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SOFTWARE TOOL ARTICLE

REVISED The Salem simulator version 2.0: a tool for predicting the productivity of pure and mixed forest stands and simulating management operations

[version 2; peer review: 2 approved]

Previously titled: 'The Salem simulator version 2.0: a tool for predicting the productivity of pure and mixed stands and simulating management operations'

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Abstract

A growing body of research suggests mixed-species stands are generally more productive than pure stands as well as less sensitive to disturbances. However, these effects of mixture depend on species assemblages and environmental conditions. Here, we present the Salem simulator, a tool that can help forest managers assess the potential benefit of shifting from pure to mixed stands from a productivity perspective. Salem predicts the dynamics of pure and mixed even-aged stands and makes it possible to simulate management operations. Its purpose is to be a decision support tool for forest managers and stakeholders as well as for policy makers. It is also designed to conduct virtual experiments and help answer research questions.

In Salem, we parameterised the growth in pure stand of 12 common tree species of Europe and we assessed the effect of mixture on species growth for 24 species pairs (made up of the 12 species mentioned above). Thus, Salem makes it possible to compare the productivity of 36 different pure and mixed stands depending on environmental conditions and user-defined management strategies. Salem is essentially based on the analysis of National Forest Inventory data. A major outcome of this analysis is that we found species mixture most often increases species growth, in particular at the poorest sites. Independently from the simulator, foresters and researchers can also consider using the species-specific models that constitute Salem: the growth models including or excluding mixture

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effect, the bark models, the diameter distribution models, the circumference-height relationship models, as well as the volume equations for the 12 parameterised species. Salem runs on Windows, Linux, or Mac. Its user-friendly graphical user interface makes it easy to use for non-modellers. Finally, it is distributed under a LGPL license and is therefore free and open source.

Keywords
forest, growth model, mixture effect, bark model, allometry, diameter distribution, circumference-height relationship, volume equation

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REVISED **Amendments from Version 1**

In this new version we added the word 'forest' in the title. We pointed out in the abstract and introduction that forest managers may want to shift from pure to mixed stands not only for a productivity gain but also to reduce risks against disturbances. In the last paragraph of the introduction we removed the information that is redundant with the Grant information section and the reference to the maturity and reliability of Salem. In the Implementation section, we specified that the only mortality factor simulated in Salem is competition. We added the number of cores collected in pure and mixed stands in Table 2 and Table 5. We corrected a mistake in Table 4: the BAI of *Pinus nigra* subsp. *Laricio* is not calculated using Equation 3 but Equation 4. This minor error has crept into the source code of Salem deposited on zenodo. We uploaded a revised version of the code and updated its doi in the Software availability section as well as in the References section. We discussed the limitations of Salem regarding the reliability of its predictions under the future climate.

Any further responses from the reviewers can be found at the end of the article

1 Introduction

Over the last decades, mixed-species stands have received growing attention. From the perspective of forest managers, they have a number of advantages compared to monospecific stands. They can be more productive (Ammer, 2019; Liang *et al*., 2016) as well as less sensitive to various disturbances such as windstorms (Schütz *et al*., 2006), pathogen invasions (Haas *et al*., 2011) or insect outbreaks (Castagneyrol *et al*., 2013; Jactel & Brockerhoff, 2007; Klapwijk & Björkman, 2018). However, these effects of mixture are highly variable and depend on species and environmental conditions. As a result, forest managers often lack information to consider mixed stands as a possible alternative to pure stands. Forest dynamics models (Pretzsch, 2009; Weiskittel *et al*., 2011) can help fill this information gap. In this article, we will focus on the potential benefit of shifting from pure to mixed stands from a productivity perspective, we will not cover the aspect of risk reduction against disturbances.

At present, numerous models simulate mixed stand management and dynamics (see for example Courbaud *et al*., 2015; Lasch-Born *et al*., 2020; Schumacher *et al*., 2006; Wernsdörfer *et al*., 2012). Four different approaches are used to represent mixed stand productivity (Pretzsch *et al*., 2015): (1) by deriving their productivity as a weighted mean of the productivity of their constituent species using species-specific models; (2) by integrating species-specific growing space competition indices in individual-tree growth models; (3) by using empirical multipliers affecting growth rates and stand density depending on species assemblages and environmental conditions; and (4) via a process-based approach by incorporating within-stand environmental conditions, species-specific structures, and resource uptake and availability. Models simulating mixed stand management and dynamics also differ in the type of calibration data they require and in the spatial scale at which they operate (tree, stand, landscape). These different calibration data, operation scales and ways of representing mixed stand productivity each have their advantages, but they are not all of equal interest to forest managers.

With a view to being used by forest managers, models using the multiplier approach (3) have an advantage: their generally simpler functioning makes them less data-and prescription-intensive. On the other hand, models based on approach (2) and (4) require fine-scale spatial data that forest managers are unlikely to have. As for approach (1), it does not take into account species interactions and can therefore only partially render the mixture effect on stand productivity.

Data from national forest inventories (NFI) are particularly relevant for modelling pure and mixed stand dynamics with a view to assisting forest managers. The wide geographical coverage of these data makes it possible to study the dynamics of a large variety of pure and mixed stands under diverse environmental and silvicultural conditions (e.g., Fortin & Langevin, 2012; Lessard *et al*., 2001; Li *et al*., 2011). Such datasets make it possible, in particular, to compare the dynamics of pure and mixed stands and thus to estimate the effect of mixture on stand productivity for different species assemblages, while controlling for the effect of environmental conditions on this composition - productivity relationship. NFI data are therefore suitable for modelling various stands in a variety of contexts, which is useful for managers looking to compare different strategies before defining a management strategy. Conversely, experimental plots and smaller plot networks are generally less capable of producing reliable simulations in different contexts due to their limited coverage of environmental gradients, species assemblages and management practices. Their usefulness lies more in their contribution to the understanding of the mechanisms underlying stand dynamics.

Models with a stand-level approach (Pretzsch, 2009; Weiskittel *et al*., 2011) are particularly convenient for forest managers, and especially for even-aged stand managers, as they are in line with the spatial scale at which management is usually planned. Stand-level models run with data that forest managers are likely to have, such as

mean diameter or total basal area, and management strategies can be prescribed as in a traditional management plan by formulating stand-level prescriptions defining, for example, a thinning intensity or a target mean diameter. On the other hand, landscape models are too large in scale to plan silvicultural operations, while tree-level models can be too data- or prescription-intensive. Landscape models are more relevant for large-scale spatial planning, while tree-level models can be more relevant for studying interactions among trees, for example.

Here we present the Salem (for StAnd LEvel Model) simulator. Salem predicts the dynamics of even-aged pure and mixed stands and makes it possible to simulate management operations. Its purpose is to be a decision support tool for forest managers and stakeholders as well as for policy makers. Salem is calibrated on stand-level data from the French National Forest Inventory (NFI) as well as on environmental data and it simulates stand-level processes. The mixture effect on stand productivity is explicitly implemented in Salem using the multiplier approach (3) mentioned above. To date, this approach has been adopted very little in stand-level models despite its advantage over the other approaches (but see: Vospernik, 2021). Altogether, 12 common tree species of Europe are parameterised, making it possible to simulate the same number of pure stands and 24 different bispecific mixed stands corresponding to frequently observed assemblages of these 12 species. In France, these 12 species represent 72% of the total volume of wood available in the production forests, excluding poplar stands (IGN, 2020). Salem is distributed under a LGPL license and is therefore free and open source.

We present the general functioning of Salem in Section 2. We then provide details on the different models used in Section 3. Finally, we show how to simulate stands with Salem and how to implement management operations in Section 4.

2 Implementation

Salem consists of different models chained together to simulate forest dynamics and management operations. The general functioning of Salem is summarised in Figure 1, which shows how the different models are connected to each other.

In the first instance, Salem requires the stand initial state as input, *i.e.* the basal area (BA), the mean quadratic diameter (Dg), and the site indices for one or two species (for mono- or bi-specific stands). In Salem, site indices are calculated from a species-specific combination of environmental variables (Section 3.1). Salem then calculates the under bark species BA using species-specific bark models (Section 3.3). Thereafter, Salem calculates the under bark stand basal area increment (BAI) using species-specific growth models (Section 3.1). If the simulated

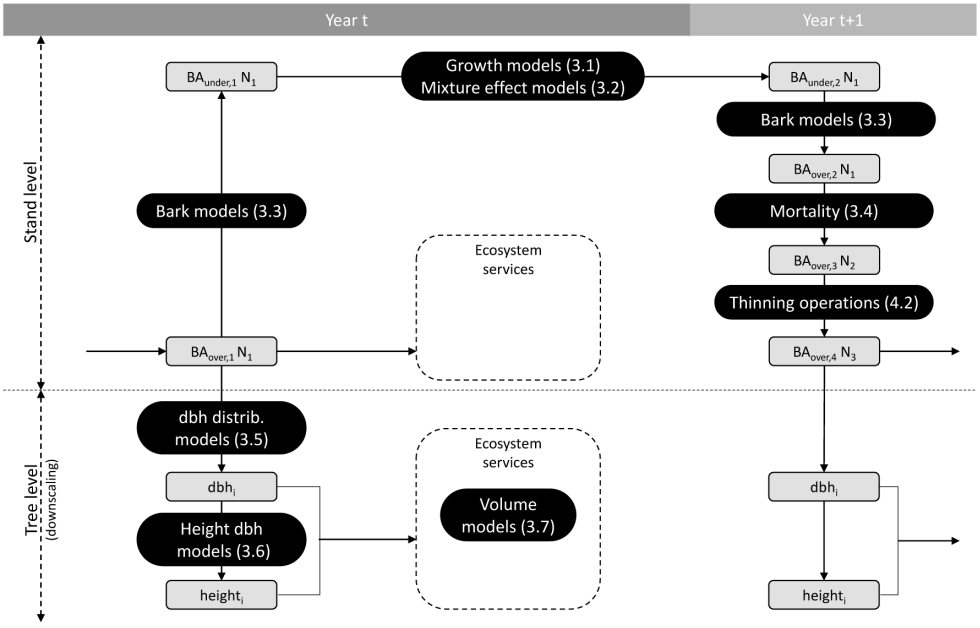


Figure 1. General functioning of Salem. Grey boxes indicate the state of the following variables: over or under bark basal area (BA), number of trees (N), tree diameter at breast height (dbh), and tree height. Black boxes indicate the models used to change variables from one state to another. Numbers in brackets correspond to the section numbers in which the models are presented.

stand is composed of two species, the effect of each species on the other species growth is simulated (Section 3.2). Next, the stand under bark BA is converted back into over bark BA. At that stage, if the simulated stand density exceeds the self-thinning boundary, mortality is triggered and a certain amount of BA is removed to bring back the stand below this boundary (Section 3.4). The only mortality factor simulated in Salem is therefore competition. Mortality due to natural disturbances such as storms, droughts or insect outbreaks is not simulated. Finally, thinning operations can be simulated by removing a certain amount of BA per species (Section 4). The procedure described above is repeated for each simulated year.

At each annual time step stand level variables can be downscaled to tree level variables. Salem uses species-specific models to generate tree diameter distributions from the stand level values Dg and N of each species (Section 3.5). From these predicted diameters as well as from environmental and stand variables, tree height is predicted (Section 3.6). Finally, a two-entry (diameter and height) volume equation is applied to predict tree volume (Section 3.7).

The modelling framework presented here is the result of successive developments, some of which have been presented in previous studies. Table 1 summarises the differences between previous work and the work presented in this article.

3 Model descriptions

3.1 Growth models in pure stands

3.1.1 Data. We calibrated our growth models using French NFI data collected between 2006 and 2013 in pure stands according to the following criteria:

- Stands had to be classified as even-aged stands by the French NFI.
- Stands must have not been logged in the five years preceding the measurements.
- A single species was to make up the total stands BA.

French NFI data are collected on temporary plots that are measured only once. Trees equal or greater than 7.5 cm in diameter at breast height (dbh) are identified and measured. Tree radial growth in the five years preceding their measurement is assessed using tree cores. In order to develop a predictive growth model, we calculated the stand dendrometric values BA and Dg at the beginning of the five-year growing periods using the diameter measurements and the radial growth measurements.

Table 1. Differences between previous work and the work presented in this article. [a] the self-thinning boundary is used to calculate the pure and mixed stands density indices (DI) and to trigger mortality.

	Already published	Published here
Growth models in pure stands	Method: Vallet & Pérot (2011) Model calibrated on five species: Toïgo *et al.* (2015) with data from NFI 2006-2010 Model calibrated on two species: Vallet & Perot (2018) with data from NFI 2006-2012	Models (re)calibrated on 12 species with data from NFI 2006-2013
Models of the mixture effect on growth	Method: Vallet & Pérot (2011) Model calibrated on five species pairs: Toïgo *et al.* (2015) with data from NFI 2006-2010	Models (re)calibrated on 25 species pairs with data from NFI 2006-2013
Models of bark proportion		Models calibrated on nine species with data from Bouvet & Deleuze (2013)
Self-thinning boundary[a] and mortality	Method and calibration: Toïgo *et al.* (2018) (appendices) with data from NFI 2006-2012	Models recalibrated with more stands with data from NFI 2006-2012
Models of individual tree diameter distribution		Models calibrated on 12 species with data from NFI 2006-2013
Models of individual tree height		Models calibrated on 12 species with data from NFI 2006-2013
Models of individual tree volume		Models calibrated on 30 species with data from Deleuze *et al.* (2013)

All pure stands were considered, regardless of their location. However, we removed all pure *P. pinaster* stands with a Dg at the beginning of the five-year growing periods smaller than 5 cm. These stands are the result of two major storms: Martin (1999) and Klaus (2009) and have distinctive dynamics. In fact, *P. pinaster* has strong juvenile dynamics, and due to the reconstruction of initial dendrometric values and the minimum inventory dbh of 7.5 cm, stands with very small Dg were only very productive ones, which unbalanced the data. The problem did not appear for other species. We also removed stands with missing environmental variables. Finally, we only modelled the growth of species that were found on at least 100 plots. Table 2 presents the number of inventory plots in pure stands we obtained for those species.

3.1.2 Models. We modelled species growth in pure stand with a multiplicative model where species potential growth, estimated by a set of environmental variables (X_m), is limited by the stage of development of the stand, estimated by its mean quadratic diameter (Dg) and by a stand density index (DI). The generic form of our growth model is given by:

$$BAI_{ik} = f_{1,i}(X_m).f_{2,i}(DI_k).f_{3,i}(Dg_{ik}) + \epsilon_{ik} \quad (1)$$

where BAI_{ik} is the observation k of the basal area increment per hectare of species i over five years (in $m^2.ha^{-1}.yr^{-1}$), X_m is a species-specific combination of environmental variables, DI is the stand density index (see Equation 6), Dg is the mean quadratic diameter (in cm) and ϵ is the model residuals assumed to be normally distributed and independent. Dendrometric variables (DI and Dg) are those estimated at the beginning of the five-year growth period.

The f_1 function represents species potential growth and therefore corresponds to a species-specific site index (SI). It is given by:

$$f_{1,i}(X_m) = a_{0,i} + \sum_{m=1}^{n} (a_{m,i}.X_m) = SI_i \quad (2)$$

where SI_i is the site index of species i; and a_0 and a_m are parameters to be estimated. We chose to work with these site indices integrating environmental variables rather than with the site indices commonly used by foresters (defined by the dominant height of stands at a given age) as they are better adapted to describe or predict species growth over wide gradients of environmental conditions (Bontemps & Bouriaud, 2014).

Table 2. Number and features of inventory plots in pure stands for each species. Only species found on at least 100 plots are considered. Plots nb is the number of NFI plots used for the models calibration; Nb stems is the mean number of stems per hectare on which cores were collected, 52543 cores were collected in total; Dg is the mean quadratic diameter in cm; T is the mean annual temperature in °C over the 1981–2010 period and P is the annual sum of precipitation in mm over the 1981–2010 period. The climate data comes from the French national meteorological service and were processed following the Aurelhy method (Benichou & Le Breton, 1986). Column Sp indicates the abbreviations of species names used throughout this article.

		Plots	Nb stems	Dg		T		P	
Species	Sp	nb	mean	min	max	min	max	min	max
Quercus robur	*Qu. ro.*	489	332	2.6	106.5	6.9	14.3	612	1836
Quercus petraea	*Qu. pe.*	612	429	1.2	87.7	6.4	13.5	584	1741
Quercus pubescens	*Qu. pu.*	229	545	2.4	64.5	8.0	13.8	613	1607
Fagus sylvatica	*Fa. sy.*	553	387	2.2	117.0	5.8	13.6	641	2532
Pinus pinaster	*Pi. pi.*	1150	514	5.1	66.8	10.7	15.2	598	1526
Pinus sylvestris	*Pi. sy.*	615	636	0.8	59.0	5.9	13.4	636	2088
Pinus nigra subsp. *laricio*	*Pi. la.*	225	723	0.5	78.8	7.8	13.7	603	1687
Pinus nigra subsp. *nigra*	*Pi. ni.*	157	753	2.5	48.3	7.3	14.2	632	1469
Pinus halepensis	*Pi. ha.*	162	453	2.8	56.2	11.7	15.3	483	970
Abies alba	*Ab. al.*	262	483	3.5	87.0	5.4	11.2	771	2029
Picea abies	*Pi. ab.*	526	745	1.5	67.0	3.3	12.9	676	2622
Pseudotsuga menziesii	*Ps. me.*	542	518	1.3	61.2	6.5	12.9	630	2331

The f_2 and f_3 functions are detailed in Equation 3 and Equation 4. We retained two forms for the density related reduction function (f_2), leading to the following two equations:

$$BAI_{ik} = \left(a_{0,i} + \sum_{m=1}^{n} (a_{m,i}.X_{m,k}) \right).DI_k^{b_i}.\left(\frac{e^{(c_{1,i}.Dg_{ik})} + c_{2,i}}{1 + c_{2,i}} \right) + \epsilon_{ik} \quad (3)$$

$$BAI_{ik} = \left(a_{0,i} + \sum_{m=1}^{n} (a_{m,i}.X_{m,k}) \right).\left(\frac{(1+b_i).DI_k}{b_i + DI_k} \right).\left(\frac{e^{(c_{1,i}.Dg_{ik})} + c_{2,i}}{1 + c_{2,i}} \right) + \epsilon_{ik} \quad (4)$$

where a_0, a_m, b, c_1 and c_2 are parameters to be estimated. The f_2 and f_3 functions were chosen according to scatter plot analyses described in Toïgo *et al*. (2015) appendices.

Each species was assigned the model that best fitted its data, *i.e.* the model with the lower Akaike information criterion value (AIC, Akaike, 1974). We also selected environmental variables to be included in X_m according to the AIC. We used Equation 4 to model *Abies alba* and *Pseudotsuga menziesii* growth and Equation 3 to model the growth of all other species. To account for heteroscedasticity, a variance function based on the power of the fitted values was included in the model (Pinheiro & Bates, 2006). Models were fitted using the *gnls* function from the *nlme R* package (Pinheiro *et al*., 2020). The general fit statistics of the models as well as the environmental variables and their associated parameter estimates are presented in Table 4.

The stand density index DI is calculated independently from the growth model. It is defined relative to the species-specific self-thinning boundary which indicates for all values of Dg the maximum number of trees (N_{max}) above which some individuals may die. N_{max} is given by:

$$N_{max} = e^{p+q.log(Dg)} \quad (5)$$

where p and q are species-specific parameters which estimates are presented in Table 3. We fitted p and q using quantile regressions following the method presented in Toïgo *et al*. (2018).

Table 3. Parameter estimates of the self-thinning boundary. Values presented in this table differ from those presented in Toïgo *et al.* (2018) because here the self-thinning boundary is fitted over a larger number of NFI plots (Nb of pure plots). Correspondence between species full names and their abbreviations is presented in Table 2.

Species	Intercept (p)	Slope (q)	Nb of pure plots
Qu. ro.	12.60	-1.86	424
Qu. pe.	13.10	-2.01	494
Qu. pu.	11.98	-1.66	186
Fa. sy.	13.99	-2.18	517
Pi. pi.	12.48	-1.80	946
Pi. sy.	13.44	-2.03	544
Pi. la.	10.66	-1.14	155
Pi. ni.	12.90	-1.81	111
Pi. ha.	12.83	-1.92	135
Ab. al.	13.08	-1.86	261
Pi. ab.	12.88	-1.76	464
Ps. me.	11.15	-1.30	425

Table 4. Parameter estimates of pure stand growth models for each species. [a] calculated from aspect (in degrees) as follows: cos(aspect * 2π/360); [b] soil water holding capacity; [c] ecological regions. Monthly temperature and potential evapotranspiration (PET) values are 30-year means calculated over the 1981–2010 period. The climate data comes from the French national meteorological service and were processed following the Aurelhy method (Benichou & Le Breton, 1986). Soil water holding capacity (SWHC) is calculated using NFI soil description and Piedallu *et al.* (2018) method. pH and C/N ratio are bioindicated from NFI flora description (Gégout *et al.*, 2005). All other variables come from the NFI service. Correspondence between species full names and their abbreviations is presented in Table 2.

	Unit	Param.	*Qu. ro.*	*Qu. pe.*	*Qu. pu.*	*Fa. sy.*	*Pi. pi.*	*Pi. sy.*	*Pi. la.*	*Pi. ni.*	*Pi. ha.*	*Ab. al.*	*Pi. ab.*	*Ps. me.*
Equation			3	3	3	3	3	3	4	3	3	4	3	4
Power of variance model			0.912	1.047	0.906	0.817	0.942	0.823	0.762	1.015	0.826	0.771	0.951	0.892
Std dev of residual error (m^2/ha/5yrs)			0.434	0.342	0.388	0.421	0.379	0.456	0.582	0.424	0.577	0.535	0.363	0.343
Intercept	-	a_0	22.00	55.87	6.95	39.71	117.64	291.25	73.41	199.47	19.30	-7.43	94.06	71.36
Elevation	m	a_m				-0.0083					-0.0108			
Aspect (North)[a]	-	a_m					-4.369						-3.705	
Mask	gr	a_m								-0.549				-0.277
Feb. min T°	°C	a_m											5.566	
May min T°	°C	a_m												-4.301
Dec. min T°	°C	a_m		4.372										
Feb. mean T°	°C	a_m	0.790											
July max T°	°C	a_m						-3.302		-3.593				
June PET	mm	a_m										0.446		
May water budget	mm	a_m											0.179	
May water deficit	mm	a_m	-0.171											
June water deficit	mm	a_m					-0.374							
July water deficit	mm	a_m		-0.354										
May available water	mm	a_m							0.275					
SWHC[b]	mm	a_m	0.0282	0.0372	0.0305	0.0531								
SWHC[b] 1st horiz.	mm	a_m										0.5948	1.2870	

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	Unit	Param.	*Qu. ro.*	*Qu. pe.*	*Qu. pu.*	*Fa. sy.*	*Pi. pi.*	*Pi. sy.*	*Pi. la.*	*Pi. ni.*	*Pi. ha.*	*Ab. al.*	*Pi. ab.*	*Ps. me.*
pH	-	a_m						-23.311						2.941
pH^2	-	a_m						1.359						
C/N	-	a_m	-0.384	-0.592	-0.167	-0.417	-1.383	-4.455	-1.020	-1.621		-0.891	-0.938	
C/N^2	-	a_m						0.066						
Limestone bedrock	Boul.	a_m	-3.358	-11.097			-32.884						-8.100	
Hydromorphic soils	Boul.	a_m							-8.713					
Weakly hydromorphic soils	Boul.	a_m			2.426		6.394							
Carbonate rock	Boul.	a_m				2.625								
Brown soil	Boul.	a_m			0.840									
Rock outcrop	[0–10]	a_m					-1.403							
Rock content 40cm	[0–10]	a_m						-0.931	-2.705					
Slope	%	a_m	-0.079			-0.086	-0.197	-0.110		-0.350			-0.255	
GRECO A[c]	Boul.	a_m										17.83		
GRECO B[c]	Boul.	a_m			3.54	4.64								
GRECO C[c]	Boul.	a_m						15.37						
GRECO D[c]	Boul.	a_m		-7.94										
GRECO H[c]	Boul.	a_m						-7.52				-11.56		
GRECO I[c]	Boul.	a_m												-26.72
GRECO J[c]	Boul.	a_m					-9.6825							
Density (RDI)		b	0.588	0.625	0.631	0.585	0.699	0.591	0.603	0.693	0.600	0.234	0.637	0.450
Mean diameter (Dg)		c_1	-0.078	-0.111	-0.080	-0.083	-0.106	-0.146	-0.165	-0.158	-0.118	-0.077	-0.129	-0.157
Mean diameter (Dg)		c_2	0.098	0.063	0.345	0.073	0.051	0.048	0.092	0.058	0.169	0.119	0.104	0.180

DI is then given by:

$$DI = \frac{N}{N_{max}} \quad (6)$$

where N is the number of stems and N_{max} is the maximum number of trees given by the self-thinning boundary for the corresponding Dg. DI is therefore expected to range between 0 and 1. In Salem, when DI reaches 1, *i.e.* when N reaches N_{max}, mortality is triggered (see Section 3.4). This DI has been commonly used in pure stands (Charru *et al*., 2012; Reineke, 1933) but also in mixed stands (Del Río *et al*., 2016).

3.2 Models of the mixture effect on growth

3.2.1 Data. We modelled the effect of mixture on stand growth using French NFI data collected in mixed stands according to the following criteria:

- Stands had to be classified as even-aged stands by the French NFI.
- Stands must have not been logged in the five years preceding the measurements.
- The sum of the BA of the two species had to account for at least 80% of the total BA. In addition, each of the two species had to account for a greater proportion of the total BA than all the remaining species combined.
- In our approach, we compared the observed growth of mixed stands to their expected growth given by the models in pure stands (Vallet & Pérot, 2011). To avoid using our pure stand growth models outside their geographical range of validity, we only considered mixed stands in *sylvoécorégions* (homogeneous areas defined by the French NFI service; Inventaire-Forestier-National, 2011) where at least five pure stands were found for the adjustment of the growth models of the corresponding species.

Table 5 presents the number of inventory plots in mixed stands we obtained. We analysed the effect of mixture only for species pairs found on at least 20 plots. Altogether, 24 species pairs were studied.

3.2.2 Modelling of the mixture effect. The effect of mixture is defined here as the relative difference between the observed productivity of a species in a mixed stand and its expected productivity if it was in pure stand. It is calculated as follows:

$$u_{ij} = \frac{BAI_{ij} - E_i}{E_i} \quad (7)$$

Table 5. Number of inventory plots for each species pair. Only species pairs found on at least 20 plots (in bold) were considered. Overall, 33747 cores were collected in mixed stands. Correspondence between species full names and their abbreviations is presented in Table 2.

	Qu. ro.	*Qu. pe.*	*Qu. pu.*	*Fa. sy.*	*Pi. pi.*	*Pi. sy.*	*Pi. la.*	*Pi. ni.*	*Pi. ha.*	*Ab. al.*	*Pi. ab.*
Qu. pe.	**185**										
Qu. pu.	**61**	15									
Fa. sy.	**174**	**561**	6								
Pi. pi.	**106**	15	6	0							
Pi. sy.	**79**	**86**	**81**	**150**	3						
Pi. la.	14	11	2	7	**25**	**23**					
Pi. ni.	7	7	11	9	0	**77**	0				
Pi. ha.	0	0	17	0	0	0	0	1			
Ab. al.	2	**24**	0	**284**	0	**56**	0	1	0		
Pi. ab.	**29**	19	0	**126**	0	**79**	2	6	0	**278**	
Ps. me.	**23**	**24**	1	15	0	**34**	3	1	0	**68**	**63**

where u_{ij} is the mixture effect on the basal area increment of species i when mixed with species j; BAI_{ij} is the observed basal area increment of species i when mixed with species j; and E_i is the expected basal area increment of species i in a mixed stand predicted from its productivity in pure stand and weighted by its proportion in the mixed stand. E_i is therefore given by:

$$E_i = x_i.\widehat{BAI_i} \tag{8}$$

where $\widehat{BAI_i}$ is the basal area increment of species i predicted from pure stand growth models (Equation 3 and Equation 4); and x_i is the mixture proportion, calculated as the ratio of species i density index (DI_i) over the total density (DI). In mixed stands, the total DI is calculated as the sum of the species partial densities (DI_i) following the method presented in Del Río *et al*. (2016). In mixed stands DI is thus given by:

$$DI = \sum_i DI_i = \sum_i \frac{N_i}{e^{p+q.log(Dg_i)}} \tag{9}$$

where N_i is the number of trees of species i and DG_i is species i mean quadratic diameter; p and q are the same parameters as those used in Equation 5, which estimates are presented in Table 3.

After calculating the mixture effects u_{ij} (with Equation 7) for all plots, we modelled it as a function of mixture proportion as follows:

$$u_{ijk} = s_{0,ij}.(1 - x_{ik}) + \epsilon_{ik} \tag{10}$$

where u_{ijk} is the observation k of the mixture effect on the basal area increment of species i when mixed with species j and for a proportion of species i of x_{ik}; s_0 is a parameter to be estimated, representing the effect of species j on the basal area increment of species i, and ϵ is the residual error term. In this equation, the effect of mixture (u) tends towards 0 when the proportion of the species under consideration (x) tends towards 1 (*i.e.* when tending towards a pure stand). $s_0 > 0$ indicates a positive effect of mixture on the growth of species i while $s_0 < 0$ indicates a negative effect.

Several authors identified a variation of the mixture effect with site productivity (Paquette & Messier, 2011; Toïgo *et al*., 2015). To account for this, we first calculated the species-specific site indices (SI) for every mixed stand inventory plots using Equation 2 and the parameter estimates shown in Table 4. We then added the site indices to the mixture effect model (described in Equation 10) as follows:

$$u_{ijk} = (s_{0,ij} + s_{1,ij}.SI_{ik}).(1 - x_{ik}) + \epsilon_{ik} \tag{11}$$

where s_0 and s_1 are parameters to be estimated. $s_1 > 0$ indicates the mixture effect on species productivity increases with site productivity. Conversely, $s_1 < 0$, indicates the mixture effect decreases with site productivity. We fitted the models presented at Equation 10 and Equation 11 with the *gnls* function from the *nlme R* package (Pinheiro *et al*., 2020).

Salem uses either of these models to simulate species growth in mixed stands. If site productivity has a significant effect on the mixture effect, then Equation 11 is used to simulate the growth of the species under consideration. Conversely, if site productivity has a non-significant effect on the mixture effect, Salem only considers the average mixture effect and Equation 10 is used. Table 6 presents the parameter estimates of Equation 10 and Equation 11 used in Salem. All parameter estimates of Equation 10 and Equation 11 are presented in Tables A.1 and A.2 of the supplementary information (see extended data; Aussenac *et al*., 2021).

In Salem, species growth in mixed stands is therefore calculated by multiplying species growth in pure stands (BAI as defined in Equation 1) by the species proportion in the stand (x as defined in Equation 8) and by the mixture effect (u as defined in Equation 10 and Equation 11). Thus, if site productivity has a significant effect on the mixture effect, then species growth in mixed stand is calculated as follows:

$$BAI_{ijk} = SI_{ik}.f_{2,i}(DI_k).f_{3,i}(Dg_{ik}).x_{ik}.(1+(s_{0,ij} + s_{1,ij}.SI_{ik}).(1 - x_{ik})) + \epsilon_{ijk} \tag{12}$$

Table 6. Estimates of the s_0 ans s_1 parameters in Equation 10 and Equations 11 used in Salem. ns.: non-significant. For a given species pair, if s_1 is non-significant, then the s_0 estimate presented comes from Equation 10. On the contrary, if s_1 is significant, then both s_0 and s_1 estimates come from Equation 11. Correspondence between species full names and their abbreviations is presented in Table 2.

			Effect of										
		param.	*Qu. ro.*	*Qu. pe.*	*Qu. pu.*	*Fa. sy.*	*Pi. pi.*	*Pi. sy.*	*Pi. la.*	*Pi. ni.*	*Ab. al.*	*Pi. ab.*	*Ps. me.*
On the growth of	*Qu. ro.*	s_0		ns.	ns.	ns.	0.692	0.374				ns.	ns.
		s_1		ns.	ns.	ns.	ns.	ns.				ns.	ns.
	Qu. pe.	s_0	0.215			0.618		0.253			ns.		ns.
		s_1	ns.			-0.022		ns.			ns.		ns.
	Qu. pu.	s_0	2.133					ns.					
		s_1	-0.323					ns.					
	Fa. sy.	s_0	2.299	0.833				0.714			0.544	0.435	
		s_1	-0.058	-0.019				ns.			ns.	ns.	
	Pi. pi.	s_0	0.384						ns.				
		s_1	ns.						ns.				
	Pi. sy.	s_0	ns.	ns.	0.902	0.110			1.025	ns.	-0.406	ns.	ns.
		s_1	ns.	ns.	ns.	-0.012			ns.	ns.	ns.	ns.	ns.
	Pi. la.	s_0					ns.	ns.					
		s_1					ns.	ns.					
	Pi. ni.	s_0						1.419					
		s_0						-0.017					
	Ab. al.	s_0		2.080		0.996		0.991				0.910	2.371
		s_1		-0.060		-0.032		ns.				-0.024	-0.060
	Pi. ab.	s_0	ns.			ns.		0.417			1.792		1.176
		s_1	ns.			ns.		ns.			-0.024		-0.016
	Ps. me.	s_0	ns.	ns.				ns.			0.259	ns.	
		s_1	ns.	ns.				ns.			ns.	ns.	

On the other hand, if site productivity has a non-significant effect on the mixture effect, then species growth in mixed stand is calculated as follows:

$$BAI_{ijk} = SI_{ik}.f_{2,i}(DI_k).f_{3,i}(Dg_{ik}).x_{ik}.(1+(s_{0,ij}).(1-x_{ik}))+\epsilon_{ijk} \quad (13)$$

3.2.3 Results synthesis. As an example, Figure 2 synthesises the results obtained on the mixture effect on fir (*Abies alba*) growth. At the poorest sites (*i.e.* at sites with lowest SI) *Quercus petraea* and *Fagus sylvatica* tend to increase fir growth while they tend to decrease its growth at the richest sites (*i.e.* at sites with highest SI). At the poorest sites, *Picea abies* and *Pseudotsuga menziesii* also tend to increase fir growth but as sites become richer, this effect tends towards zero. For those two species a positive average mixture effect is also present. As for *Pinus sylvestris*, it increases fir growth by about 50% whatever the site richness, the effect of site richness being non-significant.

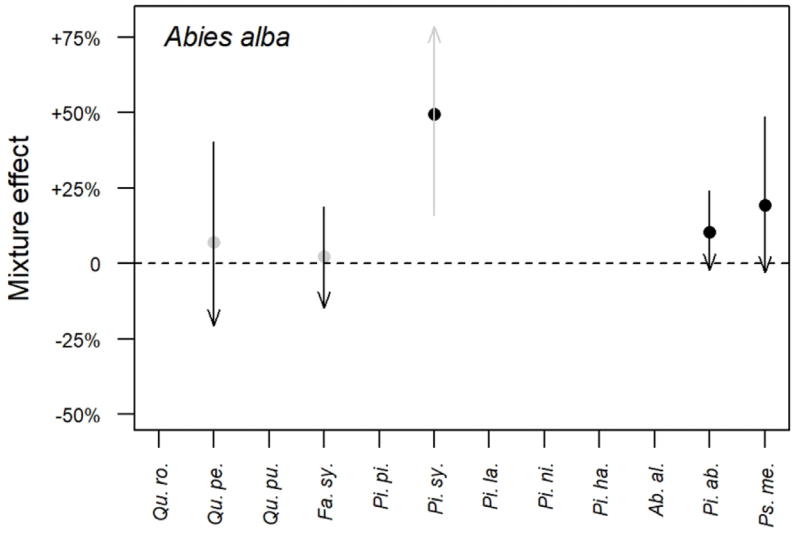


Figure 2. Mixture effect on fir (*Abies alba*) growth. Dots indicate the average mixture effect calculated at Equation 10. Arrows indicate the variation of the mixture effect with site productivity calculated at Equation 11: the beginning of the arrows represents the poorest sites (5% quantile) while the tip of the arrows represents the richest sites (95% quantile). A grey colour indicates that the effect is non-significant, while a black colour indicates a significant effect. Correspondence between species full names and their abbreviations is presented in Table 2.

The mixture effect on the other species is presented in Figure A.1 of the supplementary information (see extended data; Aussenac *et al*., 2021). Overall, we found the mixture effect on species growth was most often positive (*i.e.* $s_0>0$ in Equation 10) when significant. Only *F. sylvatica* and *A. alba* had a negative effect on *P. sylvestris* growth. In addition, we found the effect of site productivity on the mixture effect was always negative ($s_1<0$ in Equation 11) when significant. This indicates the effect of mixture is always stronger at poor sites than at richer sites, consistent with the stress gradient hypothesis (Bertness & Callaway, 1994). These results complement those presented in Toïgo *et al*. (2015) for five species pairs.

3.3 Models of bark proportion

***3.3.1 Data*.** We calibrated our bark models using measurements of bark proportion (expressed as a proportion of the trees BA) collected by the French NFI service. We had at our disposal, for nine species or groups of species and for four to five dbh classes: the number of sampled trees, their mean dbh and the mean and variance of their bark proportion. All data can be found in Bouvet & Deleuze (2013). In this dataset, *Q. robur* and *Q. petraea* are not differentiated and no data are available for *P. halepensis*. We therefore built a single bark model for both *Quercus* species and Salem applies the *P. sylvestris* bark model to *P. halepensis* because these two species have a very similar bark proportion (Deleuze, personal communications).

***3.3.2 Models*.** We built three different models to describe the relationship between bark proportion (BP) and dbh. Each species was assigned the model that best fitted its data, *i.e.* the model with the lower AIC value (Table 7). We calibrated the models by maximising likelihood, taking into account the error of each bark proportion value. We calculated this error using the number of sampled trees and the variance associated to each bark proportion value. Models were fitted with the *mle2* function from the *bbmle R* package. The models parameter estimates are presented in Table 7 and the models predictions are presented in Figure 3. For tree diameters below 10 cm, or above the maximum dbh value indicated in Table 7, Salem uses the predicted bark proportion at 10 cm or at the maximum dbh value in order to avoid using the models outside their calibration range. We defined the minimum dbh value of 10 cm and the maximum dbh values of 60 or 80 cm by rounding the species minimum value of dbh down to the nearest ten and their maximum value of dbh to the upper ten.

Table 7. Bark models and their parameter estimates for each species or group of species. Standard errors are shown in parentheses. Levels of significance: *p<0.05, **p<0.01, ***p<0.001. Correspondence between species full names and their abbreviations is presented in Table 2.

Species	Model	a	b	c	Max dbh
Quercus spp.	$a + b * dbh + c/dbh$	0.1426*** (0.0011)	-0.000496*** (0.000018)	1.028*** (0.013)	80
Fa. sy.	$a + b * dbh + c/dbh$	0.0502*** (0.0007)	-0.000042*** (0.000012)	0.162*** (0.008)	80
Pi. pi.	$a + b * dbh + c/dbh$	0.4792*** (0.004)	-0.003252*** (0.000074)	-0.765*** (0.043)	80
Pi. sy.	$a + b * dbh$	0.2711*** (0.001)	-0.00128*** (0.000032)		60
Pi. la.	$a + b * dbh + c * dbh^2$	0.2948*** (0.0045)	-0.000679* (0.000344)	-1.21e-5* (0.59e-5)	60
Pi. ni.	$a + b * dbh + c/dbh$	0.3311*** (0.0079)	-0.001611*** (0.000161)	-0.263*** (0.082)	60
Ab. al.	$a + b * dbh + c/dbh$	0.1084*** (0.0016)	-0.000139*** (0.000025)	0.148*** (0.019)	80
Pi. ab.	$a + b * dbh + c/dbh$	0.0864*** (0.0015)	0.000151*** (0.000027)	0.522*** (0.016)	80
Ps. me.	$a + b * dbh + c/dbh$	0.1659*** (0.0018)	-0.001409*** (0.000136)	3.0e-5*** (0.2e-5)	60

3.4 Mortality

Mortality is triggered when stand density exceeds the self-thinning boundary, *i.e.* when DI (in Equation 6 or Equation 9) is greater than or equal to 1. In that case, DI is reduced to 1 using the Kg parameter, with

$$Kg = Dg_d^2 \big/ Dg^2 = 0.68 \tag{14}$$

where Dg_d is the mean quadratic diameter of killed trees and Dg is the mean quadratic diameter of trees before mortality is applied. This value of Kg = 0.68 is based on an analysis of the French NFI mortality data.

To reduce DI to 1, the number of trees in the stand is reduced while the mean quadratic diameter is increased, which amounts to preferentially killing small trees. In mixed stands, the number of trees killed for each species is defined according to their proportion in the stand before mortality process.

In practice in Salem, the number of trees and the mean quadratic diameter after mortality are found using a system of two equations: Equation 6, which links DI, Dg and N, and Equation 14, which quantifies the size of the trees to be killed, while knowing that DI after mortality equals 1. This system cannot be solved analytically; we use a dichotomy algorithm to obtain the post-mortality values.

3.5 Models of individual tree diameter distribution

3.5.1 Data. We worked with the same NFI plots as those used to calibrate our growth models, *i.e.* with NFI data collected between 2006 and 2013 in pure stands (Table 2). We used the tree diameter measurements to calibrate our distribution models.

3.5.2 Models. We built species-specific models predicting the diameter distribution of individual trees from their mean quadratic diameter and their total number in the stands. For that, we followed a three-step procedure: first, we grouped the NFI plots by Dg classes. Second, within each class we fitted a normal distribution

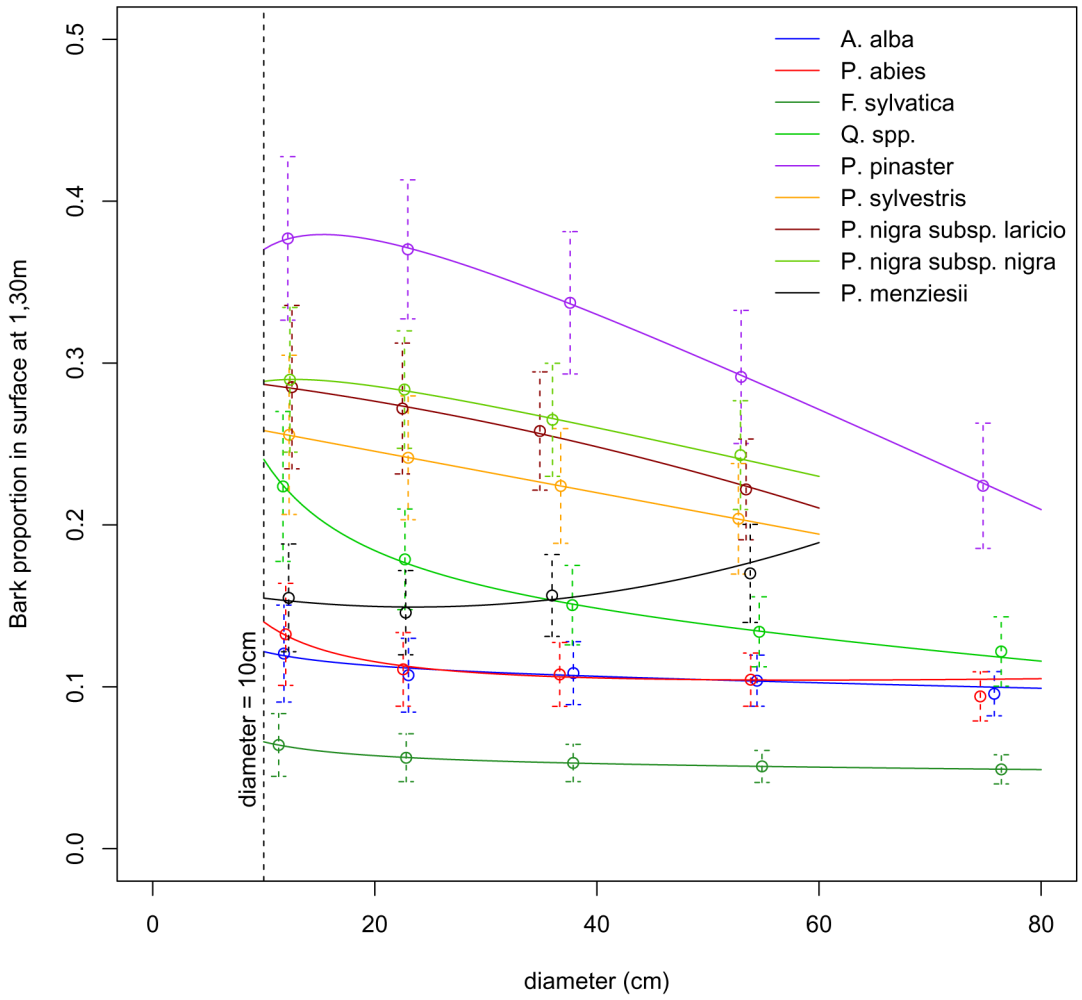


Figure 3. Prediction of bark proportion as a function of diameter at breast heigh (dbh). Dots show the mean bark proportion for each species or group of species and each dbh class. Dashed vertical lines show the dispersion of the bark proportion measures. Solid lines show the models predictions.

to the observed distribution of individual tree diameter, *i.e.* the number of stems per diameter value (Figure A.2 of the supplementary information, see extended data; Aussenac *et al.*, 2021). Each fit provides a standard deviation (σ) for the normal distribution. Third, we modelled the obtained standard deviations as a function of the mean quadratic diameter (Figure 4). For that we used the following sigmoidal equation (Chapman-Richards type model; Pienaar & Turnbull, 1973):

$$\sigma_{ik} = \alpha_i . \left(1 - e^{(-\gamma_i \cdot Dg_{ik})}\right)^{\beta_i} + \epsilon_{ik} \tag{15}$$

where σ_{ik} corresponds to the observation k of the standard deviations of the normal distributions fitted at the second step for species i; Dg corresponds to the mean quadratic diameter of all plots within each diameter class; α, β, and γ are three parameters to be estimated and ϵ is the residual error term. The parameter estimates are presented in Table 8.

In practice in Salem, to generate the diameter distribution of a stand we calculate the number of trees for each diameter class within the stand using the following equation:

$$N_c = N_{tot} . W_c . \frac{1}{\sigma . \sqrt{2\pi}} . e^{-\frac{1}{2}\frac{(dbh_c - Dm)^2}{\sigma^2}} \tag{16}$$

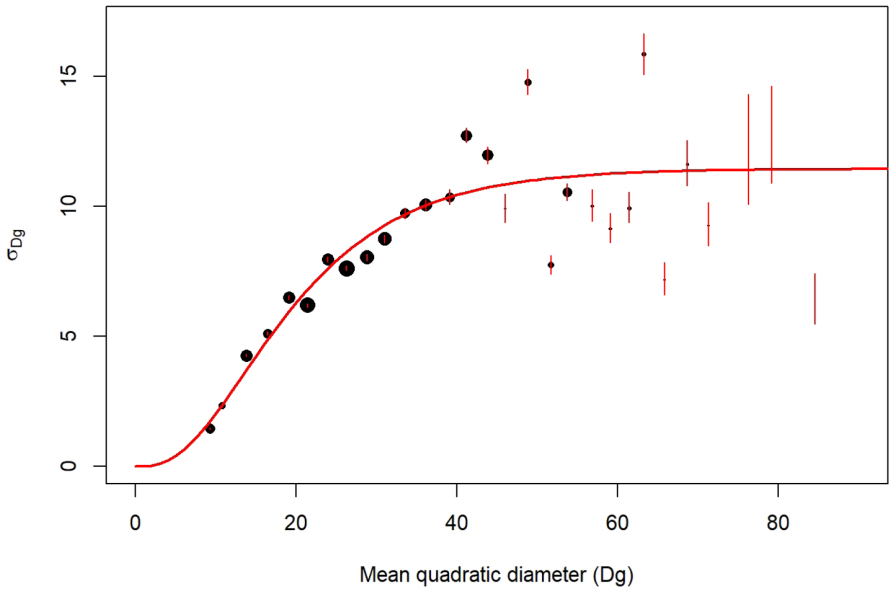


Figure 4. *σ* parameter variation with mean quadratic diameter (Dg in cm). Example for *Quercus robur*. Point size is proportional to the number of NFI plots. The red segments are the confidence interval of σ. The red line corresponds to the predictions of σ modelled with Equation 15.

where N_c is the number of trees of diameter class c, N_{tot} is the total number of trees within the stand, W_c is the c class width, σ is predicted from Equation 15, dbh_c is the central dbh value of diameter class c and Dm is the arithmetic mean diameter of the diameter distribution. Thanks to the properties of the normal distribution, the arithmetic mean Dm and the quadratic mean Dg are linked by the following equation:

$$Dm = \sqrt{Dg^2 - \sigma^2} \tag{17}$$

3.6 Models of individual tree height

3.6.1 Data. We calibrated our height-circumference relationship models using the same data used to calibrate our growth models, *i.e.* French NFI data collected between 2006 and 2013 in pure stands. However, here we excluded trees with defects: broken trees and pollards. Differences in the number of plots used to calibrate our growth models and our height-circumference relationship models is due to the fact that (1) here we removed a few plots consisting solely of broken trees and/or pollards and (2) here we considered pure stands excluded for growth modelling: those with missing environmental variables and *P. pinaster* stands with a quadratic diameter smaller than 5 cm. The number of plots and trees per species are presented in Table 9.

3.6.2 Models. We modelled tree height from tree circumference while taking into account the effects of stand development stage and site productivity. Our models are given by the following generic equation:

$$h_{tot,ik} = 1.3 + (\alpha_i + g_{1,i}(Dg_{ik}) + g_{2,i}(SI_{ik}))\left(1 - e^{-\beta_i c_{130,ik}^{\gamma_i}}\right) + \epsilon_{ik} \tag{18}$$

where $h_{tot,ik}$ and $c_{130,ik}$ are the total height and circumference at 1.30 m of tree k of species i; Dg is the stand mean quadratic diameter used as a proxy of the stand development stage; SI is the site index as described in Equation 2; α, β and γ are parameters to be estimated and ϵ is the residual error term. Functions g_1 and g_2 could be either linear ($a.x$), quadratic ($a.x + b.x^2$), exponential towards an asymptote ($a(1 - e^{-b.x})$) or logarithmic ($a.ln(x)$).

For each species, we selected the combination of g_1 and g_2 functions giving the lowest AIC value. When the difference between models was less than 4 AIC points, monotonic functions were chosen in preference to polynomial functions to avoid possible prediction errors outside of the calibration range. The selected models are presented in Table 10 and their associated parameter estimates are presented in Table 11. As an example, height predictions for *Quercus robur* are presented in Figure 5.

Table 8. Species-specific parameter estimates for the models of individual tree diameter distribution. Levels of significance: * p<0.05; ** p<0.01; *** p<0.001; ns.: non-significant. Correspondence between species full names and their abbreviations is presented in Table 2.

Species	Parameter	Estimate	Std. error	Significance
Qu. ro.	α	11.43876	0.72894	***
	γ	0.09017	0.02740	**
	β	3.33197	1.71724	ns.
Qu. pe.	α	10.97643	0.58223	***
	γ	0.08640	0.01970	***
	β	3.22690	1.17333	*
Qu. pu.	α	7.72100	0.39835	***
	γ	0.18849	0.04261	**
	β	8.74034	5.05425	ns.
Fa. sy.	α	12.24093	0.65589	***
	γ	0.07743	0.01841	***
	β	2.85483	1.04041	**
Pi. pi.	α	6.65825	0.23426	***
	γ	0.08697	0.01528	***
	β	2.14814	0.52160	***
Pi. sy.	α	8.56996	0.90385	***
	γ	0.08513	0.03516	*
	β	2.10282	1.07330	ns.
Pi. la.	α	7.57343	1.01858	***
	γ	0.07817	0.02498	*
	β	2.57583	0.84827	*
Pi. ni.	α	6.35432	0.45823	***
	γ	0.16440	0.05525	*
	β	5.72509	4.07794	ns.
Pi. ha.	α	8.95631	0.50538	***
	γ	0.18881	0.05684	**
	β	9.68719	7.70238	ns.
Ab. al.	α	13.25233	1.49189	***
	γ	0.05094	0.02006	*
	β	1.76612	0.73376	*
Pi. ab.	α	30.18095	62.23563	ns.
	γ	0.00754	0.02397	ns.
	β	0.94366	0.38691	*
Ps. me.	α	7.38019	0.32657	***
	γ	0.12265	0.02533	***
	β	4.59548	1.80814	*

Table 9. Number and features of inventory plots in pure stands used for the height-circumference relationship models for each species. Plots nb is the number of NFI plots used for the models calibration; Nb stems is the total number of trees at the plots; c_{130} corresponds to the tree circumferences in cm and h_{tot} to the tree heights in m. Correspondence between species full names and their abbreviations is presented in Table 2.

Species	Plots nb	Nb stems total	c_{130}		h_{tot}	
			min	max	min	max
Qu. ro.	487	2903	24	338	3.9	37.8
Qu. pe.	612	4310	24	370	3.7	43.1
Qu. pu.	229	1303	24	314	3.0	30.0
Fa. sy.	554	4412	24	427	3.0	45.0
Pi. pi.	1276	8597	24	349	3.5	38.4
Pi. sy.	613	4797	24	259	2.5	33.4
Pi. la.	224	1725	24	362	3.1	36.5
Pi. ni.	156	1167	24	200	3.2	28.7
Pi. ha.	165	1153	24	249	3.4	24.8
Ab. al.	261	2782	24	345	4.4	42.7
Pi. ab.	525	5019	24	347	3.8	42.8
Ps. me.	542	4646	24	246	4.3	43.6

Table 10. Height-circumference models used for each species. Correspondence between species full names and their abbreviations is presented in Table 2.

Species	Models
Qu. ro.	$(\alpha + a_{1.1}(1 - e^{-a_{1.2}Dg}) + a_2 SI)(1 - e^{-\beta c_{130}^{\gamma}}) + 1.3$
Qu. pe.	$(\alpha + a_1 Dg + a_{2.1} SI + a_{2.2} SI^2)(1 - e^{-\beta c_{130}^{\gamma}}) + 1.3$
Qu. pu.	$(\alpha + a_{2.1} SI + a_{2.2} SI^2)(1 - e^{-\beta c_{130}^{\gamma}}) + 1.3$
Fa. sy.	$(\alpha + a_{1.1}(1 - e^{-a_{1.2}Dg}) + a_{2.1} SI + a_{2.2} SI^2)(1 - e^{-\beta c_{130}^{\gamma}}) + 1.3$
Pi. pi.	$(\alpha + a_{1.1} Dg + a_{1.2} Dg^2 + a_{2.1} SI + a_{2.2} SI^2)(1 - e^{-\beta c_{130}^{\gamma}}) + 1.3$
Pi. sy.	$(\alpha + a_{1.1}(1 - e^{-a_{1.2}Dg}) + a_2 SI)(1 - e^{-\beta c_{130}^{\gamma}}) + 1.3$
Pi. la.	$(\alpha + a_{1.1}(1 - e^{-a_{1.2}Dg}) + a_{2.1} SI + a_{2.2} SI^2)(1 - e^{-\beta c_{130}^{\gamma}}) + 1.3$
Pi. ni.	$(\alpha + a_{1.1}(1 - e^{-a_{1.2}Dg}))(1 - e^{-\beta c_{130}^{\gamma}}) + 1.3$
Pi. ha.	$(\alpha + a_{1.1}(1 - e^{-a_{1.2}Dg}) + a_2 log(SI))(1 - e^{-\beta c_{130}^{\gamma}}) + 1.3$
Ab. al.	$(\alpha + a_{1.1}(1 - e^{-a_{1.2}Dg}) + a_2 log(SI))(1 - e^{-\beta c_{130}^{\gamma}}) + 1.3$
Pi. ab.	$(\alpha + a_{1.1}(1 - e^{-a_{1.2}Dg}) + a_{2.1}(1 - e^{-a_{2.2}SI}))(1 - e^{-\beta c_{130}^{\gamma}}) + 1.3$
Ps. me.	$(\alpha + a_{1.1}(1 - e^{-a_{1.2}Dg}))(1 - e^{-\beta c_{130}^{\gamma}}) + 1.3$

Table 11. Parameter estimates of the height-circumference models for each species. Standard errors are shown in parentheses. Levels of significance: * p<0.1; ** p<0.05; *** p<0.01; ns.: non-significant. Correspondence between species full names and their abbreviations is presented in Table 2.

	Qu. ro.	*Qu. pe.*	*Qu. pu.*	*Fa. sy.*	*Pi. pi.*	*Pi. sy.*	*Pi. la.*	*Pi. ni.*	*Pi. ha.*	*Ab. al.*	*Pi. ab.*	*Ps. me.*
α	-1.3624ns (4.0668)	2.1484* (1.2733)	-3.7295*** (1.4019)	-5.8023*** (1.9697)	-5.1515*** (0.7774)	-4.4002** (1.8007)	-20.9182*** (4.5868)	-6.342* (3.244)	-26.1684*** (8.0869)	0.8475* (2.4901)	-30.0783*** 8.4595	-5.5879*** (1.7884)
a_1		0.1692*** (0.0065)										
$a_{1.1}$	17.9437*** (4.0668)			15.8848*** (1.5124)	0.6972*** (0.026)	16.303*** (1.4992)	45.475*** (5.212)	29.5273*** (3.5529)	24.4999*** (7.0713)	23.0394*** (1.6357)	45.4929*** 3.4257	50.3923*** (2.8952)
$a_{1.2}$	0.099*** (0.0159)			0.0491*** (0.0071)	-0.0058*** (0.0004)	0.0656*** (0.0097)	0.0645*** (0.0059)	0.0725*** (0.0101)	0.1001*** (0.0164)	0.0411*** (0.0059)	0.0897*** 0.0052	0.0487*** (0.0027)
a_2	0.4222*** (0.0336)					0.1541*** (0.0049)			7.659*** (1.7059)	3.1832*** (0.3481)		
$a_{2.1}$		0.8495*** (0.0815)	5.4023*** (0.4581)	1.1844*** (0.065)	0.3408*** (0.0246)		0.3808*** (0.095)				17.3624** 7.4193	
$a_{2.2}$		-0.0114*** (0.0013)	-0.3118*** (0.0341)	-0.0145*** (0.0011)	-0.0026*** (0.0002)		-0.0037*** (0.0008)				0.0497*** 0.0127	
β	0.0314*** (0.005)	0.0067*** (0.0008)	0.0102*** (0.0026)	0.0137*** (0.0016)	0.0238*** (0.0025)	0.0168*** (0.003)	0.0348*** (0.007)	0.0224*** (0.0069)	0.0689*** (0.0131)	0.0075*** (0.0009)	0.016*** 0.0019	0.0355*** (0.0046)
γ	0.8341*** (0.046)	1.2896*** (0.0312)	1.1533*** (0.0727)	1.0219*** (0.0313)	0.9357*** (0.0288)	1.0502*** (0.0519)	0.7536*** (0.0701)	0.9475*** (0.0958)	0.6054*** (0.0968)	1.1343*** (0.0328)	0.9984*** 0.0337	0.7609*** (0.0441)

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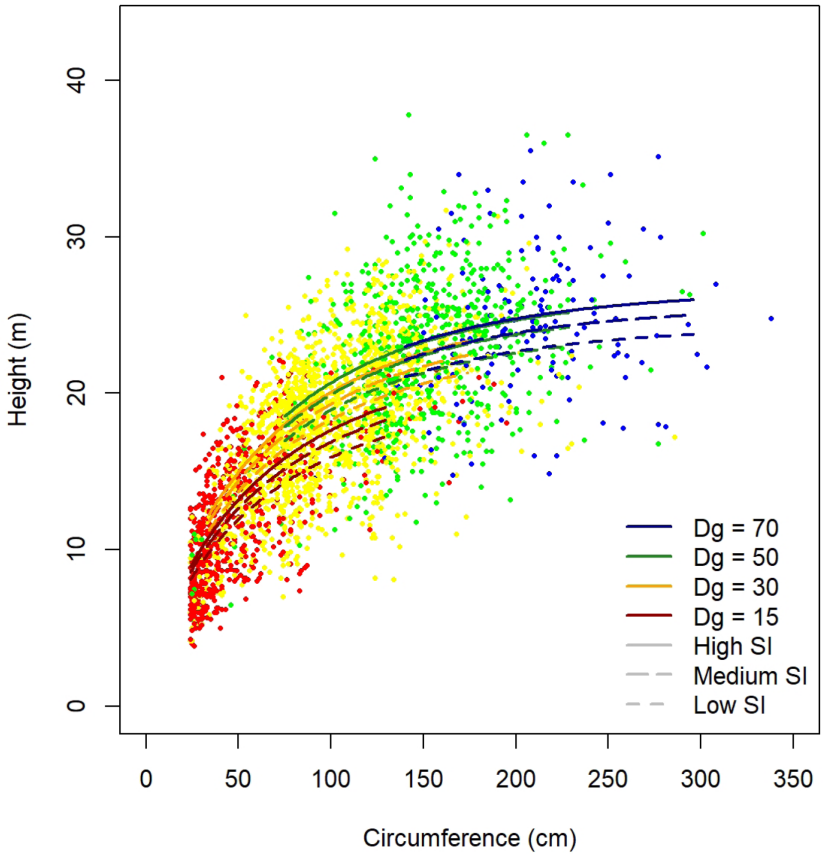


Figure 5. Height predictions for *Quercus robur* as a function of tree circumference, stand quadratic diameter (Dg) and site index (SI).

3.7 Models of individual tree volume

3.7.1 Data. The models of individual tree volume were fitted to a large dataset that was mainly collected by the French National Institute of Agricultural Research between 1920 and 1983. During that period, a large sample of harvested trees was selected and the volume of each individual tree was measured from the base up to a 7 cm small-end diameter (Deleuze *et al.*, 2013). This large dataset was later complemented by two field campaigns in 2009 and 2010. Before screening, it included 44,173 volume measurements of individual trees. Trees that did not reach the French commercial limit (dbh = 7.5 cm) were discarded.

The dataset originally included 52 species, but some of them were scarce and therefore we focused on those for which we had at least 30 volume observations. After discarding the scarce species, the dataset that was used to fit the species-specific models contained 42,959 observations shared among 30 species. The characteristics of the dataset for the species relevant to Salem are shown in Table 12. The information on the other species can be found in Table A.3 of the supplementary information (see extended data; Aussenac *et al.*, 2021).

3.7.2 Models. We modelled tree volume from their dbh and total height. We built species-specific models to account for the differences in tree form across species. These models were given by:

$$v_{ik} = \beta_{1,i}\frac{h_{tot,ik}}{dbh_{ik}} + (\beta_{2,i} + \beta_{3,i} dbh_{ik})\frac{\pi dbh_{ik}^2 h_{tot,ik}}{40} + \epsilon_{ik} \quad (19)$$

where v_{ik} is the commercial volume (dm^3) of tree k of species i, that is the over bark volume of the bole from the base to a small-end diameter of 7 cm excluding the branches; h_{tot} is the tree total height (m); dbh is the tree diameter (cm); β_1, β_2, and β_3 are parameters to be estimated and is the residual error term. This error term is

Table 12. Mean diameter at breast heigh (dbh), height and volume of trees in the volume dataset, for species that are relevant to Salem. Minimum and maximum values are shown in parentheses. [a]Number of observations. Correspondence between species full names and their abbreviations is presented in Table 2. [b]Undistinguished *Quercus sp.* used for *Quercus pubescens.*

Species	n[a]	dbh (cm)	height (m)	volume (dm³)
Qu. ro.	84	15.6 (7.6, 27.7)	14.6 (6.0, 20.8)	174 (17, 711)
Qu. pe.	8018	20.9 (7.6, 146.7)	19.8 (2.0, 42.0)	604 (4, 15991)
Qu. sp.[b]	1416	23.2 (7.6, 101.9)	18.2 (7.0, 42.5)	715 (11, 10114)
Fa. sy.	7099	24.2 (7.6, 108.5)	22.2 (3.0, 44.0)	776 (6, 16234)
Pi. pi.	2881	19.8 (7.6, 66.5)	11.6 (4.5, 27.0)	218 (5, 4125)
Pi. sy.	5216	23.7 (7.6, 81.8)	19.3 (4.0, 31.2)	552 (6, 7862)
Pi. la.	1163	28.3 (8.0, 70.3)	22.4 (8.9, 36.4)	907 (18, 5908)
Pi. ni.	847	19.2 (7.6, 47.7)	15.6 (6.2, 27.9)	294 (7, 1739)
Pi. ha.	257	24.8 (7.6, 64.0)	14.6 (7.8, 21.5)	401 (13, 2315)
Ab. al.	5835	32.9 (7.6, 103.0)	23.7 (4.0, 41.0)	1528 (14, 11878)
Pi. ab.	2715	23.9 (7.6, 79.9)	21.5 (5.5, 43.5)	803 (7, 9215)
Ps. me.	2355	18.6 (7.6, 57.3)	17.7 (5.4, 41.5)	365 (7, 4425)

assumed to be normally distributed with mean 0 and variance $dbh_{ik}^4\sigma_i^2$. Term $\pi dbh_{ik}^2 h_{tot,ik}/40$ represents the volume of a cylinder and the factor 40 ensures a proper unit conversion. Parameter β_2 is considered as a form factor, that is the ratio between the volume of the tree and that of the cylinder (Pretzsch, 2009, p. 183). Parameter β_3 represents an adjustment to this form factor that increases or decreases with the diameter. Parameter β_1 is related to the non commercial part of the the tree, that is the part beyond the 7-cm small-end diameter. Its value is expected to be negative.

The model shown in Equation 19 was fitted to each species. Whenever an effect was found to be non-significant, it was removed from the model. The parameter estimates for the species that are relevant to Salem are presented in Table 13. For the other species, the reader is referred to Table A.4 of the supplementary information (see extended data; Aussenac *et al.*, 2021).

4 Operation

Salem runs on the Capsis open software framework (Dufour-Kowalski *et al.*, 2012) which ensures its availability and code continuity and facilitates interactions with other forest models and simulators. It is distributed under a LGPL license and is therefore free and open source. As the underlying code of Capsis and Salem is in Java, simulations can be performed with any operating system (Windows, Linux, or Mac). Finally, Salem's clear graphical user interface makes it easy to use for non-modellers.

4.1 Stand initialisation

After choosing Salem from the menu showing the different models available in Capsis, users must first specify the composition of the stand to simulate and a starting simulation date. For this demonstration, we choose to simulate a stand made up of spruce (*Picea abies*) and beech (*Fagus sylvatica*) from 2000 onwards (Figure 6).

Then, users must specify the site indices for the simulated species. These site indices are those used in our growth models and calculated at Equation 2. If users cannot provide the site indices, they can set their values using their observed distribution at French NFI plots. Here, we set the spruce site index to 65.4, a value greater than 58.6% of the site indices observed in the French NFI stands composed of spruce and beech. We set the beech site index to 26.8, a value greater than 68.2% of the site indices observed in the same stands (Figure 7).

Table 13. Species-specific parameter estimates of the volume models (Equation 19), for species that are relevant to Salem. Standard errors are shown in parentheses. All the parameter estimates are highly significant ($p < 0.001$). Correspondence between species full names and their abbreviations is presented in Table 2. [a]Undistinguished *Quercus sp.* used for *Quercus pubescens.*

Species	β_1	β_2	β_3	σ^2
Qu. ro.		5.057×10^{-1} (0.074×10^{-1})		6.355×10^{-3}
Qu. pe.	-4.438 (0.193)	5.455×10^{-1} (0.016×10^{-1})	-1.397×10^{-3} (0.041×10^{-3})	6.835×10^{-3}
Qu. sp.[a]	-3.319 (0.387)	5.664×10^{-1} (0.040×10^{-1})	-1.778×10^{-3} (0.102×10^{-3})	6.094×10^{-3}
Fa. sy.	-4.498 (0.195)	5.107×10^{-1} (0.017×10^{-1})	-1.332×10^{-3} (0.045×10^{-3})	8.037×10^{-3}
Pi. pi.	-1.712 (0.430)	5.130×10^{-1} (0.051×10^{-1})	-1.124×10^{-3} (0.196×10^{-3})	2.363×10^{-3}
Pi. sy.	-2.247 (0.271)	4.985×10^{-1} (0.027×10^{-1})	-1.212×10^{-3} (0.081×10^{-3})	6.348×10^{-3}
Pi. la.		5.215×10^{-1} (0.045×10^{-1})	-1.271×10^{-3} (0.129×10^{-3})	8.547×10^{-3}
Pi. ni.	-8.427 (0.768)	5.857×10^{-1} (0.093×10^{-1})	-2.748×10^{-3} (0.349×10^{-3})	4.618×10^{-3}
Pi. ha.		5.258×10^{-1} (0.091×10^{-1})	-2.300×10^{-3} (0.314×10^{-3})	3.110×10^{-3}
Ab. al.	-4.523 (0.494)	6.011×10^{-1} (0.019×10^{-1})	-2.243×10^{-3} (0.039×10^{-3})	7.116×10^{-3}
Pi. ab.	-8.666 (0.278)	5.839×10^{-1} (0.026×10^{-1})	-2.679×10^{-3} (0.066×10^{-3})	5.747×10^{-3}
Ps. me.	-7.150 (0.316)	5.431×10^{-1} (0.038×10^{-1})	-2.951×10^{-3} (0.121×10^{-3})	4.493×10^{-3}

In the same window, users must define the initial dendrometric values. The stand total density and the proportion represented by the first species must be provided either in terms of basal area or in terms of density index (DI as defined in Equation 1). In addition, species mean quadratic diameter must be specified. Here, we set the stand total basal area to 32 $m^2.ha^{-1}$ and defined 17.5 cm and 12.2 cm as mean quadratic diameter for spruce and beech, respectively. In this window, the corresponding number of stems for each species and the effect of each species on the other species growth are shown.

4.2 Running simulations and implementing management operations

Users must define a final date for the simulation. If they want to simulate silvicultural operations, they can set an initial and a final density (DI as defined in Equation 1; Figure 8). Instead, a final mean quadratic diameter can be provided. In that case, the simulation ends when it is reached. Here, we set the initial density to 0.6 and the final density to 0.8. In doing so, the prescribed density will gradually increase during the simulation. Variation bounds for the prescribed density must also be provided. Here, we set the variation bounds to 0.05. Thus, if the stand density exceeds the prescribed density + 0.05, then a thinning is carried out to bring the stand back to a density equal to the prescribed density - 0.05. Users must also set a minimum number of years between two thinnings and provide a Kg value (as defined in Equation 14). Here we set the minimum period between two thinnings to five years and specified Kg =0.95. Finally, users must specify the target proportion of the first species. Here, we set this proportion to 0.6.

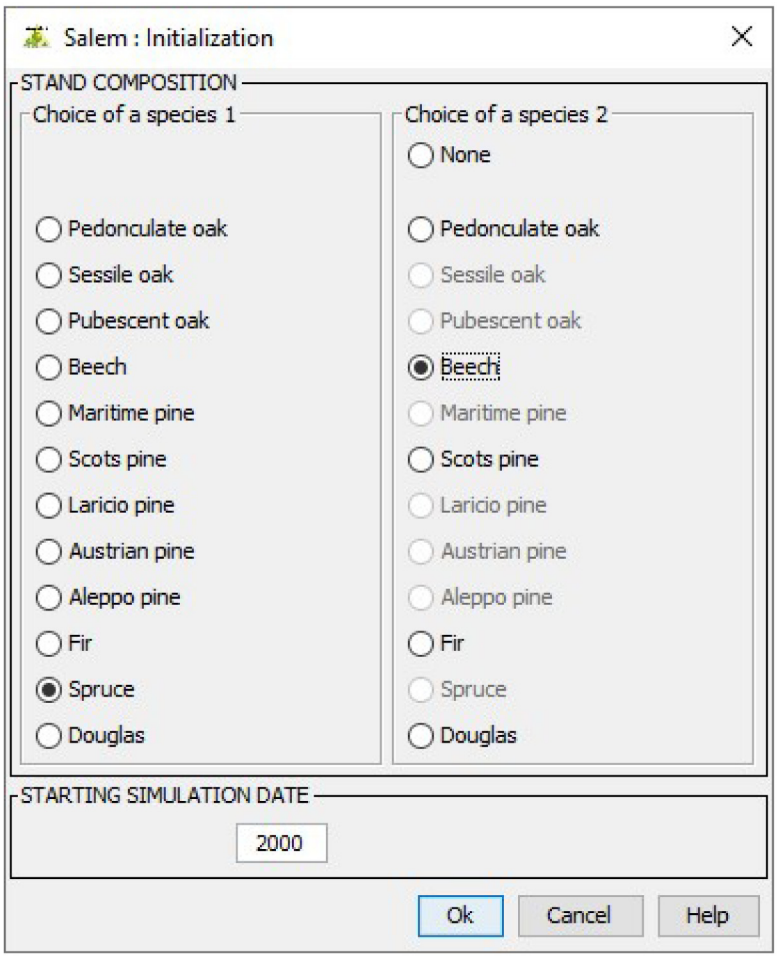


Figure 6. Choosing a composition and a starting simulation date.

4.3 Simulation output

Simulation outputs can be directly displayed within Capsis as either graphs or tables. They can also be exported or simply copied and pasted in a spreadsheet. Figure 9 shows some outputs of the simulation performed with the parameters set in the previous sections.

4.4 Use cases

Here, to illustrate the mixture effect simulated in Salem, we compare the production of the spruce - beech mixed stand used as an example in the previous sections to the production of pure stands of spruce and beech. We simulated these pure stands using the same site indices, initial dendrometric values and thinning parameters as those used for our spruce - beech mixed stand. We exported these simulations in ".txt" format and analysed them with *R*.

The positive effect of spruce on beech (see Table 6) implies that the total production of a spruce - beech mixed stand is higher than the sum of the productions of the two species in pure stands weighted by their proportion in the mixed stand. Thus, if the management objective is to produce a maximum volume of these two species, then a mixed stand is more advantageous than two separate pure stands. Here, due to the positive effect of spruce on beech, in 2090 beech trees will be 17.8% larger in diameter in the mixed stand than in the pure stand (39.2 cm in the pure stand compared to 46.2 cm in the mixed stand; Figure 10). However, despite this positive effect of spruce on beech, there is no "transgressive overyielding" (Pretzsch & Schütze, 2009): the pure stand of the most productive species (here spruce) remains more productive than the mixture (Figure 11).

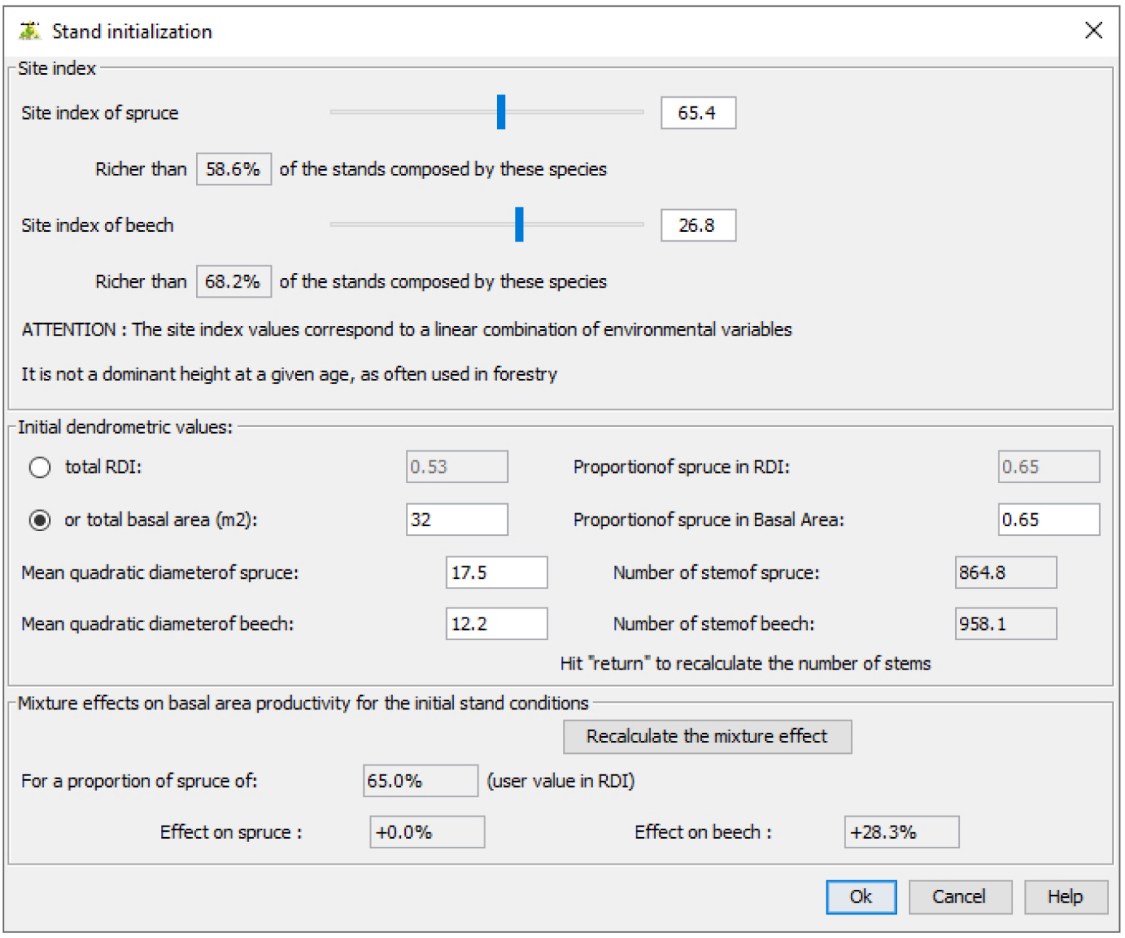


Figure 7. **Setting site indices and initial dendrometric values.**

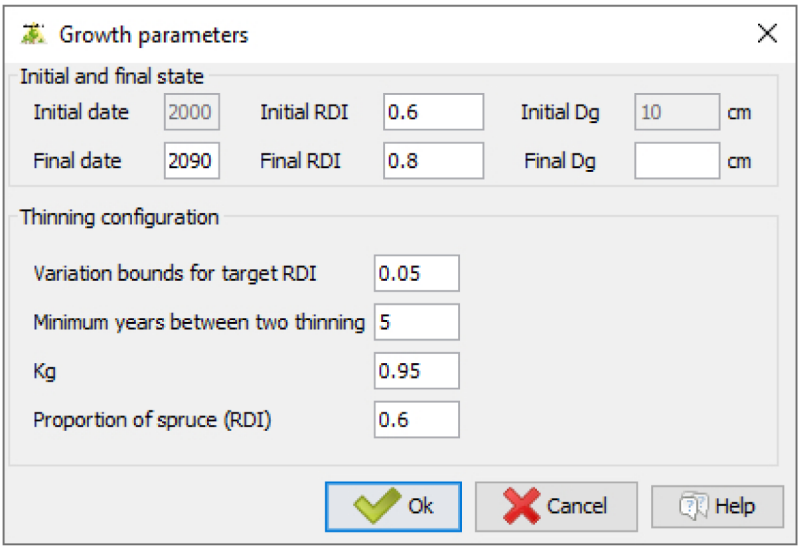


Figure 8. **Setting thinning parameters and simulation duration.**

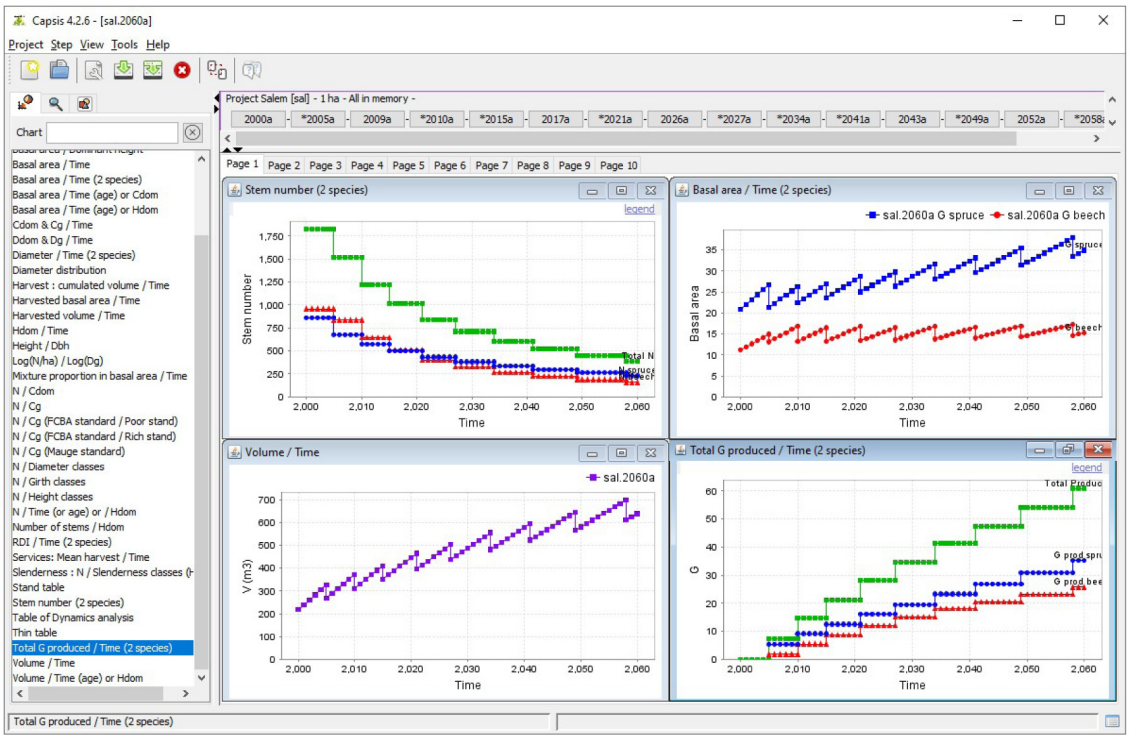


Figure 9. Simulation output visualisation in Capsis. The top left panel shows the total number of stems (green) as well as the number of spruce (blue) and beech (red) stems during the simulation. The top right panel shows the evolution of both species basal area. The bottom left panel shows the evolution of the stand total volume. Finally, the bottom right panel shows the total harvested basal area (green) as well as the harvested basal area of spruce (blue) and beech (red).

Thus, if the only management objective is to produce as much volume as possible whatever the species, then the pure stand of spruce is the most suitable.

The mixture effect presented here cannot be generalised. As a reminder, the mixture effect depends on species assemblages and environmental factors (see Section 3.2).

5 Discussion

Here, we presented the structure of Salem, a new simulator aiming at predicting the dynamics of pure and mixed even-aged stands and which makes it possible to simulate management operations. We demonstrated the functioning of Salem by simulating the dynamics and management of hypothetical stands.

In addition to provide species-specific growth and allometric models, one major outcome of Salem is the positive effect of species mixture we found on most species growth. This result is in line with a growing number of studies suggesting that the diversity - productivity relationship is most often positive in forest ecosystems (Ammer, 2019; Liang *et al.*, 2016). We also found this effect of mixture is stronger at poor sites than at richer sites. This finding is consistent with previous studies showing the benefit of species mixture on stand productivity increases as site conditions become harsher (Paquette & Messier, 2011; Toïgo *et al.*, 2015), as predicted by the stress gradient hypothesis (Bertness & Callaway, 1994).

A major limitation of Salem is due to its phenomenological nature which implies that its predictions may be less reliable as we move further away from its calibration range. Salem is therefore intended to be used above all over the French territory. Similarly, Salem being calibrated on the past climate, the validity of its predictions in the future remains uncertain. However, the great diversity of ecological and climate conditions found in the French NFI dataset, which spans over four biogeographical regions (mediterranean, alpine, continental and atlantic; Roekaerts, 2002), could make Salem predictions robust over a larger area and in a wide range of

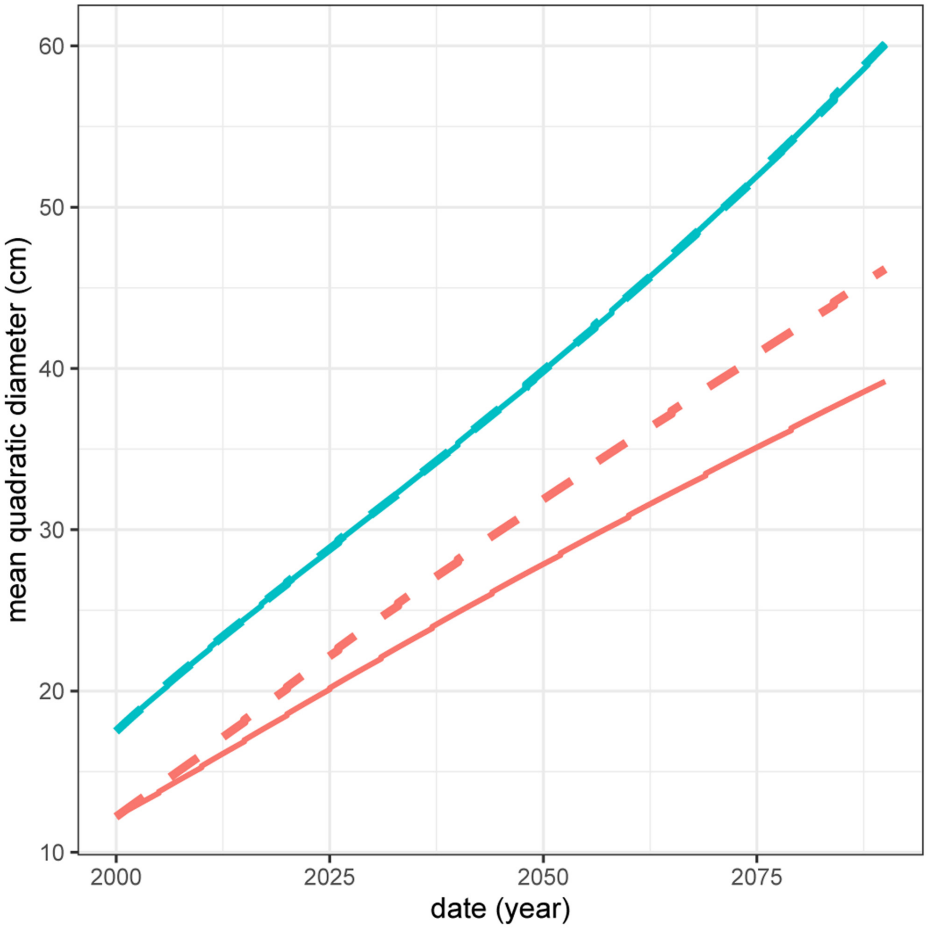


Figure 10. Mean quadratic diameter of beech (red) and spruce (blue) in pure (full line) and mixed (dashed line) stands.

climate conditions. In fact, some preliminary results indicate Salem remains reliable at various locations in Europe (Mats Mahnken, unpublished report). In the forthcoming version of Salem under development, the effect of climate fluctuations both on species growth and on the mixture effect (i.e. on species interactions) will be modelled. This integration of climate should strengthen the quality of Salem predictions under the future climate. The method has already been developed and applied to a case study (Vallet & Pérot, 2018).

Independently from the simulator, European foresters can also consider using the species-specific models that constitute Salem. Here, we presented several dendrometrical based models for 12 widespread species in Europe: growth models including or not mixture effect, bark models, diameter distribution models, circumference - height relationship models as well as volume equations.

6 Conclusion

Salem makes it possible to compare the productivity of pure and mixed stands depending on environmental conditions and according to user-defined management strategies. It can therefore help forest managers and stakeholders as well as policy makers assess the potential benefit of shifting from pure to mixed stands. Thus, Salem could facilitate the expansion of mixed stands in managed forest landscapes as recommended by international policies (Anon, 2006; European-Environment-Agency, 2008).

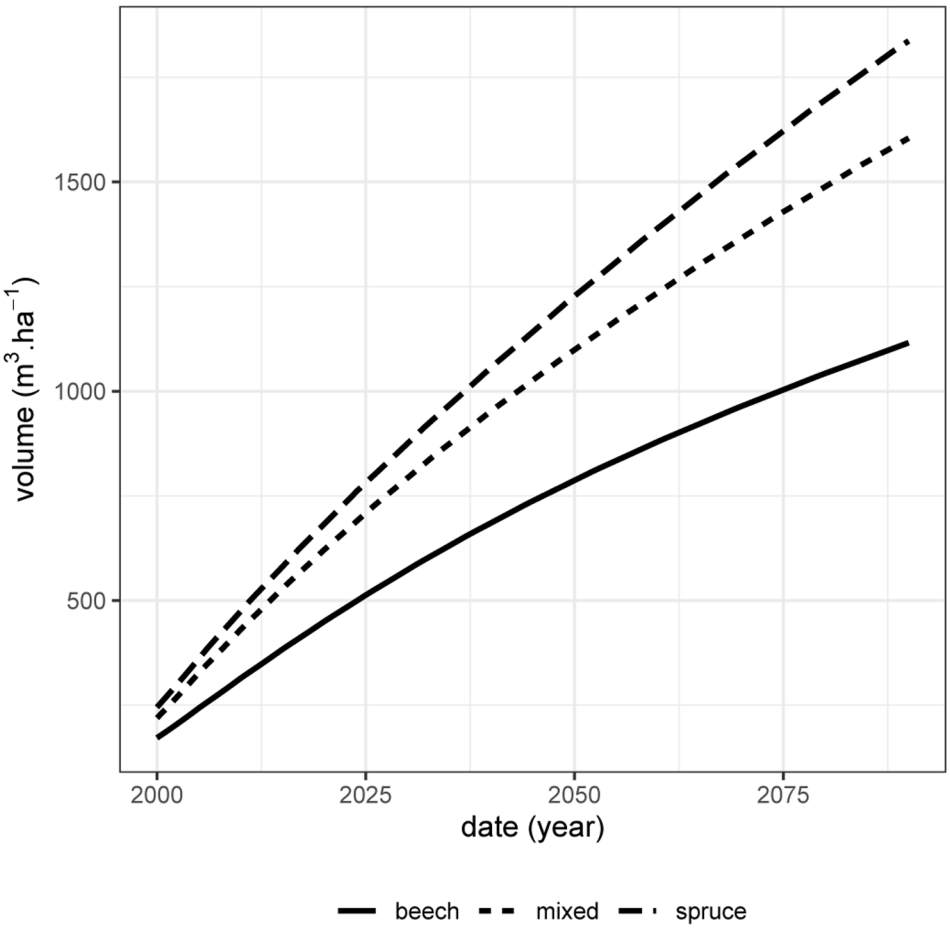


Figure 11. Total volume production over time (harvested volume + stand volume) for the spruce - beech mixed stand (short-dashed line), the pure spruce stand (long-dashed line) and the pure beech stand (full line). These volumes are given for one ha.

Data availability

Underlying data

NFI data are freely available to download from: https://inventaire-forestier.ign.fr/spip.php?rubrique270.

Extended data

Zenodo: Salem 2.0 extended data. https://doi.org/10.5281/zenodo.4742559 (Aussenac *et al.*, 2021).

This project contains the following extended data within the file 'Salem 2 0 extended data.pdf':

- Table A.1 (Estimates of the s_0 parameter in Equation 10)
- Table A.2 (Estimates of the s_0 and s_1 parameters in Equation 11)
- Figure A.1 (Mixture effect on species growth)
- Figure A.2 (Normal distributions fitted to observed distributions of individual tree diameters by classes of mean quadratic diameter. Example for *Quercus robur*)
- Table A.3 (Mean diameter at breast heigh (dbh), height and volume of trees in the volume dataset, for species that are not relevant to Salem)

- Table A.4 (Species-specific parameter estimates of the volume models (Equation 19), for species that are not relevant to Salem)

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

Software availability

Software available from: http://capsis.cirad.fr/capsis/download

Archived source code at time of publication: https://doi.org/10.5281/zenodo.5578340 (Vallet *et al.*, 2021)

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Version 2

Reviewer Report 16 November 2021

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✔ **Tomáš Hlásny**
Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Prague, Czech Republic

The authors have addressed my concerns, I would like to award the article a status of Approved.

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 13 September 2021

https://doi.org/10.21956/openreseurope.14745.r27500

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? **Tomáš Hlásny**
Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Prague, Czech Republic

The article introduces a new simulation model aimed at the productivity of mixed forest stands. The overall idea and structure of the model are well described, and the paper is suitable for indexing subject to revision. I have three major comments:

In Abstract, Introduction, and Discussion – the authors suggest the improved productivity is the main motivation for the transition from monospecific to mixed stands. However, these motivations are much broader, including risk reduction (insurance hypothesis), creating more diverse habitats, etc. In my opinion, the effort to reduce the high risk of failure of monospecific stands is currently even a higher priority than fostering productivity. I suggest highlighting these aspects in the text and supporting these statements by references.

Testing and knowing the accuracy is a crucial prerequisite for any model`s use. This aspect is, however, missing in the reviewed manuscript. I see (at least) two aspects that require rigorous testing:

1. Splitting the data into calibration and testing samples would help understand the underlying equations' generality and accuracy.

2. The authors selected one of four possible options for simulating the species mixture. It is, however, unclear, if this one is optimal. At least comparing the performance of the used approach based on multipliers with the most straightforward approach based on the weighting of pure stands would indicate if the presented solution brings the desired added value.

The authors are of course, free to come with any other testing design. However, I consider this aspect critical for both practical model`s use and research. The testing results would also indicate the ways for further model`s development.

My final comments concern lacking consideration of changing growth and competition patterns due to climate change. The model was parameterized based on the past data, which characterize certain interactions between the concurrent species. However, climate change modifies species growth performance and interspecific interactions, making it difficult to transfer past models to the future. Although such considerations are the domain of process-based models, it is necessary to discuss this limitation.

Further, I have some formal comments, which mainly aim to improve the text`s clarity.

I suggest relaxing statements such as "... model that best meet the needs of forest managers". Each model is “best” is some regard, plus there is no survey of managers` needs presented in the paper to bring such a strong statement.

Remove please the last paragraph of the introduction. Grant information is stated at the end, and there is no need to emphasize it here. Writing in the intro that Salem is mature and reliable ..... is not adequate as well. This can be stated in discussion or conclusions based on the evidence presented in the paper. The last two sentences are redundant and should be removed. Strongly recommend revising the text and removing such idle sentences.

The last paragraph of page 3 and first paragraph of page 4 – it is written three times here that the model operates at an annual scale, I suggest simplifying the text.

Model description
Stands had to be regular stands – the sentence cannot be understood.
diameter measurements and the radial growth measures. ... measurement rather than measures.
sylvoécorégions does not seem to be an English word, revise please.

Table 6 caption – On the other hand …. probably … On the contrary.

3.2.3 Results synthesis – I think a better title would be Demonstration, as no synthesis is provided, just an example of calculating mixture effect,

"The mixture effect on the other species is presented in Figure A.1 of the extended data (Aussenac et al., 2021)" – I cannot understand the meaning of citation on the end of the sentence. It should be clarified if these results were already published. I understood that parameterizing the mixture effect was done in the current study.

Section 3.2.3 and 4.4 seem to deal with the same/similar problem (exemplifying the effect of species mixture). Check please if this structure is correct.

The text contains a large number of idle clauses (mainly at the beginning of sentences), I am giving some examples here. Recommend authors improving the wording to increases the text`s clarity. (# … # indicates part to be removed)

#In the first instance#, Salem requires the stand initial state as input, *i.e.* the basal area (BA), the mean quadratic diameter (Dg), and the site indices for one or two species (for mono- or bi-specific stands).

#In Salem#, site indices are calculated from a species-specific combination of environmental variables (Section 3.1).

#At that stage#, if the simulated stand density exce …

The general functioning of Salem is summarised in Figure 1, which shows how the different models are connected to each other. -> Model structure is shown in Figure 1.

Is the rationale for developing the new software tool clearly explained?

Partly

Is the description of the software tool technically sound?

Yes

Are sufficient details of the code, methods and analysis (if applicable) provided to allow replication of the software development and its use by others?

Yes

Is sufficient information provided to allow interpretation of the expected output datasets and any results generated using the tool?

Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Ecosystem modelling, climate change impacts and adaptation, disturbance dynamics and management. I am not a model developer to comment adequately on

implementation details

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 22 Oct 2021

Raphaël Aussenac

Dear reviewer,

Thank you for your comments. In summary, in this new version we discuss the limitations of Salem regarding the reliability of its predictions under the future climate. We also point out that forest managers may want to shift from pure to mixed stands not only for a productivity gain but also to reduce risks against disturbances. We also made some minor changes to the text to improve its clarity. Please find below our replies to your comments.

In Abstract, Introduction, and Discussion – the authors suggest the improved productivity is the main motivation for the transition from monospecific to mixed stands. However, these motivations are much broader, including risk reduction (insurance hypothesis), creating more diverse habitats, etc. In my opinion, the effort to reduce the high risk of failure of monospecific stands is currently even a higher priority than fostering productivity. I suggest highlighting these aspects in the text and supporting these statements by references.

We agree with the reviewer, risk reduction may be a reason to shift from monospecific stands to mixed stands. However, we did not work at all on this aspect, Salem only focuses on the effect of mixture on species growth. We believe the point raised by the reviewer is worth mentioning in the abstract and introduction, but should probably not be mentioned in the discussion, as our work does not shed any light on this issue.

We modified the first paragraph of the abstract as follows: “A growing body of research suggests mixed-species stands are generally more productive than pure stands as well as less sensitive to disturbances. However, these effects of mixture depend on species assemblages and environmental conditions. Here, we present the Salem simulator, a tool that can help forest managers assess the potential benefit of shifting from pure to mixed stands from a productivity perspective. Salem predicts the dynamics of pure and mixed even-aged stands and makes it possible to simulate management operations. Its purpose is to be a decision support tool for forest managers and stakeholders as well as for policy makers. It is also designed to conduct virtual experiments and help answer research questions.”

We modified the first paragraph of the introduction as follows: “Over the last decades, mixed-species stands have received growing attention. From the perspective of forest managers, they have a number of advantages compared to monospecific stands. They can be more productive (Ammer, 2019; Liang et al., 2016) as well as less sensitive to various disturbances such as windstorms (Schütz et al. 2006), pathogen invasions (Haas et al. 2011)

or insect outbreaks (Jactel & Brockerhoff 2007; Castagneyrol et al. 2013; Klapwijk & Björkman 2018). However, these effects of mixture are highly variable and depend on species and environmental conditions. As a result, forest managers often lack information to consider mixed stands as a possible alternative to pure stands. Forest dynamics models (Pretzsch, 2009; Weiskittel et al., 2011) can help fill this information gap. In this article, we will focus on the potential benefit of shifting from pure to mixed stands from a productivity perspective, we will not cover the aspect of risk reduction against disturbances."

Testing and knowing the accuracy is a crucial prerequisite for any model`s use. This aspect is, however, missing in the reviewed manuscript. I see (at least) two aspects that require rigorous testing:
Splitting the data into calibration and testing samples would help understand the underlying equations' generality and accuracy.

We agree with the reviewer, testing and evaluating models is essential before any use. However, we have deliberately chosen not to include an evaluation in this paper which is already 29 pages long, so as not to make it any longer and because the evaluation work is part of a forthcoming publication. Indeed, we have carried out a multi-partner study in which we evaluated the predictions of 13 models (including Salem) against observed data from across Europe (from Spain to Scandinavia), within the ISIMIP project (https://www.isimip.org/). Salem is ranked n°1 for the accuracy of its predictions. Following the ORE guidelines, we alluded to this work in our paper (p.25): « [...] some preliminary results indicate Salem remains reliable at various locations in Europe (Mats Mahnken, unpublished report) ». In this forthcoming publication, the evaluation dataset is completely independent from the calibration dataset, which makes the evaluation particularly robust. Splitting the data into calibration and testing samples as suggested by the reviewer would not be as robust for two main reasons: (1) being calibrated on less data, Salem will lose some of its predictive power, and (2) the calibration and testing samples are not completely independent, they are linked by the NFI protocol. The fact that 13 models are being jointly evaluated also helps better apprehend the relative quality of Salem's predictions. Following a discussion with the editor, this evaluation work may be passed on to the reviewer upon request.

The authors selected one of four possible options for simulating the species mixture. It is, however, unclear, if this one is optimal. At least comparing the performance of the used approach based on multipliers with the most straightforward approach based on the weighting of pure stands would indicate if the presented solution brings the desired added value.

The comparison proposed by the reviewer is already implicitly provided. In fact, the mixture effect on a species growth is calculated as the deviation from the species expected growth in pure stand weighted by its proportion (see equation 12 and 13). Thus, if a species has a significant effect on the growth of another species (s0 significant in Table 6), this means that the multiplier approach we use brings some added value. As mentioned in our previous reply, 13 models are being jointly evaluated in the forthcoming publication. These models use a wide variety of modelling approaches. We believe this forthcoming evaluation of Salem is far more comprehensive than any evaluation we could carry out here, in particular,

to compare modelling approaches. We would rather not present an incomplete or less comprehensive evaluation of Salem in this paper.

The authors are of course, free to come with any other testing design. However, I consider this aspect critical for both practical model`s use and research. The testing results would also indicate the ways for further model`s development.

See replies to the two previous comments

My final comments concern lacking consideration of changing growth and competition patterns due to climate change. The model was parameterized based on the past data, which characterize certain interactions between the concurrent species. However, climate change modifies species growth performance and interspecific interactions, making it difficult to transfer past models to the future. Although such considerations are the domain of process-based models, it is necessary to discuss this limitation.

We agree with the reviewer and included this point in the paragraph dealing with Salem limitations in the discussion. The paragraph now reads as follows: “A major limitation of Salem is due to its phenomenological nature which implies that its predictions may be less reliable as we move further away from its calibration range. Salem is therefore intended to be used above all over the French territory. Similarly, Salem being calibrated on the past climate, the validity of its predictions in the future remains uncertain. However, the great diversity of ecological and climate conditions found in the French NFI dataset, which spans over four biogeographical regions (mediterranean, alpine, continental and atlantic; Roekaerts, 2002), could make Salem predictions robust over a larger area and in a wide range of climate conditions. In fact, some preliminary results indicate Salem remains reliable at various locations in Europe (Mats Mahnken, unpublished report). In the forthcoming version of Salem under development, the effect of climate fluctuations both on species growth and on the mixture effect (i.e. on species interactions) will be modelled. This integration of climate should strengthen the quality of Salem predictions under the future climate. The method has already been developed and applied to a case study (Vallet & Pérot, 2018).”

Further, I have some formal comments, which mainly aim to improve the text`s clarity. I suggest relaxing statements such as "... model that best meet the needs of forest managers". Each model is “best” is some regard, plus there is no survey of managers` needs presented in the paper to bring such a strong statement.

We agree with this comment and removed this statement.

Remove please the last paragraph of the introduction. Grant information is stated at the end, and there is no need to emphasize it here. Writing in the intro that Salem is mature and reliable ..... is not adequate as well. This can be stated in discussion or conclusions based on the evidence presented in the paper. The last two sentences are redundant and should be removed. Strongly recommend revising the text and removing such idle sentences.

As suggested, we removed the part of the paragraph redundant with the grant information section and the mention to Salem reliability and maturity. We revised the rest of the paragraph which now reads as follows: “We present the general functioning of Salem in Section 2. We then provide details on the different models used in Section 3. Finally, we show how to simulate stands with Salem and how to implement management operations in Section 4.”

The last paragraph of page 3 and first paragraph of page 4 – it is written three times here that the model operates at an annual scale, I suggest simplifying the text.

We could not find any mention to the annual time step in the last paragraph of page 3 and first paragraph of page 4 in the pdf. The reviewer may be referring to the last paragraph of page 4 and first paragraph of page 5. We removed the first mention to the annual time step to simplify the text, as it is indeed redundant with the end of the sentence. The two remaining mentions, however, seem to us important to keep.

Model description Stands had to be regular stands – the sentence cannot be understood.

Replaced by: “Stands had to be classified as even-aged stands by the French NFI.”

diameter measurements and the radial growth measures. … measurement rather than measures.

Modified as suggested.

sylvoécorégions does not seem to be an English word, revise please.

This word is immediately defined in the parenthesis that follows it. We have italicised it to emphasise that it is not an English word and we have removed its French acronym from the definition, as it is not needed to understand the word and may bring some confusion.

Table 6 caption – On the other hand …. probably … On the contrary.

Modified as suggested.

3.2.3 Results synthesis – I think a better title would be Demonstration, as no synthesis is provided, just an example of calculating mixture effect.

This section consists of two paragraphs. In the first one, we present as an example the results we obtained for fir, i.e. the effects on the growth of fir of different species depending on site productivity. In the second paragraph, we summarise the results obtained for all species (but see also reply to following comment). These are original results derived from the models we present in this article. We would therefore rather keep ‘results synthesis’ as title for this section. Maybe the last sentence of the first paragraph was not in the right place. We moved it to the beginning of the second paragraph. This might help better understand the section. The second paragraph therefore begins as follows: “The mixture effect on the other species is presented in Figure A.1 of the supplementary information (see

extended data; Aussenac et al., 2021). Overall, we found the mixture effect on species growth was most often positive..."

"The mixture effect on the other species is presented in Figure A.1 of the extended data (Aussenac et al., 2021)" – I cannot understand the meaning of citation on the end of the sentence. It should be clarified if these results were already published. I understood that parameterizing the mixture effect was done in the current study.

We follow here the guidelines of ORE: supplementary information must be deposited in an approved repository and cited as extended data in the main body of the article. We therefore refer here to original results that derive from the models we present in this study. The content of the extended data is summarised in the 'Data availability' section as required by ORE guidelines. To avoid any confusion we slightly modified the way we refer to the extended data throughout the document using this formulation: "Table XX of the supplementary information (see extended data; Aussenac et al. 2021)".

Section 3.2.3 and 4.4 seem to deal with the same/similar problem (exemplifying the effect of species mixture). Check please if this structure is correct.

Hopefully our replies to the two previous comments have clarified the purpose of section 3.2.3: summarising the results of our models regarding the effect of mixture on species growth. As for Section 4.4, it exemplifies the effect of mixture in a stand parameterised from Salem graphical user interface. These two sections are therefore not redundant.

The text contains a large number of idle clauses (mainly at the beginning of sentences), I am giving some examples here. Recommend authors improving the wording to increases the text`s clarity. (# ... # indicates part to be removed) #In the first instance#, Salem requires the stand initial state as input, i.e. the basal area (BA), the mean quadratic diameter (Dg), and the site indices for one or two species (for mono- or bi-specific stands). #In Salem#, site indices are calculated from a species-specific combination of environmental variables (Section 3.1). #At that stage#, if the simulated stand density exce ... The general functioning of Salem is summarised in Figure 1, which shows how the different models are connected to each other. -> Model structure is shown in Figure 1.

On the contrary, we believe that these carefully chosen formulations help understand the text. This has been confirmed to us by native English speakers who have read it. Since the preference for one writing style or another is rather subjective and since this comment is only a recommendation we would rather keep these formulations.

Competing Interests: No competing interests were disclosed.

Reviewer Report 22 July 2021

https://doi.org/10.21956/openreseurope.14745.r27123

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Thomas Knoke
Institute of Forest Management, TUM School of Life Sciences Weihenstephan, Technische Universität München, Freising, Germany

Disclaimer:

The paper reports numerous statistical formulas and coefficients. It was impossible for the reviewer to check the validity of each formula and coefficient. However, I have studied the paper carefully and searched for any possible inconsistencies from the Methods description and the Results interpretation.

"The Salem simulator version 2.0: a tool for predicting the productivity of pure and mixed stands and simulating management operations" is a very useful tool to support the analysis and management of mixed forests in France. The paper has great merits in providing basic dendrometric information about a large number of mixed forests, while these stand types comprise two tree species. The simulation model Salem can reproduce the main existing results on mixing effects, such as overyielding. It is site specific so that locally adapted simulations are possible. The database is extensive. In sum, Salem provides a very helpful tool to design successful mixed stand types and to predict likely outcomes when managing mixed forests.

Further comments:

- One could consider to make sure that the units of the variables are always indicated, when such variables are used (e.g. for all Tables).
- It would perhaps be advisable to include that "mortality" does not cover stand failure by events, such as storm, drought or barck beetles.
- Cores from how many trees have been taken?
- Has the self-thinning line been parameterized only from untreated plots?
- Is the use of the word circumference appropriate? In the equations we find only diameters.

Is the rationale for developing the new software tool clearly explained?
Yes

Is the description of the software tool technically sound?
Yes

Are sufficient details of the code, methods and analysis (if applicable) provided to allow replication of the software development and its use by others?

Yes

Is sufficient information provided to allow interpretation of the expected output datasets and any results generated using the tool?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Forest science, forest economics, optimization

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 22 Oct 2021

Raphaël Aussenac

Dear reviewer,

Thank you for your comments. In summary, in this new version we discuss the limitations of Salem regarding the reliability of its predictions under the future climate. We also point out that forest managers may want to shift from pure to mixed stands not only for a productivity gain but also to reduce risks against disturbances. We also made some minor changes to the text to improve its clarity. Please find below our replies to your comments.

One could consider to make sure that the units of the variables are always indicated, when such variables are used (e.g. for all Tables).

We added a missing unit in Figure 4 legend.

It would perhaps be advisable to include that "mortality" does not cover stand failure by events, such as storm, drought or barck beetles.

We added two sentences in section 2 (Implementation) to clarify this point: “The only mortality factor simulated in Salem is therefore competition. Mortality due to natural disturbances such as storms, droughts or insect outbreaks is not simulated.”
Cores from how many trees have been taken?

Overall 52543 cores were collected in pure stands and 33747 cores in mixed stands. We added these figures in the legends of Table 2 (Number and features of inventory plots in pure stands for each species) and Table 5 (Number of inventory plots for each species pair).

Has the self-thinning line been parameterized only from untreated plots?

The species-specific self-thinning boundaries were parameterised using NFI data collected in pure stands. A wide variety of stands is therefore represented in the data. However, as mentioned in section 3.1.2, we used a quantile regression to fit these self-thinning boundaries. The quantile of the regression was 0.95, meaning that the resulting line

corresponds to the 5% of the denser stands of the dataset. In Table 1 we specify the data used for the calibration of the self-thinning boundaries and refer the reader to Toïgo et al. (2018) for further details on the method. Subsequently, in section 3.1.2 we briefly present the calibration method and the calibration results. We would rather not expand further on this subject so as not to make this paper, which is already 29 pages long, any longer.

Is the use of the word circumference appropriate? In the equations we find only diameters.

We confirm that the word circumference is appropriate wherever it is used. We use this word in section 3.6 (Models of individual tree height) or in reference to this section, and circumference does appear in our height models (parameter c130 in equation 18, Table 9 and Table 10). Both circumference and diameter were used throughout the document because the Salem simulator is a compilation of works that have been carried out for several years and in different projects.

Competing Interests: No competing interests were disclosed.