1
2013
2023
2033
2043
2053
2063
years
No thinning
Thinning 10%
Thinning 30%



115
110
105
100
95
90
85
m2 ha-1
2013
2023
2033
2043
2053
2063
years
No thinning
Thinning 10%
Thinning 30%



1800
1700
1600
1500
1400
1300
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1100
1000
mc3 ha-1
2013
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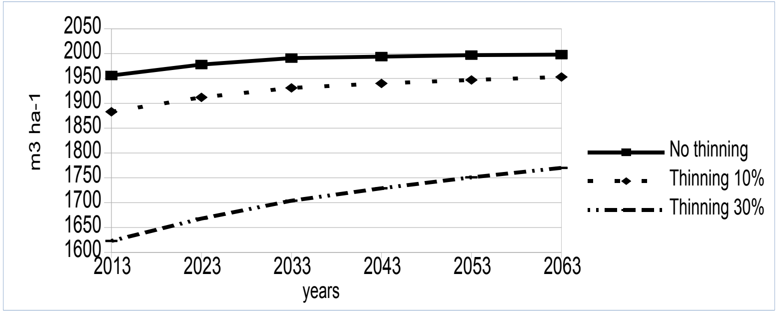
2063
years
No thinning
Thinning 10%
Thinning 30%



2050
2000
1950
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1850
1800
1750
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1650
1600
m3 ha-1
2013
2023
2033
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2053
2063
years
No thinning
Thinning 10%
Thinning 30%