The Loop Effect : How Climate Change Impacts the Mitigation Potential of the French Forest Sector

Philippe Delacote, Antonello Lobianco, Sylvain Caurla, Jean-Daniel Bontemps, Anna Lungarska, Pierre Mérian, Miguel Riviere, Ahmed Barkaoui

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[AUTHORS]

ABSTRACT:
Objectives: *Evaluate the capacity of temperate forest resources to both provide climate change mitigation and to sustain the downstream timber sector explicitly considering the cascade of biophysical and economic drivers (in particular, climate change impacts and subsequent adaptation actions) and their uncertainty.*
Methodology: *A recursive bio-economic model of French forest resources, management, and timber markets has been coupled for this study with spatial statistical models of forest response to climate change long-term scenarios and land-use change.*
Main results: *(a) Climate change impacts on tree mortality are greater than those on tree growth variations; (b) Due to increasing competition with agriculture, climate change may reverse current trends in forest area expansion; (c) Due to rising average tree sizes, volume growth strongly declines over time and may eventually cease within the next century; (d) Future climate change impacts already have strong consequences on today's forest investment profitability; (e) The relative importance of forest substitution over forest sequestration increases as the timeframe increases; (f) While the forest sector has the potential to counterbalance a significant share of the national carbon emissions, this potential is threatened by climate change and the need to adapt to it. Profit-driven forest management does increase mitigation; (g) Uncertainty derived from using different climatic models over the same IPCC storyline has the same order of magnitude as the uncertainty derived from using the same climatic model under different storylines;*

KEYWORDS: *Forest sector, Climate change, Carbon balance, Climate warming mitigation, Bio-economic model*
JEL classification *Q23,Q54,Q24*

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1 Introduction

Forest resources have always provided the society with a multitude of different services alongside the provision of timber, such as hydrogeological protection, recreational opportunities or biodiversity protection. Recently the focus has shifted to the climate change mitigation that forest resources and the timber industry may deliver, but also on its interplay with timber provision.

Climate change mitigation refers to actions that reduce emissions or enhance the sink of greenhouse gases (IPCC, 2014). The forest sector can contribute to it through carbon sequestration in forest biomass, soils and harvested wood products (Sedjo & Sohngen, 2012), which has been shown to be a competitive abatement strategy (Eriksson, 2015; Tavoni et al., 2007). Wood-based products can also substitute for more carbon-intensive products, avoiding fossil-based products and hence reducing carbon emissions in sectors such as energy and construction (Eriksson et al., 2012; Sathre & O'Connor, 2010). A major dissension point concerns the carbon neutrality of bioenergy products (Schulze et al., 2012; Sjølie et al., 2011), and several studies suggest that, depending on feedstocks and products considered, avoided emissions may only offset removals of carbon during harvest after a potentially long delay (McKechnie et al., 2011; Valade et al., 2018). Further, questions have been raised on the sustainability of an increased demand for forest services and products driven by these mitigation actions (Ceccherini et al., 2020). On the other hand, issues such as leakages, albedo changes or non-permanence may weaken sequestration strategies and render them costlier (Favero et al., 2018; Seidl et al., 2014; van Kooten & Johnston, 2016).

As a result, even though forests may strongly contribute to overall mitigation efforts (Eriksson et al., 2018; Grassi et al., 2017; Tavoni et al., 2007), the optimal combination of mitigation solutions is still up to debate. While some studies report incompatibilities or trade-offs (Eriksson, 2015; Kallio et al., 2013; Lecocq et al., 2011; Vass & Elofsson, 2016), others highlight synergies (Baker et al., 2019; Favero et al., 2017; Kim et al., 2018).

At the same time, climate change itself is expected to have a strong impact on forests. Many studies have documented positive effects on forest productivity through interplays between changes in atmospheric fertilization, temperature, precipitation and radiation (Boisvenue & Running, 2006; Hyvönen et al., 2007; Reyer et al., 2014). On the opposite, background tree mortality may also increase due to heat stress or competition (Archambeau et al., 2020; Neumann et al., 2017; Senf et al., 2018; Taccoen et al., 2019) and the magnitude and frequency of catastrophic disturbance events such as wildfires, pest outbreaks and hurricanes are expected to increase in many regions (Seidl et al., 2017). Together, these trends have the potential to influence dynamics in the forest sector, including its mitigation potential (Allen et al., 2010; Eggers et al., 2008; Le Page et al., 2013; Seidl et al., 2014; Valade et al., 2017).

Such cascading consequences can be assessed with forest sector models (FSM), i.e. simulation models of the coupled forestry-timber industry system often used for policy analysis (Latta et al., 2013*b*; Solberg, 1986). Their main strength is to endogenously represent feedbacks between timber markets, forest growth and owners' behaviours, all modelled in an economically consistent way. FSM have gradually expanded to include carbon and emissions accounting modules (Rivière et al., 2020; Wear & Coulston, 2019) and have been used to assess mitigation measures based on sequestration (Guo & Gong, 2017; Latta et al., 2016), energy substitution effects (Latta et al., 2013*a*; Moiseyev et al., 2014) or both (Caurla et al., 2013; Kallio et al., 2013). FSM have also been used to evaluate the impacts of climate change on the forest sector, either using assumptions on climate change impact (Lobianco et al., 2016*a*) or through couplings with vegetation and circulation models (Joyce et al., 1995; McCarl et al., 2000; Sohngen et al., 2001; Perez-Garcia et al., 2002; Solberg et al., 2003). These studies report general increases in timber supply while prices decrease, but also point to regional discrepancies in welfare implications (Kirilenko & Sedjo, 2007; Petucco et al., 2020). However, most of these early contributions did not allow for fully integrated feedbacks, such as management responses potentially affecting species composition or forest productivity (Lindner et al., 2002), nor did they focus on cascading impacts on forest-based climate mitigation. At the global level, Tian et al. (2016) explicitly consider mitigation measures in the energy sector and show that they would slow biological impacts and reduce the market impacts of climate change. For the case of France, Lobianco et al. (2016*a*) consider a spatially differentiated combination of increases in forest growth but also tree mortality for different species, and report 5.8-6.6% lower mitigation outcomes and a general shift to broadleaf species compared to a constant climate scenario.

In temperate areas such as continental Europe, forest-based mitigation mostly relies on afforestation-reforestation and improved management, which also needs to consider adaptation requirements. Brèteau-Amores et al. (2019) report that efficiently adapting management to drought risk in eastern France while storing carbon requires changes in species composition, planting density and timings of harvests. Hashida & Lewis (2019) showed that forest owners in the western US may favour species less sensitive to climate change. At larger scales, Nabuurs et al. (2017) estimate that the EU could double its mitigation potential by 2050 by promoting climate-smart forestry, while Yousefpour et al. (2018) report that similar practices could sequester 7-11 billion tons of carbon by 2100. In recent assessments focused on the US, Haight et al. (2019) reported afforestation to provide the largest increase in carbon sequestration benefits when compared to other options, while Tian et al. (2018) showed that constraining land-uses would strongly decrease the forest sector's sequestration potential. In Europe, afforestation may also play an important role in mitigating climate change, e.g., Eggers et al. (2008) estimated that afforestation could account for an additional increase of up to 40% in carbon stocks. However, climate change itself and the way societies respond to current global challenges may strongly impact land-use dynamics (Holman et al., 2017; Stürck et al., 2018), including in France (Lungarska & Chakir, 2018) and, consequently, disturb mitigation objectives. Similarly, climate change affects the distribution of tree species and the location of forestland (Dyderski et al., 2018; Favero et al., 2018), which in turn affects forest management and the forest sector. For example, Hanewinkel et al. (2013) reports that commercial forests in Europe may lose up to 50% of their expected value by 2100 due to natural shifts towards low-productivity, Mediterranean-type forests.

Management adaptations are often studied with detailed forest simulators and optimal rotation models (Assmuth & Tahvonen, 2018; van Kooten & Johnston, 2016; West et al., 2019), while econometric land-use models and integrated assessment models are used to investigate relationships between land-use and climate (Michetti and Zampieri, 2014). Contrary to FSM, these usually do not capture market feedbacks and distributional impacts across the value chain. On the other hand, most FSM do not take into account feedbacks between forestry and other land-uses and represent biological dynamics and forest dynamics in an aggregated and simplified manner. In this article, we seek to assess the potential of French forests to both mitigate climate change and sustain timber industries while explicitly considering the cascading biophysical and economic impacts of climate change on forest resources, management and land-use dynamics

For this purpose, we couple a spatialized FSM with endogenous management decisions to an agricultural supply model and an econometric land-use model, and we use a statistical model of climate change impacts calibrated from national forest inventory data. Our approach constitutes an important step forward for regional assessments of mitigation possibilities in the forest sector, and builds upon previous efforts (Caurla et al., 2013; Lecocq et al., 2011; Lobianco et al., 2016*b*) where the above-mentioned "loop effects" were not taken into account.

While a further area of study concerns the analysis of climate policies on the forest sector (for example Frank et al., 2016 discus the impacts of the EU energy and climate targets on the land use and forest resources in particular), we have chosen to present at this point a "politically neutral" evaluation, based on the current form of the demand and supply curves of timber products[1]. This work could eventually be used as a "baseline" in further studies where policy induced increase in the timber demand, or changes in the consumer preferences or production technologies, would be the subject of study.

The paper is organised as follows: section 2 describes the methods used and in particular: (a) the overall approach of this work; (b) the forest sector model; (c) how we model the vegetation response to climate change; (d) the land use sub-model and (e) how we chosen and implemented the simulation scenarios. Sections 3 to 5 present the results of the simulations in terms of model projections of forest resources, forest sectors, and climate change mitigation potential, respectively. While the figures and text refer to a specific scenario, results reported in the titles of these sections are consistent with all the IPCC storylines and climatic models we tested. Referenced tables and outputs from all the scenarios are available in the Supplementary Material, detailed in Appendix C. Uncertainty across the model is the subject of Section 6. Finally, Section 7 concludes the paper.

2 Methods

2.1 Overall approach

Results from this paper (sections 3 - 6) were produced by integrating several modelling tools (Fig. 1). On one side we used the French Forest Sector Model (FFSM++), a modular bio-economic model of forest resources dynamics, Harvested Wood Products (HWP) markets and forest management choices, whose essential characteristics are briefly described in section 2.2[2].

[1] We stress here (see later section 2 for the implementation of the market module) that while we are keeping fixed the *form* of the demand and supply curves, i.e. the elasticities, the actual equilibrium values are endogenous to the model.

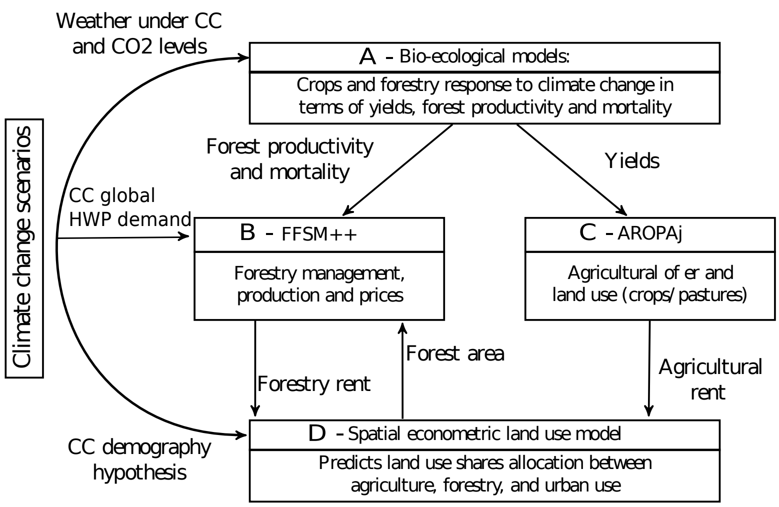
[2] While we only highlith the various modules of FFSM++ in this paper, their detailed descriptions are available in the references reported below

In order to consider the response of the vegetation (yield, mortality, probability of presence) to specific climate change scenarios, section 2.3 develop a statistical model based on National Forest Inventory (NFI) data. The output of this model is used to change the parameters of the forest dynamic module in FFSM++.

While FFSM++ can account for variation in land allocation of different forest types, it doesn't make predictions on the *total* forest area. In order to consider climate change effects also on the total forest area, we included in this studio an agricultural supply model, AROPAj (Jayet et al., 2018). While FFSM++ can produce forestry rent indicators, AROPAj can produce agricultural rent ones. Both FFSM++ and AROPAj have been run for the first time over the same set of climate change scenarios to retrieve the expected returns of the forest and agricultural sectors conditional to the scenario.

An econometric land-use model was then used (described in section 2.4), in which different categories of land use (agriculture, forestry, urban and other uses) were correlated with the land rent in agriculture and forestry produced by the two models, as well as some demographic and topographic variables (see Section 2.4). Assuming that land-use change is only driven by differences in land value, with no limitations from public intervention, the land-use model computed the effects of climate change on total forest areas. We then ran FFSM++ under the same set of scenarios once again, this time considering variations in total forest area. It is from this second set of scenarios that results are reported.

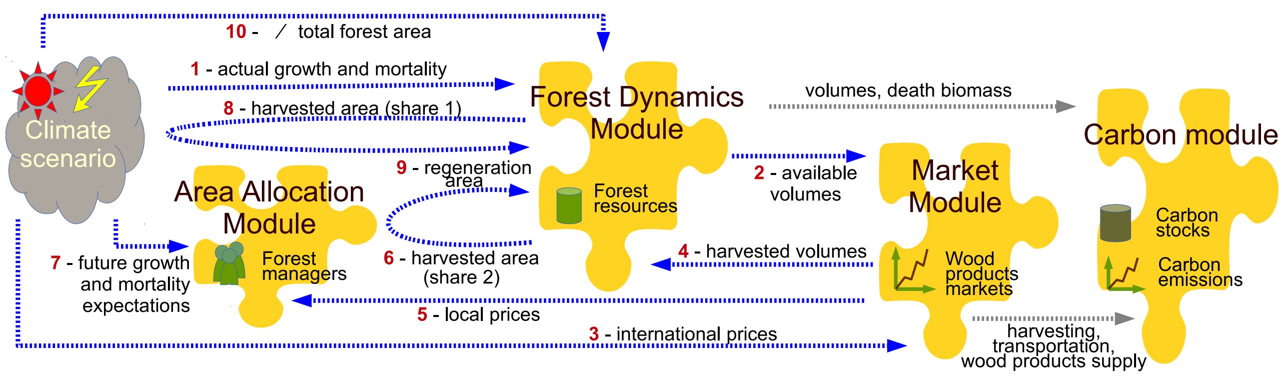
Figure 1: Overall models interplay



2.2 FFSM++

FFSM++ (Fig. 2) is a recursive bio-economic model with a demographic submodel of forest dynamic coupled with a partial equilibrium market model of HWP.

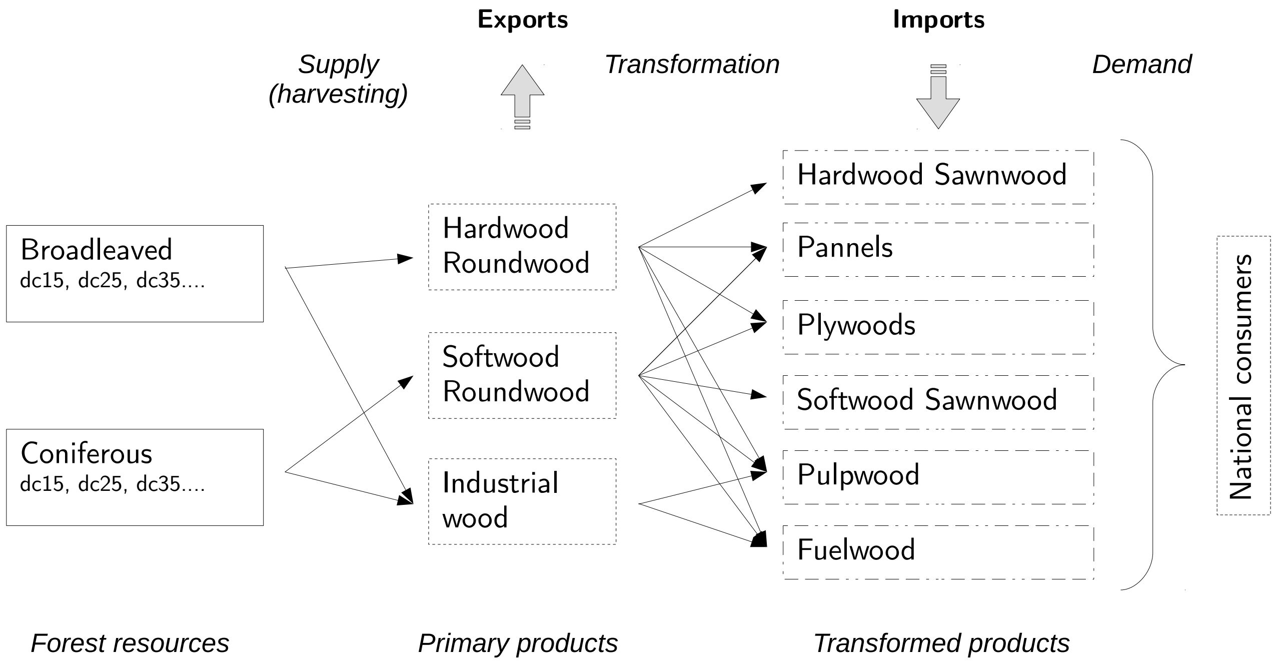
Figure 2: The French Forest Sector Model FFSM++



The **Forest Dynamics module** (FD, based on Usher, 1969 and Wernsdörfer et al., 2012) is an inventory-based Markov transition matrix model with 10 diameter classes and two species groups (coniferous and broadleaved), operating on a 8-km resolution grid. Its main task is to determine annually, for each forest type (the cross-product of species group and management regime), diameter class and geographical pixel, the forest volumes as a function of those present the previous year, the growth and mortality of trees in the forest (connection 1 in figure 2), the harvesting levels (connection 4 FIg. 2), and the regeneration (connection 9 Fig. 2). The information on forest volumes, once aggregated at regional level, is then translated into available resources for the various wood primary assortments (e.g. only timber volumes for high forests whose trees diameter is above the "35 cm" diameter class are considered as "available resource" for the sawmill industry from hardwoods) and, through an elasticity, enters in this way the supply function of the HWP market module (MK module, connection 2 FIg. 2).

HWP markets are modelled through a partial equilibrium model that establishes each year (and for each region and product) the market equilibrium (prices, quantities, interregional and international exchanges) of the first and second transformation wood products (Caurla:2010). The market module is represented in Figure 3. To start with, the supply function of primary products is modelled with constant elasticities with respect

Figure 3: The HWP module of FFSM++



to both the own price and the availability of suitable forest resources. This wood supply is then allocated to either international export or local markets using the Armington elasticity (Armington, 1969) that differentiates between national markets and international markets (that is, making local markets more or less dependent on international prices - connection 3). These elasticities depend on numerous factors, like the market's openness, different regulatory rules in the various countries but also perceived quality differences, and have been estimated ad hoc for FFSM in Sauquet et al. (2011). As for price elasticities, they have been modelled constantly with respect to time and regions, but they differ with respect to the specific wood product. The share of primary products allocated to local markets is then further adjusted to account for net inter-regional exports and, through a fixed-coefficients Leontief transformation, becomes the supply of transformed products as Panels or Plywood. Finally this supply, together with the international imports of transformed products and the net inter-regional imports, is matched with a constant elasticity demand to determine the market equilibrium. Once the market equilibrium is determined, the MK module transmits the quantities of the withdrawn volumes to the FD module (connection 4). This one converts them to the area available for new forest regeneration and transmits the equilibrium prices in the local region to the forest investment management module (Area Allocation module - AA, connection 5).

An agent-based **micro-economic AA module** (Lobianco et al., 2015, 2016*b*), also operating on an 8-km grid, makes endogenous the investment decisions of forest managers, and in particular the allocation of land following clear cuts, depending on the expected profitability of the forest ("rent"). This is computed from the expected timber value at the end of the planned rotation, which in turn depends on discounted expected timber prices (connection 5) and expected forest growth and mortality (connection 7). These determine respectively the length of the financial discounting to apply and the quantity of timber available at the end of the rotation.

We should note that in our model we implicitly decouple the long-term forest management decisions from the short term ones. Forest replanting (arrows 6 and 9) are considered "long term" decisions. In these decisions (i.e. choosing the most profitable forest specie), forest managers account for observed market prices and growth/mortality rates at time to make the decision but they can also account for the information on future prices and biological changes that we provide them from the other modules or bibliography, conditional on the climate change scenario. Following Lobianco et al. (2014), we model the forest managers as heterogeneous agents, where the exact expectation attitude for a single forest manager (biased toward the observed forest, the future predictions or any mix in between) and risk-aversion coefficient (the acceptable trade-off between an additional expected profit and an additional average mortality for that type of forest) are outcomes from a (Normal) distribution whose coefficients (mean and variance) are scenario-dependent (see Section 2.5 for the specific scenario implementation). Forest managers do not however need to solve a market equilibrium for the upcoming decades, they use as a "base price" the currently observed timber price. Conversely, the exact timing of forest final harvesting (arrow 4) is considered a short term decision and depends, conditionally on holding the forest resource of the appropriate diameter class, to the relevant timber product's current price.

Depending on a "management rate" indicating the intensity of artificial vs. natural replanting, a share of the harvested area (connection 6) is then transformed into regeneration area (connection 9) for the specific forest type chosen in the AA module, while the remaining part (connection 8) is allocated instead to forest regeneration based on exclusively ecological characteristics (i.e., without considering the possible value of the wood). More specifically, the regeneration species mix in the natural replanting share is determined by the specific climate-change scenario. An exogenous parameter, which we interpret as the "active management coefficient", determines the relationship between these two parts (with the "*_nomgm" scenarios presented in the "results" section referring to this parameter).

While the model performs the simulations, the informations on the timber volume in the forest and the quantities of HWP transformed and consumed are transmitted to the **carbon balance module** (CB module, Lobianco, 2016b), which determines for each year (a) the values of the various carbon stocks (the biomass in alive or dead trees, the biomass stored in wood products), (b) the emissions related to silvicultural operations and wood transport, and (c) through coefficients available in the literature (see Lobianco, 2016b for sources), the emissions of CO_2 avoided by using wood products directly as an energy source instead of fossil fuels (energy substitution, e.g. the use of firewood or wood pellets for heating instead of coal or kerosene) or as a material in place of other more energy-intensive materials (material substitution, e.g. wooden constructions to replace concrete constructions). The CB module allows the assessment of the overall mitigation potential of the forest sector on climate change within any given period (t_1,t_2) as the change in forest (and HWP) carbon stocks from t_1 to t_2 plus the sum of the substitution effects from t_1 to t_2 minus the (small) carbon emissions due to forest operations in the same period (McKechnie et al., 2011). This assessment avoids carbon double counting and timing allocation problems, i.e. a tree that is harvested at time t for fuelwood production would lead in the model to both a negative stock variation and an energy substitution effect at time t. The same tree harvested for sawnwood production would lead instead to a negative stock variation in forest pool, a temporary increase in HWP pool, and the accounting of a material substitution effect at time t.

Since these four modules run on different spatial scales, the core of the model includes functions to spatially aggregate/disaggregate the information when it is exchanged by the modules [3].

2.3 Statistical model of climate change impact on tree species growth and occurrence

As mentioned earlier, the FD module of the FFSM tracks timber volumes at the level of 8km-wide pixels for strata corresponding to combinations of forest compositions and diameter classes (Lobianco et al., 2015; Wernsdörfer et al., 2012). For each strata, volume changes from one year to the next are calculated as follows:

$$v_{k,t} = v_{k,t-1}\left(1 - \Delta t * g_{k,t-1} - \Delta t * m_{k,t}\right) + v_{k-1,t-1} * \Delta t * g_{k-1,t-1} * \Delta v_{k,k-1} \tag{1}$$

[3] While some modules run on a very detailed grid scale, the lack of significant information at that scale forced us to use sampled data for certain parameters, using known regional average and variance. Consequently, our results are significant only at the regional level, not on the sub-regional ones.

Where v is timber volume (m^3), g the growth rate ($year^{-1}$) from one diameter class to the next, m the mortality rate ($year^{-1}$), Δt the length of the time step and Δv the volume increment from one diameter class to the next, while k refers to diameter classes and t to years. We model the biophysical impacts of climate change on forest dynamics by applying multipliers $\tilde{G}$ to growth rates (to account for changes in forest productivity) and $\tilde{M}$ to mortality coefficients (to account for changes in tree mortality).

Both multipliers were calculated from statistically estimated models of climate change impacts on two metrics: species productivity G and species probability of presence p (Mérian & Bontemps, 2014). We provide here an overview of methods in Mérian & Bontemps (2014). The values for the two dependent variables were gathered from National Forest Inventory (NFI) (Hervé, 2006) campaigns for the years 2005 to 2009 for a set of 7 common tree species, which together account for more than 2/3 of forest cover in 10 of the country's 22 regions and more than 50% in further 7 regions[4]. Following (Charru, 2012), G_s was calculated as the increase in stand basal area for each species s, measured on tree core samples over a set of the 3,431 plots that has been retained after filtering out for pure and even-aged stands, to properly filter out factors of stand dynamics (age, density). p_s is simply the realisation of a Bernoulli variable indicating presence or absence of the species on both the "dendrometric" and "floristic" sections of the whole set of 33,471 plots. In the French forest inventory system, each surveyed plot has two sections: a "dendrometric" section that records dendrometric characteristics measured only on tree species above a certain diameter class (7.5 cm) over a circular radius that depends on the tree's size (larger trees are measured over larger circles), and a "floristic" section that record the presence of any-size plants, from seedlings to adult trees, but on a much smaller area than the dendrometric section.

For both models, independent variables comprised two sets of predictors. The first set of predictors contains seasonal meteorological variables extracted from the SAFRAN grid database (Le Moigne, 2002; Vidal et al., 2010): precipitations (P) and temperature (T) in summer and winter (sum and win), and vapour deficit (VDP) in summer. While climatic means synchronous with growth increments were used for growth modelling (e.g.. over 2000-2004 for the 2005 NFI inventory), climatic normals 1971-2000 were used for the probability of presence since the observation of species presence in the years 2005-2009 corresponds to the presence over an undefined past temporal horizon. The second set contains edaphic predictors to control for spatial variability in site conditions (Gégout et al., 2003): soil carbon to nitrogen ratio (CN), soil pH (Agr, 2008), soil water holding capacity (WHC Piedallu et al., 2013) and soil depth (D). Generalised Additive Models (Hastie & Tibshirani, 1990) were fitted with loess smooth terms and Gaussian and binomial link functions for dependent variables G_s and p_s respectively, following a K-fold cross-validation approach, in statistical analysis software R using package `gam`. Tables 1 and 1 report effects of the predictors on dependent variables Gs and ps respectively, for all 7 species (from Mérian & Bontemps, 2014):

Table 1: Summary of model effects for species probability of presence p

	pH	CN	WHC	D	Twin	Tsum	Pwin	Psum	VDPsum
A. alba		+-			+-			0+	
F. sylvatica	0-					+-		+0	
P. abies	-					0-		0+	
P. sylvestris	0+	+0			+-		-		
Q. petraea					+-		-0		0-
Q. pubescens				-				+-	+0
Q. robur			+	+	+0				

Table 2: Summary of model effects for species productivity G

	pH	CN	WHC	D	Twin	Tsum	Pwin	Psum	VDPsum
A. alba						+		+	
F. sylvatica	0+			+				+0	
P. abies					+0				-
P. sylvestris	-				+-				
Q. petraea	0-							0-	
Q. pubescens						0+		+0	
Q. robur				+					

Note: `+` and `-` denote monotonous positive and negative effects respectively, `+0` and `-0` positive and negative then saturating effects respectively, `0+` and `0-` flat then positive and negative effects respectively, and `+-` and `-+` convex and concave "bell shaped" effects respectively. Detailed responses can be found in annexes in Mérian & Bontemps (2014).

[4]We retained the coniferous species *Abies alba* Mill., *Picea abies* L. and *Pinus pinaster* Aiton, and the broadleaved species *Fagus sylvatica* L., *Quercus petraea* Liebl., *Quercus robur* L. and *Quercus pubescens* Willd.

These two models have then been used to estimate current species growth and probability of presence ($G_{s,0}$ and $p_{s,0}$) as well as to project their evolution ($G_{s,t}$ and $p_{s,t}$) under a changing climate. Estimation and prediction have been conducted at plot level and then aggregated at regional level. All values have been calculated by varying climatic predictors on the SAFRAN grid (Pagé & Terray, 2011), while edaphic predictors remained constant[5]. Values were calculated for 5-years moving periods for G_s (2013-2017 to 2083-2087) and 30 years moving periods for p_s (2001-2030 to 2071-2100).

Growth multipliers $\tilde{G}$ and $\tilde{M}$ were calculated from these predictions for each model region as follows.

According to the model above, the regional average probability of presence of each species $p_{s,t}$ is projected both for the initial period $t = 0$ and, once the climatic predictors are modified, the future. Then, for each plot observed, the "main species" of the stand is extracted from the "dendrometric" section and used to compute the initial regional frequency per species $f_{s,t=0}$. To allow the species not initially present in a given region to eventually expand over time in that region as a consequence of climate change, we lower-bounded such frequencies with a "seed" frequency of 0.001. Species frequencies for future periods are then computed as:

$$f_{s,t} = f_{s,t=0} * \frac{p_{s,t}}{p_{s,t=0}} \tag{2}$$

that is by multiplying the inital (observed) frequencies by the ratio of the regional probabilities of presence at time t versus time $t = 0$ (both predicted).

We can then use these frequencies to compute both the mortality and the growth multipliers at the level of the group of species $u = \{coniferous, broadleaves\}$ used in FFSM++. Mortality multipliers $\tilde{M}_{u,t}$ has been computed as:

$$\tilde{M}_{u,t} = \left(\frac{\sum\limits_{s \in u} f_{s,t}}{\sum\limits_{s \in u} f_{s,t=0}} \right)^{-1} \tag{3}$$

that is, variations in species group frequency are interpreted as being due to changes in mortality, e.g., decreases in species group frequency lead to $\tilde{M}_{u,t} > 1$, corresponding to an increase in mortality, although this reduced approach doesn't allow us to distinguish between direct mortality to climatic changes or indirect mortality due to disturbances (biotic or abiotic) resulting from climate change.

For growth multipliers we first need to compute the relative specie frequencies within each species group:

$$\bar{f}_{s,t} = \frac{f_{s,t}}{\sum\limits_{s \in u} f_{s,t}} \tag{4}$$

These frequencies sum to 1 for each group of species and are needed to factor out the mortality effects already accounted for in $\tilde{M}_{u,t}$.

Growth in species group G_u is computed as averages of species growth G_s for all species s in group u, weighted by the relative species frequencies $\bar{f}_{s,t}$ that we just computed:

$$G_{u,t} = \sum_{s \in u} G_{s,t} * \bar{f}_{s,t} \tag{5}$$

In other words, we use in the computation of the growth rate the relative species frequencies within each group

[5]That is, we assume in this paper that climatic changes will not be strong enough to alter the edaphic properties across the simulation period.

because $\tilde{M}_{u,t}$ already takes into account the fact that total group frequency may change over time. Similarly to equation 3, growth multipliers are computed as a ratio between species group growth at time t and $t = 0$:

$$\tilde{G}_{u,t} = \frac{G_{u,t}}{G_{u,t=0}} \tag{6}$$

Tree productivity and mortality in the future (per species group, region and year) in the Forest Dynamic Module of FFSM++ is then obtained, conditionally to the specific IPCC scenario and climatic model, multiplying the last year of the observed data (i.e., the reference period) by these multipliers.

Finally we computed normalised group frequencies (where we normalise again in order to factoring out the mortality effect already accounted in $\tilde{M}_{u,t}$) as

$$\bar{f}_{u,t} = \frac{\sum\limits_{s \in u} f_{s,t}}{\sum\limits_{s} f_{s,t}} \tag{7}$$

and used them in the AA module to assign the natural regeneration in the clear cuts areas.

2.4 Land-use model - Climate change predictions for forest areas

The main land-use changes currently ongoing in France (and in some parts of Europe) are related to urbanization and agricultural abandonment. Between 2006 and 2014, 491 thousand ha were urbanized, natural areas (e.g. forests) increased by 75 thousand ha while agricultural land was reduced by 566 thousand ha or roughly 2% of agricultural land in 2006 (Agreste, 2015).

The main drivers behind urbanization are generally acknowledged to be demography and economic attractiveness of a given region (Partridge & Rickman, 2014). Agricultural abandonment dependents not only on population demographics but also on the rate of intensification of agricultural production and the resulting concentration of this activity in the most fertile (and economically interesting) territories (MacDonald et al., 2000). Future land-use changes will be subject as well to the effects of climate change. In order to study these dynamics, scholars have often used a series of model simulations (e.g. Rounsevell et al., 2006; Verburg et al., 2010; Verkerk et al., 2016). The models employed in such modelling chains work on different spatial and temporal scales where the results from one model are used as an input to the smaller scale models. At the highest scale, there are one or more global general equilibrium models (e.g. GTAP, IMAGE, REMIND, and MAgPIE) that provide information on economic development, human demographics, commodities prices, trade, and global land-use change. The next stage consists in using global or regional models that focus on agriculture, forest, and urban. For instance, MAGNET and EFI-GTM are global models while EFISCEN and CAPRI's supply model are centered on Europe. At this point, the results of the simulations are available at a regional level (often NUTS-2) and for different temporal horizons. Some downscaling techniques and models, such as the Dyna-CLUE model based on information from the CORINE Land Cover database, are used in order to obtain high-resolution land-use projections.

2.4.1 Econometric land-use model

Econometric land-use models are commonly used for the prediction of forest area. Lubowski et al. (2006) use such models to evaluate carbon sinks in the US. Haim et al. (2011) study the response of US land allocation to climate change, and Ay et al. (2014); Lungarska & Chakir (2018) focus on the French case. Some key variables of these models are land rents associated with the different land-use possibilities. Nevertheless, these data are not readily available and are often approximated. This is even more true when it comes to climate change simulations.

In this paper, in order to assess climate change effects on future forest areas, we used a land-use share model following Ahn et al. (2000); Chakir & Lungarska (2017); Lungarska & Chakir (2018). Econometric land-use models are built on the hypothesis that landowners decide land allocation by maximising the ensuing profits. Here, we estimate a model covering metropolitan France divided into an 8-km resolution grid (as in the previous parts of the paper). The land-use classes ($k = 1, ..., K$) are: (i) agriculture, (ii) forest, (iii) urban, and (iv) other. Individuals' optimal land allocation is aggregated in land-use shares (y_{ki}) for each grid cell ($i = 1, ..., I$). These shares are expressed as:

$$y_{ki} = s_{ki} + u_{ki} \quad \forall i, \forall k. \tag{8}$$

The s_{ki} element represents the expected land-use share that can be different from the observed share y_{ki} because of random factors influencing the land-use choice. We use a logistic specification as follows:

$$s_{ki} = \frac{e^{X_i \beta'_k}}{\sum_{j=1}^{K} e^{X_i \beta'_j}}. \tag{9}$$

Here, the vector β'_k gives the coefficients of the explanatory variables X_i. Thanks to Zellner & Lee (1965), the expression in Equation 9 is approximately equal to:

$$\tilde{y}_{ki} = ln(y_{ki}/y_{Ki}) = X_i \beta'_k + \epsilon_{ki} \quad \forall i, \forall k \tag{10}$$

The land use of reference (y_{Ki}) is assumed to be the "other" class; the model is identified if β_K is constrained to be 0. The explanatory variables used in the model represent the land rent in agriculture, the expected forestry returns, and some demographic and topographic variables. More explicit information on the data is provided in Section 2.4.2. Because of the artificial grid we used, we suspected that our data might be subject to spatial autocorrelation. Starting with the pooled ordinary least squares model (OLS), we calculated Moran's (1948) I statistic , which we found positive and significant, confirming the hypothesis of spatial autocorrelation. In order to correct this flaw, we used the spatial error model (SEM) as presented in Equation 11.

$$\begin{aligned} \tilde{y}_{ki} &= X_i \beta'_k + \epsilon_{ki} \\ \epsilon_{ki} &= \lambda W \varepsilon_{ki} + u_{ki}, \end{aligned} \tag{11}$$

where W is the neighbours' matrix derived from the queen's contiguity rule and row-standardised.[6] The SEM model controls for spatial autocorrelation in the error terms. The estimated coefficient λ is positive and highly significant. The predictor that we used for this model specification is given in Equation 12.

$$\widehat{y}_{ki} = X_i \beta'_k + \lambda W \varepsilon_{ki} \tag{12}$$

This means that we keep the initially obtained error terms, multiplied by the spatial autocorrelation coefficient λ and the neighbors' matrix, and add them to the predicted trend from $X_i \beta'_k$.

2.4.2 Data

We used different data sources for the estimation of the land-use model as described below. As in Chakir & Lungarska (2015), we used economic rent variables for the different land uses along with some fine-scale topographic information.

Land-use shares are derived and aggregated from the Corine Land Cover (CLC) database.[7] As mentioned before, we modelled four exhaustive land classes: (i) agriculture, (ii) forests, (iii) urban, and (iv) other. We used the information for the year 2000.

[6] We used the `R` package `spdep` for our estimation and the calculation of the neighbourhood matrix. For more information, see Bivand et al. (2013); Bivand & Piras (2015).

[7] For more information, visit `http://land.copernicus.eu/pan-european/corine-land-cover/view` .

Agricultural land shadow price allows us to approximate agricultural land rent. This variable roughly corresponds to the marginal revenue of land in agricultural use or the additional gain to the farmer from one additional hectare of land (Chambers & Just, 1989). We use it to approximate the returns to agricultural use. Its value is estimated by the European agricultural supply model AROPAj *v.2* and *v.5* for 2002 and 2009 (Jayet et al., 2018). The objective function of AROPAj is the maximization of farm profits. One of the control variables is the allocation of land between different crops and pastures. Land shadow price is the Lagrange multiplier associated with the total area constraint. The model is parameterised with regard to the Common Agricultural Policy of the European Union, and to the different technical constraints of agricultural activity. The results of the model are available at the NUTS2 regional level (for France) and are later spatialised at the 8 by 8 km scale following the techniques proposed in Chakir (2009) and Cantelaube et al. (2012). Values under climate change scenarios are estimated following Humblot et al. (2017).

Expected returns from forestry, from the FFSM++ model, provided an estimate for forestry rent where the potential switch in tree species is taken into consideration. For the study of climate change impact on forest areas, we considered the expected returns for the business-as-usual case, A1B, A2, and B1 climate change scenarios (from the International Panel on Climate Change "Special report on emission scenarios"). The simulated values are available at the NUTS2 regional level and starting from the year 2006.

Population density and revenues served as a proxy for urban rent. The information is provided by the French Statistical Institute (INSEE) for the years 1999 (density) and 2000 (revenues). Data, originally available at the level of the French municipality (*commune*), have been aggregated at the regional level. We used demographic estimates from INSEE and the IIASA to evaluate demographic progression for the three climate change scenarios.

Topographic information here covers the average slope of the grid cells and the average texture class of soils. Data on slope are derived from the digital elevation model GTOPO30,[8] and the four texture classes are provided by the European Soil Database from the Joint Research Centre of the European Union (Panagos et al., 2012). The worst type of soil texture (TEXT1) is used as a reference class. Since the forestry and agricultural rents are available at a broad scale (the NUTS2 region), the topographic information allows us to "downscale" these variables and better account for intra-regional heterogeneity of land.

2.4.3 Estimates

Table B.2 provides the estimated coefficients for the three equations of the land-use shares model. The pseudo-R^2 is higher for agricultural land use. The signs for the different rent variables are intuitive, and the coefficients are significant. The Moran's I statistics and the spatial autocorrelation coefficient λ are both significant.

We notice that forestry rent has a positive coefficient for both the agricultural share and forestry, and, in general, returns for crops and trees are correlated. Unlike previous findings for the U.S. case (Hashida & Lewis, 2019; Haim et al., 2011; Lubowski et al., 2006), we find that in France forestry rent alone is insufficient to predict forest areas. For agricultural development, land shadow price seems to be an important driver, while the expected returns from forestry are not among the decisive factors for forestry development. We discuss some potential drivers at stake for forest areas further in the text.

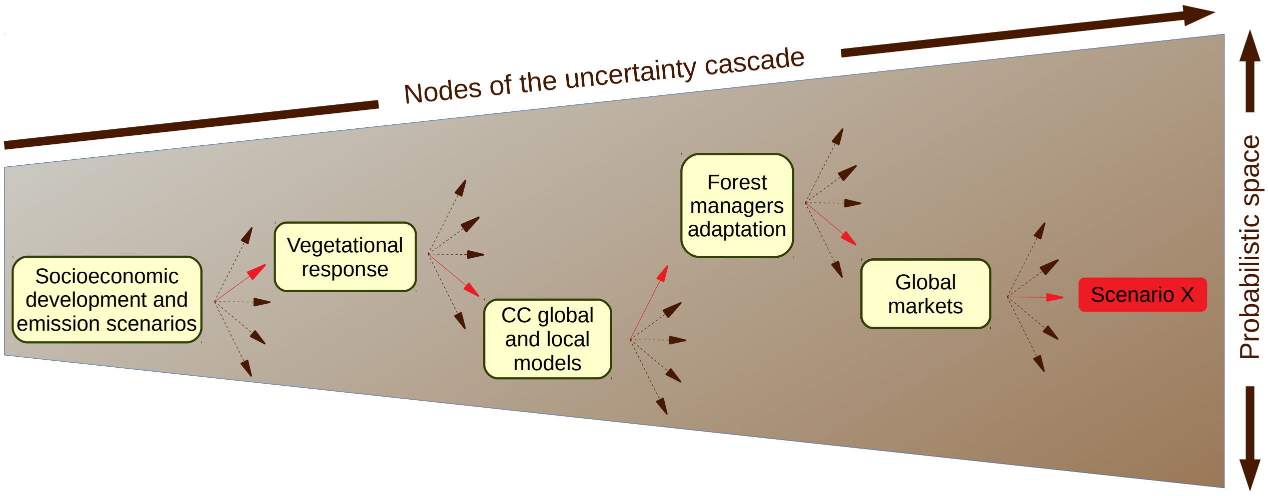
Furthermore, the results for the land-use model show a positive and highly significant coefficient for population revenues, which could mean that forests are valued for their recreational services. We should underline here that in the land-use model, forests comprise private and public woods as well as natural parks. Another important dimension of French forestry is the tax cuts associated with acquiring and maintaining forests. These economic dimensions of forestry could potentially have a substantial impact on the decision to convert or maintain a forest parcel. The econometric land-use model implicitly accounts for some of these factors (estimated coefficients for population revenues and forestry returns). We also correct our predictions with the estimated error and spatial terms. Estimated coefficients allow us to calibrate for the different temporal horizons (discounting) characterising agricultural and forestry activities (Chakir & Lungarska, 2017; Lungarska & Chakir, 2018). This way, the model allows us to compare land-use revenues which are not directly comparable because of the differences in the hypothesis of the mathematical programming models FFSM++ and AROPAj.

[8] For more information, visit `https://lta.cr.usgs.gov/GTOPO30` .

2.5 Scenario implementation

Within our framework, climate change could be accounted for in terms of both its direct and indirect effects, e.g., biophysical effects on the forest resources and HWP market shocks respectively. The necessity to consider multiple causality links to assess the overall effect of climate change (Fig. 4) makes it hard to assess the uncertainty and to represent it within the multiple model linkages. Our approach has therefore been to select what we subjectively believe are the main axes around which the uncertainty can pivot and represent it using comprehensible scenarios, i.e. choosing a specific set of outcomes - one for each node of the uncertainty cascade, represented in Fig 4 by each arrow. Table A.1 details the characteristics of all the scenarios used in this paper.

Figure 4: Graphical representation of the uncertainty cascade of climate change for the forest sector.



In particular, we consider different economic and emission storylines, as described in the IPCC Special Report on Emission Scenarios (Nakicenovic & Swart, 2000) [9].

Each of these emission scenarios translated into a specific climatic scenario using different climatic models. Once a climatic scenario is defined, a statistical procedure (described in greater detail in Section 2.3) allows us to obtain spatially and temporally explicit *Climate change multipliers* that, for each region and for a 5-year moving window, describe the effects of a climatic scenario on the variation of the average growth of tree species, and *Probability of presence* indicators, based on a 30-year moving window of climatic normals, that are used to both extend this variation from individual species to the species group used by the model and to measure the probability of additional climatically-induced mortality, by noting that a drop in the future probability of the presence of a species can be interpreted as mortality.

A third way that climate change and its uncertainty influence the model is through global-level variation in the demand and provision of harvested wood products, i.e., through changes in global prices. In this paper we used however the global timber prices reported by Buongiorno et al., 2012) that are obteined by considering only the macroeconomic variables characterizing the various IPCC storylines, but not the climate change effect themselves.

Indeed, through the Armington elasticities defined in the market module, local regional markets of HWP are more or less dependent on such international prices. The local price then influences the harvesting quantity and the investment decisions.

To sum up, in this modeling approach, climate change influences the forest sector in multiple ways: *(a)* in the

[9] In this paper we base our simulations on the Special Report on Emissions Scenarios (SRES) instead of the Representative Concentration Pathways (RCPs) used in the 5th IPCC Assessment Report or the Shared Socioeconomic Pathways (SSPs) that will form the basis of the upcoming 6th Assessment Report. One reason is the long chain of dependent models and the availability of data and bibliographic sources. Another reason is that this analysis doesn't consider specific climate policy decisions as implied instead by the SSPs scenarios. That's said, for each family of scenarios IPCC doesn't assign a specific likelihood to its members (although this is a controversial topic, see Hausfather & Peters (2020).). We can hence attempt a mapping between different families based on the CO_2 emission trajectory described, linking the SRES/B1 scenario used in this analysis to the RCP/4.5 and SSP/1, the SRES/A1B to the RCP/6.0 and SSP/2 and SRES/A2 to the RCP/8.5 and SSP/3 (van Vuuren & Carter, 2014)

forest dynamics module through the timber growth rate, probability of presence of tree species and subsequent mortality, and variations in the total forest area; *(b)* in the area allocation module through *expected* mortality and growth rate. These influence the expected forest rent both by changing the period to wait for tree's maturation (hence the discounting) and the timber provision at harvesting; *(c)* in the area allocation module through *expected* future prices (mediated by the market module); and, finally, *(d)* in the market (and harvesting) module through current global prices.

Those climate change impacts interact with the adaptation behaviours of forest managers, that is with the choice of management made by the forest managers. These options include both choosing a given forest species group but also, for a specific species group, choosing the optimal forest regime (i.e. the most profitable one from a timber revenues prospective) given the expected climate scenario (in this paper either coppices, high forests or a mixed of the two). It is important to note that this represents a long term choice that can not be later changed by the forest manager, and complements the short-term choice of the exact moment of timber harvesting, which is instead driven by the HWP market module.

Three issues arise in particular with this choice:

- The first one concerns the very capacity of forest managers to perceive the changes. As described in Section 2.2, in our modelling framework forest managers are assumed to have heterogeneous viewpoints, ranging from a myopic attitude, where behaviour is driven only by observed characteristics of the forest and the markets, to perfect foresight, where forest managers fully account for the forecasts of biophysical and market impacts of climate change in their investment choices[10]. Modelled decisions are based on an "expected" version of the growth, mortality, and timber prices parameters as a weighted average between the corresponding values provided for the relevant time period by exogenous climate change scenarios and those observed at the time of making the forest investment, the weight being an "expectation coefficient" sampled for each different agent from a normal distribution whose parameters are scenario-dependant (scenarios `*.noexp`, `*_fullexp`).
- The second issue is related to the willingness (or capacity) to adapt to the changes, where the two extremes are a passive attitude towards the species that are left to evolve "naturally" (according to the scenario-specific probability of presence) and, at the opposite end, an attempt to drive the change, actively pursuing the species and management type that best fits the new environment according to the forest manager's objectives. A parameter in the model allows leeway between these two extremes (scenarios `*_nomgm`).
- Finally, given the expectations and the forest managers' adaptation model, the latter issue concerns how the forest managers' risk aversion could influence their decisions. We assumed that forest managers are risk-averse toward forest mortality, with the expected returns (that already account for the average mortality) balanced against the risk of their own forest investment being affected by the mortality. This trade-off is modelled by a risk aversion coefficient that, as for the expectations parameter, is sampled for each manager in the model from a given scenario-specific distribution (scenarios `*_nora`).

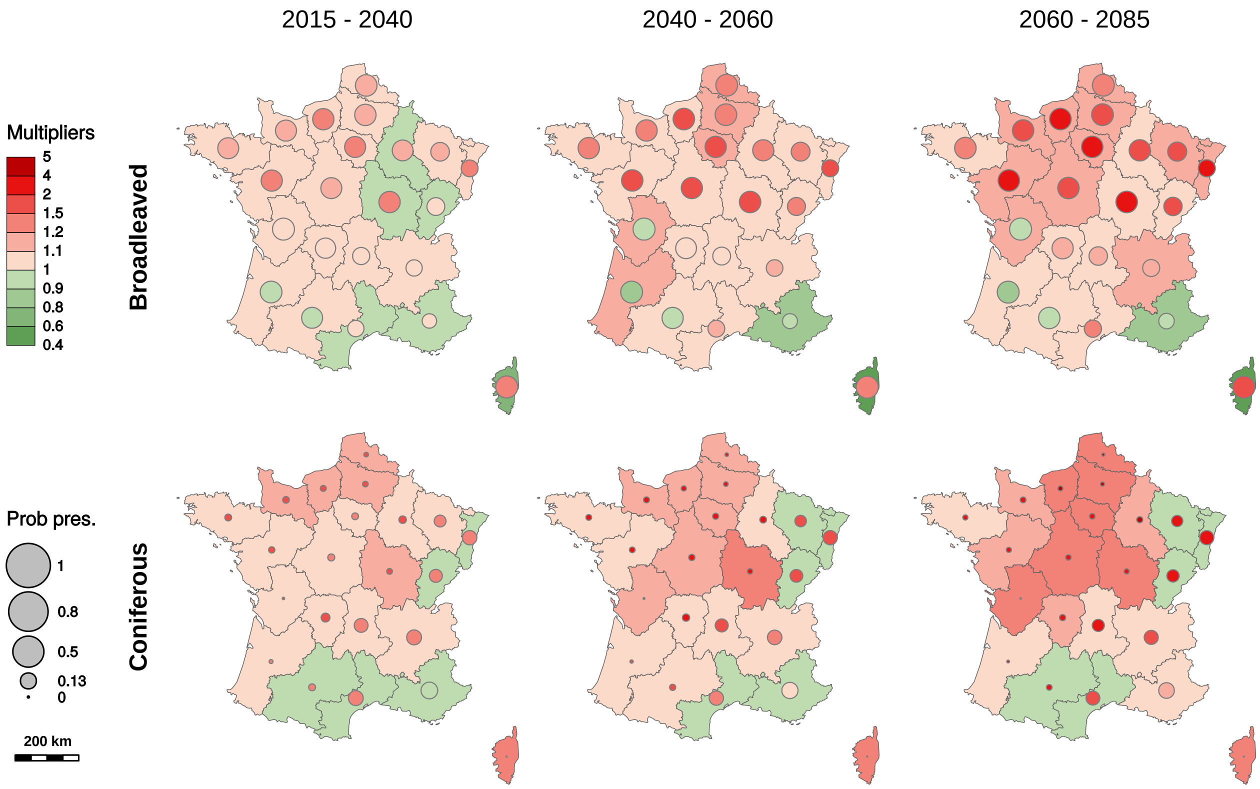
3 Forest resources results

Below we report the results of the simulations concerning the scenarios of Table A.1, obtained running the model as implemented in the software code available in the Supplementary Material for up to 2100. Such relatively long timespan is necessary to appreciate the effects of forest management and forest dynamic, like the increased frequency of larger classes in the distribution of diameter classes.

While our main interest consists in evaluating the effects of two separate but not independent drivers - climate change and management choices - on the forest sector in terms of two separate but not independent outputs - wood production and climate change mitigation -, in this section we discuss the effects on the forest ecosystems themselves, as results on wood markets (next section) and climate change mitigation (section 5) will largely depend on them. Titles (in bold) describe qualitative results consistent with all the IPCC storylines and climatic models we tested, whereas text and figures in these sections refer specifically to the `arpege_a1b` scenario, i.e. the "A1B" IPCC scenario implemented through the "Arpege" climatic model.

[10]We precise that in our model the rationality of expectations in the "perfect foresight" scenario refers uniquely to parameters that are exogenous to the model - international prices and climate change biophysical effect. Forest managers do not consider how their actions, and the optimal actions of their peers, would influence the timber markets at the end of the rotation. Further, given the discrepancy between the time when a management decision is made in forestry and the time when its outcomes are observed, we do not consider the effect of previous experience ("learning") in the expectations.

Figure 5: Direct effects of climate change: time of passage (between diameter classes) multipliers, mortality multipliers and probabilities of presence.



The colour in the background represents the multiplier for the "time of passage" between diameter classes, with red values indicating slower growth. The colour in the circles represents the mortality multipliers, with red indicating increased mortality due to climate change. Finally, the size of the circle indicates the probability of presence [scen. `arpege_a1b`].

3.1 Climate change impacts on tree mortality are greater than those on tree growth variations.

Figure 5 shows the physical impact of climate change that was considered in this study (i.e., the simulations from the statistical model of vegetational response to climate change). The time of passage for trees to reach the next diameter class (i.e., the inverse of the growth rate) increases as time passes, particularly in the central and northern part of the country. The south and the east benefit instead from better conditions to favour timber growth, initially for both broadleaved and coniferous species, and then limited to the coniferous species alone. Its multiplier is higher for coniferous than broadleaved species and it increases with time, although it remains relatively low compared to the mortality multiplier (averaging 1.07 and 1.83 for the whole period respectively, Table B.1).

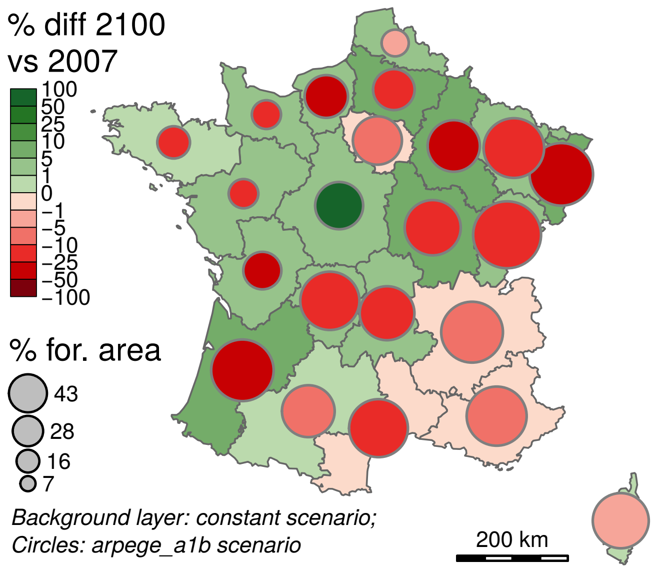
Consistent with previous studies (see Dale et al., 2000; Allen et al., 2010; Lindner et al., 2010; Seidl et al., 2017), tree mortality has the strongest climate change impacts on forestry. We observed an almost ubiquitous increase in mortality, with the sole exception of broadleaved trees in parts of the south. Once again, coniferous species seem to be more impacted than broadleaved species, since their mortality multiplier is almost double, reaching peaks as high as 5.16.

When we analyse the probabilities of presence, we observe the extreme prevalence of broadleaved forests, with coniferous species occurring only in mountainous regions in the Alps, central France (*Massif Central*) and the Northeast. It can be implied that the current distribution of coniferous species in the French forest landscape has been greatly favored by human intervention.

3.2 Due to increasing competition with agriculture, climate change may reverse current trends in forest area expansion.

Concerning changes in total forest area, the econometric model predicts a quite radical effect of climate change: while under a scenario of constant climate, forest resources in most of France are predicted (the exception is the southeastern Mediterranean and the Paris area) to continue a limited expansion (background of Fig. 6 and Table B.3). This result is consistent with recent forest area expansion, in most part ascribable to the abandonment of some low-quality agricultural areas, observed in France during the last five decades (FAO, 2015). However, when we account for climate change, the trend reverses and forest areas strongly decrease (-12% in 2100). Regional disparities are related to the spatial differences in the relative impact of climate change on agriculture and on forestry returns and on the magnitude of the land variation following these impacts. Overall, climate change has a positive impact on both the agricultural shadow prices and forest returns, except for the region "Centre" (CE), one of the major cereal producing regions in France. Following an extensive review, Miner et al. (2014) conclude that the increased demand for wood (as the one we consider in our climate change scenarios) could trigger investment in new forest areas in the US. Considering an increased demand also for agricultural products however leads to the conclusion that the agricultural land reacts more to these variations (Table B.2), resulting in a general shift of area back to agriculture. Comparing to our present study, for France Verburg et al. (2010) predict an agricultural surface expansion under the A2 scenario but a forest expansion under the B1 scenario. Rounsevell et al. (2006) project also a decrease in forest area for the A2 scenario while surplus (non-allocated) land increases. The aforementioned studies account for the effects of world trade in terms of food and wood demand, among others. As a result, scenarios with more international cooperation (as B1) lead to greater distribution of the agricultural productive effort namely in low-income countries. However, the methodology used in our study allows us to focus on the effects of climate change in France and the identification of possible tendencies.

Figure 6: Forest area.



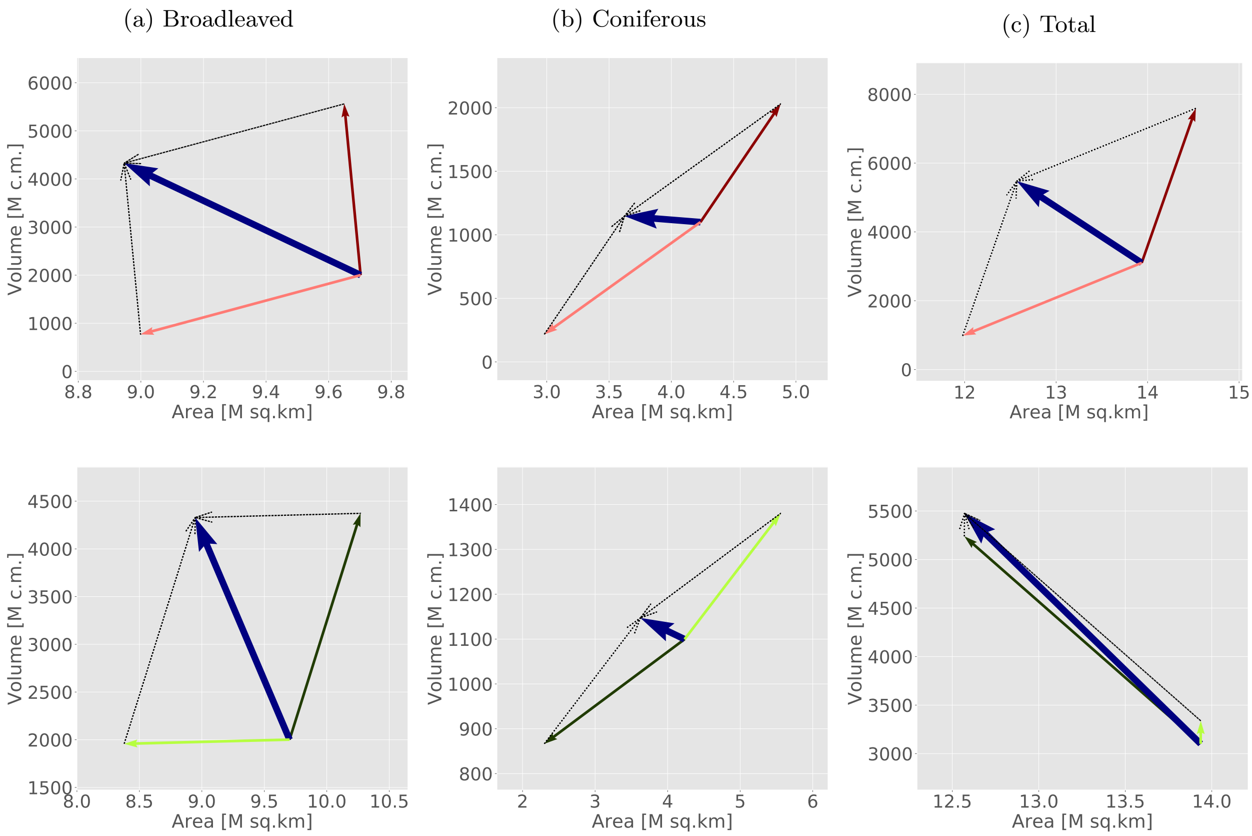
The figure depicts the simulated percent variation in forest area in 2100 compared to 2007 (green indicating an increase of forest area), with the colour in the background portraying the results under a constant climate scenario [scen. `constant`] and those in the circles under climate change [scen. `arpege_a1b`].

3.3 While management drivers favour coniferous species, climate change drivers favour broadleaved species.

Forest resources are characterised by strong inertia so that future forests will largely depend on their current state. In terms of timber volume and forest area, the thick blue arrows in Fig. 7 show the dynamics of the forest resources up to 2100 (with the origin of the arrows representing the situation in the area-volume space in 2015 and their ending representing those in 2100). We forecast a much denser (almost double) and older forest than the current one, albeit with approximately the same ratio between broadleaved and coniferous species in terms of area (70 and 30%, respectively; Table B.4).

On the contrary, due to the higher mortality and utilisation of coniferous species, the volume in the growing stock tends to accumulate more in broadleaved species, leading to a shift in the broadleaved/coniferous ratio

Figure 7: Breakdown of climate change and management effects.



The figure reveals the breakdown of the climate change effect (conditional to appropriate management) on the first row, and of the management effect (conditional to climate change) on the second row. 2015-2100 variations of volume (vertical axis) and area (horizontal axis).

Thick blue arrows: arpege_a1b scenario (including climate change and management);

First row: Dark red arrows: constant scenario (without climate change); Light red arrow: overall climate change effect (conditional to managed forest);

Second row: Dark green arrows: arpege_a1b_nomgm scenario; Light green arrows: overall management effect (conditional to climate change)

from 6/4 in 2015 to 8/2 in 2100, with several regions showing signs of over-harvesting (Table B.5). Dark red and dark green arrows (in the same figure) show the outcomes of the simulations when we do not consider climate change or forest management, respectively. The effects of these two factors are calculated by their difference (brighter arrows). Climate change reduces forest volume growth, especially for coniferous species, and favours broadleaved forests over coniferous ones in term of area. On the contrary, an active forest management favours coniferous forests, since they generally remain more profitable (however on the long term stronger climate change impacts would eventually challenge the coniferous profitability dominance, Table B.13), and both the area and the volume of coniferous species would increase.

Hence, our earlier statement of a constant ratio between the area of broadleaved and coniferous forests is actually the result of these two opposite drivers, and, without an active management policy, coniferous forests would follow their natural dynamics and be uniquely relegated to mountain regions, confirming the analysis on the probabilities of presence in section 3.1.

3.4 Despite increasing harvesting intensity and climate change impacts, forest growing stock continues to expand.

Driven by increasing international prices (Buongiorno et al., 2012), timber producer prices are expected to increase under the climate change scenarios (Table B.14). Note however that this is due to expected generally favorable global macroeconomic conditions, not global impacts of climate change. In turn, higher prices lead to

an increase in harvesting (Table B.6; see Table B.7 for the scenario without price increase - `arpege_a1b_nopr` - where harvesting remains broadly constant).
Despite the increasing harvesting - and the increasing mortality due to climate change - net forest volumes in the considered period (2015-2100) increase by 76%, implying that even under these conditions harvesting levels remain well below the forest net primary production.

3.5 Due to rising average tree sizes, volume growth strongly declines over time and may eventually cease within the next century.

As expected, this volume increase is not at all constant. Indeed, using a forest dynamic model by diameter classes, in which larger (i.e., older) trees grow slower, a size-related effect of reduced volume accumulation can be observed. Figure 8a clearly shows what is recently beginning to be observed within European forests (see Nabuurs & Pussinen, 2013), i.e. a diminishing volume accumulation that, in our simulation, may lead total forest volumes to peak at the end of the century, while coniferous forests are projected to reach such a peak as early as the middle of the century. This has important implications in terms of the capacity of the forest to continue to store carbon in its biomass (section 5.1).

4 Forest sector results

4.1 Future climate change impacts already have strong consequences on today's forest investment profitability.

Due to the long-term horizon of forest investments, future climate change impacts and forest managers' expectations toward them already have strong consequences on today's forest investment profitability: when summing up the physical impacts of climate change (generally -) and the price impact of favorable global macroeconomic conditions (generally ++), expected forest returns for today's investments more than double. In terms of forest profitability, the good news for forest owners is that the increase in international timber prices will likely overcompensate, at least initially, for any increase in mortality or reduction in timber growth rates at temperate French latitudes, leading to an overall doubling of the expected forest returns, especially for broadleaved forests, although coniferous forests remain for many decades more profitable than broadleaved forests (Table B.12).

Due to the long-term nature of forest investments, this sizable effect should already interest today's forest investments, but, in practice, it depends on the capacity of forest owners to anticipate such a long term and unclear change. The assumptions we made on physical impacts, market impacts and the expectations of forest owners, all clearly have an important effect on the current expected value of the forest (Table B.11). As time passes, however, the physical effects of climate change increase, and the expected returns of the forest drop, although only for coniferous species we find expected returns to revert marginally below the ones that we would observe today in the absence of climate change.

4.2 Increasing resources and international timber prices lead to more exports and less imports.

In terms of HWP, due to the increasing worldwide demand and the greater availability of national timber resources, the export of primary products increases, both in absolute terms and in the share of the primary production allocated to exports (from 7.7% in 2015 to 20.3% in 2100). At the same time, the imports of transformed HWP decline, and their share of consumption drops from 20.5% to 13.4%. In the scenario without forest management, coniferous forests resources would dramatically drop, since most new forest regeneration would concern broadleaved species. This implies a lower supply curve for softwood, but its large demand (both domestic and international) would still only marginally reduce the market for softwood, resulting in a very rapid depletion of the resource. In other words, we observe that the actual forest management provides the upstream needs of the HWP markets and removing it would cause a disconnection from the forest resources to the HWP markets.

4.3 The expansion of harvesting wood product markets benefits both producers and consumers.

We now analyse the welfare associated with HWP markets, comparing the situation at the ending period of our simulations with those at the beginning (Tables B.15 and B.16). We expect, despite the negative effects of climate change on mortality and growth, large gains for producers (+88.5% in producers' surplus) but also, in a more limited form, for consumers (+13.6%). The former are driven by increases in global prices, whereas the latter are driven by the larger size of the market[11] Moreover, the former are much more heterogeneous across the country, with traditional exporting regions (e.g., Aquitaine, Lorraine) performing better. Conversely, consumer surplus increases much more homogeneously within the country. These increments don't come as a complete surprise. Already in 2001, Irland et al. stated that "under climate change, the net change in consumer plus producer economic benefits may be positive" for the US forest sector.

5 Climate change mitigation

The forest sector can contribute to climate change mitigation both directly, as a carbon sink in the forest or HWP biomass, or indirectly, as the consumption of HWP substitutes for the emission of carbon-intensive fuels or material. On the other hand, the forest sector generates a limited amount of emissions in terms of forest operations, timber transport, and transformation.

5.1 The relative importance of forest substitution over forest sequestration increases as the timeframe increases.

Fig. 8b plots the simulation of the carbon balance of the forest sector for the next century, where the green area represent the forest carbon stock, the red area the stocks in HWP, and the light blue area the cumulative substitution effect. We stress that the figure returns simple quantitative measures of physical mitigation, but any evaluation of such quantities would have to consider different time values of carbon (due to inter-temporal preferences and varying marginal carbon damage costs) through appropriate discounting (Martin et al., 2011).

In this figure we once again find the same growth but concave pattern that is in Fig. 8a for timber resources, since the two are strongly interconnected. However, while the sequestration balance eventually starts to decline, the fact that substitute emissions can be modelled in a cumulative way (see Lobianco et al., 2016*b*) leads to substitution being more and more important as time passes. Our simulations therefore confirm that, in the debate between the relative importance of sequestration vs. substitution for the forest sectors (see Cowie et al., 2013 for a graphical overview, Miner et al., 2014 for a comprehensive review, or Ter-Mikaelian et al., 2015 for both), it is of fundamental importance to specify the period of time to which we are referring. If a risk of climate threshold behaviour, leading to "abrupt changes", is feared (in the sense of Collins & Knutti, 2003), even the few decades of contributions to the mitigation of climate change that carbon sequestration in forest biomass may bring are of fundamental importance. It is in this light that the emphasis over "removal" methods to mitigate climate change in the Paris agreement should be considered.

Moreover, our results seem to refute an important role for the carbon storage in HWP sinks (as suggested instead by Skog, 2008; Malmsheimer et al., 2011). Despite a substantial increase in the markets, its share in the carbon mitigation balance remains fairly negligible.

5.2 While the forest sector has the potential to counterbalance a significant share of the national carbon emissions, this potential is threatened by climate change and the need to adapt to it. Profit-driven forest management does increase mitigation.

While the forest sector could be important for climate change mitigation, it is at the same time strongly impacted by it. Our results indicate that 30% of the mitigation potential is lost due to the effect of climate change (Table B.17). Significantly, this includes, in addition to the direct effect of climate change (i.e., timber lost by increased tree mortality and lower growth), a component derived from human adaptation. Indeed, in order to maximise forest profitability under the new conditions, forest managers could partially switch from fast-growing coniferous to broadleaved species that generally, having a slower growth, also present a worse carbon mitigation balance.

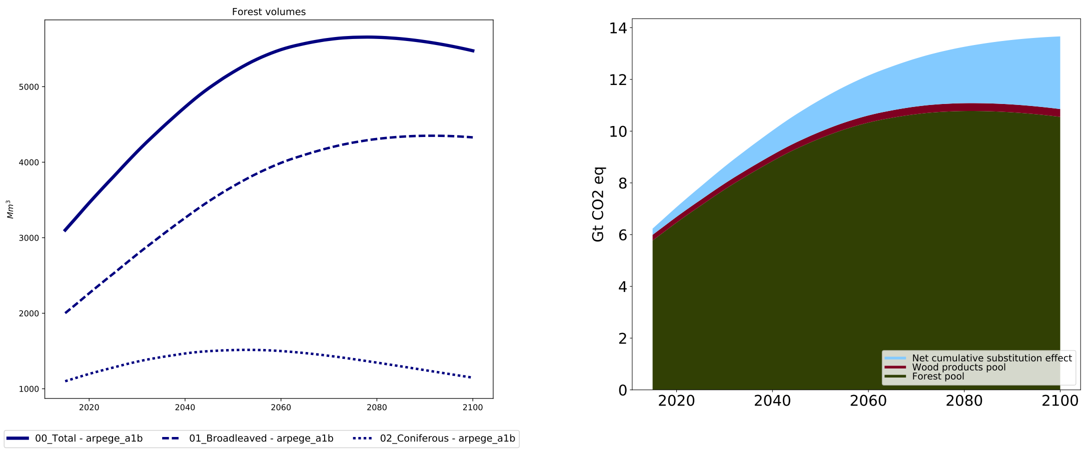
If the need to adapt has a negative impact in terms of mitigation, this is not to say that forest management in itself reduces the forest sector mitigation potential. On the contrary, the driver aimed at maximising timber production leads to a better carbon balance. Table B.18 shows that without forest management, the carbon mitigation balance would be 5% lower as there would be much less fast-growing coniferous forest. That is, even if this "management effect" is reduced by climate change, it remains positive.

Overall considering climate change, forest managers and market adaptations, as well as the decreasing efficiency

[11] We notice that because of the expansion of forest resources (shifting rightward the supply curve) and the imperfect substitutability between local and international timber products, local timber prices at the end of the simulation could remain lower than those at the beginning - leading to increased consumption and larger consumers' surplus - even when international prices are higher.

Figure 8: Dynamics of the forest volumes and carbon balance.

(a) Forest volumes (b) Carbon balance



of forest resources to act as a carbon sink, the model estimates the mitigation capacity of the forest sector in France for the next century to be at least 46.8 Mt CO_2 eq/year. This represents 15.4% of the 2014 French national carbon emissions (as reported in Boden et al., 2017). When we also consider the important but largely uncertain carbon stored in the forest biomass other than the inventoried timber and the substitution effect from using more carbon intensive materials, the forest sector could contribute up to 86.4 Mt CO_2 eq/year. Considering the 2015-2100 timeframe, sequestration is still the prevailing form of mitigation, with 56.5 Mt CO_2 eq/y arising from sequestration and 29.9 Mt CO_2 eq/y from substitution.

6 Uncertainty

While the results given in the previous sections correspond to a single outcome of the tree diagram in Fig. 4, we now assume different climate change intensities and other vegetational and management responses.

6.1 *Uncertainty derived from using different climatic models over the same IPCC storyline has the same order of magnitude as the uncertainty derived from using the same climatic model under different storylines.*

As already observed, these net effects of climate change on forest resources result from multiple chained effects and, in particular, carbon emissions and their effects on climate. Indeed, when we use the same climatic model for different assumptions on carbon emissions (Tables B.9 and B.19), we obtain the same order of magnitude of uncertainty as when we use different climatic models for the same carbon emission storyline (B.10 and B.20). In both cases, the uncertainty for coniferous forests (in terms of area and volume) is higher than those for broadleaved forests, and uncertainty concerning the economic dimension is of a larger order of magnitude, with expected returns from forests showing much wider differences across IPCC scenarios and climatic models than the other variables. In our opinion, this difference between resource and economic uncertainties comes from the inertia of the forest system: forest resource dynamics is much slower than economic dynamics, which makes the impact of uncertainties be smaller.

6.2 *Uncertainty from forest managers' behaviour leads to only minor variations.*

A third source of uncertainty, in addition to climate change intensity and vegetational response, is the type of response of forest managers as the resource changes. We have already seen how a decline in forest management could largely reduce coniferous resources (Table B.8) and mitigation potential (Table B.18). However, the other scenarios that we tested regarding the characteristics of the forest managers (such as risk aversion and degree of expectations toward the future) do not seem to significantly impact the results. The only modification in this set of scenarios is the way that forest managers choose forest investments. To start with, we assume quite large transaction costs in switching between forest types (e.g., due to specific knowledge or input factors required).

This inertia determines smaller variations in regeneration area and volume than those observed in expected returns from the forest. Inertia from forest systems then incurs variations in forest volumes and areas that are only very marginally affected by forest managers' behaviour. Although minimally, the model responds with the correct sign for considering managers without risk aversion (hence, risk-neutral): since risk is defined in the model in terms of the overall mortality, coniferous species are more risky assets, and less risk-averse managers would choose more coniferous species leading to higher carbon pools.

7 Discussion

Given the long payback period of forest investments, forest sector models have become, both for the forest manager and for the public decision-maker, important prospective tools that can provide useful information about the possible dynamic of forest resources and sectors in the long term. For example, Schwarzbauer et al. (2015); Solberg et al. (2017); Kallio et al. (2018); Petucco et al. (2020) are all recent applications of forest sector models on topics as different as (respectively) wood-based energy, biodiversity, forest product markets and forest managers adaptation to forest pathogens. Based on a building set of credible scenarios, depending on the uncertainties, these models can compute market outcomes (production and harvest, consumption, price, international trade, etc.), describe the broad dynamic of forest resources, depending on diverse market conditions, and provide an interface between biological and market outcomes.

The core of the work consists in recognising the cascade of effects and interactions between the various components that has necessarily been modelled in a stylized way. In particular, the approach is subject to the following specific assumptions and limitations:

(a) While forest managers can decide on a management strategy at the time of investment (group of species and type of management, e.g., high forest or coppice), this strategy then remains fixed until final harvesting. We implicitly assume that forest investments are long-term decisions, while the exact moment of harvesting depends on contingent market conditions. Final harvesting itself is then not explicitly endogenous (like in the Faustmann model) but is taken from the timber market module.

(b) Elasticities governing supply and demand functions remain constant over time. This assumption is not to say that actual demand and supply are fixed, but the way producers and consumers react to market signals remains constant within the studied period;

(c) Due to limitations in the available numerical data, only seven forest species, that nevertheless represent a minimum of 50% of the forest resources of each region, are considered for climate change impact. Due to the fact that we relied on inventory data, only inventoried species are simulated. While species migration over the territory can be simulated through shifts in the probabilities of presence, we could not include non-inventoried tree species that could nevertheless be appropriate candidates for future adaptation of forest resources to climate change. While this point (and the related one of genetic adaptation) could relax our results on climate change effects, the long demographic inertia of many forest species vs. the short term of climate change impacts makes the importance of this point still debatable (Vanderwel & Purves, 2014);

(d) Legal restrictions in the conversion of forest land may slow down rent-based land-use changes. In general, land-use is a complex process capturing local and global signals depending on the degree of international integration of the productive sectors at stake. In our study we focus mainly on the immediate and local effects of climate change on land-use in France. Our results should be regarded as possible tendencies and be used accordingly for policy design and impact assessments;

(e) We assume forest area allocation is driven by both (timber) profit maximisation and scenario-based natural competition between forest species, but the weight between these drivers is exogenous and constant at national level. Further, risk aversion and expectation coefficients are sampled from the same distribution nationwide. More work is needed to link actual forest managers behaviours with their characteristics and those of the forest they manage or own (e.g. private/public nature, size of the forest plots, etc..);

(f) Similarly, we consider in this paper only timber production and climate change mitigation, although forest systems provide a wide array of ecosystem services and represent an important support for biodiversity, whose value for the society (but sometimes also for the private owners) may well exceed the timber one. The spatially explicit nature of FFSM may help in defining the envelope of the production possibility set of wood and non-wood goods in forests, following the framework given in Robert (2013);

(g) While the model can account for local variations in forest mortality related to local climatic variations, mortality linked to network effects (e.g. the introduction of a pathogen favoured by the surrounding forests under ecological stress due to climate change) could not be taken into account.

In spite of the above points, the approach provided in this paper allowed us to represent and quantify the loop effect between forest managers' adaptation needs and mitigation. Table B.17 clearly shows that the mitigation potential is already strongly affected by climate change. Even more interesting, this impact on the mitigation potential is not caused by climate change alone but also arises from the necessity of forest managers to adapt to it. Under climate change, forest managers have to partially switch to the more resilient but less productive broadleaved species (hence, reducing the carbon budget). This is an interesting example of the trade-off between the need to adapt to an imminent climate change, on the one hand, and the possibility to mitigate in order to reduce further impacts, on the other.

We expect these kinds of trade-offs to become more and more common and important to investigate, not only in the forest sector, but also in agriculture and other sectors.

Further, this paper shows that, for several economic variables of the French forest sector (timber exports, surpluses, forest profitability, etc.), the global macroeconomic conditions associated with climate change scenarios appear to have potentially positive impacts. This result arises from simultaneously considering both global macroeconomic effects (through an increase in global timber scarcity and hence in international timber prices), local climate change effects (variations in mortality, growth rate and species mix), and adaptation behaviours. We recall however the reader that the exogenous world timber prices we considered in this study (Buongiorno et al., 2012) account only for these macroeconomic drivers (population, incomes, land area,..) in the various climate change scenarios, but not the actual effects of climate change. While global macroeconomic conditions are positive for the timber sector, we still don't know the global level impacts of climate change on the forest sector. We stress the importance of the *relative* level of impacts. We saw that the biophysical impact to the French forests (and, more generally, to temperate forests) could be moderate. If, in relative terms, impacts will be less pronounced than in other parts of the world, or the timber sector will be less affected than other raw material sectors, the French forest sector could benefit in both cases of a relative (geographical or sectorial) advantage. However this remains a sectoral analysis, obtained from a partial equilibrium approach. Climate change is likely to give rise to a multitude of different and intense economic and social repercussions that could put into question forest profitability even in the case of a relative advantage.

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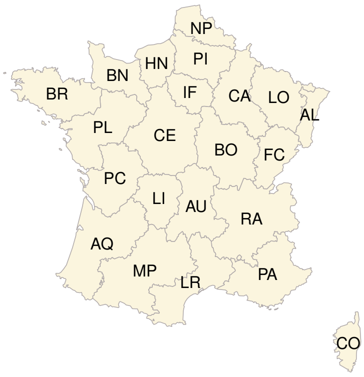
A Case study

Figure A.1: Case study area (France).



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

Table A.1: Definition of the scenarios.

Scenario	C.c. physical impact	C.c. price impact	Forest management	Risk aversion	Expectations	Forest area dynamic
constant	None	None	Included	Considered	Intermediate	Const. climate
constant_nomgm	None	None	Absent	None	None	Const. climate
constant_nora	None	None	Included	None	Intermediate	Const. climate
constant_carea	None	None	Included	Considered	Intermediate	Constant
arpege_a1b	Arpege (a1b)	a1b	Included	Considered	Intermediate	CC (a1b)
arpege_a1b_carea	Arpege (a1b)	a1b	Included	Considered	Intermediate	Constant
arpege_a1b_noexp	Arpege (a1b)	a1b	Included	Considered	None	CC (a1b)
arpege_a1b_fullexp	Arpege (a1b)	a1b	Included	Considered	Complete	CC (a1b)
arpege_a1b_carea_noexp	Arpege (a1b)	a1b	Included	Considered	None	Constant
arpege_a1b_carea_fullexp	Arpege (a1b)	a1b	Included	Considered	Complete	Constant
arpege_a1b_nora	Arpege (a1b)	a1b	Included	None	Intermediate	CC (a1b)
arpege_a1b_nomgm	Arpege (a1b)	a1b	Absent	None	Intermediate	CC (a1b)
arpege_a1b_nopr	Arpege (a1b)	None	Included	Considered	Intermediate	CC (a1b)
arpege_a1b_noph	None	a1b	Included	Considered	Intermediate	CC (a1b)
arpege_a2	Arpege (a2)	a2	Included	Considered	Intermediate	CC (a2)
arpege_b1	Arpege (b1)	b1	Included	Considered	Intermediate	CC (b1)
CNCM33_1	CNCM33_1 (a1b)	a1b	Included	Considered	Intermediate	CC (a1b)
DMIEH5C_1	DMIEH5C_1 (a1b)	a1b	Included	Considered	Intermediate	CC (a1b)
DMIEH5C_2	DMIEH5C_2 (a1b)	a1b	Included	Considered	Intermediate	CC (a1b)
DMIEH5C_3	DMIEH5C_3 (a1b)	a1b	Included	Considered	Intermediate	CC (a1b)
EGMAM2_3	EGMAM2_3 (a1b)	a1b	Included	Considered	Intermediate	CC (a1b)
HADGEM2_1	HADGEM2_1 (a1b)	a1b	Included	Considered	Intermediate	CC (a1b)
IPCM4_1	IPCM4_1 (a1b)	a1b	Included	Considered	Intermediate	CC (a1b)
IPCM4_2	IPCM4_2 (a1b)	a1b	Included	Considered	Intermediate	CC (a1b)
IPCM4_3	IPCM4_3 (a1b)	a1b	Included	Considered	Intermediate	CC (a1b)
MPEH5C_1	MPEH5C_1 (a1b)	a1b	Included	Considered	Intermediate	CC (a1b)
MPEH5C_2	MPEH5C_2 (a1b)	a1b	Included	Considered	Intermediate	CC (a1b)
MPEH5C_3	MPEH5C_3 (a1b)	a1b	Included	Considered	Intermediate	CC (a1b)

"Included" management: 70% of harvested land replanted following timber profit expectations;
"Considered" risk aversion: risk aversion of individual forest manager (avg. mortality vs avg. profitability) sampled from $\mathcal{N}(\mu = 0.8, \sigma = 0.2)$;
"Intermediate" expectations: individual forest manager expectation weight (between observed parameter at time of making decision and exogenous forecasted one for the time of interest) sampled from $\mathcal{N}(\mu = 0.5, \sigma = 0.3)$;
The C.C. physical impact column includes the names of the climatic models and under parhentesis the IPCC storyline over which they are applied. All scenarios use a constant discount rate of 4%.

Further details about the scenario are available in the input file spreadsheet `ffsmInput_oracle.ods` included in the Supplementary Material.

B Result tables

B.1 *Forest response to climate change*

Table B.1: Climate change multipliers and probability of presence (`arpege_a1b`, 2015-2080).

	Prob. presence		**Mort. mult.**			**Tp mult.**		
	Broad	Con	Broad	Con	All forest	Broad	Con	All forest
Avg	0.83	0.17	1.33	2.33	1.83	1.04	1.10	1.07
Max	1.00	0.57	2.33	5.16	5.16	1.18	1.43	1.43
Min	0.43	0.00	0.86	1.00	0.86	0.49	0.91	0.49
SD	0.17	0.17	0.36	1.00	0.90	0.12	0.12	0.12
CV	19.80	100.02	26.96	42.99	49.38	11.19	10.88	11.37
Avg 2015-2040	0.82	0.18	1.12	1.49	1.30	1.02	1.06	1.04
Avg 2040-2060	0.84	0.16	1.33	2.30	1.81	1.04	1.09	1.07
Avg 2060-2080	0.85	0.15	1.55	3.21	2.38	1.07	1.14	1.10

"Broad" refers to broadleaf forests while "Con" refers to coniferous forests.

B.2 *Land-use change*

Table B.2: Parameters used in land use model estimates.

	Dependent variable:		
	ln(agr/oth)	ln(for/oth)	ln(urb/oth)
	(1)	(2)	(3)
Constant	0.857**	0.451	−4.644***
	(0.393)	(0.376)	(0.353)
Agr. shadow price	2.067***	0.373	1.326***
	(0.395)	(0.373)	(0.325)
Forestry returns	0.007***	0.006***	0.009***
	(0.001)	(0.001)	(0.001)
Pop density	−0.0002***	−0.0003***	0.0004***
	(0.0001)	(0.0001)	(0.0001)
Pop revenues	0.070***	0.085***	0.293***
	(0.014)	(0.014)	(0.015)
Slope	−0.197***	−0.020*	−0.229***
	(0.011)	(0.011)	(0.011)
Soil texture cl. 2	0.650***	0.241**	0.412***
	(0.101)	(0.101)	(0.110)
Soil texture cl. 3	1.164***	0.523***	0.782***
	(0.118)	(0.117)	(0.128)
Soil texture cl. 4	1.393***	0.382**	0.461***
	(0.163)	(0.161)	(0.177)
R2	0.647	0.467	0.586
λ	0.801***	0.784***	0.693***
Observations	8,927	8,927	8,927
Log Likelihood	−20,383.440	−20,325.690	−21,226.720
σ^2	4.962	4.936	6.244
Akaike Inf. Crit.	40,788.890	40,673.390	42,475.440
Wald Test (df = 1)	8,290.630***	7,216.702***	4,294.251***
LR Test (df = 1)	4,395.450***	4,074.524***	2,826.322***

Note: *p<0.1; **p<0.05; ***p<0.01

Table B.3: Total forest area forecasted in 2100 by different scenarios and comparison with current area (2006).

	2100 constant	2100 arpege_a1b	2100 arpege_a2	2100 arpege_b1
Mha	14.54	12.40	13.52	12.81
Diff	0.43	-1.70	-0.59	-1.30
Diff %	3.05	-12.08	-4.17	-9.21
Yearly rate	3.2E-4	-1.4E-3	-4.6E-4	-1.0E-3
Max diff pos%	7.35	83.14	120.22	94.86
Max diff neg %	-0.54	-45.68	-37.58	-42.65

B.3 Forest resources

Table B.4: Forest area by region and species group [Mha, *_a1b scenarios].

Reg	2015			2100		
code	Br	Con	Total	Br	Con	Total
AL	0.192	0.115	0.307	0.148	0.056	0.204
AQ	0.713	0.766	1.479	0.657	0.333	0.990
AU	0.385	0.342	0.727	0.388	0.259	0.647
BN	0.115	0.025	0.140	0.090	0.026	0.116
BO	0.828	0.098	0.926	0.744	0.079	0.822
BR	0.189	0.081	0.271	0.161	0.053	0.214
CA	0.590	0.055	0.645	0.423	0.047	0.470
CE	0.753	0.159	0.912	1.019	0.528	1.547
CO	0.205	0.051	0.256	0.203	0.047	0.250
FC	0.524	0.170	0.693	0.458	0.110	0.568
HN	0.192	0.019	0.211	0.131	0.009	0.140
IF	0.249	0.021	0.270	0.198	0.049	0.247
LI	0.380	0.172	0.552	0.337	0.134	0.471
LO	0.603	0.196	0.799	0.495	0.162	0.658
LR	0.572	0.321	0.893	0.541	0.263	0.805
MP	1.037	0.143	1.179	0.949	0.134	1.083
NP	0.084	0.003	0.086	0.083	0.002	0.085
PA	0.443	0.626	1.069	0.482	0.510	0.992
PC	0.299	0.047	0.345	0.209	0.035	0.244
PI	0.298	0.013	0.311	0.248	0.026	0.274
PL	0.180	0.082	0.263	0.142	0.078	0.220
RA	0.871	0.731	1.602	0.874	0.652	1.526
France	9.702	4.234	13.936	8.978	3.593	12.571
%	0.70	0.70		0.71	0.69	

"Broad" refers to broadleaf forests while "Con" refers to coniferous forests.

Table B.5: Forest volumes by region and species group [Mm^3, *_a1b scenarios].

Reg	2015			2100		
code	Br	Con	Total	Br	Con	Total
AL	50.78	39.33	90.11	111.85	50.59	162.45
AQ	158.45	175.53	333.98	385.79	83.56	469.35
AU	99.24	106.17	205.40	270.99	120.95	391.93
BN	27.43	7.67	35.10	26.04	2.37	28.41
BO	181.80	40.58	222.38	427.20	16.51	443.71
BR	56.33	26.58	82.91	145.77	16.51	162.28
CA	121.72	26.14	147.86	135.30	10.78	146.08
CE	154.86	36.46	191.32	407.77	150.21	557.98
CO	27.10	10.92	38.02	45.06	26.93	71.99
FC	121.48	61.10	182.58	292.00	48.80	340.80
HN	43.78	7.11	50.89	47.44	0.57	48.02
IF	46.80	4.16	50.96	46.33	10.16	56.50
LI	90.75	46.17	136.92	126.57	23.15	149.72
LO	144.90	76.38	221.29	266.29	82.90	349.20
LR	61.10	58.49	119.59	102.70	40.81	143.51
MP	187.00	47.50	234.50	545.18	94.79	639.96
NP	24.20	1.60	25.79	57.03	0.39	57.42
PA	58.74	96.79	155.53	122.13	75.20	197.32
PC	58.19	11.76	69.95	100.40	12.93	113.33
PI	52.34	5.92	58.27	17.64	1.69	19.33
PL	47.30	23.50	70.80	88.02	25.04	113.06
RA	183.99	192.62	376.61	616.92	320.49	937.41
France	1,998.27	1,102.48	3,100.76	4,384.41	1,215.34	5,599.75
%	0.64	0.36		0.78	0.22	

"Broad" refers to broadleaf forests while "Con" refers to coniferous forests.

Table B.6: Forecasted forest dynamic [2100 vs. 2015].

	2015 `constant`	2100 `constant`	2100 `arpege_a1b`
Expected returns (€/ha)			
- 00_Total	106.675	-25.17%	8.88%
- 01_Broadleaved	44.387	-29.36%	44.09%
- 02_Coniferous	71.446	-23.20%	-28.46%
Harvested area (ha)			
- 00_Total	35059.234	77.53%	129.30%
- 01_Broadleaved	15401.979	109.05%	196.13%
- 02_Coniferous	19657.255	52.83%	76.93%
Harvested volumes (Mm^3)			
- 00_Total	48.142	10.64%	28.73%
- 01_Broadleaved	24.381	18.10%	54.83%
- 02_Coniferous	23.761	2.99%	1.94%
Regeneration area (ha)			
- 00_Total	39382.798	69.54%	73.12%
- 01_Broadleaved	15995.068	76.78%	125.31%
- 02_Coniferous	23387.729	64.59%	37.43%
Regeneration volumes (Mm^3)			
- 00_Total	2.781	-36.46%	-37.76%
- 01_Broadleaved	2.275	-67.81%	-59.34%
- 02_Coniferous	0.507	104.27%	59.11%
Forest area (ha)			
- 00_Total	14151301.470	2.66%	-11.17%
- 01_Broadleaved	9793475.810	-1.47%	-8.65%
- 02_Coniferous	4357825.660	11.93%	-16.84%
Forest volumes (Mm^3)			
- 00_Total	3107.993	144.26%	76.19%
- 01_Broadleaved	2000.020	178.06%	116.43%
- 02_Coniferous	1107.973	83.25%	3.54%

Table B.7: CC effects by components [yearly avg. 2015-2100].

	constant	arpege_a1b	arpege_a1b_nopr	arpege_a1b_noph
Expected returns (€/ha)				
- 00_Total	87.096	58.35%	-17.71%	91.59%
- 01_Broadleaved	34.930	93.74%	-12.51%	127.16%
- 02_Coniferous	59.265	22.65%	-29.99%	73.70%
Harvested area (ha)				
- 00_Total	51374.200	18.96%	1.97%	17.50%
- 01_Broadleaved	25033.334	24.22%	3.82%	22.71%
- 02_Coniferous	26340.866	13.96%	0.22%	12.54%
Harvested volumes (Mm^3)				
- 00_Total	51.781	12.55%	-1.48%	13.82%
- 01_Broadleaved	27.762	18.59%	1.44%	18.83%
- 02_Coniferous	24.020	5.56%	-4.85%	8.02%
Regeneration area (ha)				
- 00_Total	55799.026	-19.26%	-34.17%	-20.61%
- 01_Broadleaved	23369.989	-4.96%	-30.70%	-17.17%
- 02_Coniferous	32429.037	-29.58%	-36.67%	-23.09%
Regeneration volumes (Mm^3)				
- 00_Total	1.559	-25.37%	-36.25%	-25.59%
- 01_Broadleaved	0.708	-14.63%	-32.12%	-21.47%
- 02_Coniferous	0.851	-34.30%	-39.69%	-29.01%
Forest area [2100] (ha)				
- 00_Total	14527511.250	-13.47%	-13.23%	-13.47%
- 01_Broadleaved	9649832.770	-7.29%	-8.12%	-9.51%
- 02_Coniferous	4877678.480	-25.70%	-23.33%	-21.30%
Forest volumes [2100] (Mm^3)				
- 00_Total	7591.652	-27.87%	-18.43%	-19.49%
- 01_Broadleaved	5561.296	-22.16%	-13.49%	-14.97%
- 02_Coniferous	2030.356	-43.50%	-31.95%	-31.88%

Table B.8: Elements that interact with the change [yearly avg. 2015-2100].

	arpege_a1b	arpege_a1b_nomgm	arpege_a1b_nora	arpege_a1b_noexp	arpege_a1b_fullexp	arpege_a1b_carea
Expected returns (€/*ha*)						
- 00_Total	137.916	0.87%	-0.00%	-25.79%	24.32%	1.56%
- 01_Broadleaved	67.673	0.01%	26.95%	-23.02%	23.83%	3.15%
- 02_Coniferous	72.688	1.75%	22.11%	-28.30%	21.97%	0.82%
Harvested area (*ha*)						
- 00_Total	61114.351	-0.18%	-0.00%	-0.08%	-0.08%	0.28%
- 01_Broadleaved	31096.587	2.29%	-0.07%	-0.20%	-0.03%	-1.44%
- 02_Coniferous	30017.764	-2.73%	0.07%	0.04%	-0.13%	2.06%
Harvested volumes (Mm^3)						
- 00_Total	58.278	-0.58%	0.00%	-0.05%	-0.06%	1.12%
- 01_Broadleaved	32.923	1.85%	-0.01%	-0.14%	-0.00%	-0.66%
- 02_Coniferous	25.355	-3.74%	0.03%	0.06%	-0.13%	3.43%
Regeneration area (*ha*)						
- 00_Total	45049.543	-0.26%	-0.00%	-0.10%	-0.10%	36.04%
- 01_Broadleaved	22211.708	69.10%	1.88%	-0.39%	2.74%	39.77%
- 02_Coniferous	22837.835	-67.72%	-1.83%	0.19%	-2.86%	32.40%
Regeneration volumes (Mm^3)						
- 00_Total	1.163	-7.78%	0.59%	-0.07%	0.19%	39.94%
- 01_Broadleaved	0.604	47.74%	2.38%	-0.44%	3.21%	40.00%
- 02_Coniferous	0.559	-67.81%	-1.35%	0.33%	-3.08%	39.87%
Forest area [2100] (*ha*)						
- 00_Total	12570776.470	-0.01%	0.00%	0.00%	0.00%	12.23%
- 01_Broadleaved	8946601.380	14.80%	0.43%	-0.03%	0.61%	9.72%
- 02_Coniferous	3624175.090	-36.56%	-1.06%	0.07%	-1.50%	18.43%
Forest volumes [2100] (Mm^3)						
- 00_Total	5475.869	-4.32%	0.07%	-0.06%	0.06%	9.22%
- 01_Broadleaved	4328.712	1.02%	0.18%	-0.28%	0.11%	6.06%
- 02_Coniferous	1147.157	-24.47%	-0.37%	0.77%	-0.14%	21.16%

Table B.9: Uncertainly from IPCC scenario [yearly avg. 2015-2100].

	constant	arpege_* scenarios	difference	cv
Expected returns (€/*ha*)				
- 00_Total	87.096	105.762	18.666 (21.432%)	26.42 %
- 01_Broadleaved	34.930	49.454	14.524 (41.580%)	31.91 %
- 02_Coniferous	59.265	58.489	-0.777 (-1.311%)	21.90 %
Harvested area (*ha*)				
- 00_Total	51374.200	57097.614	5723.414 (11.141%)	6.10 %
- 01_Broadleaved	25033.334	28628.618	3595.283 (14.362%)	7.49 %
- 02_Coniferous	26340.866	28468.996	2128.131 (8.079%)	4.72 %
Harvested volumes (Mm^3)				
- 00_Total	51.781	54.869	3.088 (5.963%)	5.38 %
- 01_Broadleaved	27.762	30.632	2.870 (10.337%)	6.48 %
- 02_Coniferous	24.020	24.238	0.218 (0.908%)	4.00 %
Regeneration area (*ha*)				
- 00_Total	55799.026	46028.702	-9770.324 (-17.510%)	7.46 %
- 01_Broadleaved	23369.989	21743.233	-1626.756 (-6.961%)	14.30 %
- 02_Coniferous	32429.037	24285.469	-8143.568[a] (-25.112%)	5.26 %
Regeneration volumes (Mm^3)				
- 00_Total	1.559	1.209	-0.350 (-22.455%)	7.48 %
- 01_Broadleaved	0.708	0.602	-0.106 (-14.933%)	10.31 %
- 02_Coniferous	0.851	0.607	-0.244 (-28.715%)	7.50 %
Forest area [2100] (*ha*)				
- 00_Total	14527511.250	13032272.370	-1495238.880 (-10.292%)	3.98 %
- 01_Broadleaved	9649832.770	9130549.003	-519283.767 (-5.381%)	3.62 %
- 02_Coniferous	4877678.480	3901723.367	-975955.113 (-20.009%)	6.25 %
Forest volumes [2100] (Mm^3)				
- 00_Total	7591.652	5915.561	-1676.091 (-22.078%)	6.47 %
- 01_Broadleaved	5561.296	4603.461	-957.835 (-17.223%)	5.22 %
- 02_Coniferous	2030.356	1312.100	-718.256 (-35.376%)	10.90 %

Table B.10: Uncertainly from climatic model [yearly avg. 2015-2100].

	constant	*_a1b scenarios	difference	cv
Expected returns (€/ha)				
- 00_Total	87.096	155.156	68.060^b (78.143%)	6.55 %
- 01_Broadleaved	34.930	71.244	36.314^b (103.963%)	4.12 %
- 02_Coniferous	59.265	86.648	27.382^b (46.203%)	10.60 %
Harvested area (ha)				
- 00_Total	51374.200	61255.407	9881.207^b (19.234%)	0.58 %
- 01_Broadleaved	25033.334	30998.376	5965.042^b (23.828%)	0.57 %
- 02_Coniferous	26340.866	30257.031	3916.165^b (14.867%)	0.81 %
Harvested volumes (Mm^3)				
- 00_Total	51.781	58.430	6.648^b (12.839%)	0.47 %
- 01_Broadleaved	27.762	32.827	5.065^b (18.245%)	0.31 %
- 02_Coniferous	24.020	25.602	1.583^b (6.590%)	1.10 %
Regeneration area (ha)				
- 00_Total	55799.026	45195.930	-10603.095^b (-19.002%)	0.77 %
- 01_Broadleaved	23369.989	22481.725	-888.264 (-3.801%)	5.17 %
- 02_Coniferous	32429.037	22714.205	-9714.831^b (-29.957%)	4.28 %
Regeneration volumes (Mm^3)				
- 00_Total	1.559	1.164	-0.395^b (-25.338%)	0.42 %
- 01_Broadleaved	0.708	0.605	-0.103^b (-14.490%)	3.59 %
- 02_Coniferous	0.851	0.558	-0.292^b (-34.366%)	3.64 %
Forest area [2100] (ha)				
- 00_Total	14527511.250	12571233.817	-1956277.433^b (-13.466%)	0.01 %
- 01_Broadleaved	9649832.770	8977909.754	-671923.016^b (-6.963%)	1.03 %
- 02_Coniferous	4877678.480	3593324.063	-1284354.417^b (-26.331%)	2.56 %
Forest volumes [2100] (Mm^3)				
- 00_Total	7591.652	5599.750	-1991.902^b (-26.238%)	3.05 %
- 01_Broadleaved	5561.296	4384.406	-1176.890^b (-21.162%)	2.40 %
- 02_Coniferous	2030.356	1215.344	-815.012^b (-40.141%)	5.51 %

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

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

Table B.11: Effect of different assumptions on today [2015] forest profitability.

	constant	arpege_a1b	arpege_a1b_nopr	arpege_a1b_noph	arpege_a1b_noexp	arpege_a1b_fullexp
Expected returns (€/ha)						
- 00_Total	106.675	+109.30%	-10.38%	+129.96%	-6.16%	+217.58%
- 01_Broadleaved	44.387	+131.31%	-5.53%	+143.33%	+3.39%	+248.24%
- 02_Coniferous	71.446	+87.38%	-17.62%	+124.43%	-14.51%	+176.03%

Table B.12: Regional distribution of climate change effects on today's expected forest returns [€/ha, 2015].

spGroup scenGroup region	All forest *_a1b	 constant	Broadleaved *_a1b	 constant	Coniferous *_a1b	 constant
AL	307.87	128.84	139.54	65.21	211.31	83.07
AQ	190.96	98.16	76.02	38.72	126.47	69.25
AU	216.75	104.97	80.21	34.08	140.33	74.05
BN	387.65	208.30	159.16	80.10	245.43	144.80
BO	314.96	176.36	125.38	49.53	221.36	141.44
BR	268.64	124.65	117.50	58.81	172.93	84.16
CA	493.27	226.65	242.10	97.41	382.42	183.52
CE	176.52	85.28	42.33	20.74	152.81	76.41
CO	393.33	91.83	207.49	26.34	78.09	58.94
FC	270.29	102.05	182.91	73.50	116.46	39.84
HN	380.74	202.23	212.23	110.25	204.73	123.40
IF	203.31	99.74	32.49	18.02	159.00	81.80
LI	177.24	87.70	63.69	29.40	134.09	70.20
LO	247.24	102.03	160.54	69.78	148.50	59.02
LR	67.81	26.04	23.16	8.72	24.18	9.81
MP	226.21	90.55	65.05	27.58	174.21	68.91
NP	451.71	231.96	351.51	170.32	63.40	48.74
PA	128.83	40.38	80.60	23.30	22.54	8.29
PC	200.40	102.66	23.53	12.35	180.96	94.97
PI	554.99	311.24	406.86	206.85	196.92	140.28
PL	356.93	169.51	136.39	66.17	310.03	149.38
RA	154.75	66.53	46.53	21.54	79.04	33.36
France	232.38	106.67	102.92	44.39	143.08	71.45

Table B.13: Dynamics of expected forest returns [€/ha, a1b scenarios].

year spGroup	2015	2040	2060	2080	2100
All forest	232.38	154.25	128.12	139.06	141.20
Broadleaved	102.92	63.11	61.72	71.37	70.60
Coniferous	143.08	94.69	68.27	66.82	68.94

B.4 HWP Markets

Table B.14: Market balance of HWP [Mm^3, a1b scenarios].

	2015			2100		
	Prim. Products	Transf. Products	Total	Prim. Products	Transf. Products	Total
Production	48.20	39.41	87.61	62.36	43.49	105.86
Imports	0.00	10.13	10.13	0.00	6.74	6.74
Total Supply	48.20	49.54	97.74	62.36	50.24	112.60
Consumption	50.23	49.54	99.77	56.18	50.24	106.42
Exports	3.69	0.00	3.69	12.66	0.00	12.66
Total Demand	53.92	49.54	103.46	68.84	50.24	119.07
Regional trade	3.35	11.99	15.35	3.22	13.66	16.88
Producer price (e/m^3)	36.61	120.07	.	54.13	132.86	.
Local price (e/m^3)	37.75	132.90	.	32.02	121.60	.

Notice: Balance in the table doesn't close (total supply doesn't equal total demand) as the by-product production of industrial wood is not included in the supply figures.

Table B.15: Economic surplus by region [M€, *_a1b scenarios].

	Producer surplus			Consumer surplus			Total surplus		
	2015	2100	% Diff	2015	2100	% Diff	2015	2100	% Diff
AL	24.00	71.13	196.43	111.29	125.88	13.11	135.29	197.01	45.62
AQ	68.79	195.64	184.39	178.35	204.98	14.93	247.14	400.62	62.10
AU	33.61	77.34	130.10	73.25	82.83	13.09	106.86	160.17	49.89
BN	21.91	26.37	20.35	82.20	94.28	14.70	104.11	120.65	15.89
BO	59.36	120.07	102.26	95.05	107.41	13.01	154.41	227.48	47.32
BR	37.75	52.21	38.30	193.86	221.64	14.33	231.61	273.84	18.23
CA	69.11	92.17	33.36	84.41	95.97	13.70	153.52	188.14	22.55
CE	54.54	129.49	137.43	153.49	172.24	12.21	208.03	301.73	45.04
CO	3.35	5.00	49.26	16.08	17.85	10.98	19.43	22.85	17.58
FC	47.18	116.39	146.69	64.05	72.12	12.60	111.23	188.51	69.47
HN	30.42	40.94	34.59	116.63	134.04	14.92	147.05	174.97	18.99
IF	25.67	31.09	21.10	1,285.70	1,453.42	13.05	1,311.37	1,484.51	13.20
LI	39.43	78.64	99.42	39.28	45.21	15.11	78.71	123.85	57.35
LO	67.41	148.44	120.20	125.17	141.37	12.94	192.58	289.81	50.49
LR	23.47	36.71	56.37	131.79	149.83	13.69	155.26	186.53	20.14
MP	36.02	99.50	176.23	167.96	188.58	12.28	203.98	288.07	41.23
NP	14.00	25.80	84.33	132.52	150.55	13.60	146.52	176.35	20.36
PA	56.13	74.87	33.40	322.09	364.15	13.06	378.22	439.03	16.08
PC	18.25	39.02	113.82	95.67	109.14	14.08	113.92	148.16	30.06
PI	57.51	43.73	-23.95	105.04	120.83	15.04	162.55	164.57	1.24
PL	39.29	61.05	55.38	218.72	249.58	14.11	258.01	310.63	20.40
RA	79.78	142.42	78.51	424.74	476.39	12.16	504.52	618.81	22.65
France	906.99	1,708.01	88.32	4,217.35	4,778.31	13.30	5,124.34	6,486.32	26.58

Table B.16: Economic surplus by scenario [M€].

	Producers surplus		Consumers surplus		Total surplus	
year	2015	2100	2015	2100	2015	2100
scen						
arpege_a1b	907	1,710	4,217	4,791	5,124	6,501
arpege_a1b_noph	906	1,733	4,217	4,753	5,123	6,486
arpege_a1b_nopr	905	811	4,222	4,146	5,127	4,957
constant	904	759	4,221	4,089	5,125	4,848

B.5 Climate change mitigation

Table B.17: CO_2 balance [yearly avg. 2015-2100].

	constant	arpege_a1b
Carbon balance (Mt $CO_2eq.$ y^{-1})		
Pools		
- Inventoried forest pool	52.544	-43.87%
- Extra forest pool (branches and roots)	41.961	-37.83%
- Wood products pool	0.304	214.36%
- Total pools	94.810	-40.37%
Emissions		
- Energy substitution	13.599	-0.81%
- Material substitution	15.159	10.97%
- Emissions from forest operations	-0.395	12.10%
- Net substitution	28.362	5.31%
Total CO_2 balance	123.172	-29.85%

Table B.18: CO_2 balance by forest system assumptions [yearly avg. 2015-2100, all arpege_a1b based scenarios].

	arpege_a1b	_nomgm	_nora	_noexp	_fullexp	_carea
Carbon balance (Mt $CO_2eq.$ y^{-1})						
Pools						
- Inventoried forest pool	29.491	-8.00%	0.20%	-0.13%	0.18%	19.39%
- Extra forest pool (branches and roots)	26.087	-6.34%	0.17%	-0.16%	0.14%	16.27%
- Wood products pool	0.957	-7.34%	0.03%	-0.23%	-0.34%	11.38%
- Total pools	56.535	-7.22%	0.18%	-0.15%	0.15%	17.82%
Emissions						
- Energy substitution	13.489	-0.21%	0.00%	-0.04%	-0.04%	0.43%
- Material substitution	16.822	-0.91%	0.00%	-0.03%	-0.05%	1.33%
- Emissions from forest operations	-0.443	-0.09%	-0.01%	0.03%	0.02%	0.80%
- Net substitution	29.868	-0.60%	0.00%	-0.04%	-0.05%	0.94%
Total CO_2 balance	86.403	-4.94%	0.12%	-0.11%	0.08%	11.98%

Table B.19: CO_2 balance for different IPCC storylines [yearly avg. 2015-2100, arpege climatic model].

	`constant`	`arpege_* scenarios`	difference	cv
Carbon balance (Mt $CO_2eq.$ y^{-1})				
Pools				
- Inventoried forest pool	52.544	34.522	-18.022 (-34.299%)	12.73 %
- Extra forest pool (branches and roots)	41.961	29.189	-12.772 (-30.439%)	9.27 %
- Wood products pool	0.304	0.607	0.303 (99.542%)	49.83 %
- Total pools	94.810	64.318	-30.492 (-32.161%)	10.57 %
Emissions				
- Energy substitution	13.599	13.485	-0.114[a] (-0.836%)	0.10 %
- Material substitution	15.159	15.870	0.711 (4.693%)	5.20 %
- Emissions from forest operations	-0.395	-0.419	-0.023 (5.880%)	5.09 %
- Net substitution	28.362	28.937	0.574 (2.025%)	2.79 %
Total CO_2 balance	123.172	93.255	-29.917 (-24.289%)	6.44 %

Table B.20: CO_2 balance for different climatic models [yearly avg. 2015-2100, a1b].

	`constant`	`*_a1b scenarios`	difference	cv
Carbon balance (Mt $CO_2 eq.$ y^{-1})				
Pools				
- Inventoried forest pool	52.544	31.050	-21.494^b (-40.907%)	5.85 %
- Extra forest pool (branches and roots)	41.961	27.173	-14.788^b (-35.243%)	5.10 %
- Wood products pool	0.304	0.982	0.677^b (222.522%)	2.94 %
- Total pools	94.810	59.204	-35.605^b (-37.555%)	5.46 %
Emissions				
- Energy substitution	13.599	13.501	-0.098^b (-0.720%)	0.27 %
- Material substitution	15.159	16.888	1.729^b (11.406%)	0.50 %
- Emissions from forest operations	-0.395	-0.444	-0.048^b (12.242%)	0.16 %
- Net substitution	28.362	29.945	1.583^b (5.580%)	0.40 %
Total CO_2 balance	123.172	89.149	-34.023^b (-27.622%)	3.75 %

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

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

C Supplementary Material

This article is accompanied by the following supplementary material that can be found, in the online version, at [[FINAL DOI OF THE ARTICLE]]]:

Input data and replication information

This archive contains, on the one hand, the complete set of files used to run the scenarios presented in the paper. On the other hand, it contains the instructions for transforming these data into those used as input by the model.

The main file containing settings and data is an OpenDocument spreadsheet (" `ffsmInput.ods`").

Spatial data are included in the `gis` folder.

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.

Detailed model documentation

A much more in-depth documentation of the model in the form of a PDF directly generated from the annotated source code using the Doxygen documentation tool.

Complete model output

A (large) collection of files containing the detailed output of the model for each French region. Raw output results from Forest Dynamic, Market and Carbon Modules are available in the "results" folders. Spatialised results are given in folder "maps". The archive also contains the scripts used to analyse these results.