Accounting for economic drivers in forest modelling: a spatially explicit bio-economic model of the French forest sector

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Abstract

Given the importance of anthropogenic determinants in forest ecosystems within Europe, the objective of this paper is to link the evidence arising from biological models with socio-economic determinants, where the expected returns of forest investments represent the main driver.

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++).

Running long-term scenarios (until 2100) we show that only considering the heterogeneous environment and the risk aversion of forest managers we can explain the rich diversity in forest ecosystems and in particular the mix of broadleaved and coniferous forest investments that otherwise, on average, would see the latter as always being the most profitable one.

We further show the strong resilience of forest ecosystems that, due to the very long cycles, undergoes very small variations in the stocks even in scenarios where the initial forest regeneration is strongly influenced.

Contents

1 Introduction

Forest ecosystems are characterised by very long delays between any perturbation is introduced and the system responds with measurable effects. For example, timber production, biodiversity capacity and CO_2 accumulation are all processes that can be measured only decades after any policy devoted to interact with them is implemented. Hence, it is not surprising that the forest sector has long been the subject of careful planning initiatives. Historically this planning has took the form of normative, empirically derived rules. With the increased complexity of accounting for multi-purpose objectives on one side and the better availability of simulations tools on the other side, these planning methods have switched from normative rules to the usage of mathematical models, able to forecast in the future the status of forest ecosystems conditionally to agent's today actions. This switch was also due to major price variations after the two first energy shocks in the 70's. Simple 'gap analysis' models were not sufficient and more integrated tools were required.

Within the multitude of forest models (Buongiorno et al., 2003; Kallio et al., 2004; Sjølie et al., 2011), the French Forest Sector Model (FFSM) distinguishes itself by explicitly considering both international and interregional trade, accounting for the full heterogeneity of regions and, using the Armington theory (Armington, 1969), of products.

It also aims to combine the modelling part of the forest dynamic, taking into account each forest specific conditions, with those of forest markets, using a partial equilibrium approach.

In order to achieve its goal, the traditional FFSM (FFSM 1.0) considers two separate modules: the first one simulating the forest dynamics,the "resource module"; the second one determining wood market prices, demand, supply and trade: the "market module". These two modules are combined together and exchange informations as detailed in Table 6. However the two modules runs 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) forecasts 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), our approach has been to decouple the spatial scale of the market module with those of the resource and the newly introduced management module. This grid-based approach has the potential to allow FFSM to consider local-scale environmental characteristics and therefore to simplify the linkage with detailed biological models.

While the resource module has been designed to forecast the status of the current forests, it was particularly weak in making long-term projections, especially if environmental conditions are likely to change, due to the exogenous nature of the forest regenerations, derived uniquely from current forest inventory datasets. In order to include possible changes in environmental conditions (*in primis* climate changes) and incorporate forest managers response to these changes, a third module, namely the "management module" (MG), has been introduced to allow for possible switches in forest types (species composition and/or management type) given expected market and ecological conditions. In particular forest managers risk aversion is explicitly considered.

This paper is therefore organised as follow: section 2 presents an overview of FFSM as a viable method to produce forecasts of the forest sector at a national and regional level, highlighting its history and providing a short bibliography of results already published.

Sections 3 and 4 are devoted to describe the new enhancements made to the model, where the former spatializes the forest dynamics module, from a regional basis toward a pixelized basis and the latter focuses on the management module.

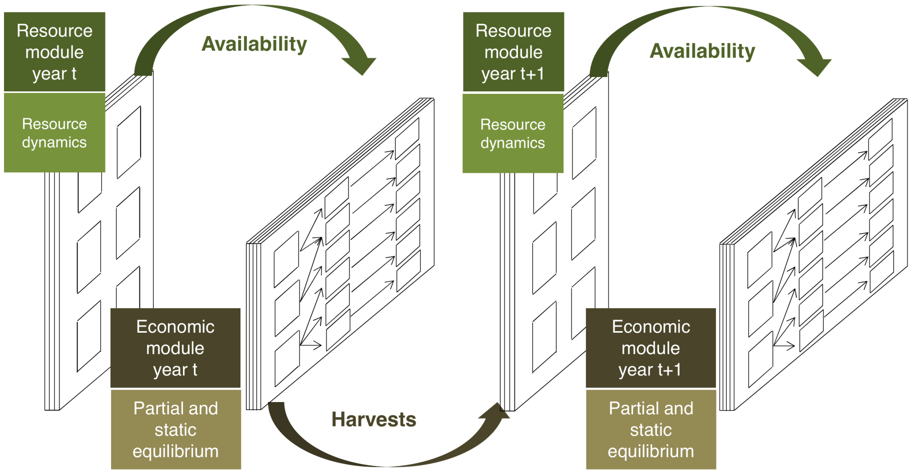
Once the model has been presented, section 5 objective is to make evident, looking at the model results, the implications of the enhancements described in the previous two sections. Simulations focuses in particular on three aspects: (a) the role of an active management, where results from FFSM++ are compared with those derived using exogenous forest regeneration; (b) the effects of spatial heterogeneity, where Monte-Carlo simulations of forest growth rates, where each plot specific "modifier" is sampled from a normal distribution $\mathcal{N}(\mu = 1, \sigma^2_{r,sp})$ having average set to one and standard deviation derived from national inventory data are compared to simulations made using homogeneous regions; and finally (c) the effect of heterogeneous risk aversion within the forest manager community.

Finally section 6 concludes.

2 Overview of the model

The French Forest Sector Model (FFSM, Caurla et al., 2010) is a recursive simulation model of the French forest sector. It articulates two modules: a forest dynamics module (FD) and a markets module (MK). At each period (year), given available timber resources, timber supply functions, transformation technologies and capacities, and demand functions for (first-transformed) timber products, the MK module computes all market equilibria in the forest sector, from which it deducts the annual harvest. Harvest then enters the FD module, which computes available timber resource at year t + 1. This enters the MK module, and so forth (see Figure 1). The first version of FFSM was implemented under the General Algebraic Modelling Software (Bussieck & Meeraus, 2004), and runs for periods of 10-20 years.

Figure 1: The Markets module of FFSM



The FD module (Wernsdörfer et al., 2012) simulates regional timber stock dynamics using a diameter-class approach. Since French forests are very diverse in terms of climate, soils, species and types of management, the FD module breaks down timber resource into 2574 cells differing by region (22 administrative regions), type of management (high forests, coppice, mixed), species (coniferous and broadleaved) and diameter classes (13 total). Resource dynamics in each cell is calibrated using data from the 2005-2007 French forest inventories (Colin & Chevalier, 2010).

The MK module is a partial-equilibrium model of the French forest sector, from timber production to the consumption of first-transformation products. There are four raw timber products: fuelwood, pulpwood, hardwood and softwood roundwood, and six processed timber products: hardwood sawn- wood, softwood sawnwood, plywood, pulp, fuelwood, and fiber and particle board (Table 1).

Three groups of agents are represented in the model: wood suppliers (either forest owners or forest managers on behalf of forest owners), transformation industry and consumers (either final consumers or second- transformation industries). The transformation industry is modelled using Leontief production functions. Under our assumption of perfectly competitive markets, the transformation industry makes zero profit at equilibrium (Caurla et al., 2010).

The MK module distinguishes 22 administrative regions within France, and inter-regional trade is modelled assuming perfect competition and full substitutability of products across regions, à la Samuelson (1952). International trade (exports of raw products and imports of processed products) is modelled assuming imperfect substitutability within the Armington (1969) framework. The MK module is calibrated using literature data and specific estimates, as presented in Caurla et al. (2010) and Sauquet et al. (2011).

So far, FFSM 1.0 has been used to assess the impact of climate mitigation policies on forest sectors (Delacote & Lecocq, 2011; Delacote et al., 2013) at a relatively short-term horizon (2020): a comparison of sequestration and substitution policies (Lecocq et al., 2011); an assessment of the impact of fuelwood stimulation policies (Caurla et al., 2013*b*); an economy-wide carbon tax and potential substitution effects (Caurla et al., 2013*a*).

Along this paper the following indexes will be extensively used:

Table 1: Commonly used index symbols

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. 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 ∪ tp]

3 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 resource and management modules (Table 2). Each pixel encompass 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, pixels in the simulations proposed in Section 5 has been set at 8x8 km resolution.

Using 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 MK the Euclidean distance between regions drives the formation of transport costs in the market module; in FD and MG heterogeneous ecological conditions influence the forest dynamic, both observed and expected, and hence the investment decisions.

Figure 2: FFSM++ spatial representation

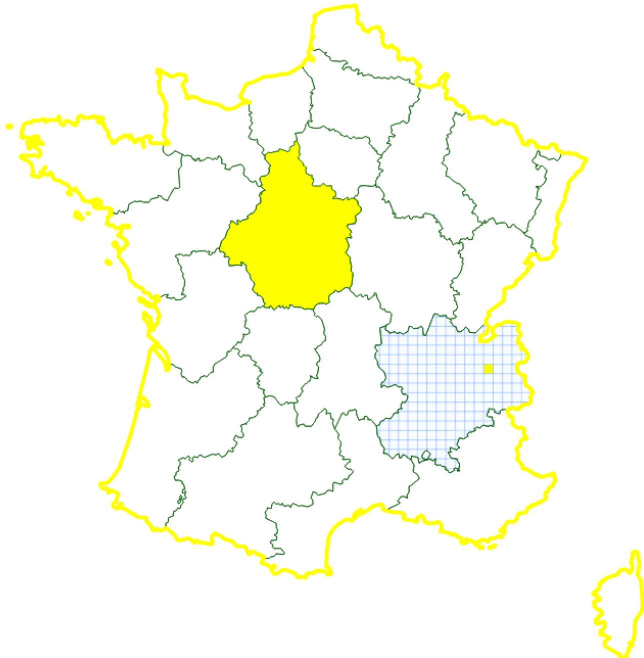


Table 2: Modules, spatial levels and interface variables

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	$Price_{r,pp,t}$, $HArea_{px,ft,t}$	$RegArea_{px,ft,t}$

3.1 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:

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

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

$$V_{px,ft,dc} = V_{r,ft,dc} * \frac{area_{px,ft}}{area_{r,ft}} \quad (2)$$

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 constant distribution of forest in diameter classes within the regions.

3.2 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/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 demand, 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:

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

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.

4 Management module

4.1 Introduction

The forest dynamic module, using inventory data and exogenous modifiers, is able to forecast the forest status and to consider environmental changes that affect the forest system. The market module of FFSM can already be used to account for economic and policy drivers that impact forest usage, for example an increased fuelwood demand (Caurla et al., 2013*b*) or a substantial change in wood prices.

The management module under risk integrates the FD and MK modules recognising the role of forest management in the French context and the interaction of these biophysical and economic drivers in forest dynamics.

The FD module is responsible for accounting the volumes of wood available for any given forest type and region. Every year it calculates the available volumes recursively from the volumes of wood of the previous year, taking into account natural tree growth, mortality and harvesting.

In the original version of FFSM, the calculation of new volumes reaching the first productive diameter class (that is, the result of the regeneration of the forest after the harvesting) is taken exogenously from inventory datasets. The objective of the MG module is to make endogenous this regeneration, explicitly linking it on one side to the level of harvesting activity and on the other side to the expectations that forest agents would make at replanting time given current market prices of wood products and expected forest growth. In order to achieve this objective, the harvesting volumes computed in the resource module are transformed in harvesting area and then expected returns are computed for each forest type to allow its allocation among the most profitable forest type. This regeneration area will then became the regeneration volumes (Figure 3).

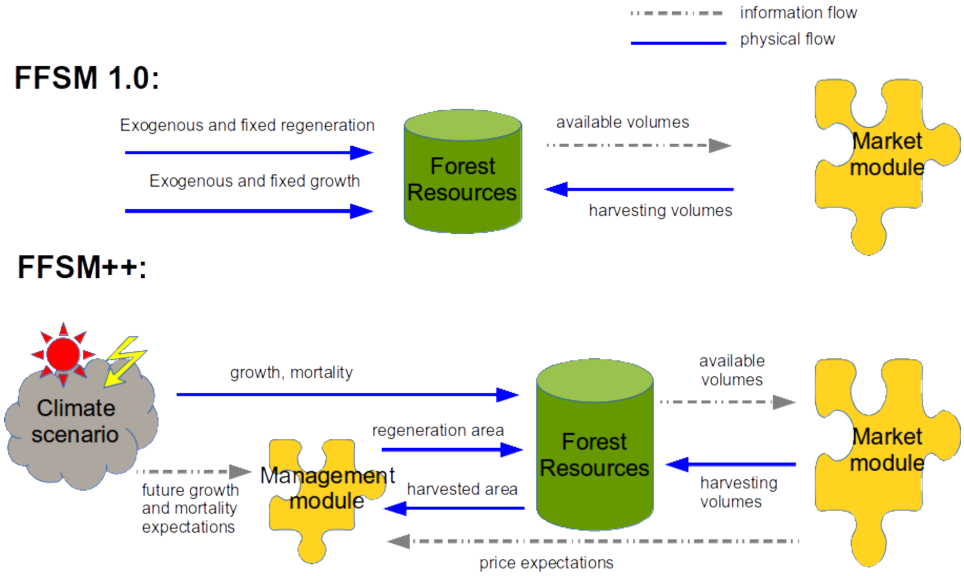
While this section is devoted to detail the above methodology, the role of an active forest management is the focus of the simulations run in section 5(a).

4.2 Computation of regeneration volumes

The management module is responsible to compute the wood volumes entering the first production diameter class for each forest type.

The first step is represented by the conversion of wood demand from the market module into harvested volumes hV (eq. 3). The share of these

Figure 3: Flowchart



volumes arising from final harvesting is in turn converted to harvested area ($harvestedArea$).

$$harvestedArea_{px,ft,dc,t} = hV_{px,ft,dc,t} * finHrFlag_{ft,dc} / vHa_{px,ft,dc,t} \tag{4}$$

where $finHrFlag_{ft,dc}$ is a binary variable that indicate if a harvesting of a given diameter class and forest type has to be considered as a final harvesting (thus, freeing land for potential regeneration) or a thinning (that is not supposed to free any land).

For each forest type the model computes the expected returns as:

$$expReturns_{px,ft,t} = \max_{dc,pp} \frac{PW_{r,pp,t} * vHa_{px,ft,dc,t} * finHrFlag_{ft,dc} * sflag_{ft,dc,pp} * r}{(1+r)^{cumTp_{px,dc,t}} - 1} \tag{5}$$

where PW is the observed price of primary products that can be realised from the forest resource, r is the chosen discount rate and $cumTp$ is the (expected) cumulative time for trees to reach a certain diameter class.

Expected returns are given as an equivalent annual income (EAI) to consider forest types with different production cycles and to facilitate comparison with agricultural activities gross margins. However any direct comparison between $expReturns$ and agricultural gross margins should be taken with caution, as the former includes revenues only from final harvesting overly simplistic assuming that revenues from thinning compensate exactly forest management costs[1]. Nevertheless the trend of the ratio between them

[1] A proper comparison of gross margins would require to include in the expected returns

could still give insight on possible changes in the relative convenience between these two broad land uses.

Once all the expected returns for any forest types have been computed, harvested land is allocated to the forest type with the highest one ($\hat{ft}$):

$$regArea_{px,ft,t} = \sum_{dc} harvestedArea_{px,ft,dc,t} * (1 - mr) \tag{6}$$

$$regArea_{px,\hat{ft},t} \mathrel{+}= \sum_{ft} \sum_{dc} harvestedArea_{px,ft,dc,t} * mr \tag{7}$$

where mr is the management rate, a coefficient [0,1] that reflects the consideration that not all the forest is managed according to strictly economic criteria. Instead, a share of the harvested area (1-mr) is allocated according to ecological considerations. While in the scenarios described in section 5 this area is simply reallocated on the same harvested forest type, a probability of presence function, derived from ecological and biophysical data, could also be used.

Finally the regeneration area for a given forest type is then converted back in wood volumes entering the first diameter class using the vHa of the first productive diameter class (an exogenous parameter that has been estimated from national inventory data):

$$vReg_{px,ft,t} = regArea_{px,ft,\tau} * vHa_{px,ft,dc=1,t} \tag{8}$$

It is important to note that there is a time lag between the harvested year and the one when the new shrubs enter the first production diameter class:

$$\tau = t - tp_{px,ft,dc=0,t} \tag{9}$$

Due to this time lag between harvesting and regeneration, in the first $tp_{px,ft,dc=0,t}$ years the model doesn't have enough information to compute the regeneration volumes, hence it is forced to use exogenous regenerations. This is the reason leading to many parameters being very similar across scenarios on the initial years of the simulations.

5 Simulations

test

Figures 4 to 7 present the numerical output of simulations run under scenarios selected to highlight specific topics. 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 increase the stock of volumes for a

also informations on the cost side, while currently the management module works with information only on the revenues side, assuming similar costs between forest types.

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.

Due to the initial time lag in regeneration of Equation 9 some curves shows an initial "S" shape that last for the first 20-30 years and hence the percent comparison between scenario, when not otherwise stated, are given as average for the period 2040-2100 for flow variables (expected returns and volume regenerations) and on the last year of the simulations (2100) for stock variables (forest volumes), the exception being the harvesting volumes that while being a flow variable depends on the stock volumes and hence they are reported for 2100.

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

5.1 Active management

Effects of an active management, where profit maximisation drives the forest investments, are shown in Figure 4, based on scenarios of Table 3.

Table 3: Active management scenarios

scenario	mr	description
vRegFixed	–	exogenous regeneration (derived from national inventory data)
vRegFromHr	0.0	regeneration linked with the harvesting activity but without the possibility to switch between forest type
reference	0,5	intermediate level of active forest management
vRegEnd070	0,7	stronger importance to economic drivers

The first plot on Figure 4 shows the clear economic superiority of coniferous investments over broadleaved forest at national level, with the former showing over double expected returns than the latter.

Expected returns are almost identical in all the scenarios, with the exception of the final years of the simulations for the coniferous.

Regeneration volumes are in contrast strongly influenced by the scenario, as result of the different algorithm used. Compared with `vRegFromHr` in the `reference` scenario broadleaved forests suffer a reduction of 0.50 $Mm^3/year$ while coniferous benefit of a increase of an average of 0.67 $Mm^3/year$. If we increase the quota of forest managed according to economic criteria

[2]Results for forest dynamic and markets are available in the attached ZIP archive under the files "data/output_{scenario_name}/results/forestData.csv" and "data/output_{scenario_name}/results/productData.csv" respectively. Input data is located in the "data/ffsmInput.ods" speadsheet and in the gis maps under "data/gis".

(`vRegEnd070`) we see this effects to amplify (-0.68 and +0.92 $Mm^3/year$ respectively).

While this switch is evident at individual forest type, the aggregated effect is much lower and due uniquely to the higher productivity of the coniferous.

The central variable that differentiate the four scenarios is the regeneration of new volumes. However in the model it is produced only as a consequence of an harvesting operation, and moreover after a consistent delay. As harvesting rate remains relative low, the effect on the forest stock remains in all case very limited even after a century. In 2100 the effects on forest volumes of the `reference` scenario over the `vRegFromHr` one is of -140 and +398 Mm^3 for broadleaved and coniferous respectively.

As expected, the increasing coniferous (decreasing broadleves) stocks influence the harvesting volumes in the same direction with coniferous harvesting that in 2100 outmatch broadleaved harvesting in the `vRegEnd070 scenario`.

At regional level the distance between coniferous and broadleaved expected returns vary, but the broadleaved never overtake the coniferous in any of the discussed scenarios, with the exception of two regions in the North of France, namely *Picardie* and *Nord-Pas-de-Calais*, where forest is very rare and therefore the input data is much more unreliable.

5.2 Heterogeneous environment

While FFSM works on administrative regions, the French National Geographic Institute (IGN) recognises 86 "sylvoecoregions" (IGN, 2010) and the 2012 IGN data identified plots 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 the relative diameter growth. Data on Table 4 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 represented in 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.

In this context, considering regions as homogeneous would lead to an error that we tried to asses in these scenarios. 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 is introduced that is sampled from a normal distribution $\mathcal{N}(\mu = 1, \sigma^2_{r,sp})$ having average set to one and standard

Table 4: 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

deviation derived from the IGN data and specific to the species group and region.

As the expected value of the growth rate doesn't 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 deviation for species groups and region have been estimated from volume growth at plot level in the IGN datasets 2007-2012 and corrected by volume density[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 `withVariance` we used the sampled modifiers. Result are reported in Figure 5.

As expected, `nonspatial` and `reference` lead to identical results, validating the new algorithm. Adding regional heterogeneity (`withVariance`) leads instead to little bit higher expected returns, especially for coniferous (+1.76€ versus +1.04€ of broadleaved). Even if the average expected returns is increasing more for coniferous than for broadleaved, in some plots

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

the situation is the opposite and broadleaved forests result more profitable, while in regional homogeneous conditions all the managed regeneration is allocated to coniferous as this has the highest expected returns. Hence we can notice a shift of volume regenerations in favour of broadleaved.

However this shift leads to only marginal effects on total volumes (-1.39% and +0.12% in broadleaved and coniferous respectively in 2100) and harvested volumes (+1.13% and -0.80%).

5.3 Risk Aversion

In all the scenarios above the investment choice is determined only by the forest type showing the highest expected return, without any consideration for the risk that the investment bears.

Risk indeed is a fundamental element of a forest investment decision and in `withRiskXX` scenarios the overall mortality rate at time of cutting is interpreted as a risky element that it is tried to be avoided by forest managers.

Mortality rate is already accounted in the expected returns of forest investment in all scenarios, but economic agents decide uniquely on the base of the expected value (that is, they are risk neutral). In `withRiskXX` scenarios instead we suppose that agents have utility functions with harmonic absolute risk aversion (HARA) and more specifically a constant relative risk aversion (CRRA), that is the relative risk premium that the agents are ready to pay to escape the risk doesn't depend on its wealth (Gollier, 2001). The equivalent risk-free investment expected return is computed as:

$$expReturns = origExpReturns * (1 - ra * cumMort); \tag{10}$$

where ra is an individual specific risk-aversion coefficient sampled from a normal distribution with $(\overline{x}_{ra}, \sigma^2_{ra})$ constant within the scenario. As pixels are in FFSM++ the minimum level at which forest investment decisions are applied, at each pixel in `withRiskXX` scenarios correspond an agent.

Figure 6 compares the reference results with the $\overline{x}_{ra}$ coefficient set to 0.6 (`withRisk06`), 0.8 (`withRisk08`) and 1 (`withRisk10`). As we increase the risk aversion coefficient we notice that the equivalent expected returns drop significantly, especially for coniferous (broadleaved: -8.77%; coniferous: -14.19%).

However this large drop in expected returns leads only to minor effects to the rest of the model, and the reason is possibly in the small standard deviation used to build the normal curve from which the agents ra are sampled (0.2). Hence, even if the expected return of the two group of species get much closer, they do not intersect and hence the switch from the decision to replant coniferous to replanting broadleaved is very limited.

If spatial heterogeneity has a limited (positive) impact on expected returns and on regeneration while introducing risk aversion has a high (nega-

tive) impact on expected returns but a negligible one in regeneration a logical extension is to check for the two effects simultaneously (`withSpVarianceAndRisk`)
.

At national level ($\overline{x}_{ra} = 0.8$) the impact on expected returns turns out to be negative (broadleaved: -14.47%, coniferous: -13.45%), with a significant impact on regeneration (+20.88% and -7.15% respectively). However, even with such impacts in forest regeneration, the stock volumes do not change much: +1.41% for broadleaved and -0.05% for coniferous.

Only at regional level the impact on forest volumes can be noticeable. In *Provence-Alpes-Côte d'Azur* for example the two groups of species have relatively close expected returns and the spatial heterogeneity is very high. Therefore when it is considered together with risk (Figure 7) space heterogeneity leads to very significant changes in the regeneration (+189.45% for broadleaved and -30.71% for coniferous) that in the long term (2100) impact on stock volumes (+9.13% and -8.60% respectively) and harvested volumes (+8.65% and -6.84%).

5.4 Stability of stochastic simulations

As both the heterogeneous environment and, in much a less extent, the risk simulations employ 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 run 30 times the `withVariance` scenario and followed the Fortin & 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) `withVariance` scenario is equal to the (deterministic) `reference` scenario (Table 5). All variables except stock volumes for coniferous 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, simulations at national level lead to 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 situation is often similar, but there are a few cases where, given the very small effects of regeneration over the forest stocks and hence over harvesting, a larger batch of runs would be needed to achieve statistical significance for all the variables. We report results for *Aquitaine* (Table 6) as example of the former and *Bourgogne* (Table 7) for the latter.

6 Conclusions

In France forests, as well as in most temperate climates ones, socio-economic drivers works on top of (conditionally to) biophysical drivers and hence represent an important determinant of forest distribution, composition and

Table 5: Significance test of the stochastic scenario, France

	reference	sthocastic	difference	cv
France (8,580 pixels)				
Expected returns (€/ha)				
- 00_Total	20.059	21.278	1.219^{b} (6.079%)	0.45 %
- 01_Broadleaved	13.652	14.619	0.968^{b} (7.088%)	0.41 %
- 02_Coniferous	34.620	36.411	1.791^{b} (5.174%)	0.73 %
Regeneration Volumes (Mm^3)				
- 00_Total	2.165	2.143	-0.023^{b} (-1.049%)	0.08 %
- 01_Broadleaved	0.638	0.709	0.071^{b} (11.131%)	0.75 %
- 02_Coniferous	1.528	1.434	-0.094^{b} (-6.136%)	0.38 %
Forest Volumes (Mm^3)				
- 00_Total	6977.522	7049.006	71.484^{b} (1.024%)	0.17 %
- 01_Broadleaved	4985.847	5055.014	69.168^{b} (1.387%)	0.13 %
- 02_Coniferous	1991.676	1993.992	2.316 (0.116%)	0.46 %
Harvested Volumes (Mm^3)				
- 00_Total	55.194	55.294	0.100^{b} (0.182%)	0.03 %
- 01_Broadleaved	28.048	28.366	0.318^{b} (1.132%)	0.11 %
- 02_Coniferous	27.145	26.928	-0.217^{b} (-0.801%)	0.14 %

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

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

Table 6: Significance test of the stochastic scenario, Aquitaine

	reference	sthocastic	difference	cv
Aquitaine (654 pixels				
Expected returns (€/ha)				
- 00_Total	37.272	39.669	2.396^{b} (6.429%)	1.18 %
- 01_Broadleaved	11.181	12.695	1.514^{b} (13.539%)	1.76 %
- 02_Coniferous	60.428	63.607	3.180^{b} (5.262%)	1.41 %
Regeneration Volumes (Mm^3)				
- 00_Total	0.228	0.227	-0.001^{b} (-0.506%)	0.21 %
- 01_Broadleaved	0.045	0.047	0.001^{b} (2.493%)	2.06 %
- 02_Coniferous	0.183	0.180	-0.002^{b} (-1.253%)	0.47 %
Forest Volumes (Mm^3)				
- 00_Total	811.400	826.751	15.351^{b} (1.892%)	0.52 %
- 01_Broadleaved	516.043	524.178	8.135^{b} (1.576%)	0.49 %
- 02_Coniferous	295.357	302.573	7.216^{b} (2.443%)	1.09 %
Harvested Volumes (Mm^3)				
- 00_Total	8.161	8.180	0.019^{b} (0.238%)	0.19 %
- 01_Broadleaved	2.417	2.403	-0.014^{b} (-0.591%)	0.51 %
- 02_Coniferous	5.743	5.777	0.034^{b} (0.586%)	0.38 %

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

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

structure. In models that aim to predict the status of forest ecosystems the role and interaction of both these drivers must be represented, as market forces depend on and influence forest resources. Often however the two do-

Table 7: Significance test of the stochastic scenario, Bourgogne

	reference	sthocastic	difference	cv
Bourgogne (496 pixels)				
Expected returns (€/ha)				
- 00_Total	22.654	23.760	1.106[b] (4.884%)	0.80 %
- 01_Broadleaved	14.992	15.812	0.820[b] (5.470%)	1.07 %
- 02_Coniferous	85.694	89.157	3.463[b] (4.042%)	1.44 %
Regeneration Volumes (Mm^3)				
- 00_Total	0.122	0.122	0.000 (0.055%)	0.13 %
- 01_Broadleaved	0.043	0.043	-0.000[b] (-0.267%)	0.18 %
- 02_Coniferous	0.079	0.080	0.000[b] (0.228%)	0.14 %
Forest Volumes (Mm^3)				
- 00_Total	549.223	549.768	0.545[a] (0.099%)	0.16 %
- 01_Broadleaved	493.821	493.502	-0.319 (-0.065%)	0.18 %
- 02_Coniferous	55.402	56.266	0.864[b] (1.559%)	0.35 %
Harvested Volumes (Mm^3)				
- 00_Total	4.038	4.036	-0.001 (-0.030%)	0.12 %
- 01_Broadleaved	2.903	2.893	-0.011[b] (-0.362%)	0.16 %
- 02_Coniferous	1.134	1.144	0.009[b] (0.822%)	0.30 %

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

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

mains are modelled separately resulting in either forest-dynamic models on one side and forest markets models on the other, with their linkage obtained running them in iterative steps, with the data produced from one model used as input data for the other model and the opposite, until a satisfactory integration is obtained. For example, the European Forest Sector Outlook (EFSON) II (UNECE/FAO 2011; Van Brusselen et al. 2009) uses this approach to link together the EFISCEN (Nabuurs et al., 2002; Schelhaas et al., 2007) and the EFI-GTM (Kallio et al., 2006) models.

One of the reasons of this dualism in forest modelling is that the tools used are themselves different. Ecologists often utilise a general programming approach to build their models (C++, matlab, python..) while economists often use programs specialised in solving equilibrium problems like GAMS (Bussieck & Meeraus, 2004).

Our approach has been to utilise instead a generic programming language (C++) that gives us the flexibility required to build a complete forest dynamic and management module with specialised software libraries, namely IPOPT (Wächter & Biegler, 2006, ADOL-C (Walther & Griewank, 2012) and ColPack (Gebremedhin et al., 2013), used to solve the Samuelson equilibrium and hence build the market module.

In FFSM++ the three modules can hence continuously exchange information and the model is able to catch the effect of their iteration.

When the combined 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. The preference for broadleaved forest investments in particular increases when we consider in the model the risk aversion of forest managers due to the lower risk associated with broadleaved forests.

Results presented on this paper originate from variables of forest inventory origin (growth rate, mortality..) that has been kept fix among the temporal scale. The integration between the economic and ecological drivers, and in particular the presence of an inter-regional and international forest products market, can be appreciated even more when environmental variation, *in primis* related to the climate change, is introduced as the model would be able to simulate cascade effects between neighbouring regions and between the ecological and economic components of forest systems.

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7 Simulation outputs figures

Figure 4: Active management simulations, France

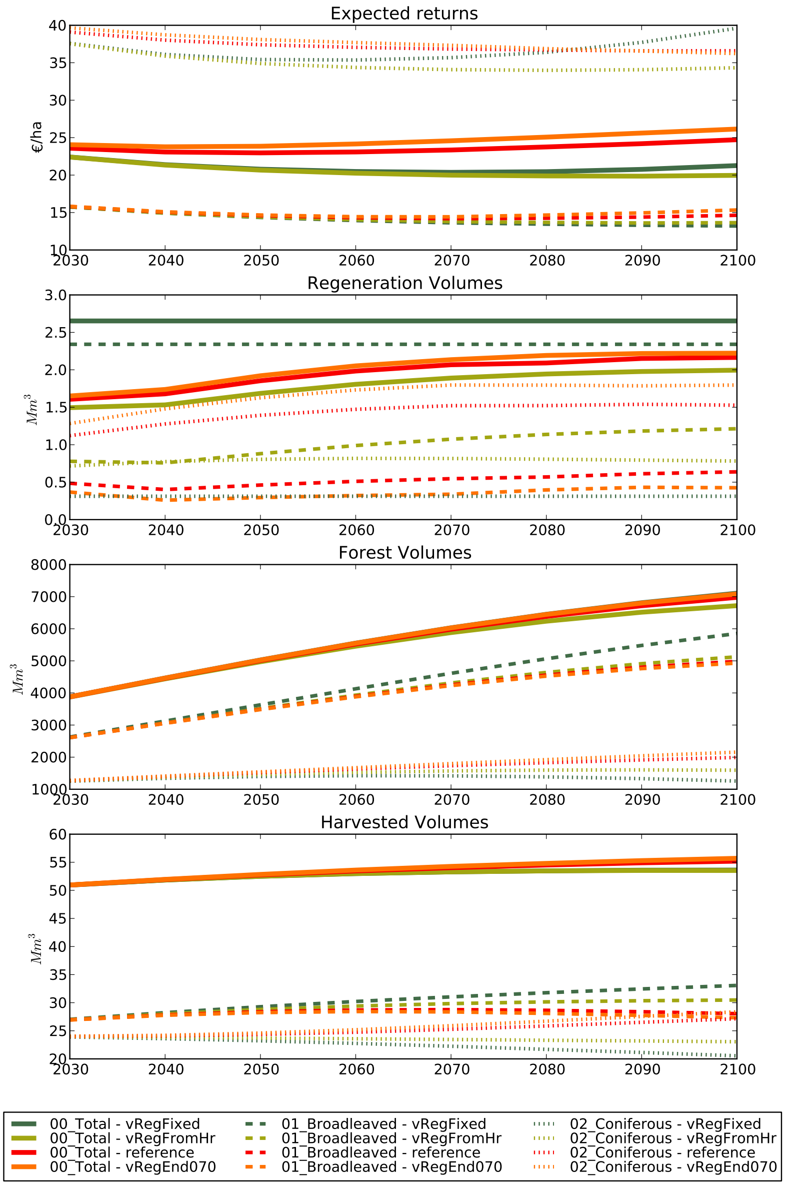

Figure 5: Heterogeneous spatial simulations, France

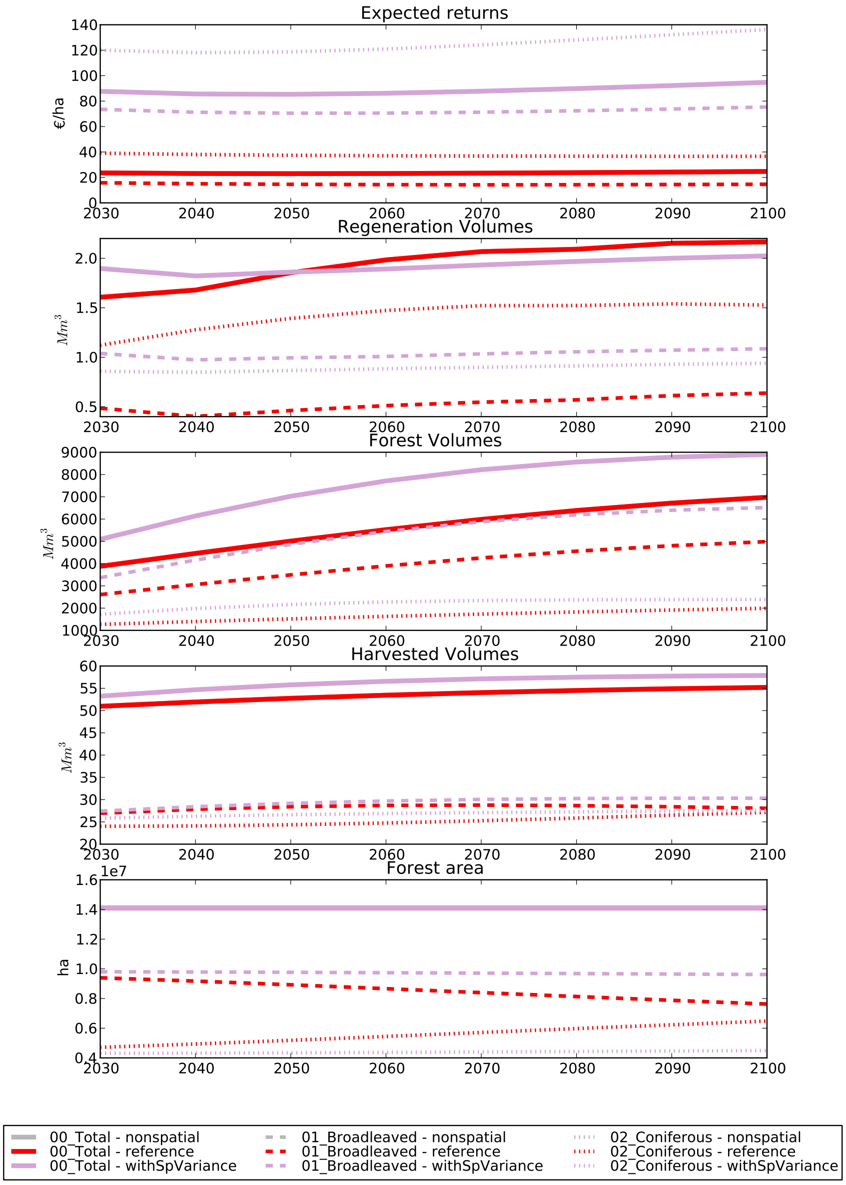

Figure 6: Heterogeneous risk aversion, France

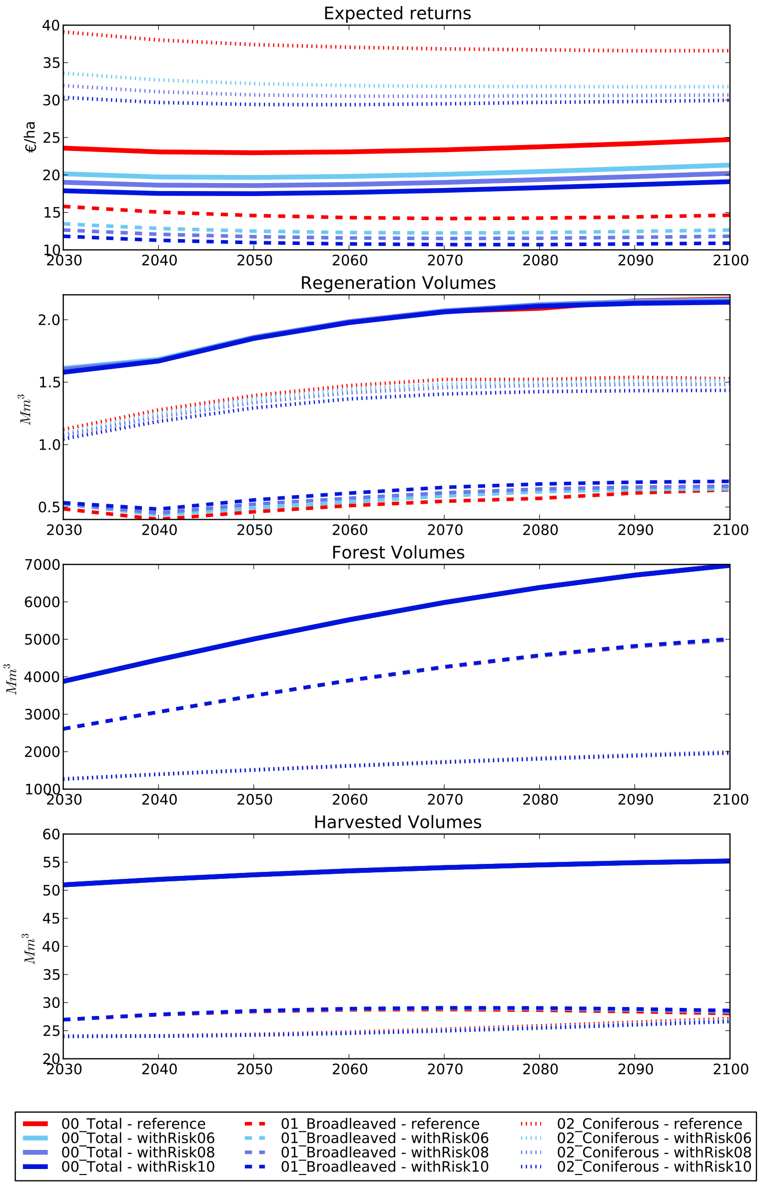

Figure 7: Heterogeneous risk aversion and space, PACA