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Introducing spatial heterogeneity in forest sector modelling: insights from the French forest Sector Model

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Abstract

Given the importance of anthropogenic determinants in forest ecosystems within Europe, the objective of FFSM++ is to link the evidence arising from biological models with socio-economic determinants, where the expected returns of forest investments represent the main drivers. An inventory-based forest dynamic model is hence coupled with a market module and a management one in a national level forest sector model for France (FFSM++). In this paper we show that only considering the environment heterogeneity, and hence considering the local characteristics of the forest under management, we can realistically model the micro-based management module. In particular, an application is proposed that spatialises the forest growth rate and long-term scenarios (until 2100) are run to examine the effects on the forest dynamic, and notably the interaction with forest management strategies, of a potential increase of coniferous mortality in certain areas due to climate change.

Key words: Forest sector modelling, Spatial model, Bio-economic model, Forest mortality

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1 Introduction

Forest ecosystems change relatively slow. While this is a relative advantage for modellers and policy makers, as it allows to make very long predictions concerning their status, it isn't necessarily an advantage for forests themselves. As pointed 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 on forests "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 models focus on either ecological drivers (Nabuurs et al., 2002; Schelhaas et al., 2007; Wernsdörfer et al., 2012) on one side or on market forces (Kallio et al., 2006; Buongiorno et al., 2003) on the other side, few studies try to asses their interplay (UNECE/FAO, 2011; Van Brusselen et al., 2009).

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

In order to achieve its goal, FFSM++ considers three separate modules: the first one simulating the forest dynamics using a matrix approach, the "Forest Dynamic module"; the second one determining wood market prices, demand, supply - hence harvesting - and trade using a partial equilibrium model: the "Market module"; the third one allocating harvested area to new forest investments using a micro-economic approach: the "Management module". These three modules are combined together and exchange data as detailed in Table 1.

However the three modules run at the same spatial scale, that is, regional. While a regional scale is reasonably adequate to model markets, it neglects intra-regional differences that, for the forest dynamics, could be significant. Indeed most recent applications of dynamic global vegetation models (for example Cheaib et al., 2012 or Lafont et al., 2011) forecast their results on a much smaller scale, typically on an 8x8km grid.

Given the wide availability of forest spatial data, for example in Europe with the Corine Land Cover project (JRC-EEA, 2005), the method described in Section 2 decouples the spatial scale of the Market module (regional) with those of the Forest Dynamics and the Management modules (pixels). This grid-based approach allows FFSM++ to consider local-scale environmental characteristics and therefore to simplify the linkage with detailed biological models. We show that it is also essential to avoid corner solutions and to realistically represent the indisputable richness in forest types that exists within each region.

In many countries, however, the set of information required to run at national scale a high-resolution forest model is not available. Therefore in Section 3.1 we develop a Monte Carlo method to spatialise the forests growth rates starting from their regional mean and variance and we compare simulations ran under this heterogeneous space with those produced under an homogeneous growth rate.

We employed this framework to answer a new type of questions that would have been difficult to address without an explicit spatial framework, that is the impacts of spatially-dependant exogenous shocks. As suggested by Guarín & Taylor (2005), climate change may have, together with broader impacts, local-scale impacts that strongly interact with topographic characteristics, like slope and altimetry. In particular, Allen et al. (2010) report an increase of mortality for coniferous at their lower or souther edges of range. An increased risk of mortality in forests due to climate changes is expected by many authors, for example Lindner et al. (2010) and Dale et al. (2000).

In this context, we want to understand the overall impacts when accounting for market forces and resulting adaptation strategies that may compensate the effects in the impacted areas. In Section 3.2 we hence simulate an increase of coniferous mortality in lowlands of southern France and observe the strong implications on adaptation strategies (and hence on the impacts) depending on the spatial framework assumed.

Finally in Section 4 we discuss implications and limitations of our findings.

2 Modelling spatially explicit resources and management

2.1 Overview of FFSM++

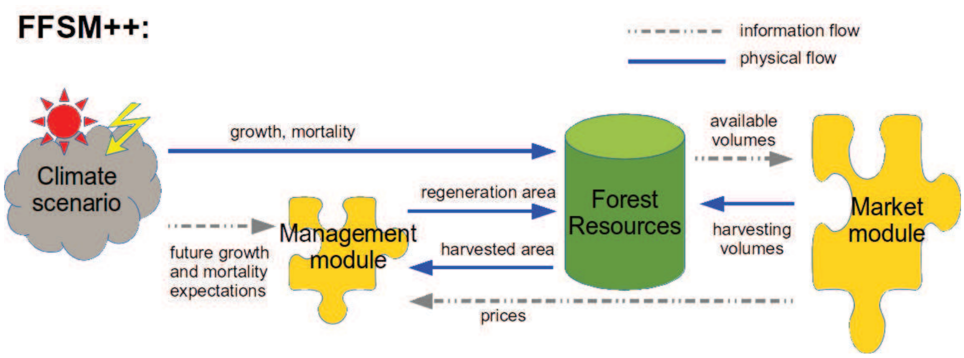
FFSM++ is a bio-economic model that describes the French forest system explicitly considering the relations that exist between the forest biological dynamic and the forest management, where both the markets of forest products and the individual management decisions are modelled.

In FFSM++ (Figure 1) forest resources evolve according to parameters that are driven by the specific climate scenario. The resource availability is used in the Market module to determine the supply curve that, together with an exogenous demand is used to compute a market equilibrium à la Samuelson (1952).

The Market module produces two outputs. The harvesting levels are subtracted from the existing forest resources and the prices of the obtainable products from the forest resources are passed to the Management module. Here the prices information and the expectations on the future forest parameters are used to allocate the harvested area to regeneration area for the forest type promising the highest expected return per hectare (that is, the Equivalent Annual Income - EAI - computed from marketing the harvested loggings). Finally the regeneration area is used to compute the new regeneration volumes in the Forest Dynamic module.

The model is multidimensional, in the sense that it manages different forest resources, by diameter class and in yearly steps. The dynamic of the first version of the model (without the management) is described in Caurla et al. (2010, 2013) while the management module is detailed in Lobianco et al. (2014).

Figure 1: FFSM++ Flowchart



2.2 Spatial representation

The spatial representation of FFSM++ is organised along three levels (Figure 2). Of these, the first two (Countries and Regions) are used in the Market module while the Pixel level is used only in the Forest Dynamic and Management modules (Table 1). Each pixel encompasses the information of the area share for each forest type within the pixel, but the exact land allocation inside the pixel is not defined. While the model itself is independent on the spatial resolution, simulations proposed in Sections 3.1 and 3.2 have been run applying a 8x8 km resolution.

Adopting this approach, FFSM++ is able to represent ecological and social phenomena at the scale that is more appropriate for their analysis. In particular, with the inclusion in the model of a micro-economic management module, a detailed spatial representation is essential to describe the conditions in which the economic agents operate. Indeed, in a homogeneous region (and with homogeneous agents) the “optimal” forest investment would be wherever the same, 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: in the Market module the

Euclidean distance between regions drives the formation of transport costs in the market module; in the Forest Dynamic and Management modules heterogeneous ecological conditions influence the forest dynamic, both observed and expected, and hence the investment decisions.

Figure 2: FFSM++ spatial representation

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 Dynamic (FD)	Counties, regions, pixels	$Supply_{r,pp,t}$, $RegArea_{px,ft,t}$	$Inv_{px,pp,t+1}$, $HArea_{px,ft,t}$
Management (MG)	Countries, regions, pixels	$Price_{r,pp,t}$, $HArea_{px,ft,t}$	$RegArea_{px,ft,t}$

2.3 Forest layers initialisation

In FFSM++, a forest "layer" is defined with both its predominant group of species (either *broadleaved* or *coniferous*) and management type (either *high forest*, *coppice* or *mixed*).

The initial status of the forest ecosystem, including information on wood volumes for each forest type and diameter class, is likely not to be available at pixel level.

To begin with, information about forest management is missing from our original forest land cover source, that is Corine Land Cover 2006 (CLC2006, JRC-EEA, 2005). Moreover CLC2006 is available as a vector shapefile and it has an extra category "Mixed forests" that is not implemented in the model. We therefore needed to rasterize each forest category and use the information on forest volumes available from the French Forest Inventory (at a regional scale) as a weight to compute the area at the pixel levels for all the needed layers:

$$area_{px,sp,mt} = area_{px,sp} * \frac{V_{r,sp,mt}}{\sum_{mt} V_{r,sp,mt}} + area_{px,sp=mix} * \frac{V_{r,sp,mt}}{\sum_{sp}\sum_{mt} V_{r,sp,mt}} \tag{1}$$

We then used this information itself as a weight to compute the volumes available for each diameter class at pixel level:

$$V_{px,ft,dc} = V_{r,ft,dc} * \frac{area_{px,ft}}{area_{r,ft}} \tag{2}$$

This reclassification implies three strong assumptions: (a) eq. (1) implies that the density (vHa) is the same for each forest type and that (b) the density is constant within the region; (c) eq. (2) assumes a uniform distribution of 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 in the spatial aggregation and disaggregation of data between the various modules. While the aggregation from pixel data to regional data is a straightforward procedure, not the same can be said for the opposite: in particular, the model has to deal with the distribution of the wood harvested supply, computed from the market module at a regional scale, to the various pixels. The assumption made is that the product within the region is homogeneous and the harvesting conditions constant, therefore the harvesting demand is driven only by the amount of available resource and we can write the harvesting volumes (hV) as:

$$hV_{px,ft,dc,t} = \left(\sum_{pp} sflag_{ft,dc,pp} * \frac{supply_{pp,t}}{inv_{pp,t}} \right) * V_{px,ft,dc,t-1} \tag{3}$$

where $sflag$ is a binary variable that links each wood product with its possible sources in terms of forest types and diameter classes and the first multiplicand is the harvested rate h appearing in eq. (33) of Caurla et al. (2010). An interesting extension of the model could be to break this assumption so that harvesting depends from other local characteristics, for example altimetry.

2.5 A spatially explicit resource model

The original forest volumes equation of FFSM (equation 33 of Caurla et al., 2009) is here adapted to work at pixel level and with dynamic information[1]:

$$\begin{aligned} V_{px,dc,t} &= (1-\frac{1}{tp_{px,dc,t}} - mort_{px,dc,t}) * V_{px,dc,t-1} - hV_{px,dc,t} \\ &+ \frac{1}{tp_{px,dc-1,t}} * beta_{r,dc} * V_{px,dc-1,t-1} \end{aligned} \tag{4}$$

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 when a tree pass from the previous to the current diameter class.

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

$$\begin{aligned} tp_{px,dc,t} &= tp_{r,dc,t=0} * tpMultiplier_{px,dc,t} \\ mort_{px,dc,t} &= mort_{r,dc,t=0} * mortMultiplier_{px,dc,t} \end{aligned} \tag{5}$$

The Forest Dynamic module, while converting the harvested volumes in harvested area needs a forest density parameter, that is $vHa_{px,dc,t}$. This is obtained recursively by diameter class according to equation 6:

$$vHa_{px,dc,t} = vHa_{px,dc-1,t} * beta_{r,dc} * mortCL_{px,dc-1,t} \tag{6}$$

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

$$mortCL_{px,dc,t} = 1 - (1 - mort_{px,dc,t})^{tp_{px,dc,t}} \tag{7}$$

Similarly, the Management module needs 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, on 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. 8). Then this is used to compute the overall mortality rate by diameter class that it is expected in the future ($mortCL\_exp$ in eq. 9), that in turn replaces the observed mortality in eq. 6:

$$cumTp_{px,dc,t} = cumTp_{px,dc-1,t} + tp_{r,dc,t=0} * tpMultiplier_{px,t=\tau_{px,dc-1,t}} \tag{8}$$

$$mortCL\_exp_{px,dc,t} = 1 - (1 - mort_{r,dc,t=0} * mortMultiplier_{px,t=\tau_{px,dc,t}})^{tp_{px,dc,t=\tau_{px,dc,t}}} \tag{9}$$

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

[1] For clarity purposes Equations 4 to 9 omit the forest type index.

Using a weighting factor the two methods can be combined in order to simulate a different propensity of the economic agents to take investment decisions based on (a) the forest conditions that are observed at the time the decisions are made or (b) the future predictions as forecast by the exogenous climate/vegetational models.

3 Simulations

Figures 4 to 7 present the numerical output of the run simulations. Each Figure is designed to highlight a specific topic comparing different scenarios. Variables are reported in the order they influence each other in the model: expected returns drive forest investments in specific forest types leading to regeneration volumes (forest recruitment) that in turn dynamically modify the stock of volumes for a given forest type and finally the volume stocks influence the harvesting levels through a positive elasticity of supply (described in Caurla et al., 2010).

Harvesting levels represent the raw material supply within the Market module. As FFSM++ does not introduce any modification to the Market module, we didn't include any market-based scenario and consequently market results are not discussed in this section[2].

Due to the initial time lag in regeneration, some curves show an initial "S" shape that lasts for the first 20-30 years and hence comparisons between scenario, when not otherwise stated, are given as average for the period 2030-2100 for flow variables (expected returns and volume regenerations) and on the last year of the simulations (2100) for stock variables (forest volumes and areas), the exception being the harvesting volumes that while being a flow variable depend on the stock volumes and hence they are reported for 2100.

3.1 Heterogeneous environment: Does it matter ?

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

The French National Geographic Institute (IGN) recognises 86 "sylvoecoregions" (IGN, 2010) and the 2012 IGN raw data includes plots that are qual-

[2]The full set of results, including regional ones, is however available in the digital archive that comes along with this paper.

Results for forest dynamic and markets are available in the attached ZIP archive as raw data under the files "data/output_{scenario_name}/results/forestData.csv" and "data/output_{scenario_name}/results/productData.csv" respectively and as preformatted tables and charts in file "ffsm_output.pdf".

Input data is located in the "data/ffsmInput.ods" speadsheet and in the gis maps under "data/gis" directory.

ified 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 on Table 2 shows how, for the four main forest species in France, that intra-regional variance (between individual plots in the region) in diameter growth is generally higher than the national one (between the regional averages), that is regions differ not only in "regional forest growth averages" but also in how this growth rate is spread throughout the region: variance levels can be over 6 times higher in one region compared with an other for broadleaved species and over 16 times higher for coniferous.

Table 2: Variance relative to diameter growth in a subset of 3740 trees with D between 45-75 cm ("moyen bois"), IGN data, 2010

	Peduncolate Oak	Sessile Oak	Common Beech	Scots Pine
AL	0,0880	0,0526	0,0859	0,1208
AQ	0,0742	0,0933	0,1118	0,0573
AU	0,0605	0,0583	0,0731	0,0784
BN	0,0437	0,1127	0,0944	0,0135
BO	0,0614	0,0581	0,0657	0,0597
BR	0,0527	0,0712	0,1006	0,0603
CE	0,0805	0,0445	0,0771	0,0870
CA	0,0337	0,0757	0,0646	0,0882
CO			0,1484	
FC	0,1067	0,0380	0,0614	0,0146
HN	0,0529	0,0629	0,0948	0,2197
IF	0,0882	0,0845	0,0299	0,1069
LR	0,0436	0,0675	0,0678	0,0672
LI	0,0609	0,1034	0,0607	0,0476
LO	0,0643	0,0750	0,0793	0,0801
MP	0,0545	0,0497	0,0782	0,0967
NP	0,0261		0,0236	
PL	0,0641	0,0573	0,0992	0,0485
PI	0,0872	0,0337	0,1404	
PC	0,0584	0,0751	0,0253	0,0471
PA			0,093	0,0542
RA	0,0682	0,0665	0,0628	0,0663
France	0,0066	0,0058	0,0113	0,0128

In this context, considering regions as homogeneous would lead to an error that we tried to asses 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 at national scale a high-resolution forest model is still missing.

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

As 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 hence indirectly to the relative importance of considering the full spatial characteristics compared to using average regional values.

Standard deviations for species' groups and regions have been estimated from volume growth at plot level in the IGN datasets 2005-2012[3].

We created three scenarios: in `nonspatial` the model run without spatial modifiers at all, in `reference` we tested the spatial algorithm setting all the modifiers equal to one, in `withSpVariance` we used the sampled modifiers. Results are reported in Figure 4, where the `nonspatial` scenario is totally hidden by the overlapping `reference scenario`, and Table 3.

As expected, `nonspatial` and `reference` lead to identical results, validating the new algorithm. Adding regional heterogeneity (`withSpVariance`) change instead the results substantially. 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 hence found that (Equation 10):

$$E[EAI|gr] > EAI(E[gr]) \tag{10}$$

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 in some plots the situation is turned down and broadleaved forests result locally more profitable, while in regional homogeneous conditions all the managed regeneration is allocated to coniferous as these have the highest expected returns. Hence we can notice a shift of volume regenerations in favour of broadleaved.

Even if regeneration volumes for coniferous decrease, due to the non linearity nature of forest growth both forest types volumes in 2100 increase (+30.8% and +18.0.7% in broadleaved and coniferous respectively) as well as harvested volumes (+8.4% and +0.4%).

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

Stability of stochastic simulations

As the heterogeneous environment scenario employs a stochastic component, we investigated the fact if the effects we obtained were just part of this random component or can be considered as a structural result.

We hence ran 30 times the `withVariance` scenario and followed the Fortin & Langevic (2012) approach to perform a student's t test on results

[3]The python script used to obtain the estimation from the raw IGN data is included in the digital archive.

Table 3: Spatial variance effect, France [2100]

	reference	withSpVariance	difference	cv
Expected returns (€/ha)				
- 00_Total	24.724	93.037	68.314[b] (276.308%)	1.04 %
- 01_Broadleaved	14.634	75.465	60.832[b] (415.690%)	1.22 %
- 02_Coniferous	36.597	131.429	94.832[b] (259.124%)	1.93 %
Regeneration Volumes (Mm^3)				
- 00_Total	2.165	2.015	-0.150[b] (-6.948%)	0.28 %
- 01_Broadleaved	0.638	1.101	0.463[b] (72.634%)	0.90 %
- 02_Coniferous	1.528	0.914	-0.614[b] (-40.179%)	1.08 %
Forest Volumes (Mm^3)				
- 00_Total	6977.522	8872.439	1894.917[b] (27.157%)	0.68 %
- 01_Broadleaved	4985.847	6521.321	1535.474[b] (30.797%)	0.57 %
- 02_Coniferous	1991.676	2351.118	359.443[b] (18.047%)	1.69 %
Harvested Volumes (Mm^3)				
- 00_Total	55.194	57.672	2.478[b] (4.491%)	0.18 %
- 01_Broadleaved	28.048	30.417	2.369[b] (8.445%)	0.32 %
- 02_Coniferous	27.145	27.255	0.110[b] (0.405%)	0.58 %
Forest area (ha)				
- 00_Total	14108175.377	14108174.618	-0.759 (-0.000%)	0.00 %
- 01_Broadleaved	7626911.297	9678890.173	2051978.876[b] (26.904%)	0.34 %
- 02_Coniferous	6481264.080	4429284.446	-2051979.634[b] (-31.660%)	0.74 %
Regeneration area (ha)				
- 00_Total	85849.736	81710.323	-4139.413[b] (-4.822%)	0.38 %
- 01_Broadleaved	27719.281	46942.651	19223.370[b] (69.350%)	0.93 %
- 02_Coniferous	58130.455	34767.672	-23362.783[b] (-40.190%)	1.19 %
Harvested area (ha)				
- 00_Total	85849.726	81710.321	-4139.405[b] (-4.822%)	0.38 %
- 01_Broadleaved	52575.345	49476.816	-3098.529[b] (-5.894%)	0.54 %
- 02_Coniferous	33274.381	32233.506	-1040.876[b] (-3.128%)	0.49 %

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

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

in 2100 to check that we can reject the null hypothesis that the average of the (stochastic) `withVariance` scenario is equal to the (deterministic) `reference` scenario. All variables are significantly different from the reference scenario at $\alpha = 0.001$. Further, given the relatively large number of plots employed (8,580) and the law of large numbers, aggregated results at 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 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 hence over the harvesting, a larger batch of runs would be needed to achieve statistical significance for all the variables.

3.2 A spatial application: effects of an increased mortality in coniferous at the lower/souther edges of ranges

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

Allen et al. (2010) report indeed a numerous (and growing) literature of observed climate-change induced mortality within forest ecosystems. In Europe in particular, a large number of cases involves coniferous species (20 over 25 cases) at their lower elevation/southern edge of ranges (13 over 20 cases). Using a Digital Terrain Model (DTM) from IGN (2013) we hence introduced in the model an exogenous increase of mortality of 30% (from observed levels) for coniferous forests in the lowlands (elevation $\leq$ 500m) of Aquitaine (AQ), Midi-Pyrenees (MP), Languedoc-Roussillon (LR), Provence-Alpes-Cote d'Azur (PA), Rhone Alpes (RA) and Corse (CO) starting in 2020, 50% starting 2050 and doubling (100%) starting 2080 (`ccstrong` scenario). As there is no common consensus on the quantification of coniferous mortality due to climate change, to better understand the response of the model we also simulated a milder scenario where the increase of mortality is 10%, 20% and 30% starting in the same years (`cc1`). The region affected by this increased mortality is shown in red in Figure 3a.

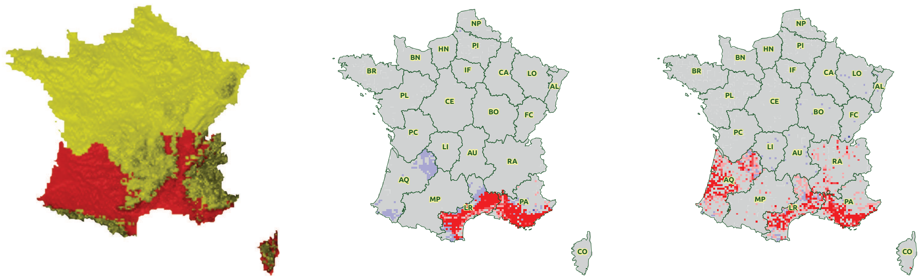
We compared the result of `ccstrong` with a business as usual (`bau`) scenario that is having heterogeneous space, intermediate management levels and moderate risk aversion between forest managers. Allocation of coniferous forests at the end of the simulation (2100) is shown in Figure 3 (red: reduced allocation; blue: increased areas), while the temporal dynamic of key variables is given in Figures 5 to 7.

Increased coniferous mortality influences the model in several ways. Some responses are common to all the regions involved to the increased mortality, while some others depend on the relative convenience between coniferous and broadlaved forest investments in the region.

In this respect, we identified two groups of regions in terms of overall

Figure 3: Affected regions end coniferous area allocation effects of `ccstrong` over `bau` scenario [2100]

(a) Regions (b) Homogeneous space (c) Heterogeneous space



impact (Table 4). We report *Rhône-Alpes* (Table 5) as example of a region showing a limited impact and *Provence-Alpes-Côte d'Azur* (Table 6) as example of a region with an higher impact.

Table 4: Coniferous area allocation in 2100, `ccstrong` over `bau`

Region	Homogeneous space	Heterogeneous space
Low impact regions		
- Aquitaine	+0.37%	-7.31%
- Midi-Pyrénées	+0.24%	-1.20%
- Rhône-Alpes	+0.02%	-1.22%
- Corse	+0.02%	-0.18%
High impact regions		
- Languedoc-Roussillon	-31.60%	-25.54%
- Provence-Alpes-Côte d'Azur	-33.14%	-35.53%

In all involved regions the increased coniferous mortality reduces their volume stocks. Secondly it increases, often intensely, the area freed for new regeneration at harvesting time: as mortality increases, density decreases, and to harvest the amount of timber required by the market module the harvesting area, and hence the regeneration area, must increases (+25.5%)[4].

As expected at national level the adaptation strategies of forest managers respond with a substitution of the most vulnerable coniferous with the more resilient broadleaved, and overall coniferous area drops of 7.4%. However this process is very heterogeneous both between and within the regions. Indeed while the regions of the first group (low impact) show a reduction

[4]The average density (forest volumes over forest area) surprisingly seems to increase for *Provence-Alpes-Côte d'Azur*. However this is just a result of a different diameter class distribution, where in the `ccstrong` scenario due to the managers decision to switch to other forest types the diameter distribution became much more oriented toward higher classes compared with `bau`.

Table 5: Mortality effect, Rhône-Alpes [2100]

	bau	ccstrong	difference
Expected returns (€/ha)			
- 00_Total	52.420	51.444	-0.975 (-1.861%)
- 01_Broadleaved	39.172	39.398	0.226 (0.576%)
- 02_Coniferous	69.187	67.028	-2.159 (-3.120%)
Regeneration Volumes (Mm^3)			
- 00_Total	0.165	0.174	0.009 (5.691%)
- 01_Broadleaved	0.077	0.083	0.006 (7.456%)
- 02_Coniferous	0.087	0.091	0.004 (4.135%)
Forest Volumes (Mm^3)			
- 00_Total	1233.430	1224.010	-9.420 (-0.764%)
- 01_Broadleaved	810.622	812.006	1.384 (0.171%)
- 02_Coniferous	422.808	412.004	-10.804 (-2.555%)
Harvested Volumes (Mm^3)			
- 00_Total	4.564	4.569	0.006 (0.122%)
- 01_Broadleaved	1.377	1.384	0.007 (0.534%)
- 02_Coniferous	3.187	3.185	-0.002 (-0.056%)
Forest area (ha)			
- 00_Total	1610608.700	1610609.300	0.600 (0.000%)
- 01_Broadleaved	899721.700	908385.300	8663.600 (0.963%)
- 02_Coniferous	710887.000	702224.000	-8663.000 (-1.219%)
Regeneration area (ha)			
- 00_Total	5869.360	6287.532	418.172 (7.125%)
- 01_Broadleaved	3079.240	3302.852	223.612 (7.262%)
- 02_Coniferous	2790.120	2984.680	194.560 (6.973%)
Harvested area (ha)			
- 00_Total	5869.345	6287.538	418.193 (7.125%)
- 01_Broadleaved	2855.835	2869.058	13.223 (0.463%)
- 02_Coniferous	3013.510	3418.480	404.970 (13.438%)

Table 6: Mortality effect, Provence-Alpes-Côte d'Azur [2100]

	bau	ccstrong	difference
Expected returns (€/ha)			
- 00_Total	22.572	24.960	2.387 (10.575%)
- 01_Broadleaved	26.349	26.472	0.123 (0.468%)
- 02_Coniferous	17.906	21.227	3.320 (18.543%)
Regeneration Volumes (Mm^3)			
- 00_Total	0.190	0.297	0.107 (56.239%)
- 01_Broadleaved	0.102	0.181	0.079 (76.817%)
- 02_Coniferous	0.088	0.116	0.028 (32.210%)
Forest Volumes (Mm^3)			
- 00_Total	297.515	296.315	-1.201 (-0.404%)
- 01_Broadleaved	181.833	190.407	8.574 (4.716%)
- 02_Coniferous	115.682	105.907	-9.775 (-8.450%)
Harvested Volumes (Mm^3)			
- 00_Total	2.406	2.397	-0.010 (-0.395%)
- 01_Broadleaved	1.270	1.343	0.073 (5.763%)
- 02_Coniferous	1.136	1.053	-0.083 (-7.282%)
Forest area (ha)			
- 00_Total	1078862.300	1078861.900	-0.400 (-0.000%)
- 01_Broadleaved	596257.300	767725.900	171468.600 (28.757%)
- 02_Coniferous	482605.000	311136.000	-171469.000 (-35.530%)
Regeneration area (ha)			
- 00_Total	11266.300	20850.320	9584.020 (85.068%)
- 01_Broadleaved	6977.570	11993.340	5015.770 (71.884%)
- 02_Coniferous	4288.730	8856.980	4568.250 (106.518%)
Harvested area (ha)			
- 00_Total	11266.300	20850.280	9583.980 (85.068%)
- 01_Broadleaved	5553.620	5690.180	136.560 (2.459%)
- 02_Coniferous	5712.680	15160.100	9447.420 (165.376%)

between 0.18 and 7.31% the forest area in the regions of the second group drops between 25.5 and 35.6%.

In the first group, the difference in expected returns (in favour of coniferous) is very high, even when accounting for the increased mortality. Hence forest managers prefer to internalise the loss due to an increased mortality rather than switch investments to broadleaved forests.

As substitutability between broadleaved and coniferous exists in our model for some timber products (e.g. Pulpwood and Fuelwood), in order to compensate the reduction in the supply from coniferous, the quota of timber from broadleaved must increases (and in fact, even if limited, Pulpwood and Fuelwood prices increase). The Market module demands hence to the Forest Dynamic module an increased logging from broadleaved as well, leading to an increase harvesting that, given the higher expected returns of coniferous, it ends up to be allocated to them. When space is considered homogeneous (Figure 3b) this market feedback leads to even an increased coniferous area compared with `bau`. In other words, when market mechanisms are accounted for, a limited increased mortality of the most profitable forest type may leads to an acceleration in a trend of substitution of the other forest types. Hence optimal adaptation strategies are the opposite to those that one would expects, favouring the most vulnerable species. We call this the “harvest effect”, to distinguish it from the substitution effect deriving from the change in relative profitability.

In *Languedoc-Roussillon* and *Provence-Alpes-Côte d’Azur* instead the difference between expected return of broadleaved and coniferous investments is low or even in favour of broadleaved, and the effect of the increased mortality is enough to trigger an overall switch in forest owners investment decisions toward broadleaved. In these regions, due to the increases in price, the highland areas excluded from the increase in mortality partially compensate the strong changes in the lowlands and attenuate the impact at regional level.

Similarly, outside the regions involved by the increased mortality we notice a general increase in the coniferous allocation due to their higher prices.

The role of spatial variance in the mortality simulation

Both `bau` and `ccstrong` are stochastic scenarios, that is the volume growth is regionalised starting from the regional average and standard deviation as described in Section 3.1. However the two simulations share the same random generator seed. This guarantees that the random multiplier assigned to a given pixel is the same within the two scenarios.

Neverless, the spatial heteogenity strongly influences the impact compared to use a growth rate homogeneous within the regions. We can distinguish two cases: (a) in the low impacts regions when the space is homogeneous there is no forest switch and, at the opposite, it may appears the harvest effect described in the previous section in favour of coniferous (here the most profitable). Adding spatial heterogeneity to these regions 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 land allocation at regional level; (b) in high impact regions the situation is the opposite: due to the low distance between expected returns, in homogeneous space forest mortality is enough to switch to broadleaved all the harvested area under management. In heterogeneous space some plots maintain instead a distance large enough to avoid the shift, hence the shift to coniferous forests is mitigated.

Provence-Alpes-Côte d'Azur is yet another case. In this region, under homogeneous space coniferous are only slightly more profitable, hence when adding mortality all harvested area is converted to broadleaved investments. In heterogeneous space, however, the average broadleaved expected return is slightly higher than the coniferous ones. In this situation, adding mortality cause the same harvesting effect described in the previous section but this time in favour of broadleaved (here the most profitable, on average). This effect largely predominates over the attenuation effect of sampling a few pixels having coniferous expected returns high enough to avoid the shift.

4 Discussion

This paper deals with the introduction of the spatial dimension in the coupled forest resource, management and market model FFSM++ using a grid (pixel) approach.

When the model is used to asses the long term dynamic of the French forest sector the clear prevalence in the profitability of the coniferous forest in comparison of broadleaved forests strongly emerges. However we show that when we consider the environmental heterogeneity even those forest types that would have never been selected if we would have considered homogeneous regional characteristics can instead represent the locally optimal forest investment.

In particular, the spatial framework is employed to simulate the effects of an increased coniferous mortality in lowlands of southern France, that is at the lower or souther edge of their distributional 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 the coniferous may cause an increased rate of conversion toward coniferous forests that mitigate, 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 world phenomena offsets the disadvantages.

Two main possibilities are now opened. Firstly we can model scenarios where the exogenous shocks are characterized by a spatial dimension, like we did 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 employed 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 pre-requisite of the management module. Indeed, in homogeneous regions it would not be possible to realistically model forest managers behaviour using a micro-economic approach, as this would lead to corner solutions. 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 in the utility function of forest managers in order to choose the "optimal" forest investment.

The request for an explicit spatial model conflicts with the availability of inventory data that are significant only on a more aggregate scale. To overcome to this shortage, in section 3.1 a Monte Carlo simulation is employed where spatial data (forest growth) is sampled from a normal distribution to obtain a simulated forest having the same distribution properties, in terms of variance and mean, of the inventory data. 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 supposed 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 grow very slow, but no forest growths mature in a few years). If spatial multipliers are correlated between forest types then the spatial heterogeneity effect of attenuate the management decisions in switching forest type toward the most profitable one may has been overestimated, as in the individual pixels the expected returns of different forest type would move in the same direction and hence the relative distance would be maintained. Stronger the correlation, stronger the impacts would converge toward the homogeneous space. Considering a skew distribution, given Equation 10, would also reduce the impacts on expected return, even if it is not clear the impact on the relative forest profitability.

More advanced sampling techniques that consider the correlation and skewing aspects may help in quantifying this aspects.

While considering the limitations above, this paper shows the importance, in terms of difference in the expected impacts to an exogenous shock, of considering an heterogeneous space in forest models. The integration of the Forest Dynamic, Market and Management modules that is proposed allows us to appreciate the effects of that systemic relations that are not possible to observe using individual models alone.

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A Simulation outputs figures

Figure 4: Heterogeneous spatial simulations, France

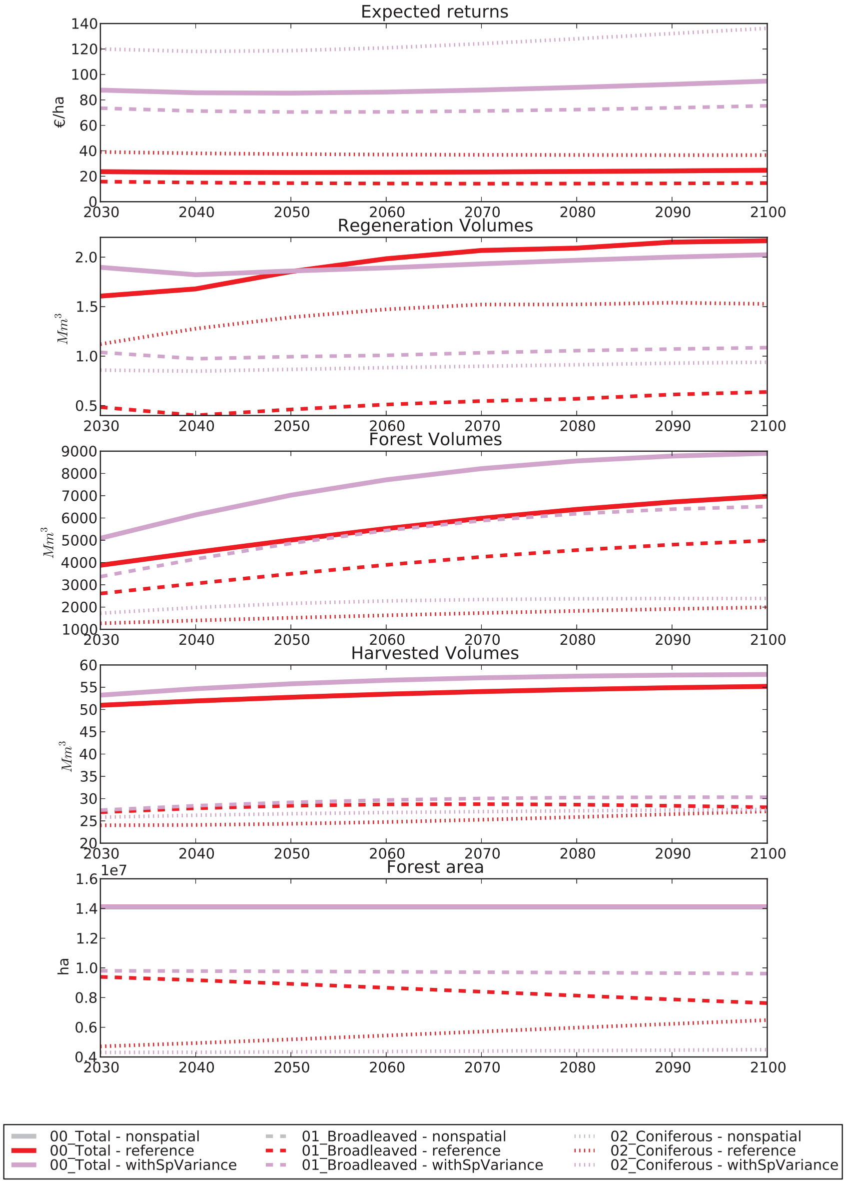


Figure 5: Effects of increased mortality in lowland south coniferous, France

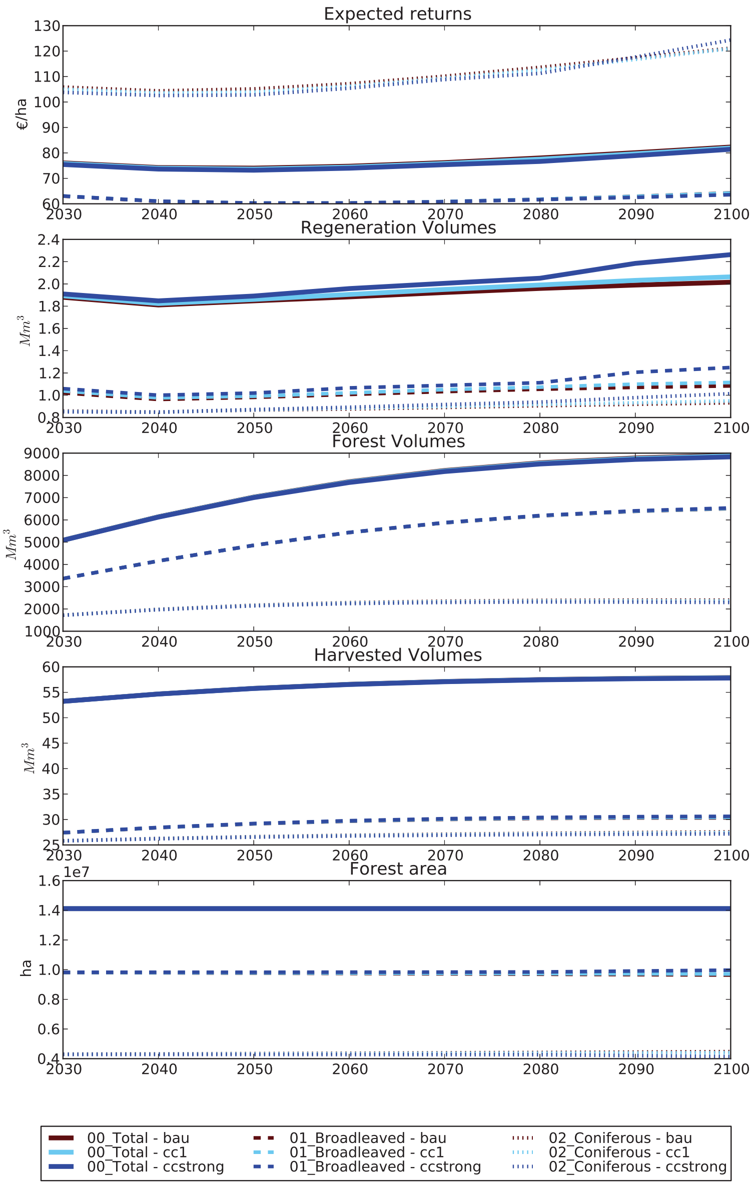


Figure 6: Effects of increased mortality in lowland south coniferous, Rhône-Alpes (RA)

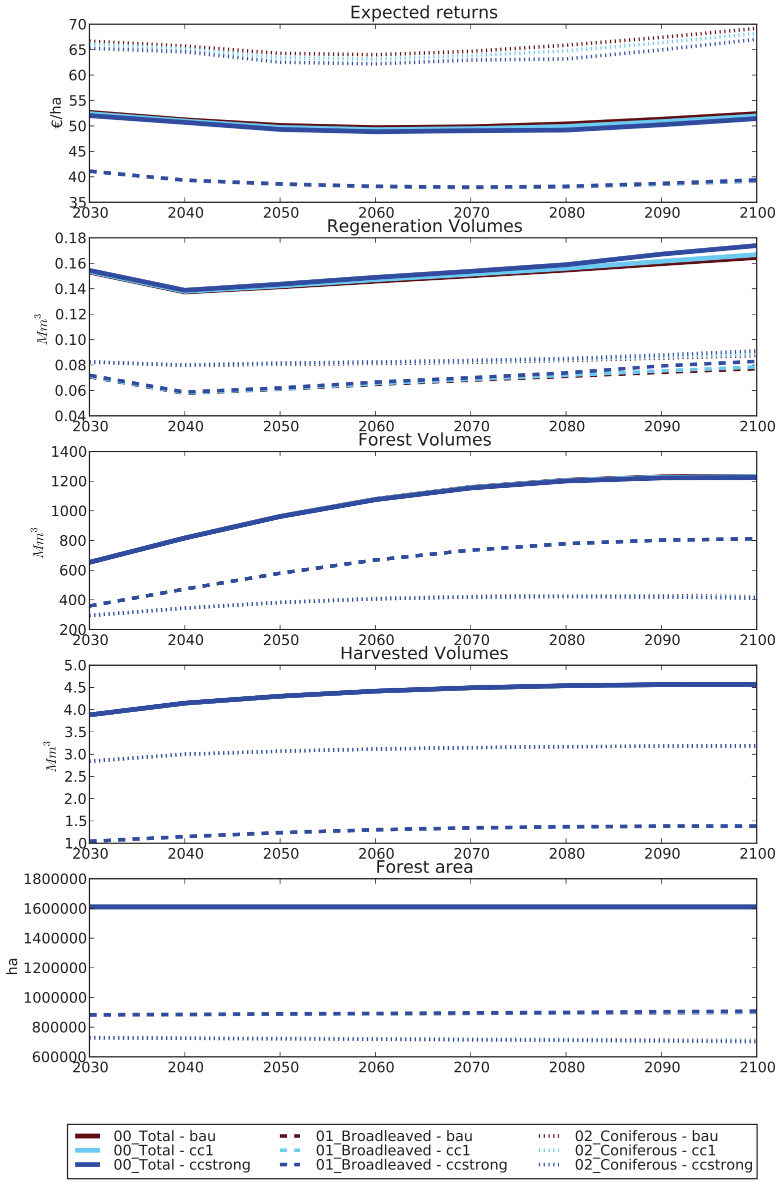
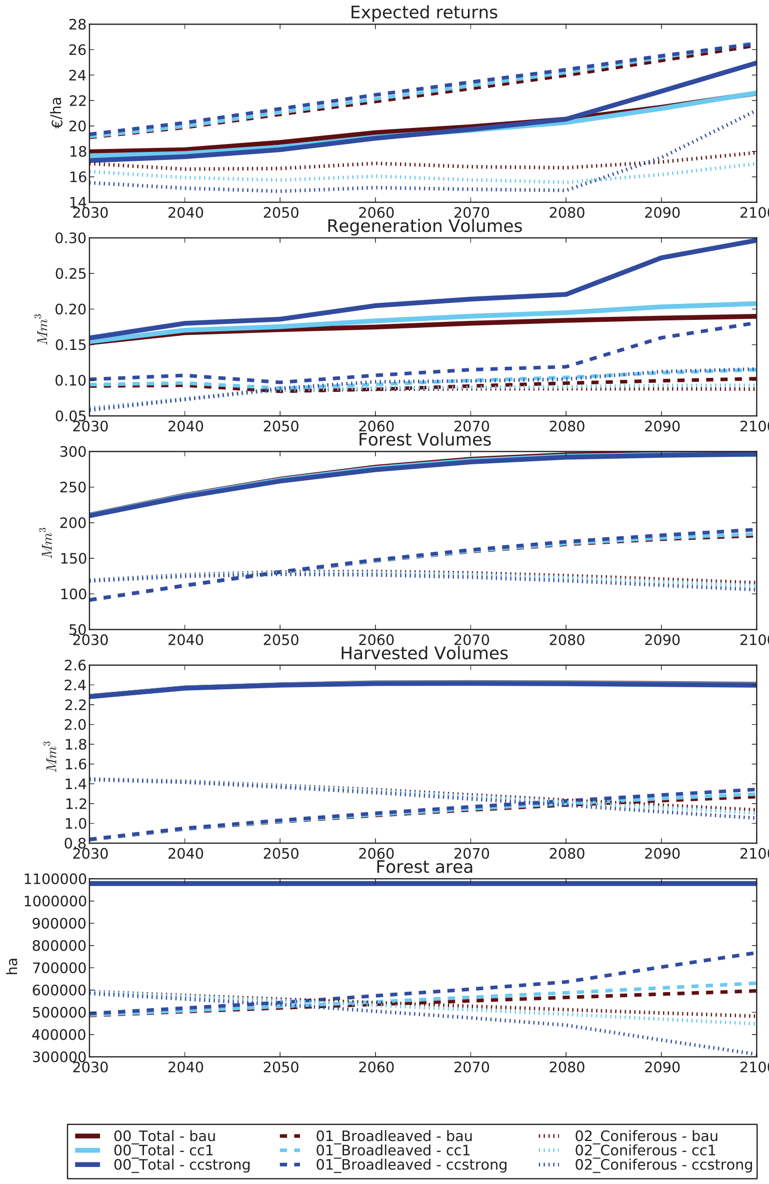


Figure 7: Effects of increased mortality in lowland south coniferous, Provence-Alpes-Côte d'Azur (PA)



B Model notations

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 $\times$ mt] (e.g. coppices broadleaved or high forest coniferous)
dc	diameter class	{0, 15, 25, 35, 45, 55, 65, 75, 85, 95, 150}
pp	primary product (that is, deriving 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 $\cup$ tp]