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forest management

Projecting Nonnative Douglas Fir Plantations in Southern Europe with the Forest Vegetation Simulator

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In Italy, Douglas-fir has great 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 the Forest Vegetation Simulator (FVS) for Douglas-fir plantations in Italy and then ran the calibrated model to test management alternatives. We calibrated the height-diameter, crown width, crown ratio, and diameter increment submodels of the FVS using multipliers fitted against tree measurements ($n = 704$) and increment cores ($n = 180$) 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-year simulations was more satisfactory for tree diameter (−6% to +1% mean percent error) than for height (−10% to +8%). Calibration reduced the error, relative to that of yield tables, of the predicted basal area and yield after 50 years. Simulated responses to thinning diverged, depending on site index and competition intensity. The FVS is a viable option for modeling the yield of Douglas-fir plantations in Italy, reflecting the 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

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 usually has a high growth rate in comparison with those of other forest tree species in Europe, has a higher resistance to drought (Eilmann and Rigling 2012), and may provide high-value-added 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 were suitable for the species (Pavari 1958). Currently, Douglas-fir plantations cover an area of approximately 0.8 million ha in Europe (Forest Europe 2015). In Tuscany (Central Italy), Douglas-fir covers 3,360 ha in pure stands and 2,112 ha 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, particularly, by Cantiani (1965), who established a yield table for stands up to 50 years old, based on 115 plots of different ages.

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This article uses metric units; the applicable conversion factors are: millimeters (mm): 1 mm = 0.039 in.; centimeters (cm): 1 cm = 0.394 in.; hectares (ha): 1 ha = 2.471 ac; meters (m): 1 m = 3.28 ft; square meters per hectare (m^2/ha): 1 m^2/ha = 4.356 ft^2/ac.

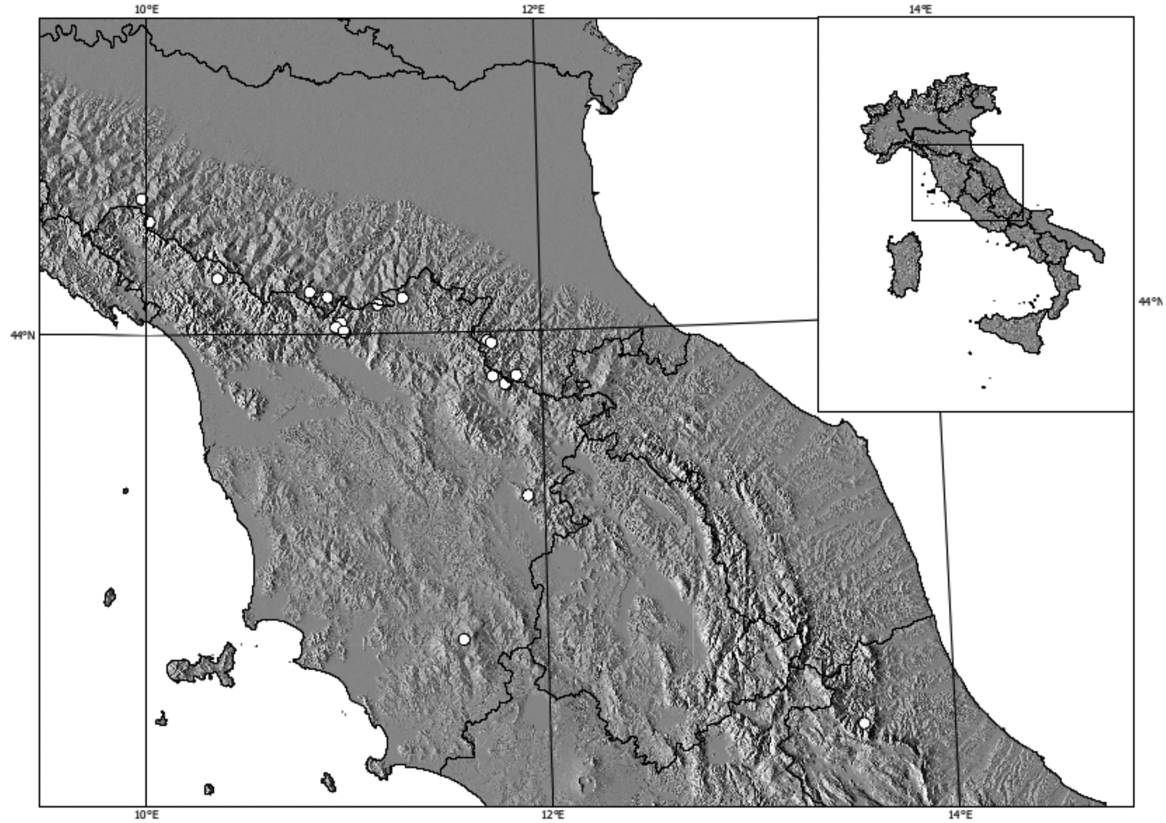

Figure 1. Location of the study areas.

Growth and yield models simulate forest dynamics through time (i.e., growth, mortality, and 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 decisionmaking (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 the Forest Vegetation Simulator (FVS) to simulate the growth of such stands.

The 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). The FVS can simulate many forest types and stand structures, ranging from even-aged to uneven-aged, single to mixed species, and single-story to multistory canopies. There are more than 20 geographical variants of the FVS, each with its own parameterization of tree growth and mortality equations for a particular geographic area of the United States. In addition, the FVS incorporates extensions that can simulate pest and disease impacts, fire effects, fuel loading, and regeneration (Crookston 2005).

The FVS has rarely been used in Italy (Vacchiano et al. 2014). The aims of this work are as follows: to calibrate and validate the Pacific Northwest Coast variant of the FVS to Douglas-fir plantations in Italy; to compare predictions from the calibrated model against available yield tables for Douglas-fir in Italy; and to use the calibrated model to test silvicultural alternatives for Douglas-fir plantation management.

Materials

Data for this work were collected in 20 stands of Douglas-fir planted between 1927 and 1942 over a 2,000 km^2 area in the northern Apennines, mostly within and near the region of Tuscany (Figure 1), at elevations ranging between 770 and 1,260 m above sea level. For each stand, Table 1 reports climatic data derived from ClimateEU (Hamann et al. 2013) and ecopedological units from the Ecopedological Map of Italy (Costantini et al. 2012), corresponding to the Forest-Alpine Meadows of Western Oceanic (Mediterranean) climate of Bailey's Ecoregions of the World (Bailey 1989). For each stand, Table 2 reports age, aspect, slope, number of trees in the plot, stand density index (SDI) (Reineke 1933), crown competition factor (CCF) (Krajicek et al. 1961), percentage of canopy cover (PCC) (Crookston and Stage 1999), quadratic mean diameter (QMD), dominant height (HDOM). and site index (SI), i.e., the top height at 50 years assessed according to Maetzke and Nocentini (1994).

Tree measurements were carried out in a circular plot with a 20-m radius (except for Pietracamela, which had a radius of 10 m) located at the center of each sampled stand. The center was detected in a geographic information system (GIS) environment as the centroid of the polygon of the management unit of the approved management plan and was reached in the field using global positioning systems (GPS). For each living tree (for a total of 704 trees), we measured the following: stem diameter at 130 cm height (dbh), total height, crown length, and crown width as the average of two orthogonal crown diameters. After tree measurements, a second stratified

Table 1. Main climatic and geographic parameters of the sampled stands.

Stand	Latitude	Longitude	Elevation	MAT	MWMT	MCMT	MAP	MSP	EU code
	(°)		(m above sea level)	(° C)			(mm)		
Acquerino44	44.009	11.002	950	9.5	19.2	0.9	1,485	463	8.07
Acquerino58	44.005	11.009	900	9.8	19.5	1.2	1,458	455	8.07
Amiata	42.872	11.581	1,100	10.0	19.7	2.0	622	246	16.01
Berceto	44.498	9.978	950	9.0	18.9	−0.2	1,301	444	8.08
Camaldoli152	43.807	11.812	1,030	9.3	18.9	0.9	1,148	394	8.07
Camaldoli209	43.805	11.819	1,020	9.3	18.9	0.9	1,142	393	8.07
Campalbo	44.129	11.301	950	9.1	18.9	0.2	1,365	415	10.01
Campamoli	43.836	11.750	920	9.8	19.4	1.2	1,134	390	10.04
Cavallaro	43.959	11.748	880	9.8	19.7	0.8	986	362	10.03
Cottede	44.105	11.175	1,100	8.4	18.3	−0.6	1,268	392	10.01
Frugnolo	43.395	11.916	770	11.0	20.6	2.5	734	275	10.04
Gemelli	43.968	11.728	1,000	9.2	18.9	0.4	1,211	424	10.03
Lagdei	44.415	10.018	1,250	7.5	17.0	−1.0	1,780	578	8.07
Lama	43.838	11.869	860	10.2	19.9	1.6	1,103	384	8.07
Lizzano	44.155	10.831	1,120	8.5	18.1	0.0	1,128	428	8.07
Montelungo	44.024	10.962	1,090	8.8	18.4	0.2	1,464	456	8.07
Orecchiella	44.206	10.364	1,260	7.7	17.2	−0.6	1,671	527	8.05
Ortodicorso	44.040	10.988	1,074	8.8	18.5	0.02	1,482	459	8.07
Pietracamela	42.515	13.548	1,120	9.8	19.4	1	806	319	11.07
Porretta	44.135	10.922	1,057	8.8	18.5	0.2	1,179	407	8.07

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.

Stand	Age	Aspect	Slope	Trees	SDI	CCF	PCC	QMD	HDOM	SI
	(yr)	(°)		(*n*)			(%)	(cm)	(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	28.0
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	28.0
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	28.0
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	59.0	42.0	31.1
Ortodicorso	80	45	40	34	411.5	335	66	58.0	42.6	28.0
Pietracamela	80	315	85	21	783.5	619	76	49.2	43.1	28.0
Porretta	85	40	25	46	556.0	453	58	57.9	40.6	28.0

random sampling was performed, aggregating trees in social classes (dominant-intermediate-dominated). Depending on tree density, a subset of 8–10 trees per plot was cored twice, with an angle of 90° between cores, selecting an equal number of candidates in each class. Tree cores were prepared for measurement in the laboratory 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.

Calibration

To adjust the 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. Because of the lack of repeated field measurements, this article focuses on the first four submodels, leaving the others unchanged.

Because the populations of Douglas-fir considered come from the Pacific Northwest coast of the United States (Pavari and De Philippis 1941), the Pacific Northwest (PN) variant of the FVS (Keyser 2014) was used as a basis for model calibration and runs. The original range considered by this variant extends 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).

The FVS includes two options for calibrating model performance to local growing conditions (Dixon 2002): automatic calibration (scaling) by the model and 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; for the crown width and crown ratio submodels, we fitted user-defined multipliers. The following paragraphs illustrate, for each of the four submodels, the calibration strategy adopted and its results.

All the variables in the FVS equations are expressed in imperial units; conversion to and from the metric system was performed outside the calibration algorithms. The simulation cycle was 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 the locally calibrated confidence intervals, model adjustment was deemed necessary. In addition, we compared the fit of noncalibrated 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).

Height-Diameter Submodel

Height-diameter relationships in the 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 (Curtis 1967, Arney 1985). The height-diameter submodel (HT) uses an internal self-calibration method; if users provide more than three but not all stem heights, the height-diameter equation is calibrated:

$$HT = 4.5 + p_2 \cdot \exp(-p_3 \cdot \text{dbh}^{p_4}) \quad (1)$$

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, 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 an R^2 of 0.6 and an MPE of 1.18%, corresponding to an MBE of 33 cm and an 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 of -0.3 m and an RMSE of 4.16 m.

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 2: Stage 1973) as a function of tree, stand, and site characteristics:

$$\begin{aligned}\ln(\text{DDS}) = {} & b_1 + (b_2 \cdot \text{EL}) + (b_3 \cdot \text{EL}^2) + (b_4 \cdot \ln(\text{SI})) \\ & + (b_5 \cdot \sin(\text{ASP}) \cdot \text{SL}) + (b_6 \cdot \cos(\text{ASP}) \cdot \text{SL}) + (b_7 \cdot \text{SL}) \\ & + (b_8 \cdot \text{SL}^2) + (b_9 \cdot \ln(\text{dbh})) + (b_{10} \cdot \text{CR}) + (b_{11} \cdot \text{CR}^2) \\ & + (b_{12} \cdot \text{dbh}^2) + \left(b_{13} \cdot \frac{\text{BAL}}{\ln(\text{dbh} + 1.0)}\right) + (b_{14} \cdot \text{CCF}) \\ & + (b_{15} \cdot \text{RELHT}) + (b_{16} \cdot \ln(\text{BA})) + (b_{17} \cdot \text{BAL}) + (b_{18} \cdot \text{BA})\end{aligned} \quad (2)$$

Table 3. Confidence intervals for the parameters of the HT-CW-CR-ln(DDS) submodels.

Submodel	Statistical parameters	Confidence interval 2.5%	Confidence interval 97.5%	PN-FVS default
HT	p_2	177.0510	244.5944	407.1595
	p_3	5.4390	16.9760	7.2885*
	p_4	−1.2743	−0.6851	−0.5908
CW	a_1	3.5911	23.8843	5.884*
	a_2	0.8060	1.3119	0.544
	a_3	−0.7422	−0.3086	−0.207
	a_4	−0.0269	0.1428	0.204
	a_5	−0.0869	0.1565	−0.006*
	a_6	−0.0153	−0.0034	−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)	b_1	95.4030	513.1177	−0.1992
	b_2	0.2484	2.7490	−0.0098
	b_3	−0.0403	−0.0029	0
	b_4	7.3606	17.8550	0.4951
	b_5	0.0974	3.735	0.0032
	b_6	−1.1976	1.9429	0.0141*
	b_7	−13.8183	7.2918	−0.3404*
	b_8	−14.5224	14.4274	0*
	b_9	2.0051	24.9242	0.8029
	b_{10}	−10.7218	20.6353	1.9369*
	b_{11}	−25.7924	16.8879	0*
	b_{12}	−0.0076	0.0074	0*
	b_{13}	−0.0379	0.3021	−0.0018*
	b_{14}	0.0344	0.1262	0
	b_{15}	0.2204	9.9165	0
	b_{16}	−125.8779	−42.5621	−0.1294
	b_{17}	−0.1000	0.0065	−0.0016*
	b_{18}	−0.0020	0.2295	0*

* Default PN-FVS value within 95% confidence interval of the uncalibrated submodel.

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, b_1 is a location-specific coefficient that defaults to -0.1992, and b_2–b_{18} 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 observed values from all the plots considered here, Equation 2 had nine parameters whose confidence intervals did not include the FVS default values (Table 3): submodel adjustment was therefore needed.

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, the 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 for the base growth equations, bound to a range of 0.08 to 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 1. The rate of attenuation is dependent only on time and has a half-life of 25 years (Dixon 2002).

To check for bias, we disabled the self-calibration and variation algorithms of the large tree diameter growth model using the keywords NOCALIB and NOTRIPLE and scrutinized scale factors

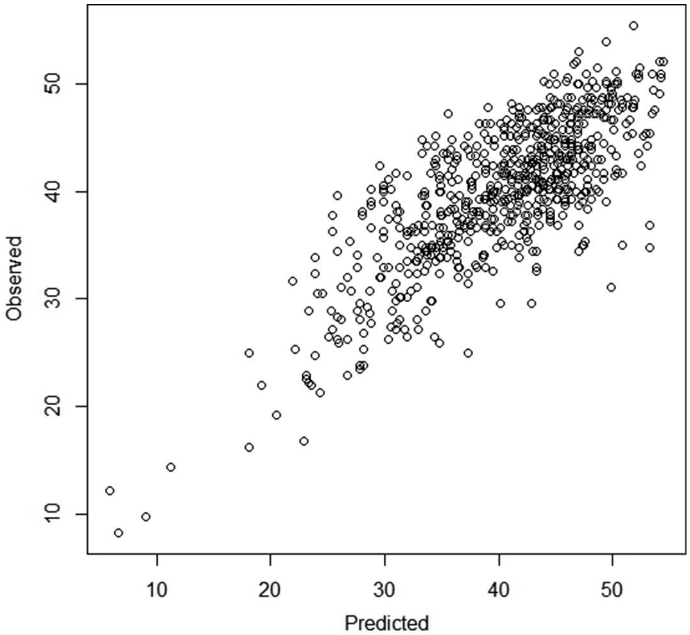

Figure 2. Observed versus predicted tree heights (meters) by default PN-FVS height-diameter submodel.

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

Stand	No. of tree records	FVS scale factor	Ratio SE	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	1.560	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	5.190	1.589	1	5.19
Lizzano	9	3.299	2.500	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

for ln(*DDS*) automatically calculated against observed periodic increments.

These scale factors ranged from 1 to >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 SD of the residuals for the growth sample to the model standard error, which is consistently higher than 1.0. Bayes weights (Krutchkoff 1972) (Table 4) are an expression of confidence that the growth sample represents a different population than 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).

Crown Width Submodel

In PN-FVS, crown width (CW) is computed as a function of tree and stand characteristics (Equation 3: Crookston 2005) and bound to ≤24 m:

$$CW = (a_1 \cdot BF) \cdot dbh^{a_2} \cdot TH^{a_3} \cdot CL^{a_4} \cdot (BA + 1.0)^{a_5} \cdot (\exp(EL))^{a_6} \quad (3)$$

where BF is a species- and location-based coefficient (default BF for Douglas-fir = 0.977), TH is total height, CL is crown length, BA is stand basal area, EL is stand elevation in hundreds of feet, and a_1–a_6 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 3 was fitted against observed data, only three parameters were within the 95% confidence intervals of the uncalibrated equation (Table 3): submodel adjustment was therefore needed.

To that end, we used the keyword CWEQN to enter user-defined coefficients for a new species-specific crown width model (Equation 4):

$$CW = s_0 + (s_1 \cdot dbh) + (s_2 \cdot dbh^{s_3}) \quad (4)$$

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 to 0.2 cm, and RMSE from 2.12 to 1.87 m.

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

PN-FVS uses a Weibull-based model to predict the 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 5: Johnson and Kotz 1995):

$$ACR = d_0 + d_1 \cdot RELSDI \cdot 100 \quad (5)$$

where d_0–d_1 are species-specific coefficients ($d_0 = 5.666442$; $d_1 = -0.025199$) and RELSDI is the 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 (Pretzsch and Biber 2005, Vacchiano et al. 2005, Shaw 2006, Comeau et al. 2010). SDI (Reineke 1933) is calculated according to Equation 6:

$$SDI = TPA\left(\frac{QMD}{25}\right)^{1.605} \quad (6)$$

where TPA is the number of trees per acre. Maximum SDI is provided as the species-specific default (SDImax for Douglas-fir = 950).

ACR is then used to estimate the parameters A, B, and C of the Weibull distribution of individual crown ratios (Equations 7–11):

$$A = A_0 \quad (7)$$

$$B = B_0 + B_1 \cdot \text{ACR (bound to } B > 3) \quad (8)$$

$$C = C_0 + C_1 \cdot \text{ACR (bound to } C > 2) \quad (9)$$

$$\text{SCALE} = 1 - (0.00167 + (\text{CCF} - 100)) \quad (10)$$

$$\text{CR} = A + B \cdot \left(\left(-\log \left(1 - \left(\text{SCALE} \cdot \frac{\text{RANK}}{N} \right) \right) \right)^{\frac{1}{c}} \right) \quad (11)$$

where A_0, B_0 and B_1, and C_0 and C_1 are species-specific coefficients (Keyser 2014) ($A_0 = 0$; $B_0 = -0.01206$; $B_1 = 1.119712$; $C_0 = 3.2126$; $C_1 = 0$), 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 $0.3 < \text{SCALE} < 1.0$, and CCF is the stand crown competition factor (Krajicek et al. 1961), computed as the summation of individual CCF (CCF_t) values from trees with dbh >2.5 cm (Equation 12: Paine and Hann 1982):

$$\text{CCF}t = r_1 + (r_2 \cdot \text{dbh}) + (r_3 \cdot \text{dbh}^2) \quad (12)$$

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, the confidence interval of Equation 11 only includes the PN-FVS default value for one parameter (C) (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, and RMSE = 4.47 m).

Crown ratio calibration was attained using 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 crown ratio as the dependent variable and the independent variables from Equations 5–11. CRNMULT improved the fit of the crown ratio 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.

Model Validation

We used independent data sets 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 on a total of 275 trees. Using the keyword TIMEINT, we ran a simulation from 1995 to 2015 with a cycle length of 5 years. We compared predicted versus observed dbh and height (Mercurella: year 2012; Vallombrosa: year 2015). Initial stem heights in Mercurella (1996) were calculated with the 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), whereas the R^2 value for height was lower (0.54 in Mercurella and 0.72 in Vallombrosa).

Comparison with Yield Tables

We ran the locally calibrated PN variant of FVS 50 years into the future using site characteristics based on the measured 20 plots and starting from bare ground. Initial plantation density was set at 2,745 trees/ha, i.e., similar to the initial density of the yield table by Cantiani (1965), using the keyword PLANT. We instructed the FVS to reproduce the same treatments prescribed by the Cantiani yield table, by using the keyword THINBTA (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 that predicted by the yield table, with an MBE of 9.23 $\text{m}^2\ \text{ha}^{-1}$, RMSE of 13.05 $\text{m}^2\ \text{ha}^{-1}$, and MPE of 26%.

Calibration reduced the difference between the Cantiani yield table established for Douglas-fir plantations in Tuscany and the simulated mean basal area, volume, quadratic mean diameter, and the number of trees per hectare (Figure 3) across all stands.

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

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

Model Runs and Management Options

Finally, 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 indices but different competition intensity. SDI controls the FVS mortality model, and density-related mortality begins when the stand SDI is more than 55% of SDImax (Dixon 1986). We chose the plots Acquerino58 (relative SDI, 60.94%; site index, 31.1 m) and Campamoli (relative SDI, 48.15%; site index, 36.9 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 keyword THINBTA with three different basal area removal intensities (10%; 30%; 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 4).

Discussion

The 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 the first model calibration, i.e., in the presence of growth bias for any given species, geographic area, site, or forest type (Dixon 2002).

Self-calibration reduced the error of the height-diameter submodel from 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

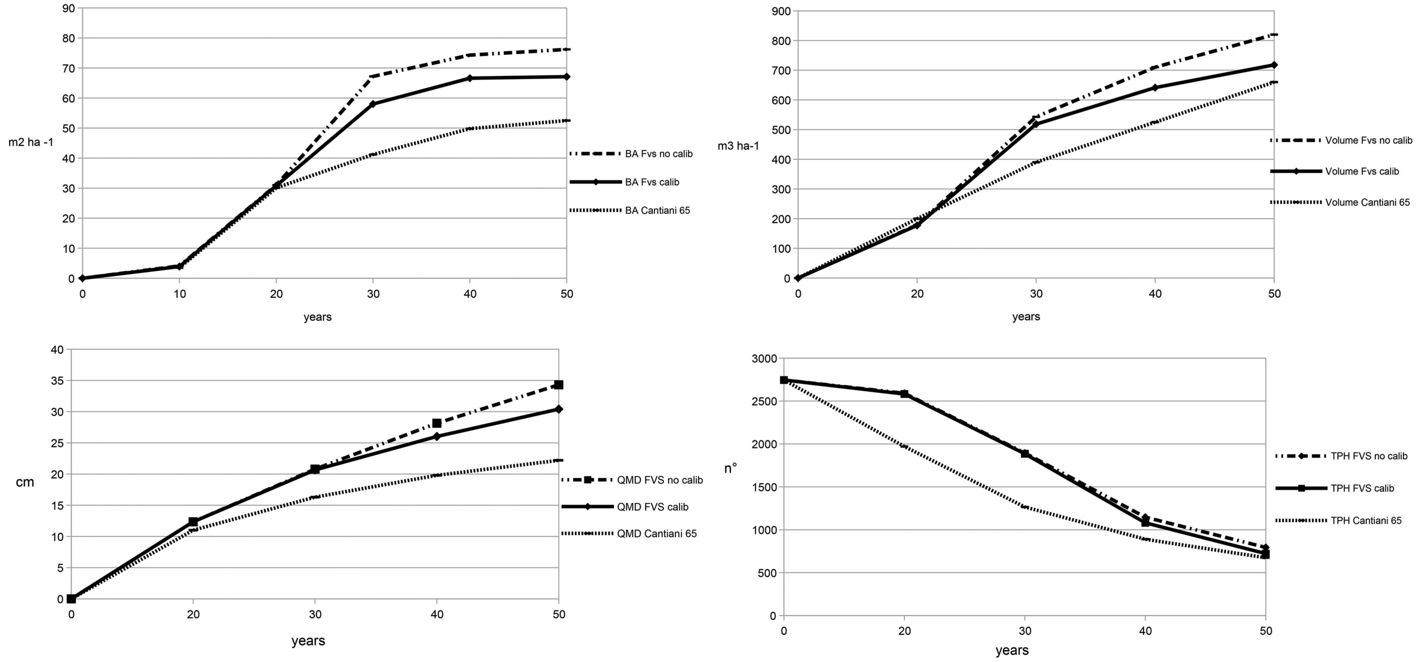

Figure 3. Mean basal area (BA), volume, quadratic mean diameter (QMD) and the number of trees per hectare (TPH), predicted by PN-FVS default, by calibrated PN-FVS, and by Cantiani yield table (Cantiani 1965).

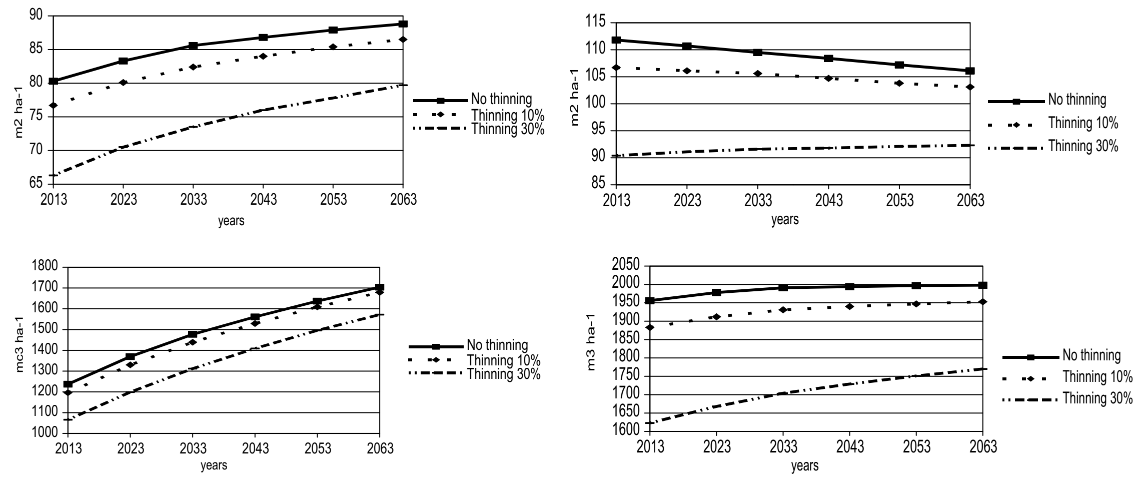

Figure 4. Simulation of the response of stand basal area (top) and volume (bottom) to thinning from below in the Campamoli (left) and Acquerino58 (right) stands.

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 crown width 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 4) reduced MBE by 82.8 cm and MPE by 19%, showing a satisfactory adjustment for this submodel.

The crown ratio is generally the second most important predictor of tree growth, after dbh. The uncalibrated crown ratio submodel underestimated the crown ratio in our plots. Observed crowns were 22% longer than those predicted by the default PN-FVS, possibly as a result of different forest management in these plots than in their geographic range of origin (e.g., more intense thinning), altered competitive relationships (no interspecific 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 crown ratio submodel improved considerably, although the 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. The 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 2). 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 the measured to the predicted increment are then added to the simulations as multipliers. Scale factors higher than 1, like the ones 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 identified as important in tree growth recovery after drought spells (Sergent et al. 2014b). Previous calibrations of the FVS empirical diameter growth submodels found the 18-parameter functional form to be too complicated to calibrate reliably and to discern the ecological effects of individual predictors, suggesting replacement by much simpler model forms (Shaw et al. 2006) based on sensitivity analysis of the most influential parameters (Vacchiano et al. 2008).

In this study, it was not possible to calibrate other dynamic submodels of the FVS, namely the height increment and mortality components, because of the lack of repeated measures as a calibration data set. We acknowledge that mortality is an especially important component, as the FVS has previously been found to be highly sensitive to small differences in the self-thinning algorithm (DeRose et al. 2008). More research and monitoring are needed to understand both density-dependent and density-independent mortality in the nonnative range of Douglas-fir, especially regarding tree susceptibility to drought stress (Ruiz Diaz Britez et al. 2014) or extreme weather events.

The validation using independent data from the Mercurella and Vallombrosa stands showed that the dbh was predicted with a higher accuracy than height, probably because of the lack of measured heights and, consequently, the absence of height-diameter self-calibration for Mercurella in the initial simulation year (1996), and possibly because of the lack of calibration of the height growth submodel. The validation against these independent data sets showed that the calibrated model generally had a much lower prediction error than the original PN-FVS models, particularly for predicting dbh at Vallombrosa.

Even after calibration, PN-FVS overpredicted stand basal area at 50 years by 26% compared to a local yield table (Cantiani 1965). With only one direct measurement, it is impossible to ascertain whether this might be related to differences in species-specific carrying capacity (maximum SDI) or to 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 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 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 the growth and yield of mature nonnative Douglas-fir plantations some decades into the future. Notwithstanding the inherent limitation of an empirical approach to forest modeling (Pretzsch 2009, Vacchiano et al. 2012), the wealth of management options, model extensions, open access, and continuity of support by the developers make the FVS an attractive option for managers and forest owners wishing to implement their management plans with scientifically based decision support tools.

Conclusion

This work has partially calibrated an age-independent, individual-tree, distance-independent growth and yield simulator for Douglas-fir for Central Italy. A tree-level simulator may 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 considered here (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 of the 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 the 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 the 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 distinctive to specific treatments. 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, the FVS has been shown to be a suitable type of yield modeling for Douglas-fir forest growth in Italy: (1) it suitably represents the current understanding of the dynamic forest ecosystem and how it responds over time to management interventions; (2) it provides a monitoring target with which to test our assumptions (e.g., stand yield after different silvicultural treatments and successional pathways when no treatments are applied); (3) it provides a modeling framework for integrating existing modeling components such as crown equations, site index curves, and ecological land classification; (4) it provides tools with which to develop and compare various silvicultural treatments; (5) it simulates a stand over time to inform and instruct forest managers; and (6) it can be effectively adopted to update inventory data.

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