# Modeling forest stand structure within a process-based model

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**Highlights:** A new empirical between-tree interaction module was implemented in the CASTANEA process-based forest stand model. The resulting functional-structural plant model demonstrates its ability to predict the morphological trajectories of individual trees grown in contrasted site condition. The presented stand structure modeling can be profitably used to investigate forest responses to global changes and to design new silvicultural guidelines.

**Keywords:** process-based model, CASTANEA, stand structure, forest management, tree competition

## INTRODUCTION

In the context of global changes, process-based (PB) models validated at the stand rotation time scale (i.e. 100-150 years) have become important tools in forest sciences. Most of them simulate the functioning of an "average tree" to predict growth, or carbon (C) and water fluxes at the stand scale, where they obtain more robust results than aggregated predictions from tree-centered models (Cao, 2006). By definition, these models are not able to simulate the realistic evolution of the stand structure, i.e. the morphological changes of the individual trees. In particular, they fail to predict the circumference and volume increments of the individual trees, as well as the evolution of the tree density along the forest rotation.

This shortcoming strongly limits their explorative capacity and their potential applications. First, they cannot accurately simulate forest management, precluding i) the design of adaptive silvicultural guidelines taking into account current and future impacts of climate changes ii) the accurate assessment of  biomass stocks and sink capacities of the increasingly managed part of the world's forests (Bellassen *et al.*, 2010). Secondly, "average tree" models cannot be directly validated with the most abundant available data: dendrometric measurements from forest inventories (tree density or basal area) and dendrochronological series, both being obtained from the aggregation of individual measurements. The simulation of the stand structure at individual tree scale would therefore allow modelers to formalize and to test functional hypothesis at larger time and spatial scales, e.g. along contrasted conditions of regional or continental gradients. Finally, the explicit representation of within-stand heterogeneity in multi-decade simulations would allow for investigation of long-term processes potentially involved in drought-induced forest diebacks, such as competition or individual C balances.

By contrast to the PB approach, empirical tree - centered growth models proved their ability to predict the retrospective evolution of forest structure on a purely statistical basis. The way resources, and therefore growth increment, are distributed within the individual trees is the focal point of these morphological models. Resources distribution partly depends on the mode of tree competition, which can be size-symmetric (i.e. the growth is proportional to the size) in the case of below-ground resources limitation or size-asymmetric when growth is limited by light. Recent papers have shown that the mode of competition strongly varies spatially, along fertility gradients, but also temporally (Metsaranta and Lieffers, 2010), making it an important stand structure driver which is poorly considered in tree - centered growth models. In any case, these empirical models cannot be used to predict future impacts of climate changes on forest functioning as they do not rely on explicit biological mechanisms.

In this study, our aim was to couple the CASTANEA forest PB model to a new empirical stand structure module (SSM) which we used to study the spatial and temporal variability of the tree competition mode. An attempt to couple forest management module to global vegetation model has recently been made (Bellassen *et al*., 2010), but an approach allowing new insights in species-specific functioning and management is still lacking. The resulting functional-structural plant model (FSPM) has been validated on forest inventories data from 11 beech (*Fagus sylvatica*) permanent plots distributed on the French territory.

## DATA AND MODELING METHODOLOGY

Growth data were obtained from the French permanent plot network RENECOFOR. Dendrochronological series were extracted on all plots in 1994. Additionally, circumference inventories were conducted regularly from 1991 to 2009, time intervals between 2 measurements ranging from 1 to 5 years.

We first studied the spatial and temporal variability of the competition mode in *F. sylvatica* by relating the stand productivity to an index of competition asymmetry. The stand productivity (obtained from site index for the study of spatial variability and annual circumference increments for the study of time variability) has been used as a proxy to characterize the stand growing conditions (Metsaranta and Lieffers, 2010). The competition index ($\gamma_{data}$) is the slope of the linear regression between tree circumferences in year (n) and their respective basal area increments. Statistical analyses were conducted within the linear framework and results, after check of the underlying test hypotheses, were used to calibrate the SSM.

The CASTANEA model (Dufrêne *et al*., 2005) has been thoroughly used and validated in long term growth and flux simulation (Delpierre *et al*., 2009). A new allocation scheme for *F. sylvatica* has recently been validated on stand growth across France (C. François, *unpubl. res.*). The SSM structure is inspired from the growth and yield model FAGACÉES, successfully used for 2 decades on beech even-aged forests in France (Le Moguedec and Dhôte, 2011). SSM allocates annually the biomass increment calculated by CASTANEA to a distribution of individual trees, through a non-linear relationship with 2 parameters: $\sigma$ and $\gamma_{castanea}$, which are respectively the slope and threshold of the relationship between tree circumferences in year (n) and their respective basal area increments (Fig. 1). SSM is also able to simulate silvicultural thinning or competition-induced mortality (i.e. self-thinning). It includes a forest management module, which allows for the setting of multiple silviculture guidelines and different biomass export scenarios. SSM finally returns back to CASTANEA the changes in LAI and in biomass stocks resulting from the mortality simulation.

We initialized simulations with field measurement (e.g. LAI, leaf nitrogen, soil water capacity, biomass), completed with species-specific parameters from the bibliography. The SAFRAN database was used for half-hourly climatic forcing. On each year of inventory, the tree distribution simulated by the FSPM was compared with measurements, through usual dendrometric variables (stand basal area and mean circumference, see Fig. 1). The distribution was then re-initialized with the corresponding data.
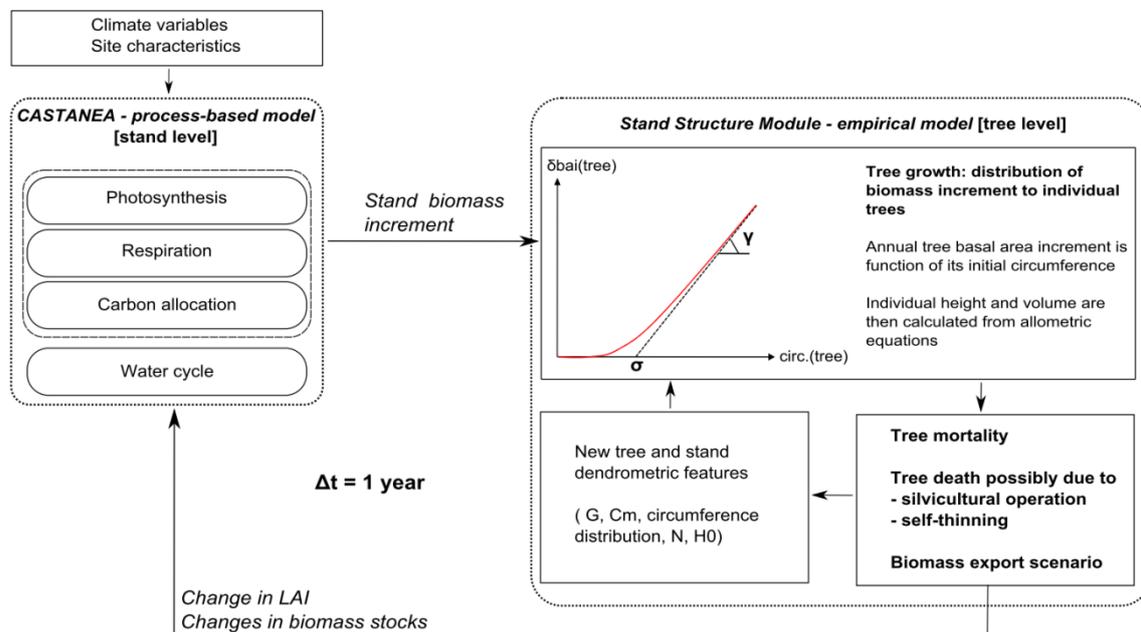


Fig. 1. Conceptual diagram of the coupled CASTANEA – SSM model. Abbreviations*: G (Stand Basal Area), Cm (mean circumference), N (stem density), H0 (dominant height), circ. (circumference), δbai (basal area increment.)*

## RESULTS AND DISCUSSION

As expected, the index of competition asymmetry $\gamma_{data}$ was positively correlated to stand productivity. The correlation was high along the spatial gradient (*p-value* < 0.001, $R^2$ = 0.53). Similarly, the

within-site index variability was well explained by the annual productivity (*p-value* < 0.001, $R^2$ = 0.71). The annual calibration of SSM was then designed as follows: 1) σ, which corresponds to the minimum circumference of trees with access to direct sunlight, was estimated from an empirical model fitted on the inventory data (σ = 0.43 * Cm + 0.04 * V – where Cm and V represent mean circumference and stand volume, respectively – , *p-value* < 0.001, $R^2$ = 0.87). 2) $\gamma_{castanea}$ is then adjusted so that the resulting individual circumferences increments was consistent with CASTANEA stand growth simulations. SSM simulates explicitly the observed temporal and spatial variability of the mode of tree competition, through the $\gamma_{castanea}$ positive dependence on CASTANEA stand growth predictions. The resulting FSPM predicted efficiently both stand volume (Fig. 2A) and stand structure evolutions (Fig. 2B & C) of the 11 beech plots over the 1991-2009 period, without systematic bias. The empirical modeling of the between-tree interaction allowed the CASTANEA physiologically-based stand model to reproduce morphological trajectories of individual trees, grown in contrasted site conditions. There is a strong need of the forest science community to upscale knowledge obtained from tree-centered FSPM to stand level for decision support, and some attempts have been made in this way (e.g. Sievänen *et al.*, 2008). However they did not so far obtain the required predictive capacity to be profitably used in forest applications (Cournède *et al.*, 2010). The presented new FSPM, which considers structure at the stand scale in a "top-down" approach, can alternatively be useful to investigate forest responses to global changes and to design new adaptive silvicultural guidelines.
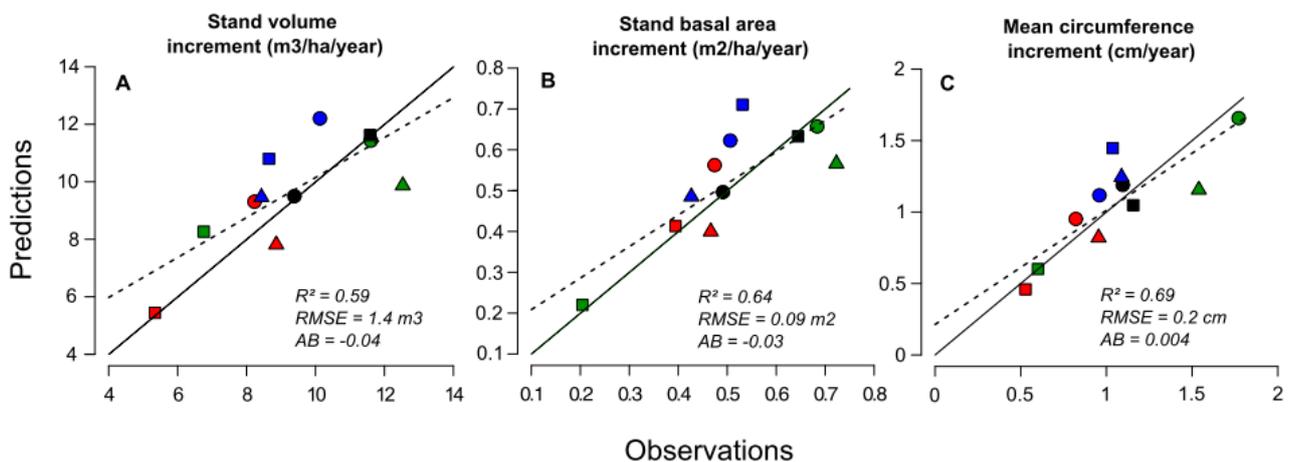


Fig. 2. Spatial validation of the FSPM. Each symbol is the averaged increment (over the 1991-2009 period) of the corresponding variable on one of the 11 plots. Solid and dashed lines are first bisector and regression line. AB and RMSE are average bias and root mean square error.

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