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The importance of introducing spatial heterogeneity in bio-economic forest models: Insights gleaned from FFSM++

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ABSTRACT

Given the importance of anthropogenic determinants in forest ecosystems within Europe, the objective of the FFSM++ model is to link the evidence arising from biological models to socio-economic determinants, where the expected returns of forest investments represent the main drivers. Consequently, an inventory-based discrete-time Markov chain model of the forest resources is coupled with a partial equilibrium model of the market of forest products and with a microeconomic model of allocation of the harvested area to form a national-level forest sector model for France (FFSM++).

In this paper, we present the model with emphasis on its spatial aspects, and we show that by only considering environmental heterogeneity and, therefore, the local characteristics of the forest under management, it is possible to realistically model management decisions such as forest investments. In particular, we propose an application that spatialises the forest growth rate, normally reported by inventory sources at the regional level, and we run long-term scenarios (until 2100) in order to simulate the effects on the forest dynamics of a potential increase in coniferous mortality in certain areas due to climate change when interactions between forest management strategies are explicitly considered.

1. Introduction

Forest ecosystems change relatively slowly. While this is a relative advantage for modellers and policy makers since it allows for very long predictions concerning their status, it is not necessarily an advantage for forests themselves. As pointed out in Milad et al. (2011), the long generation times and low migration rates of many forest species may cause natural adaptation to lag behind the predicted high rate of climate change.

Even if changes in forest "stock" properties (area, timber volumes) are slow, modelling their "flow" properties (regeneration, mortality, harvesting) remains challenging due to the multiple and interconnected drivers, both ecological and anthropogenic.

While most forest sector models focus on either ecological drivers, on the one hand (Nabuurs et al., 2002; Schelhaas et al., 2007; Wernsdörfer et al., 2012) or on market forces, on the other (Kallio et al., 2006; Buongiorno et al., 2003), few studies have attempted to assess their interplay (UNECE/FAO, 2011; Van Brusselen et al., 2009).

The main objective of the French Forest Sector Model (FFSM++, Lobianco et al., 2014) is to describe the French forest system, explicitly considering the relationships that exist between forest biological dynamics and forest management, where both forest product markets and individual management decisions are modelled.

In order to achieve its goal, FFSM++ considers three separate modules: (1) the first one that simulates forest dynamics using a matrix approach, the "Forest Dynamics Module"; (2) the second one that determines wood market prices, demand, supply – hence harvesting – and trade using a partial equilibrium model: the "Market Module"; and (3) the third one that allocates harvested area to new forest investments using a micro-economic approach: the "Area Allocation Module". These three modules are combined together and exchange data, as detailed in Table 1 and Fig. 1.

However, in previous versions of FFSM, these three modules were run at the same spatial scale, that is, regional. While a regional scale is reasonably detailed enough to model markets, it neglects intra-regional differences that could be significant for forest dynamics. Indeed, most recent applications of dynamic global

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Table 1
Modules, spatial levels and interface variables.

Module	Levels	Var Input	Var Output
Market (MK)	Countries, regions	$Inv_{r,pp,t}$	$Supply_{r,pp,t}$, $Price_{r,pp,t}$
Forest Dynamics (FD)	Countries, regions, pixels	$Supply_{r,pp,t}$, $RegArea_{px,ft,t}$	$Inv_{px,pp,t+1}$, $HArea_{px,ft,t}$
Area Allocation (AA)	Countries, regions, pixels	$Price_{r,pp,t}$, $HArea_{px,ft,t}$	$RegArea_{px,ft,t}$

vegetation models (e.g., Cheaib et al., 2012 and Lafont et al., 2011) forecast their results on a much smaller scale, typically on an 8 × 8 km grid.

Given the wide availability of forest spatial data in Europe with the Corine Land Cover project (EEA, 2007), for example, the method described in Section 2 decouples the spatial scale of the Market Module (regional) with those of the Forest Dynamics and the Area Allocation Modules (pixels). This grid-based approach allows FFSM++ to consider local-scale environmental characteristics and to therefore simplify the linkage with spatially explicit vegetation models. When considered in relation to forest management, the grid approach also makes it possible to consider its very heterogeneous nature, accounting, for example, for the different objectives and behaviour of small vs. large forest owners, private vs. public owners, etc.

In this paper, however, we focus on forest heterogeneity and we show that a detailed spatial scale is also essential to avoid corner solutions, one where forest managers would respond equally to environmental change, and to realistically represent the indisputable richness in forest types that exists within each region.

In many countries, the set of information required to run a high-resolution forest model at the national scale is not available. Therefore, in Section 2.6, we develop a Monte Carlo method to spatialise forest growth rates, starting from their regional means and variance, and in Section 3, we apply this framework to question the impacts of spatially dependent exogenous shocks, comparing simulations run under this heterogeneous space with those produced under a homogeneous growth rate. As suggested by Guarín and Taylor (2005), climate change may have, together with broader impacts, impacts on the local scale that strongly interact with topographic characteristics such as slope and elevation. In particular, Allen et al. (2010) report an increase in mortality in coniferous forests at the lower or southern edges of their distribution ranges. An increased risk of mortality in forests due to climate changes is expected by many authors, e.g., Lindner et al. (2010) and Dale et al. (2000).

In this context, we are attempting to understand the overall impacts when accounting for market forces and resulting adaptation strategies that may compensate for the effects in the impacted areas. In Section 3.2, we therefore simulate an increase in coniferous mortality in the lowlands of southern France and observe the implications in terms of forest profitability, regeneration, utilisation and land cover, conditionally on the different spatial framework assumed.

Finally, whereas the scenarios modelled in this paper cover only a single aspect of what could be climate change implications, they still serve as an example of the type of elements that could be considered in more exhaustive scenarios. Section 4 is devoted to a discussion of the implications and limitations of our findings.

When variables and dimensional indices are not self-explanatory, they are explained the first time that they are encountered in the text. Nevertheless, Tables 7–9 in the Appendix list indices, variables and regional codes, respectively, used throughout the text.

2. Modelling spatially explicit resources and management

2.1. Overview of FFSM++

FFSM++ is a bio-economic model that describes the French forest system, explicitly considering the relationships that exist between forest biological dynamics and forest management, where both forest product markets and individual management decisions are modelled.

In FFSM++ (Fig. 1, arrow 1), forest resources evolve according to parameters that are driven by the specific climate scenario.

Resource availability is used in the Market Module (arrow 2) to determine the supply curve that, together with an exogenous demand, is used to compute a market equilibrium *à la* Samuelson (1952).

Each year, the Market Module computes the regional supply of primary forest products pp (*Hardwood Roundwood*, *Softwood Roundwood*, *Pulpwood and Fuelwood*) to local and international markets ($supply_{r,pp,t}$) using Eq. (1), where eSP_{pp} is the elasticity of supply to price ($P_{r,pp,t}$) and eSR_{pp} is the elasticity of supply to available resources ($avRes_{r,pp,t}$, defined in Section 2.4). Both elasticities are derived from Buongiorno et al. (2003) and are exogenous in the context of this study:

$$\frac{supply_{r,pp,t}}{supply_{r,pp,t-1}} = \left(\frac{P_{r,pp,t}}{P_{r,pp,t-1}}\right)^{eSP_{pp}} \left(\frac{avRes_{r,pp,t}}{avRes_{r,pp,t-1}}\right)^{eSR_{pp}} \quad (1)$$

Likewise, the demand curves use exogenous elasticities of demand to price (specifically estimated for FFSM in Sauquet et al., 2011) and the Armington framework (Armington, 1969), allowing the model to endogenously compute "local" regional prices based on exogenous international prices (in this paper, based on the a1b scenario of Buongiorno et al., 2012, arrow 3).

Using the Armington framework also makes it possible to simultaneously consider international trade, where products are considered to be heterogeneous, with inter-regional trade, where products are instead considered to be homogeneous. Due to the

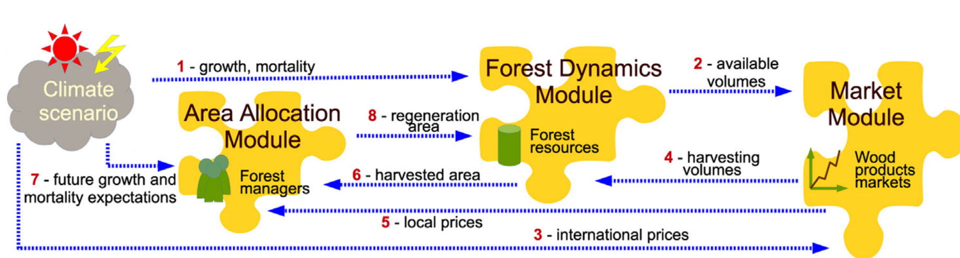

Fig. 1. FFSM++ flowchart.

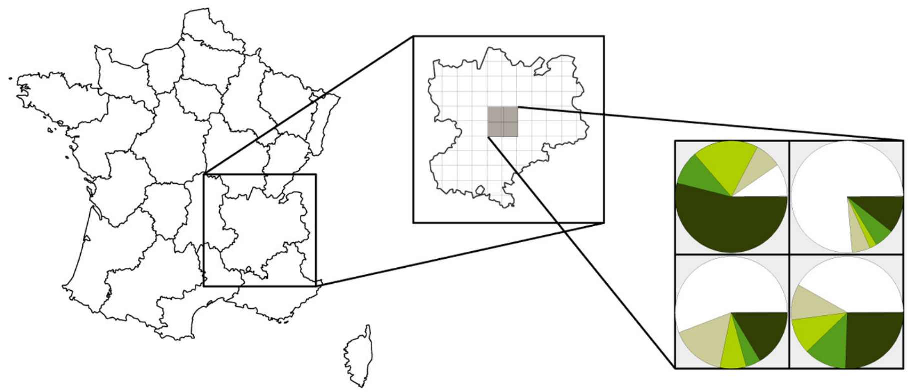

Fig. 2. FFSM++ spatial representation. The three-level hierarchical representation of the spatial dimension in FFSM++, where each pixel contains information about the different forest areas (in green) as well as about the non-forested area (in white). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

homogeneity hypothesis, the market equilibrium prices in the regions differ uniquely due to the transport costs between regions.

The Market Module provides two outputs to other modules. The harvesting levels are subtracted from the existing forest resources in the Forest Dynamics Module (arrow 4), and the prices of the obtainable products from the forest resources are passed to the Area Allocation Module (arrow 5). In this latter module, expectations in terms of prices and future forest growth and mortality (arrow 7) are used to allocate the harvested area to the regeneration area for the forest type, guaranteeing the highest expected return per hectare (i.e., the Equivalent Annual Income – EAI – computed from marketing the wood harvested). Finally, the regeneration area is used (arrow 8) to compute the new regeneration volumes in the Forest Dynamics Module.

The model is multidimensional in the sense that it manages different forest resources by diameter class and in yearly steps, and the market structure (supply, demand, prices and trade) is defined among a set of multiple wood products.

The dynamic of the first version of the model (without the management) is described in Caurla et al. (2010, 2013), whereas the Area Allocation Module is detailed in Lobianco et al. (2014).

2.2. Spatial representation

The spatial representation of FFSM++ is organised along three levels (Fig. 2). Of these, the first two (Countries and Regions) are used in the Market Module, whereas the pixel level is used only in the Forest Dynamics and Area Allocation Modules (Table 1).

Whereas raster layers are generally used in most applications to define a unique land use over the pixel (usually through an integer value that defines the land use), they are used in this application to define the total area for the various forest types (and for the non-forested area) within the pixel, using one layer for each possible forest type. However, the exact land allocation inside the pixel is not defined. For example, a given pixel may define values of 40 ha, 10 ha and 5 ha for high broadleaved forests, coppices and high coniferous forests, respectively (with the remaining area considered as non-forested).

Since there is no perfect match between forest type definitions in our original forest land cover source, i.e., the 2006 Corine Land Cover (CLC2006, EEA, 2007), and the forest types defined in FFSM++, Section 2.3 illustrates how we initialised these values.

Whereas the model itself is independent of the spatial resolution, simulations proposed in Section 3 have been run, applying a 8 × 8 km resolution.

Adopting this approach, FFSM++ is able to represent ecological and social phenomena at a scale that is more appropriate for their analysis. In particular, with the inclusion in the model of a microeconomic Area Allocation Module, a detailed spatial representation is essential to describe the conditions in which the economic agents operate.

In FFSM++, pixels are defined as the minimum level at which forest investment decisions are applied. Therefore, a single forest manager in the Area Allocation Module corresponds to each pixel. While the model makes it possible to sample forest managers with different behavioural characteristics (level of risk aversion, expectations toward future prices or toward climate change impact) according to a given probability distribution, we focus in this paper on the spatial heterogeneity of the forest, meaning that all managers share the same behaviour and differ only as to the forest resources managed in their corresponding pixel.[1]

Indeed, in a homogeneous region (and with homogeneous agents, i.e., with identical behaviour), the "optimal" forest investment would be the same throughout and the model would not be able to represent the indisputable richness in forest types that exists within each region.

Space affects the model in all of its modules: (i) in the Market Module, the Euclidean distance between regions drives the formation of transport costs in the Market Module; and (ii) in the Forest Dynamics and Area Allocation Modules, heterogeneous environmental conditions influence the forest dynamics, both observed and expected and, consequently, the investment decisions.

2.3. Forest layer initialisation

In FFSM++, a spatial "layer" is defined as a raster grid that can either be loaded from a file before the simulation or that can be created by the model itself in order to save and report spatially explicit data. Examples of the first case include the original Corine Land Cover data (by forest cover category), the Digital Terrain Model, the administrative borders and the availability coefficients. When the original data was in vector format, it was rasterised using the GRASS command (Neteler et al., 2012) `g.raster`. Concerning land use data, in order to obtain the value of the total area for a given forest type standing on a pixel, we used an intermediate 20 × 20 m raster file that we then summed up to obtain the land cover value at the

[1] However, the supplementary material includes two extra scenarios `cc1_hetAgents` and `cc4_hetAgents` where forest managers are sampled from a normal distribution $\mathcal{N}(\mu = 1, \sigma)$ and the results are compared with the `cc1` and `cc4` scenarios, respectively. The description of the supplementary material provided with this paper is given in Appendix C.

8×8 km pixel level.[2] Mortality coefficients used in climate change scenarios `cc1-cc4` are also exogenously loaded at the beginning of the simulation, even if they can refer to subsequent years.

In particular, a forest type *ft* is defined with both its predominant group of species *sp* (either *broadleaved* or *coniferous*) and management type *mt* (either *high forest*, *coppice* or *mixed*), i.e., $ft = sp \times mt$.

At the pixel level, FFSM++ requires the initial volumes for each forest type and diameter class $V_{px,ft,dc}$. We use CLC2006 to distribute these volumes, known at the regional level, down at the pixel level. However, information about forest management is missing from CLC2006. Moreover, CLC2006 has an extra category, "Mixed broadleaved/coniferous forests", which is not defined in the model. Nevertheless, from the national inventory, we have the information on the volumes by forest type and diameter class at the regional level $V_{r,ft,dc}$.

The first step is to use these volumes as a weight to compute the area at the pixel levels for all the required layers ($area_{px,sp,mt}$):

$$area_{px,sp,mt} = area_{px,sp} * \frac{V_{r,sp,mt}}{\sum_{mt} V_{r,sp,mt}} + area_{px,sp=mix} * \frac{V_{r,sp,mt}}{\sum_{sp}\sum_{mt} V_{r,sp,mt}} \quad (2)$$

The first addend simply distributes the area by management type in the pixel according to its volume distribution at the regional level. The second addend distributes the area of mixed broadleaved/coniferous forests (that is not defined in our national inventory data and, consequently, in FFSM++) according to the relative volumes.

We then use $area_{px,sp,mt}$ as a weight to compute the volumes available for each diameter class at the pixel level ($V_{px,ft,dc}$):

$$V_{px,ft,dc} = V_{r,ft,dc} * \frac{area_{px,ft}}{area_{r,ft}} \quad (3)$$

This distribution implies three strong assumptions: (i) Eq. (2) implies that the density (*vHa*) within a given group of species is the same for each management type, and that (ii) such density is constant within the region; (iii) Eq. (3) assumes a uniform distribution of the forest in diameter classes within the regions.

2.4. Aggregation and disaggregation functions

With some components of the model working at one scale and others at a different scale, an obvious problem arises as to the spatial aggregation and disaggregation of data between the various modules.

In the Forest Dynamics Module, the units represented are the standing volumes of the main logs (without branches) as defined by the IGN (2011) for each forest type.

To use them in the Market Module, we need to aggregate them from pixel to region and from forest type and diameter class to primary products. The available resource for a given product $avRes_{r,pp,t}$ is therefore the sum of each volume at suitable forest types and diameter classes in each pixel (the binary parameter $sFlag_{ft,dc,pp}$ accounts for this linkage, according to technical requirements), multiplied by an "availability coefficient" $avCoef_{px}$ to account for actual availability of forest to be harvested[3]:

$$avRes_{r,pp,t} = \sum_{px}\sum_{ft}\sum_{dc} sFlag_{ft,dc,pp} * V_{px,ft,dc,t-1} * avCoef_{px} \quad (4)$$

$avCoef_{px}$ is a [0,1] coefficient computed in this paper from the presence of protected areas and the elevation levels given in Table 2.

While we recognise that computing *avCoef* from Table 2 is a naive and subjective approach, we recall that the supply function in the marked model is based on the ratio of $avRes_{pp,t}$ over $avRes_{pp,t-1}$.

From Eqs. (1) and (4), it is easy to see that a scalar multiplication of the *avCoef* vector (i.e., if availability coefficients change in a fixed ratio), the ratio $avRes_{pp,t}/avRes_{pp,t-1}$ does not change. The ratio remains constant as well, regardless of $avCoef_{px}$, if the ratio $V_{px,t}/V_{px,t-1}$ remains constant in each pixel or, with a large enough number of pixels, if this ratio is spatially uncorrelated with *avCoef*. On the basis of the above propositions, it would be tempting to conclude that the introduction of *avCoef* is actually irrelevant. However, since the availability coefficient also influences the harvesting in the pixel, the pixels with the higher *avCoef* are also those that are more extensively harvested and, consequently, those where the $V_{px,t}/V_{px,t-1}$ is smaller. Therefore, introducing the *avCoef* slightly reduces the $avRes_{pp,t}/avRes_{pp,t-1}$ ratio.

Once the Market Model has computed the harvested wood supply at a regional scale and for each primary product, it distributes the harvesting back to the Forest Dynamics Module, over the various pixels, forest types and diameter classes.

The assumption made is that the harvesting rate, computed over the available resources *avRes* (that already account for the spatial heterogeneity of the resources), remains constant in the region, i.e., the harvesting demand is driven only by the amount of available resources and we can therefore express the harvesting volumes (*hV*) as:

$$hV_{px,ft,dc,t} = \left(\sum_{pp} sflag_{ft,dc,pp} * \frac{supply_{r,pp,t}}{avRes_{r,pp,t}}\right) * V_{px,ft,dc,t-1} * avCoef_{px} \quad (5)$$

where *sflag* is the same binary parameter of Eq. (4) that links each wood product with its possible source in terms of forest type and diameter class (e.g., roundwood for sawnwood has larger diameter class requirements than logs for pulp and fuel), and *supply*/*avRes* is the harvested rate *hr* of the region.

Table 2
Components of the availability coefficients.

IUCN Protected Area Categories System		Elevation (m)	
Ia Strict Nature Reserve	0%	<500	100%
Ib Wilderness Area	10%	500–1000	90%
II National Park	80%	1000–2000	70%
III Natural Monument or Feature	10%	>2000	30%
IV Habitat/Species Management Area	10%		
V Protected Landscape/Seascape	90%		
VI Protected area with sustainable use of natural resources	95%		

[2] Supplementary material includes both the data layers themselves and the instructions to recreate them and, in particular, the GIS script used to rasterise the land cover starting from the vector data in CLC2006

[3] The lag in the time index is due to the discrete modelling of the time when total volumes *V* are defined at the end of the year, while available resources to be harvested *avRes* are defined at the beginning of the year.

Table 3
Coefficient of variations in relation to diameter growth.

	Peduncolate oak *Quercus robur*	Sessile oak *Quercus petraea*	Common beech *Fagus sylvatica*	Scots pine *Pinus sylvestris*
AL	0.072	0.158	0.110	0.194
AQ	0.095	0.101	0.085	0.139
AU	0.073	0.140	0.083	0.174
BN	0.071	0.050	0.103	0.143
BO	0.095	0.158	0.090	0.148
BR	0.038	0.058	0.130	0.160
CE	0.064	0.075	0.127	0.204
CA	0.077	0.169	0.068	0.179
CO	0.003	0.080	0.296	0.765
FC	0.116	0.151	0.069	0.234
HN	0.067	0.077	0.098	0.190
IF	0.054	0.084	0.071	0.156
LR	0.017	0.138	0.178	0.434
LI	0.048	0.099	0.080	0.079
LO	0.095	0.131	0.057	0.151
MP	0.080	0.124	0.127	0.275
NP	0.034	0.136	0.036	0.079
PL	0.049	0.051	0.081	0.243
PI	0.050	0.115	0.054	0.097
PC	0.084	0.110	0.091	0.198
PA	0.009	0.050	0.179	0.474
RA	0.076	0.181	0.113	0.252
France	0.066	0.122	0.089	0.268

2.5. A spatially explicit resource model

The original forest volume equation of FFSM (Eq. (34) of Caurla et al., 2010) is adapted here to work at the pixel level and with dynamic information[4]:

$$V_{px,dc,t} = \left(1 - \frac{1}{tP_{px,dc,t}} - mort_{px,dc,t}\right) * V_{px,dc,t-1} - hV_{px,dc,t} + \frac{1}{tP_{px,dc-1,t}} * beta_{r,dc} * V_{px,dc-1,t-1} \quad (6)$$

where tP is the time of passage to reach the next diameter class; *mort* is the yearly mortality rate in the specific diameter class; and *beta* is the relative volume growth of a tree moving from the previous diameter class to the current one.

The spatial and dynamic dimensions are added, with regard to regional averages in the base year, though exogenous multipliers that are loaded as GIS layers:

$$\begin{aligned} tP_{px,dc,t} &= tP_{r,dc,t=0} * tpMultiplier_{px,t} \\ mort_{px,dc,t} &= mort_{r,dc,t=0} * mortMultiplier_{px,t} \end{aligned} \quad (7)$$

The Forest Dynamics Module requires a forest density parameter to convert the harvested volumes into harvested area, i.e., $vHa_{px,dc,t}$. This is obtained recursively by diameter class according to Eq. (8):

$$vHa_{px,dc,t} = vHa_{px,dc-1,t} * beta_{r,dc} * mortCL_{px,dc-1,t} \quad (8)$$

where *mortCL* is the overall mortality in a given diameter class, obtained in turn as:

$$mortCL_{px,dc,t} = 1 - (1 - mort_{px,dc,t})^{tP_{px,dc,t}} \quad (9)$$

Similarly, the Area Allocation Module requires a density parameter in order to forecast the future expected returns in the land allocation. In this case, however, the model needs to look at future values. Firstly, for every year, it is necessary to dynamically compute a cumulative time of passage in order to obtain the overall time necessary for trees to reach a given diameter class (Eq. (10)). This is then used to compute the overall mortality rate by diameter class that is expected in the future (*mortCL_exp* in Eq. (11)) that in turn replaces the observed mortality in Eq. (8):

$$cumTp_{px,dc,t} = cumTp_{px,dc-1,t} + tp_{r,dc,t=0} * tpMultiplier_{px,t=\tau_{px,dc-1,t}} \quad (10)$$

$$mortCL\_exp_{px,dc,t} = 1 - (1 - mort_{r,dc,t=0} * mortMultiplier_{px,t=\tau_{px,dc,t}})^{tp_{px,dc,t=\tau_{px,dc,t}}} \quad (11)$$

where $\tau_{px,dc,t} = t + ceil(cumTp_{px,dc,t})$ makes it possible to select the right multiplier that will be in place at the time when the trees will have reached the specified diameter class.

Using a weighting factor, the present and (expected) future parameters can be combined in order to simulate a different propensity of the economic agents to take investment decisions based on (i) the forest conditions that are observed at the time the decisions are made, or (ii) the future predictions as forecasted by the exogenous climate/vegetation models.

2.6. Heterogeneous growth rates

While the original FFSM (1.0) spatial level comprises only administrative regions, we have evidence of a much higher heterogeneity for French forests.

The French National Geographic Institute (IGN) recognises 86 "sylvo-eco-regions" (IGN, 2010) and the 2012 IGN raw data includes plots that are qualified by a minimum of 13 different principal species per region (Corse) to a maximum of 35 (Rhône-Alpes).

IGN data can also be used to measure the variance relative to diameter growth. Data in Table 3 shows that, for the four main forest species in France, intra-regional variance (between individual plots in the region) in diameter growth is often higher than the national one (between the regional averages), i.e., regions differ not only in "regional forest growth averages" but also in how this growth rate is spread throughout the region.

[4] For the purpose of clarity, Eqs. (6)–(11) omit the forest type index.

Table 4
Spatial variance effect, France [2100].

	bau_nospvar	bau	Difference	cv
Expected returns (€/ha)				
- 00_Total	29.540	61.669	32.129[b] (108.766%)	1.37%
- 01_Broadleaved	21.336	53.271	31.935[b] (149.674%)	1.90%
- 02_Coniferous	41.547	78.911	37.364[b] (89.931%)	1.99%
Regeneration volumes (Mm^3)				
- 00_Total	2.062	2.013	−0.049[b] (−2.367%)	0.19%
- 01_Broadleaved	0.533	0.942	0.409[b] (76.715%)	1.36%
- 02_Coniferous	1.529	1.071	−0.458[b] (−29.939%)	1.07%
Forest volumes (Mm^3)				
- 00_Total	6201.517	6912.485	710.969[b] (11.464%)	0.40%
- 01_Broadleaved	4522.944	5107.139	584.194[b] (12.916%)	0.30%
- 02_Coniferous	1678.572	1805.347	126.775[b] (7.553%)	1.35%
Harvested volumes (Mm^3)				
- 00_Total	62.142	63.526	1.384[b] (2.228%)	0.10%
- 01_Broadleaved	34.044	35.118	1.074[b] (3.155%)	0.32%
- 02_Coniferous	28.098	28.408	0.310[b] (1.104%)	0.54%
Forest area (ha)				
- 00_Total	14108173.210	14108174.598	1.388[a] (0.000%)	0.00%
- 01_Broadleaved	8381565.340	9487950.940	1106385.600[b] (13.200%)	0.29%
- 02_Coniferous	5726607.870	4620223.658	−1106384.212[b] (−19.320%)	0.59%
Regeneration area (ha)				
- 00_Total	77763.889	76141.782	−1622.108[b] (−2.086%)	0.17%
- 01_Broadleaved	19039.040	35281.742	16242.702[b] (85.313%)	1.24%
- 02_Coniferous	58724.849	40860.040	−17864.809[b] (−30.421%)	1.00%
Harvested area (ha)				
- 00_Total	77763.864	76141.780	−1622.084[b] (−2.086%)	0.17%
- 01_Broadleaved	40021.540	40158.092	136.552[b] (0.341%)	0.35%
- 02_Coniferous	37742.324	35983.687	−1758.636[b] (−4.660%)	0.29%

[a] Significantly different from 0 at $\alpha = 0.01$.
[b] Significantly different from 0 at $\alpha = 0.001$.

In this context, considering regions as homogeneous would lead to an error that we attempted to assess in this paper. On the other hand, even in a country with a detailed forest inventory like France, the set of information required to run a high-resolution forest model at the national scale is still lacking.

We hence adopted a mixed approach where regional averages are still used, but a modifier of the time of passage that directly reflects the growth rate is introduced for each pixel. This is sampled from a normal distribution $\mathcal{N}(\mu = 1, \sigma = CV_{r,sp})$ with the average set to one and the standard deviation derived from the IGN data and specific to the species group and region.

Since the expected value of the growth rate does not differ from the regional average, all differences in the results can be attributed to the non-linearity of the model and, therefore, indirectly to the relative importance of considering the full spatial characteristics compared to using average regional values.

Standard deviations for species' groups and regions were computed from volume growth at the plot level in the IGN datasets 2005–2009.[5]

3. Simulations

This section presents the numerical output of the simulations that we ran. Since FFSM++ does not introduce any modification to the Market Module compared with the first version (FFSM 1.0), we did not include any market-based scenario and, consequently, market results are not discussed in this section.[6]

Furthermore, due to the initial time lag in regeneration, some curves show an initial "S" shape that lasts for the first 20–30 years and, as a result, comparisons between scenarios, when not otherwise stated, are given as averages for the period 2030–2100 for flow variables (expected returns and volume regenerations), and over the last year of the simulations (2100), for stock variables (forest volumes and areas), the exception being the harvesting volumes, which although they are a flow variable, depend on the stock volumes and are therefore reported for 2100.

We created two sets of scenarios: in `*_nospvar`, all modifiers discussed in Section 2.6 remain fixed to 1. Consequently, no variation between pixels exists and in the remaining scenarios, we used the sampled modifiers. Results are reported in Table 4.

We can observe that adding regional heterogeneity has a strong impact on the model's output. Expected returns become much higher, given the exponential nature of both forest growth and the economic discounting used to compute the Equivalent Annual Income (EAI). We therefore found that:

$$E[EAI(gr)] > EAI(E[gr]) \tag{12}$$

where gr is the volume growth rate on each pixel.

The average expected returns remain much higher for coniferous compared to broadleaved forests. Nevertheless, under heterogeneous space conditions in some plots, the situation is reversed and broadleaved forests are more profitable at the local level, while under regional homogeneous conditions, all the managed regeneration is allocated to coniferous forests since they have the highest expected returns. We can therefore observe a shift of volume regenerations in favour of broadleaved forests.

Even if regeneration volumes for coniferous forests decrease due to the non-linear nature of forest growth, the volumes of both forest types increase in 2100 (+12.9% and +7.5% in broadleaved and coniferous forests, respectively).

Overall, considering spatial heterogeneity in the model favours forest types that are sub-optimal while "penalising" the most profitable ones under homogeneous space.

[5] We thank Jean-Daniel Bontemps and Pierre Mérian from the Laboratory of Forest Resources (LERFoB) for providing this information.

[6] The full set of results, including regional ones and market-related variables is, however, available in the supplementary material.

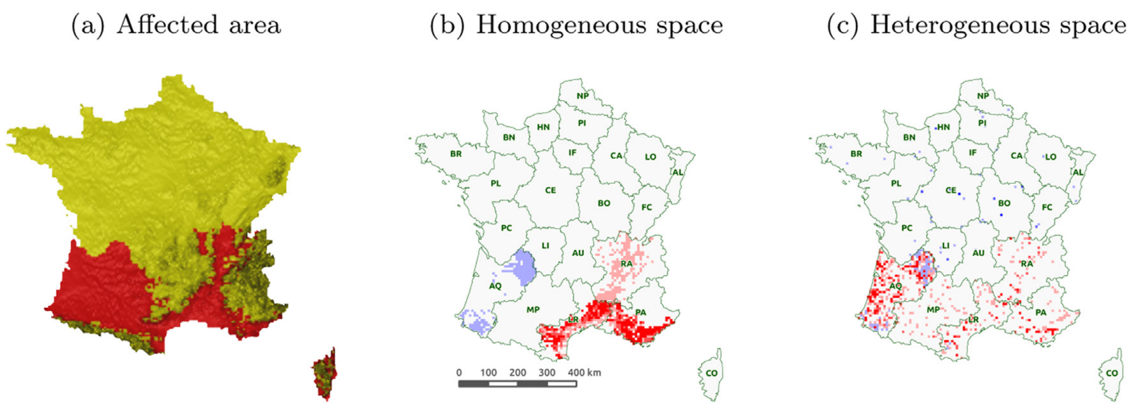

Fig. 3. Regions affected by the increased mortality and coniferous area allocation effects of `cc2` compared to the `bau` scenario [2100]. Map (a): red: increased coniferous mortality due to cc; yellow: unaffected areas. Maps (b) and (c): red: reduced coniferous area; blue: increased coniferous areas; white: no changes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.1. Stability of stochastic simulations

Since the heterogeneous environment scenario uses a stochastic component, we investigated the possibility that the effects we obtained were just part of this random component or could be considered as a structural result.

We therefore ran the `bau` scenario 30 times and followed the Fortin and Langevic (2012) approach to perform a Student's t test on results in 2100 to check that we can reject the null hypothesis that the average of the (stochastic) `bau` scenario is equal to the (deterministic) `bau_nospvar` scenario. All variables are significantly different at $\alpha = 0.001$. Furthermore, given the relatively large number of plots used (8,580), aggregated results at the national level have very small coefficients of variation, so that a single run is enough to forecast results that are not influenced by the specific run.

At the regional level, the vast majority of variables remains significant, but there are a few cases where, given the very small effects of regeneration over the forest stocks and, consequently, over the harvesting, a larger batch of runs would be needed to achieve statistical significance for all of the variables.

3.2. A spatial application: effects of an increased mortality in coniferous forests at the lower/southern edges of their distribution ranges

In this case study, we use the spatial framework introduced in Section 2 to simulate a likely effect of climate change on forestry, i.e., an increase in forest mortality for coniferous forests in lowland areas of southern France.

Allen et al. (2010) in fact report a numerous (and growing) literature concerning observed climate change-induced mortality within forest ecosystems. In Europe, in particular, a large number of cases involve coniferous species (20 out of 25 cases) at the lower/southern edges of their distribution ranges (13 out of 20 cases). Using a Digital Terrain Model (DTM) from IGN (2013), we therefore introduced an exogenous increase in mortality in the model for coniferous forests in the lowlands (elevation $\leq$500 m) of Aquitaine (AQ), Midi-Pyrenees (MP), Languedoc-Roussillon (LR), Provence-Alpes-Cote d'Azur (PA), Rhone Alpes (RA) and Corse (CO). Since there is no common consensus on the quantification of coniferous mortality due to climate change, we simulated a set of four scenarios to better understand the response of the model, where `cc1` is the mildest one – a moderate increase in coniferous mortality – and `cc4` is the most extreme one – up to a 10-fold increase in the mortality rate.[7] The area affected by this increased mortality is shown in red in Fig. 3.

We compared the results of these scenarios with a business-as-usual (`bau`) scenario where the mortality rates do not change from the current observed values. Allocation of coniferous forests at the end of the simulation (2100) is shown in Fig. 3 (red: reduced allocation; blue: increased areas) and Table 5, while the temporal dynamic of key variables is given in Fig. 4 for Aquitaine, the leading region in terms of softwood production in France.

Model simulations show that an increase in coniferous mortality has several impacts on forest patterns. Some responses are common to all of the regions where mortality increases, while some others depend on the relative profitability between coniferous and broadleaved forest investments in the region.

In all of the regions involved, the increased coniferous mortality reduces the volume of their standing stocks in the forest. In addition, it increases, often intensely, the area freed for new regeneration at harvesting time. Indeed, as mortality increases, density decreases, and harvesting the same amount of timber leads to a wider harvesting area, which then frees up a wider regeneration area.

As expected, when increasing the intensity of the scenario, forest managers at the national level employ what could be interpreted as "adaptation strategies", switching from the more vulnerable coniferous forests toward the more resilient broadleaved forests, leading to a drop in the overall coniferous area of 0.58% in the `cc1` scenario and up to 7.02% in the `cc4` scenario.

However, this process is very heterogeneous both between and within the regions. Indeed, while some regions (hereafter referred to as "low impact regions") show a significant coniferous area reduction only for high levels of mortality, other regions (hereafter referred to as "high impact regions") already have a strong impact in mild scenarios.

In low impact regions, the difference in expected returns between coniferous and broadleaved forests is very high (in favour of coniferous forests), even when accounting for the increased mortality. Forest managers therefore prefer to internalise the loss due to an increased mortality rather than to switch investments to broadleaved forests.

Since substitutability between broadleaved and coniferous exists in our model for some timber products (e.g., Pulpwood and Fuelwood), in order to compensate for the reduction in the supply from coniferous forests, the quota of timber from broadleaved forests must increase.

[7] Details on the settings of each scenario are reported in Table 6.

Table 5
Coniferous area allocation in 2100 [% variation over `bau`].

Region	cc1		cc2		cc3		cc4	
	het. s.	hom. s.	het. s.	hom. s.	het. s.	hom. s.	het. s.	hom. s.
France	−0.579	*−0.995*	−1.832	*−2.094*	−7.021	*−11.543*	−7.021	*−11.543*
Impacted regions:								
- AQ	−2.180	+0.159	−7.502	+0.449	−32.280	*−47.428*	−32.280	*−47.428*
- MP	−0.364	+0.073	−1.136	+0.178	−5.700	−3.795	−5.700	−3.795
- RA	−0.264	+0.004	−0.800	−0.640	−2.379	*−6.458*	−2.379	*−6.458*
- LR	−0.914	+0.080	−2.884	*−13.899*	−7.314	*−17.486*	−7.314	*−17.486*
- PA	−0.820	*−9.277*	−1.891	*−10.135*	−4.497	*−10.770*	−4.497	*−10.770*
- CO	−0.015	+0.004	−0.037	+0.010	−0.174	+0.035	−0.174	+0.035
Other regions:								
- LI	+0.047	+0.057	+0.198	+0.163	+1.290	+0.601	+1.290	+0.601

Variation compared to `bau` of the coniferous area in selected regions under gradually higher coniferous mortality. Cases where the decrease is greater under homogeneous space settings compared with heterogeneous space settings are shown in italics and become more frequent as the scenario becomes stronger.

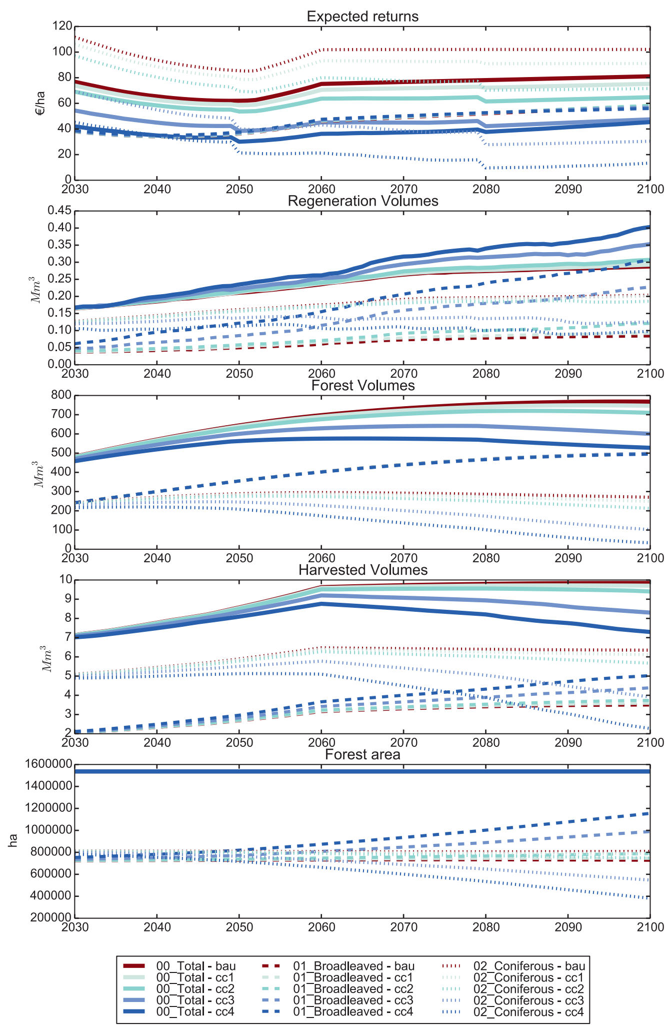

Fig. 4. Effects of increased mortality in lowland southern coniferous forests, Aquitaine (AQ).

This translates into an additional demand for broadleaved loggings, leading to additional harvesting and, therefore, to additional areas freed up for regeneration. Yet, given the higher expected returns of coniferous forests, it ends up being allocated to them. In other words, this result shows that an increase in coniferous mortality leads to a counter-intuitive switch from broadleaves to coniferous stands. When space is considered as homogeneous, this market feedback even leads to an increased coniferous area compared with `bau`.

We call this the “harvest effect”, to distinguish it from the substitution effect derived from the change in relative profitability.

This mechanism is even enhanced in the model by the Samuelson spatial price equilibrium framework, since low impact regions undergo spillover effects from the high impact regions that narrow the drop in expected returns of coniferous forests due to the increased mortality.

When we instead further increase the mortality rate, the difference between the expected returns of broadleaved and coniferous forest investments diminishes or even begins to favour broadleaved forests, triggering an overall switch in forest owners’ investment decisions toward broadleaved forests. In these conditions, due to the increases in price, the highland areas excluded from the increase in mortality partially compensate for the strong changes in the lowlands and attenuate the impact at the regional level.

Similarly, outside the regions concerned by the increased mortality, we observe a general increase in the coniferous allocation due to the lower exports (or higher imports) from the impacted regions and the consequently higher prices (as shown in the last row of Table 5).

3.3. *The role of spatial variance in the mortality simulation*

Both `bau` and `cc*` are stochastic scenarios, i.e., the volume growth is regionalised starting from the regional average and standard deviation, as described in Section 2.6. However, all the simulations share the same random generator seed. This guarantees that the random multiplier assigned to a given pixel is the same, regardless of the scenario.

Nevertheless, we ran the `bau` and `cc*` scenarios under homogeneous space settings and found that the assumed spatial framework strongly influences the impacts, as shown in Table 5 where italics are used to highlight when the decrease in coniferous areas is higher in a homogeneous space setting compared to a heterogeneous setting.

We can distinguish two cases: (i) in mild scenarios when the space is homogeneous, there is no forest switch and, to the contrary, the harvest effect described in the previous section in favour of coniferous forests (still the most profitable investment here) may appear. Adding spatial heterogeneity means that, in some pixels, the difference between expected returns may be enough to induce an investment shift (multipliers of different forest types are uncorrelated), causing the observed reduction in coniferous land allocation at the regional level; (ii) in more extreme scenarios, the situation is the opposite: increased mortality causes expected returns from coniferous forests to decrease below those of broadleaved forests, so that in homogeneous space, all of the harvested area under management switches to broadleaved forests. In heterogeneous space, some plots instead maintain a distance large enough to avoid the shift, so that the shift to coniferous forests in these cases is mitigated.

The level of mortality that triggers the two cases is specific to each region, with *Provence-Alpes-Côte d'Azur* already showing the high impact behaviour in the `cc1` setting, while *Corse* does not react, even to the most extreme scenario.

4. Discussion

This paper deals with the introduction of the spatial dimension within the Forest Dynamics and Area Allocation Modules of the FFSM++ model using a grid (pixel) approach.

Since FFSM++ makes it possible to consider both spatially explicit exogenous modifiers of the forest (e.g., climatic change) and the management response that it would follow (or which would precede it since expectations are explicitly modelled), the model can be used to assess the long-term dynamics of the French forest sector where the clear prevalence in the profitability of coniferous forests in comparison to broadleaved forests strongly emerges. However, we show that when we consider the environmental heterogeneity, even those forest types that would never have been selected if we had considered homogeneous regional characteristics can instead represent the locally optimal forest investment.

In particular, the spatial framework is used to simulate the effects of an increased coniferous mortality in the lowlands of southern France, i.e., at the lower or southern edge of their distribution range, as reported by Allen et al. (2010). We show that the impact on forest resources strongly depends on the management response and that this in turn depends on the relative profitability of the affected forests. When coniferous forests are, and remain, the most profitable choice, market forces that react to a reduced production of coniferous species may cause an increased rate of conversion toward coniferous forests that mitigates and, in certain conditions, offsets the substitution effect driven by the change in relative profitability.

Despite the increased complexity, data demand and computational requirements, we believe that the gain in terms of capability of the spatial model to simulate key real-world phenomena offsets the disadvantages.

This paper paves the way for two main possibilities. Firstly, we can model scenarios where the exogenous shocks are characterized by a spatial dimension, an example of which is given in Section 3 where coniferous mortality is expected to increase only in certain areas. Exogenous spatial data is not limited to characteristics of the forest, but the same method can be used to consider those of the forests owners, e.g., in order to differentiate the behaviour of private vs. public owners. Secondly, spatial heterogeneity is a prerequisite of the Area Allocation Module. In homogeneous regions, it would in fact not be possible to realistically model forest managers' behaviour using a micro-economic approach since this would lead to corner solutions (all agents adopting the same behaviour since the decision space is the same). In other words, real-world forests are all different because the local conditions in which they are located are different. In this paper, we show a simple approach where the specific local conditions are accounted for in the forest managers' utility function in order to choose the "optimal" forest investment.

The need for an explicit spatial model conflicts with the availability of inventory data that are significant only on a more aggregate scale. To overcome this lack, a Monte Carlo simulation is used in Section 2.6 where spatial data (forest growth) is sampled from a normal distribution to obtain a simulated forest with the same distribution properties as the inventory data in terms of variance and mean. This approach is consistent with the objectives of the model to describe the national and regional forest sector rather than to provide a detailed characterization of the forest distribution and evolution in any particular pixel. In other words, we use data and perform computations on a low spatial level (pixel) to achieve results that remain significant only on a higher, aggregated level (regions).

In the application proposed in this paper each forest type multiplier is uncorrelated and the forest growth is assumed to be normally distributed. In reality, local productivity is likely to be correlated between forest types (e.g., a fertile soil would favour both coniferous and broadleaved forests) and the growth rate distribution often shows a positive skewness (a few forests may grow extremely slow, but no forest growths mature in a few years). If spatial multipliers are correlated between forest types, then the conclusion that spatial heterogeneity attenuates the forest type switch toward the most profitable one may have been overestimated, since the expected returns of different forest types in the individual pixels would move in the same direction, and the relative distance would therefore be maintained. The stronger the correlation is, the more the impacts would converge toward the homogeneous space. Considering a skew distribution, given in Eq. (12), would also reduce the impacts on expected return, even if the impact on the relative forest profitability is not clear.

More advanced sampling techniques that consider the correlation and skewing aspects may help to quantify this aspect.

Finally, while the Market Module does endogenise timber prices, it heavily relies on exogenous international prices (i.e., it assumes a small-country hypothesis). In this paper, we used forecasts of international prices that already account for climate change, but these are limited to 2060 and all scenarios are run under the same set of prices. While this simplifies the discussion and allows results in the simulations to have a causal relationship with the assumptions drawn in the scenarios, it certainly reduces the reliability of the numerical forecasts such as, for example, that stronger climate change scenarios may well alter international world prices and, as a result, the relative profitability between the two broad groups of forests discussed in this paper.

While considering the limitations above, this paper nevertheless shows the importance of considering a heterogeneous space in bio-economic forest models and paves the way to more realistic assumptions over the specific climate change effects on the forest (growth and mortality multipliers), on the markets (international timber prices) and on the forest managers (heterogeneous behaviours).

Supplementary material

This paper is accompanied by the following supplementary material:

Input data: The complete set of files used to run the scenarios presented in the paper. The main file containing settings and data is an OpenDocument spreadsheet ("`ffsmInput.ods`"). Spatial data is included in the `gis` folder.

Input data replication instructions: The instructions to replicate the creation of the data as used by the model starting from publicly available sources. In particular, GIS scripts are provided in order to convert the spatial data.[8]

Model source code: The complete source code (in C++) of the model.

Model compilation and usage instructions: Instructions on how to compile and run the model.

[8] Conversely, it is not currently possible to retrieve the French forest inventory data from public sources since even the downloadable raw inventory data lack some elements (e.g., point sampling weight and precise coordinate) that make it impossible to use them as a source for the parameters required by the model.

Model detailed documentation: A much more in-deep documentation of the model, in the form of a PDF generated directly from the annotated source code using the Doxygen documentation tool.

Complete model output: A (large) PDF document containing the detailed output of the model for each French region. Raw output results from Forest Dynamics and Market Modules are also available in the "output_{scenario_name}/results/" folders. Due to space constraints, outputs for the random repetitions of the `bau` scenario are not included, and map outputs are given only for the `bau` scenario.

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Appendix A. Scenario definition

See Table 6.

Appendix B. Model notations

See Tables 7–9.

Table 6
Definition of the scenarios.

Name	Description	Characteristic parameters
bau	Business-as-usual scenario	Spatially explicit growth multipliers sampled from regional growth rate CV. No mortality change from observed rates.
cc1	A moderate climate change/increased mortality scenario	A climate change scenario where coniferous mortality coefficients of pixels in the lowlands (≤500 m) of southern France (AQ, MP, LR, PA, RA, CO) increase by 10% starting in 2020, 20% starting in 2050 and 30% starting in 2080.
cc2	Intermediate effects of cc on mortality	Similar with cc1 but stronger increase of mortality (1.3× in 2020, 1.5× in 2050 and 2× in 2080)
cc3	Intermediate effects of cc on mortality	Similar to cc1 but even stronger increase of mortality (2× in 2020, 3× in 2050 and 5× in 2080)
cc4	Stronger effect of cc on mortality	Similar to cc1 but even stronger increase of mortality (3× in 2020, 5× in 2050 and 10× in 2080)
bau_nospvar	The bau scenario using homogeneous space	Growth multipliers remain equal to 1 for all pixels
cc1_nospvar	Like cc1 without considering spatial variance	Growth multipliers remain equal to 1 for all pixels
cc2_nospvar	Like cc2 without considering spatial variance	Growth multipliers remain equal to 1 for all pixels
cc3_nospvar	Like cc3 without considering spatial variance	Growth multipliers remain equal to 1 for all pixels
cc4_nospvar	Like cc4 without considering spatial variance	Growth multipliers remain equal to 1 for all pixels

Table 7
Commonly used indexes.

Notation	Definition	Values
t	Time	[2005–2100]
c	Country	{France}
r	Region	[22 administrative regions in France]
px	Pixel	
sp	Forest species group	{Broadleaves, Coniferous}
mt	Forest management type	{High forests, Mixed forests, Coppices}
ft	Forest type (including management)	[sp × mt] (e.g., broadleaved coppices or high coniferous forest)
dc	Diameter class	{0, 15, 25, 35, 45, 55, 65, 75, 85, 95, 150}
pp	Primary product (i.e., derived directly from forest resources)	{Hardwood Roundwood, Softwood Roundwood, Pulpwood and Fuelwood}
tp	Transformed products	{Fuelwood, Hardwood Sawnwood, Softwood Sawnwood, Plywood, Pulpwood, Pannels}
prd	Products	[pp ∪ tp]

Table 8
Variables.

	Name	Definition
$area_{px,ft,t}$	Area	Land-cover area
$avCoef_{px}$	Availability coefficient	A coefficient to indicate how much of the forest resources in a given pixel is available to be harvested.
$avRes_{r,pp,t}$	Available resources	Forest biomass, of the right diameter class and species, available to be harvested to produce a given primary product
$beta_{r,dc}$	The relative volume growth of a tree moving from the previous to the current diameter class	
$cumTP_{px,ft,dc}$	Cumulative time of passage	The overall time required for a specific forest type to reach a given diameter class
dR	Discount rate	
$EAI_{px,ft}$	Equivalent annual income	
eSP_{pp}	Elasticity of supply to price	
eSR_{pp}	Elasticities of supply to available resources	
$hV_{px,ft,dc,t}$	Harvested volumes	
aRR	Active regeneration rate	The share of forest area managed that is allocated to the most profitable forest type rather than left for natural regeneration.
$mort_{px,dc,t}$	Mortality rate	The yearly mortality rate in a given diameter class
$mortCL_{px,dc,t}$	Mortality rate of the diameter class	Overall mortality rate for a given diameter class
$mortMultiplier_{px,t}$	Mortality multiplier	A spatially and time dynamic multiplier of the mortality rate
$P_{r,prd,t}$	Price	
$sFlag_{ft,dc,pp}$	Source flag	A binary variable (0–1) that links each primary product with its possible sources in terms of forest types and diameter classes
$supply_{r,pp,t}$	Supply	The supply to both local and international markets of a given primary product

Table 8 (*Continued*)

	Name	Definition
$tP_{px,ft,dc,t}$	Time of passage	The average time required for trees to grow from a given diameter class to the next one
$tpMultiplier_{px,t}$	Time of passage multiplier	A spatial and temporal dependent multiplier of the time of passage between diameter classes, i.e., of the growth rate
$V_{px,ft,dc,t}$	Volumes	(Inventoried) volumes of biomass in the forest
$vHa_{px,ft,dc,t}$	Volumes per hectare	

Table 9
French region codes.

Code	Name
AL	Alsace
AQ	Aquitaine
AU	Auvergne
BN	Basse Normandie
BO	Bourgogne
BR	Bretagne
CE	Centre
CA	Champagne Ardenne
CO	Corse
FC	Franche Comte
HN	Haute Normandie
IF	Ile de France
LR	Languedoc Roussillon
LI	Limousin
LO	Lorraine
MP	Midi Pyrenees
NP	Nord
PL	Pays de la Loire
PI	Picardie
PC	Poitou Charentes
PA	Provence Alpes Cote d'Azur
RA	Rhone Alpes

Appendix C. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolmodel.2015.04.012

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