Agricultural and Forest Meteorology 263 (2018) 258–266

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

# Coupling transversal and longitudinal models to better predict *Quercus petraea* and *Pinus sylvestris* stand growth under climate change

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ARTICLE INFO

*Keywords:*
Temperate forest
Growth modeling
Climate change
National forest inventory
Dendrochronology
Space-for-time substitution

ABSTRACT

Climate change has swept away the former general principles of long-term stability in forest productivity. New types of models are needed to predict growth and to plan forest management under future climate conditions. These models must remain robust for silvicultural practices and variations in climate. In this study, we present a new type of model development to achieve these goals.

Our study focused on pure and mixed stands of *Quercus petraea* and *Pinus sylvestris* in central France. We used National Forest Inventory (NFI) data: respectively, 525 and 548 pure plots of *Quercus petraea* and *Pinus sylvestris*, and 68 plots of mixed species. We also used 108 tree cores from an experimental site of the same species. The cores cover the period from 1971 to 2013, making a total of 4572 individual annual increments.

We coupled two types of models. One was developed with NFI data (transversal data). This model takes into account mean diameter and stand density effects on stand growth. It includes a set of biophysical factors accounting for stand fertility. The other one was developed with the data from tree cores (longitudinal data), and provides a climate modulation thanks to the correlation between ring width and yearly climate. The model with tree core data reveals the influence of December to July rainfalls on yearly variability in stand growth for *Quercus petraea* and of May to August rainfalls for *Pinus sylvestris*.

We obtained a coupled model that allowed us to project growth up to 2100 for all the different IPCC scenarios but one; the model was outside its area of validity beyond 2060 for the RCP 8.5 scenario.

## 1. Introduction

Forest management has traditionally been based on concepts, tools or rules representing the long-term stability of forest productivity. Yield tables were common tools that allowed foresters to plan for changes in wood volumes and harvesting strategies (Assmann, 1970). Empirical forest dynamics models and simulators then replaced yield tables (Dufour-Kowalski et al., 2012). Even if these newer tools are more accurate and flexible, the general underlying principles of stability in forest evolution over time remain. Climate change, as well as nitrogen deposition rates or changes in $CO_2$ concentrations, has now swept away the temporal stability of forest productivity (Pretzsch et al., 2014), and new tools are needed to plan for forest productivity according to different climatic scenarios. Process-based models are interesting options to take climate change into account (Fontes et al., 2010). Their ability to break processes down and link them to climate factors – especially water availability and temperature – allows us to predict changes in growth under yet-to-exist climate conditions for a given species. Empirical models based on long-term stand monitoring are more efficient to take stand density and the structure of individual trees into account than process-based models linked to physiological mechanisms and running at the organ level. Hybrid models are interesting options: they are made to be easy to parameterize and make it possible to assess stand-level management and silvicultural practices but still accounting for the key mechanisms driving individual tree growth, regeneration and mortality (Pretzsch et al., 2008; Fontes et al., 2010).

Recent attempts to add a stand structure module to a process-based model has given promising results related to density and individual-tree distribution effects (Guillemot et al., 2014). Hybridization in the other direction, consisting in adding a climate modulation module to an empirical model based on long-term dendrometric observation, has rarely been undertaken. Yet, this option is promising to take both silvicultural practices and climate effect into account, and requires few input parameters.

The wide range of site conditions, silvicultural treatments and development stages encountered in National Forest Inventory data makes

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https://doi.org/10.1016/j.agrformet.2018.08.021
Received 6 April 2018; Received in revised form 21 August 2018; Accepted 22 August 2018

**Table 1**
Description of the NFI dataset. Min and max values in parenthesis.

| | Number of plots | Mean annual temperature (°C) | Mean annual precipitation (mm) | Elevation (m) | *Q. petraea* mean diameter (cm) | *Q. petraea* mean basal area (m2/ha) | *P. sylvestris* mean diameter (cm) | *P. sylvestris* mean basal area ($m^2$/ha) |
|---|---|---|---|---|---|---|---|---|
| *Q. petraea* pure plots | 525 | 10.4 (7.2–12.7) | 785 (589–1673) | 226 (20–1466) | 32.3 (3.3–87.7) | 17.9 (0.3–48.1) | – – | – – |
| *Pinus sylvestris* pure plots | 548 | 8.8 (4.8–13.1) | 920 (500–1727) | 833 (37–1866) | – – | – – | 22.5 (1.6–59.0) | 20.3 (0–67.6) |
| Mixed plots | 68 | 10.0 (8.1–11.3) | 757 (604–1456) | 243 (105–869) | 26.3 (7.4–78.3) | 9.7 (0.4–32.4) | 34.6 (11.1–61.2) | 14.8 (1.7–41.8) |

it possible to develop robust models that take all these factors into account (Río and Sterba, 2009; Toïgo et al., 2015a, 2018). Thanks to the large-scale of such transversal data, the effect of climate on forest productivity can be revealed along spatial climate gradients. Considering spatial climatic effects instead of temporal variations in climate is call space-for-time substitution. However, several authors (Elmendorf et al., 2015; Roitberg and Shoshany, 2017) have shown that space-for-time substitutions could overestimate the climatic warming effect. Substituting space for time could be especially misleading when the climate effect on processes under study are weak compared to biotic interactions (Dunne et al., 2004).

Conversely, data from tree cores allow us to study the effect of temporal variations in climate on tree growth, as ring width is a reliable marker of past climate (Sheppard et al., 2002; Toïgo et al., 2015b). Analyzing past ring widths along with past climatic data makes it possible to include the effect of yearly climatic variations in growth models. However, in these dendrochronological studies, stand structure and density are generally unknown, which precludes including these parameters in dendrochronological models.

The aim of our study was to develop a new type of hybrid model, taking advantage of two types of observational data, i.e. NFI and tree cores. In a first step, we developed large-scale stand growth-models from National Forest Inventory data. These models integrate the effects of silvicultural practices as well as the site index using the biophysical factor (including mean climate of the stand). In a second step, we used tree cores to model the variation on stand growth induced by annual fluctuations of climate. Next, we built a link function between the two model types to obtain our coupled growth model. Finally, we used this growth model, which now included climatic effects, to simulate future growth under different climate-change scenarios up to the year 2100 (IPCC, 2013). We developed our method on pure and mixed stands of *Quercus petraea* and *Pinus sylvestris,* two widespread species in France and in Europe. Concerns exist about the ability of these two species to face to climate change in these regions. Cheaib et al. (2012) have shown a severe loss of their potential distribution area, whereas these species are of great importance for the forestry sector.

## 2. Materials and methods

### 2.1. Large scale models

#### 2.1.1. National Forest Inventory data

The field plots monitored by the French National Forest Inventory (NFI) are systematic temporary plots located on a 1 km x 2 km grid. Every year, about on tenth of the plots are measured, about 6000 to 7000 plots a year. Each plot is made up of three circles 6 m, 9 m, and 15 m in radius, where small, medium and large trees are measured (respectively, trees with circumferences > 23.5 cm and < 70.5 cm, > 70.5 cm and < 117.5 cm, and > 117.5 cm). Data recorded include species, circumference, the last five years' radial increment taken from a core sample and total height. Soil is described on each plot, and a floristic survey is carried out; this makes it possible to assess pH or carbon-to-nitrogen ratio with bio-indication models (Gégout et al., 2005). We applied the Aurhely model from the French Meteorological Service to the coordinates of the NFI plots to obtain 30-year mean monthly climatic data (temperature and precipitation) for the 1961–1990 period (Bénichou and le Breton, 1987). These averaged climate data are used to differentiate climate across space in NFI models.

We used data from the 2006 to 2012 annual campaigns, which are freely available on the French NFI website (https://inventaire-forestier.ign.fr/). We selected pure and mixed plots according to several criteria. For pure stands, we selected plots where 100% of the basal area was of the target species (*Quercus petraea* or *Pinus sylvestis*). For mixed stands, we selected plots where the sum of the two species was over 80% and where the total basal area of all other species was below that of either *Quercus petraea* or *Pinus sylvestris*. We focused our study on plots with only one dominant layer. We also discarded plots that had been subjected to thinning during the previous five years to avoid changing density conditions being reflected in the measured increments. Finally, to include as many different environmental conditions as possible in our data set, we did not apply any geographical criterion to select our pure stands. However, we did apply a geographical criterion for the mixed plots: we wanted to be able to apply the pure stand model to the mixed plots to assess the basal area productivity that would be expected if they were in pure stand conditions. Therefore, mixed plots had to be within the range of pure stands site conditions, even though environmental factors reflecting those conditions were included in the model. We therefore only selected mixed plots in areas with enough pure plots to calibrate the pure stand model; we discarded any "silvo-ecological-region" defined by the French NFI (IFN, 2011) with less than five pure plots.

Finally, we obtained a dataset made up of 525 pure stands of *Quercus petraea*, 548 pure stands of *Pinus sylvestris* and 68 mixed stands with the two species (Table 1).

#### 2.1.2. Modeling framework

We modeled stand basal area increment over five years for both species using the approach developed in previous studies based on French NFI data (Vallet and Perot, 2011; Toïgo et al., 2015a, 2018). The model takes the form of potential x reducer. The potential depends on site conditions, one reducer depends on the density of the stand and a second reducer depends on the quadratic mean diameter of the species (Eq. (1)).

$$BAI = \left(a_0 + \sum_{m=1}^{n} (a_m X_m)\right) \times (DI^b) \times \left(\frac{e^{(c_1 Dg)} + c_2}{1 + c_2}\right) + \varepsilon \tag{1}$$

where BAI is the basal area increment ($m^2.ha^{-1}$) of the trees in the overstorey, DI is the density index based on a self-thinning boundary calculated for the NFI dataset (Eq. (2)) (Condés et al., 2017; Toïgo et al., 2018), and Dg is the mean quadratic diameter of the stand (cm). DI and Dg are values at the beginning of the increment period (calculated using circumference measurements minus increment value). $X_m$ is a set of n environmental variables limiting the growth of the species (mean monthly climatic variables, soil or stand description variables, elevation, etc. The full list is given in appendix A). We selected the variables