Earth's Future

RESEARCH ARTICLE

10.1029/2021EF002433

A Bioeconomic Projection of Climate-Induced Wildfire Risk in the Forest Sector

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Key Points:

- Models project an intensification of wildfire regimes in southern France, losses of forest resources and carbon, disturbances to forestry
- Uncertainty in projections is dominated by annual fluctuations for wildfire activity, by choice of climate model/scenario for forestry
- Prospective bioeconomic assessments need to consider multiple possible futures but also stochasticity intrinsic to disturbance processes

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Riviere, M., Pimont, F., Delacote, P., Caurla, S., Ruffault, J., Lobianco, A., et al. (2022). A bioeconomic projection of climate-induced wildfire risk in the forest sector. *Earth's Future*, *10*, e2021EF002433. https://doi.org/10.1029/2021EF002433

Received 14 OCT 2021
Accepted 5 APR 2022

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Abstract Under the influence of climate change, wildfire regimes are expected to intensify and expand to new areas, increasing threats to natural and socioeconomic assets. We explore the environmental and economic implications for the forest sector of climate-induced changes in wildfire regimes. To retain genericity while considering local determinants, we focus on the regional level and take Mediterranean France as an example. Coupling a bioeconomic forest sector model and a model of wildfire activity, we perform spatially explicit simulations under various levels of radiative forcing. By using a probabilistic framework, we also assess the propagation of several sources of uncertainty to the forest sector, considering both climate-induced uncertainty and the intrinsic stochasticity of the fire process. By the end of the century, summer burned areas increase by up to 55%, causing moderate losses of merchantable timber and forest carbon stocks, with cascading impacts for industrial activities and climate mitigation in the forest sector. Implications for industries remain limited, but we observe price increases, especially for softwoods, as well as spatially differentiated changes in producer welfare. Inter-annual fluctuations explain most of uncertainty in wildfire activity, but their impacts on the forest sector are quickly dampened. Over time, owing to the cumulative nature of wildfire impacts on forest resources, uncertainty related to climate warming, climate models' response and stochasticity intrinsic to the wildfire phenomenon strongly increase in relative importance. Results reassert the need to consider multiple futures in prospective assessments, including uncertainty inherent to natural processes, often omitted in large-scale economic assessments.

Plain Language Summary Forest fires in the Mediterranean are expected to become more numerous, more intense, and to reach new areas due to climate change. Forest resources, carbon sequestrated in forests, as well as economic activities related to forestry, are threatened by this evolution. This article focuses on Southern France and uses large-scale model simulations to explore these dynamics. We show that burned areas in forests may increase by more than half by 2100, leading to a decrease in forest resources (timber) by up to 5%. Besides, prices for wood products may increase, especially for softwoods, with implications for the welfare of timber producers and consumers. Moreover, these results are heterogenous across space, and areas to the south and to the west are more gravely affected. However, these trends come with relatively large uncertainties. We show that uncertainties concerning the evolution of forest fires themselves are largely due to annual variability in weather conditions. On the contrary, uncertainties concerning economic activity in forestry are mostly due to the unknown future evolution of greenhouse gas emissions and to differences in climate models functioning. Our results reassert the need to consider several possible sources of uncertainty in long-term prospective assessments.

1. Introduction

Anthropogenic climate change poses a threat to ecosystems and societies worldwide, prompting commitments to stringent mitigation and adaptation objectives (IPCC, 2021; UNFCCC, 2015). The forest sector, which encompasses forest resources, forestry activities and timber industries and trade, plays a key role in addressing it, and management activities and wood uses can be leveraged to remove carbon from the atmosphere, store it in biomass and products, or to generate avoided emissions by substituting for carbon intensive products (Austin et al., 2020; Favero et al., 2020; Nabuurs et al., 2017). However, climate change is expected to affect the forest sector through changes in tree mortality and growth, species distribution and multiple natural hazard risks (Lindner et al., 2010a;

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Reyer et al., 2014; Seidl et al., 2017; Taccoen et al., 2019), with cascading implications for economic activity and the provision of ecosystem services (Hanewinkel et al., 2013; Keenan, 2015; Le Page et al., 2013).

Wildfires, or forest fires, are a disturbance whose frequency, size, severity and seasonality (or fire regime) are affected by climate change. In Europe, the Mediterranean basin is a particularly fire-prone area (Keeley et al., 2011). In this region, most fires are human-caused (Ganteaume et al., 2013), and changes in land-use patterns have led to increases in fire activity in some regions (Moreira et al., 2011; Pausas & Fernández-Muñoz, 2012), prompting improvements in fire prevention and suppression (Ruffault et al., 2015). In past decades, fire-prone weather conditions have become more frequent (Barbero et al., 2020; Fréjaville & Curt, 2015; Ruffault et al., 2013; Turco et al., 2014; Venäläinen et al., 2014), a trend which is expected to continue (IPCC, 2021), resulting in fire activity emerging from its historical range (Abatzoglou et al., 2019; Fargeon et al., 2020). In particular, fire regimes are expected to worsen, with more common extreme fires (Ruffault et al., 2020), a longer fire season and a northward expansion of fire-prone areas (Dupuy et al., 2020). While wildfires are part of natural processes (Pausas & Keeley, 2019), they can adversely affect environmental, social and economic assets (Gill et al., 2013). In the case of the forest sector, wildfires have direct impacts on its primary resource, timber, and implications for forestry activities, timber industries and other forest-related activities (e.g., tourism, agriculture). In addition, wildfires bring risks of non-permanence for carbon stocks, threatening the forest sector's climate mitigation potential (Seidl et al., 2014).

Assessing these multiple implications requires performing integrated assessments, that is, assessments that consider multiple natural, economic and technological processes and mobilize several disciplines (e.g., economics and ecology). Wildfire modeling has made significant advancements over the last years at the forest (Pimont et al., 2016), landscape (Ager et al., 2018) and continental scales (Hantson et al., 2016). In forest economics, a large literature exists on disturbance risks (Montagné-Huck & Brunette, 2018), including wildfires (e.g., Couture & Reynaud, 2011). Most of these studies concern the stand or property level, such as Daigneault et al. (2010), who use a stochastic dynamic profit maximization model to demonstrate the interest of leveraging thinning activities and rotation length to mitigate wildfire risk. Al Abri and Grogan (2019, 2021) furthered this literature by considering recent fire history and expanding to the case of two adjacent and heterogeneous forest owners using a game interaction framework. They highlighted, among others, the existence of free riding behaviors with regards to fuel management and the importance of considering landowners' interests when designing incentives. At the sectoral scale, further integration can be provided by using forest sector models, i.e., large-scale simulation models that encompass the whole value chain from forest resources to timber industries (Latta et al., 2013; Riviere & Caurla, 2020a). Forest sector models have been largely used to assess the forest sector's potential to mitigate climate change (e.g., Favero et al., 2020; Lauri et al., 2014; Riviere & Caurla, 2020b), but comparatively less studies have been dedicated to assessing the impacts of climate change. Most of these assessments focus on the global scale (Favero et al., 2018; Sohngen et al., 2001; Tian et al., 2016), which impedes taking into account local specificities on which many disturbance processes depend. A recent exception is the national study by Delacote, Caurla and Riviere (2021), but disturbances were not addressed. Besides, natural disturbances have mostly been studied through the lens of the economic costs of prevention and recovery measures (Caurla et al., 2015; Niquidet et al., 2012; Prestemon et al., 2008) and remain a marginal topic in the forest sector modeling literature (Riviere et al., 2020). More generally, assessments of risks in forest sector modeling remain a challenge, largely owing to the models' complexity and their deterministic nature (Chudy et al., 2016) that is neither suited to take into account stochastic events nor to quantify how uncertainty from climate projections spreads along the modeling chain. Yet, integrating disturbance phenomena in large-scale models is necessary given the policy needs for model-based prospective analyses (Ohrel, 2019; Riviere & Caurla, 2020a).

This paper aims to fill this gap and assesses the impacts of climate-induced changes in wildfire regimes on the forest sector, taking into account feedbacks between resources, management and industries. Our objective is twofold. First, from a policy perspective, we assess economic and environmental implications, considering impacts on timber resources, implications for forestry activities and downstream industries as well as risks of non-permanence of carbon stocks. Second, from a methodological perspective, we assess how several sources of climate-induced and fire-induced uncertainties affect projections made with a large-scale bio-economic forest model to which we add a probabilistic component for fire activity. To keep a certain level of genericity while taking into account the local context, we focus on the regional scale and take the example of Southern France (Figure 1). To reach these objectives, we establish a soft-link between a bio-economic model of the forest sector

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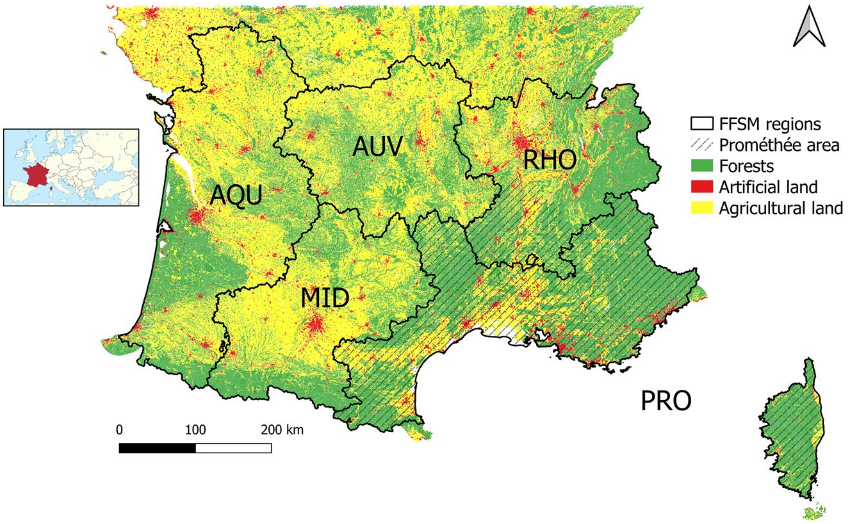

Figure 1. Map of the study area. Regions correspond to those of the FFSM model. The Prométhée area corresponds to the land covered by the fire observation database of the same name, active since 1973.

(Lobianco et al., 2015; Lobianco, Delcote, et al., 2016) and a probabilistic model of wildfire activity (Pimont et al., 2021), and perform stochastic simulations using different climate models and radiative forcing scenarios, hence considering several sources of uncertainty. We present results in several steps, first focusing on fire activity and dynamics in the forest sector, and then on the propagation of uncertainty throughout the modeled system. We finally discuss key implications for forest policy and potential avenues for future research.

2. Materials and Methods

2.1. Study Area

Our study area consists of the southern half of Metropolitan France (hereafter *Southern France,* Figure 1), where forests cover 7.9 million hectares of land (29.8%), while agriculture, and urban and other artificial land uses, represent 48.6% and 5.1% respectively. Major forested areas include the mountainous Alps, Pyrenees and Massif Central regions, Mediterranean lowlands, and the Landes massif to the west, mostly composed of monospecific *Pinus pinaster* plantations.

The study area was chosen for its important wildfire activity. Over the last 10 years, an average of 8,775 ha has burned annually, with the South-Eastern corner (*Prométhée* on Figure 1) representing 78% of it. Most fires are human-caused and are particularly numerous close to infrastructure and population centers (Ganteaume et al., 2013). Even though burned areas have decreased since the 1990s due to changes in prevention measures (Ruffault et al., 2015), wildfire activity is expected to increase in the decades to come under the influence of global warming, reaching areas little affected so far (Chatry, 2010; Dupuy et al., 2020; Fargeon et al., 2020). Stakes are particularly high. First, Southern France accounts for approximately half of national timber harvests—60% of softwoods—and there is a high concentration of timber industries, in particular paper mills and panel manufacturers (FCBA, 2020). Second, it comprises standing timber inventories of 1,421 million cubic meters and concentrates half of national annual increment (IGN, 2019). The high prevalence of wildfires relatively to northern France makes risks of non-permanence for carbon stocks significant, potentially jeopardizing the sector's climate mitigation potential. Third, tourism is an important economic sector, especially during the summer, and Southern France comprises 37 natural parks, which also concentrate valuable forest habitats and biodiversity. Fourth, the area comprises several mountain ranges where forests provide regulation services such as erosion and flood control.

2.2. Fire Modeling

We simulate wildfires using Firelihood, a probabilistic model of wildfire activity developed for Southern France (Fargeon, 2019; Pimont et al., 2021). Firelihood models summer wildfire activity (May 15th to October 31st, largely dominant in Southern France) for fires larger than 1 ha daily at the scale of 8 km pixels through two hierarchically structured components: fire occurrence, which accounts for fire ignition and spread to 1 ha, and fire size, which accounts for spread beyond 1 ha.

1. Fire occurrence is modeled as a spatio-temporal Poisson point process (where the points represent locations and times of ignition) using two predictors: the Fire Weather Index (FWI, Van Wagner, 1987) and wildland area, computed as the sum of land area belonging to forest and shrubland classes in the Corine Landcover Classification (CLC, classes 31 and 322–324; CORINE Land Cover, 2018). Two random effects account for unexplained variability in fire activity from a temporal and spatial perspective, using week numbers and pixel coordinates as predictors. This Poisson process does not take local fire history into account but, due to the generally very low occurrence probability of a wildfire for a given pixel and to the generally small size of wildfires in the study region, the model-based simulations only very rarely generate situations that are not realistic with respect to the recent local fire history.
2. Fire size is modeled using a piecewise fire size distribution with three size thresholds (10, 100, and 1.000 ha), using power law distributions for the first 3 segments and a generalized Pareto distribution for the last segment. This last distribution allows to account for a finite maximum fire size estimated conditional on the predictors. For each threshold, exceedance probability (i.e., the probability that a given fire will be larger than the threshold) is modeled using separate logistic regression models. All models of size distribution and exceedance thresholds use FWI and wildland area as predictors

Firelihood is estimated in a Bayesian framework using the Integrated Nested Laplace Approximation (INLA) implemented in the R software (Lindgren & Rue, 2015), using fire observations from the Prométhée database (Prométhée, 2020) for the 1995–2015 period, while data for 2015–2018 is retained for model evaluation. The FWI is computed with weather data from the Safran reanalysis (Vidal et al., 2010) following the procedure in (Bedia et al., 2014). The fire occurrence and fire size sub-models of Firelihood can then be used in a hierarchical manner to simulate daily fire activity by first simulating fire count and subsequently attributing a size to each fire. The model being probabilistic, each simulation of Firelihood will yield different results, that is, "likely" scenarios of fire activity. The general structure of Firelihood is available in supplementary materials and detailed information on model estimation and validation is available in Fargeon (2019) and Pimont et al. (2021). While Firelihood was initially developed and validated over southeastern France (*Promethée* area in Figure 1), Fargeon (2019) showed that it could be extrapolated to all of Southern France with reasonable accuracy thanks to comparisons with the observations from the French national database on wildfire observations (BDIFF; https://bdiff.agriculture.gouv.fr/), which we also report in supplementary material.

2.3. Forest Sector Modeling

Forest sector dynamics are simulated using the French Forest Sector Model (FFSM), a bio-economic numerical simulation model of French forestry and timber industries (Caurla et al., 2010; Lobianco et al., 2015; Lobianco, Delcote, et al., 2016) previously used to assess forests' climate mitigation potential through bioenergy production, carbon sequestration and land-use dynamics (e.g., Caurla et al., 2013, 2018; Delacote, Lobianco, et al., 2021; Riviere & Caurla, 2020b). The FFSM is recursive, uses yearly time steps and comprises 4 sub-models.

1. First, forest resources are represented as timber volumes in a matrix-based inventory model across 6 forest types, 13 diameters classes and 8.500 8-km pixels. This is calibrated from National Forest Inventory data and growth and mortality rates are set to be heterogeneous across pixels (Lobianco et al., 2015; Wernsdörfer et al., 2012).
2. Second, timber markets are represented in a spatial price equilibrium framework (Samuelson, 1952) where supply (harvests), demand, prices and trade are modeled for 9 products across 12 French regions and one world region (Caurla et al., 2010). Timber processing is represented as a set of input-output processes, and equilibrium is found by maximizing total economic surplus net of transportation and processing costs under a set of constraints as a mathematical programming problem.

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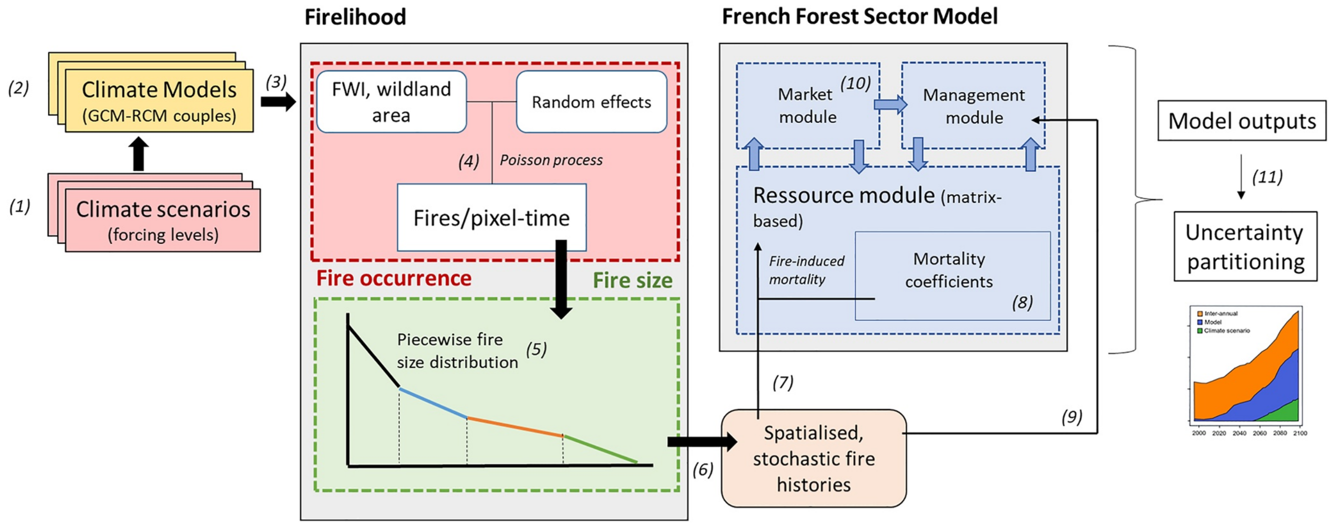

Figure 2. Illustration of the coupling framework. From left to right: simulation data from several GCM-RCM pairs (2) under various levels of radiative forcing (1) are used to drive Firelihood (3). Individual fires larger than 1 ha are simulated in a 8 km pixel grid in a hierarchical process where fire occurrence (4), fire size classes and burned areas (5) are computed daily, and several stochastic replications are carried out (6). Areas burned are distributed to the forest types of the FFSM proportionately to their fraction of forest area cover in pixels (7). Fire-induced mortality is computed using mortality coefficients (8), and fires also impact the forest sector through owners' anticipations of future fires (9) and impacts on product prices (10). Model outputs are used to partition different sources of uncertainty (11).

3. Third, forest owners' management decisions are determined by maximizing Land Expectation Value following Faustmann's (1849) model for optimal harvest scheduling, implemented at the pixel level (Lobianco, Delacote, et al., 2016), also enabling the determination of expected revenues for owners.
4. Fourth, carbon contents in forest biomass and timber products are tracked in a bookkeeping carbon registry using carbon content ratios, where dead biomass and wood products undergo exponential decay processes (Lobianco, Caurla, et al., 2016).

2.4. Soft-Coupling Between the Models and Scenarios

We establish a soft-coupling where outputs from Firelihood are used as inputs for the FFSM (Figure 2). From a set of climate data, Firelihood is used to generate *fire histories*, that is, fire numbers and sizes at the day-pixel resolution, which are subsequently included as an additional mortality in the FFSM's forest resources module. Burned areas are aggregated annually and distributed within each pixel across each forest type proportionately to their area cover shares. On affected areas, forests undergo losses of volume defined by fire-induced mortality coefficients, a common procedure in large-scale vegetation models (Hantson et al., 2016; Li et al., 2012). Such models often use coefficients specific to broad vegetation types (Arora & Boer, 2005; Kloster et al., 2010; Li et al., 2012; Thonicke et al., 2001), but our model includes information on diameter classes and forest composition. Empirical models have shown that bark thickness and tree diameter are important determinants of post-fire mortality (Cansler et al., 2020). Besides, due to fuel continuity and lower tree crowns, tree mortality tends to be higher in coppices and forests with intermediate structure compared to high forests (Dupire et al., 2019). We adapted mortality coefficients from large-scale vegetation models to take these factors into account (Table 1). Even though some species are known to be less tolerant to fires than others, we chose not to implement species-specific coefficients. Indeed, observed tree mortality for different species also depends on local weather conditions and fire intensities (Dupire et al., 2019; Fernandes et al., 2008; Fréjaville, Curt & Carcaillet, 2018, Fréjaville, Vilà-Cabrera, et al., 2018), and empirical information is scarcer for non-Mediterranean species.

Fires also affect the forest sector indirectly through forest owners' anticipation of future fire-induced mortality. In this first implementation of the coupling, we assume that forest owners have perfect knowledge of future

Table 1
Mortality Coefficients Used for Burned Areas

Forest structure	0–20 cm	20–40 cm	>50 cm
High forest	0.85	0.6	0.3
Intermediate structure	0.9	0.65	0.35
Coppice	1	0.75	0.5

fire activity. As we focus on fire-related impacts and on the propagation of uncertainty, in this work, climate is assumed not to impact forest growth beyond fire mortality, which were investigated in previous works (Delacote, Lobianco, et al., 2021; Lobianco, Caurla, et al., 2016).

Weather data is retrieved for 5 Global Circulation Models-Regional Circulation Models couples from the EURO-CORDEX experiment (Kotlarski et al., 2014). For each model, we used two "warming climate" outlooks corresponding to the RCP 4.5 (moderate warming) and RCP 8.5 (strong warming) scenarios (IPCC, 2014), for the 2015–2100 and historical periods, that is, 1985–2015.

Firelihood is used to simulate 30 different summer fire histories for each combination of climate scenario and climate model. As a reference for current climate, we also construct sets of fire histories assuming a "constant climate" scenario by performing random draws (of years) in the historical period, resulting in a continuation of current climate. This procedure yields 450 fire histories, that is, 15 simulation sets with 30 replications each. The FFSM is then used to perform simulations for the period 2020–2100 from all individual fire histories. Because fire impacts in Southern France are likely to affect sectoral dynamics in Northern France through inter-regional trade, FFSM simulations concern the whole country. The FFSM, as many other large-scale sectoral models, is deterministic. By using the probabilistic nature of Firelihood to replicate each simulation several times, we introduce and propagate uncertainty into the FFSM. We also perform a simulation of FFSM without fires, which we refer to as the "reference" simulation and use to assess changes in model behavior.

2.5. Uncertainty Analysis

We assess the propagation and contribution of four different sources of uncertainty to our simulation results. Three of these are climate-induced. They relate to the lack of knowledge concerning future greenhouse gas emissions (scenario uncertainty), climate models' response to forcing levels (model uncertainty), and the chaotic nature of climatic processes (i.e., internal climate variability, Lehner et al., 2020). These three sources drive the fire process through weather conditions. The fourth source is specific to the fire process and results from the stochastic nature of fire occurrences and spread at the daily pixel scale. It is accounted for by the sets of Firelihood replications, and is named fire uncertainty in the remainder of the article. Consequently, for a given climate model and climate scenario, variability in fire activity has two components: one linked to the chaotic nature of weather dynamics (i.e., internal climate variability), the other to randomness intrinsic to the fire process (i.e., fire uncertainty).

Climate-induced uncertainties are usually assessed on decadal time series (Hawkins & Sutton, 2009; Lehner et al., 2020). When considering fire danger, inter-annual fluctuations are particularly significant and need to be taken into account as well, hence we work with annual time series (Fargeon et al., 2020). Prior to any calculation, we smooth output data series for each metric with a 30-year Butterworth low-pass filter and Mann's (2008) adaptive padding approach: the resulting signal is called the "trend", and "annual fluctuations" for the metric considered are computed as the residuals from this trend. Besides, for each combination of climate models and climate scenarios, we also compute a "multi-replication trend" as the average trend across the 30 replications.

We compute inter-annual variability, that is, uncertainty arising from internal climate variability, as the variance of annual fluctuations averaged across all simulations. Inter-annual variability is therefore time invariant (Fargeon et al., 2020; Hawkins & Sutton, 2009). We compute fire uncertainty as the variance of the trends within each set of 30 replications, averaged over climate models and climate scenarios. We compute model uncertainty for each climate scenario as the variance of multi-replication trends across climate models. Model uncertainty is subsequently averaged across climate scenarios. We compute scenario uncertainty for each climate model as the variance of multi-replication trends across climate scenarios. Scenario uncertainty is subsequently averaged across climate models. Following Lehner et al. (2020), total uncertainty is defined as the sum of all four sources, fractional uncertainty as the ratio of each source with respect to total uncertainty, and we compute 90% confidence intervals across mean projections assuming a Gaussian distribution. An illustration of this process can be found in Supporting Information S1.

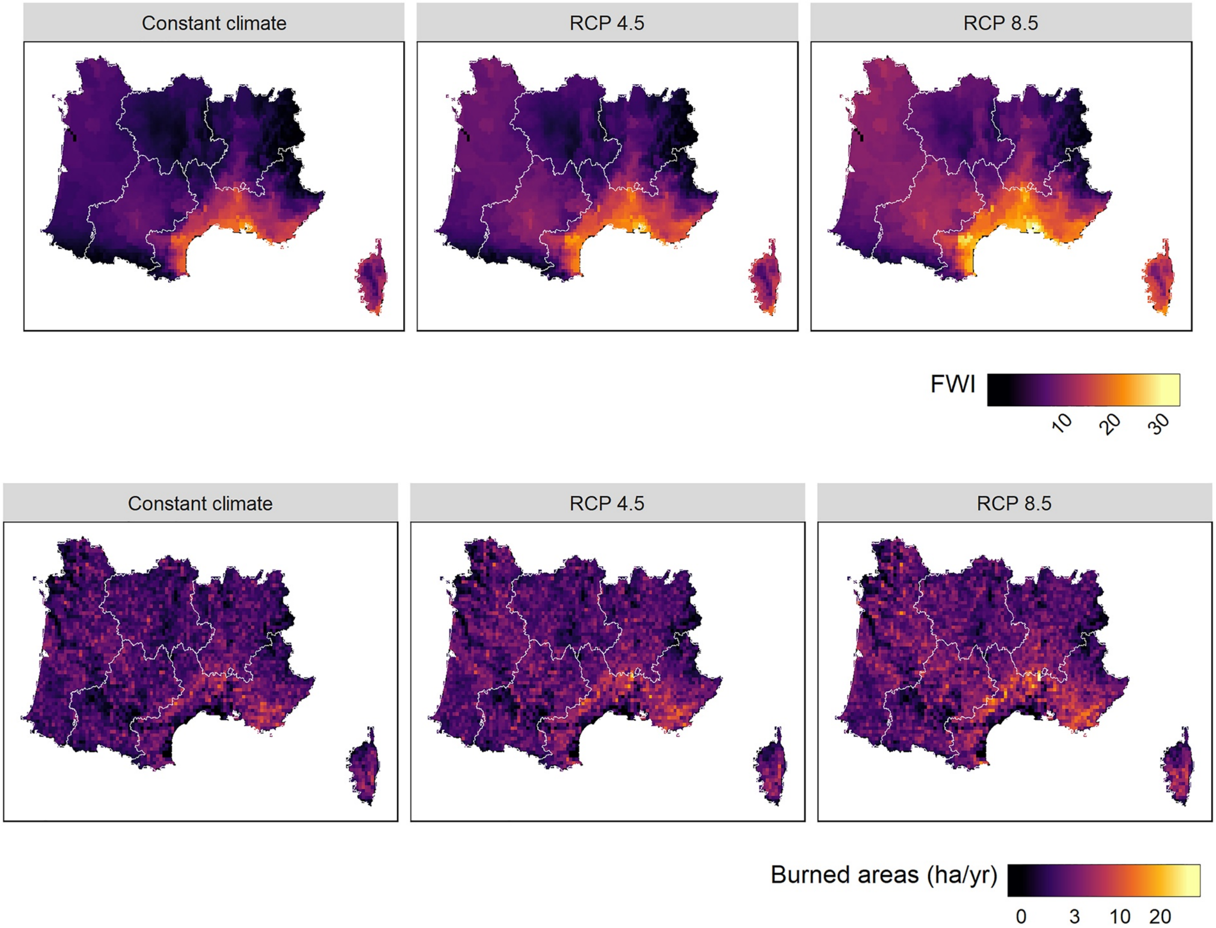

Figure 3. Spatial distribution of summer FWI (top) and burned areas (bottom) during the end of century period (2070–2100) in each of the three climate outlooks considered. Values correspond to mean values over the period.

3. Results

Most impacts tend to be cumulative over time, hence we focus on the end-of-century period (2070–2100). Figures and tables display the most important results, disaggregated results can be found as an electronic Supporting Information S1 material.

3.1. Fire Activity

Fire danger, indicated by mean FWI over the summer season, shows a marked increase over time in case of a warming climate (Figure 3). Its average value increases from 6.7 in the historical period (1985–2015) to 8.8 (+30%) and 11.2 (+67%) by the end of the century (2070–2100) for RCP 4.5 and RCP 8.5 respectively, reaching particularly high values around the Mediterranean and to the west of the study area. Burned areas (BA) during summer estimated with Firelihood follow a similar evolution: while they remain stable throughout simulations with a constant climate (6.600 ha/year), they increase with a warming climate, reaching 8.300 ha/year in RCP 4.5 and 12.000 ha/year in RCP 8.5. Besides, there are important differences depending on the climate model used, especially with a warming climate, owing to differences in predicted rainfall and temperature (Fargeon et al., 2020; McSweeney et al., 2015), for example, in RCP 8.5 from 8.000 ha/year with CNRM to 16.000 ha/year with HadGEM. Results are consistent with current fire activity and projections in Fargeon (2019).

BA is unevenly distributed: regions PRO and AQU account for 60%, while others represent 15% or less each (Table 2). When considering the BA-to-forest area ratio, the southern PRO region is the most affected, while northern regions are the least affected (AUV and RHO). Compared to the constant climate case, the relative

Table 2
Average Yearly Burned Areas in Each Region (ha) and Climate Scenario During the End of Century Period (2070–2100)

Region	Constant climate	RCP 4,5		RCP 8,5	
AQU	1511	1850	(+22%)	2258	(+49%)
AUV	812	969	(+19%)	1176	(+45%)
MID	902	1188	(+32%)	1507	(+67%)
PRO	2401	3167	(+32%)	3959	(+65%)
RHO	979	1159	(+18%)	1343	(+37%)
France	**6605**	**8334**	**(+26%)**	**10242**	**(+55%)**

Note. Figures only concern areas burned in forest land use classes (represented in the FFSM) and do not include shrubland.

increase in BA is also highest in southern regions (PRO, MID). BA also shows high spatial variability within each region (i.e., across pixels), which is consistent with fires remaining a relatively rare event (Figure 3, bottom maps).

3.2. Forest Sector Dynamics

3.2.1. Impacts in Southern France

Higher wildfire activity induces an increase in tree mortality, leading to losses of timber inventory (Table 3). With a constant climate, cumulated fire-induced mortality equals −11.8 Mm^3 over the end-of-century period, which represents a 5.2% increase compared to the reference. With a warming climate, it increases to 20.9 (+9.1%) and 27.2 Mm^3 (+11.9%) in RCP 4.5 and 8.5 respectively. In the reference, forest volumes increase steadily in the study area, going from 1495 to 2530 Mm^3 in 2100. While volumes still expand in all other simulations, introducing fires leads to a cumulated loss of 93.8 Mm^3 by 2100 for a constant climate, which represents a 3.7% loss compared to volumes in the reference. Higher levels of radiative forcing lead to additional losses of 28 (−4.8%) and 36.5 Mm^3 (−5.1%) for RCP 4.5 and RCP 8.5 respectively. Harvest levels in the FFSM are elastic to available timber inventories and decrease with higher wildfire activity. Over the end-of-century period, harvests decrease by 7.9–11 Mm^3, that is, −1 to −2% compared to the reference.

Wildfires affect carbon stocks in forest biomass, which for the most part are released into the atmosphere. Tree species have varying carbon densities and the distribution of forest types is heterogeneous across space, hence losses of carbon are not directly proportional to decreases in timber volume. Under a constant climate, losses of forest carbon equal −137.4 $MtCO_2eq$ by 2100, (−2.9% loss compared to the reference). With a warming climate, we observe an additional loss of 35.8 (−3.6%) and 43.3 (−3.8%) $MtCO_2eq$ for RCP 4.5 and RCP 8.5 respectively. Due to decreases in harvest levels, carbon stocks in harvested wood products also go down, but this loss remains small due to the limited size of the pool (around 1 $MtCO_2eq$).

Products supply is directly linked to harvests and therefore declines in the study area. In the first decades, decreases in supply are low and display similar values for all climate scenarios and products, but diverge in the latter half of simulations. By the end of the century, industrial outputs undergo a decrease of 10.5 Mm^3 (−1.1%) with a constant climate. The decrease is 33% and 41.8% larger under RCP 4.5 and 8.5 respectively, with higher relative reductions for softwood roundwood production. Following supply reductions, products prices increase. This increase remains limited for hardwood and industrial wood products (+0.5% to +1%), but is higher for softwood products (up to +3%).

Producer surplus, that is, benefits timber suppliers derive from their activity, retracts slightly in the short term but increases by the end of the century (e.g., 128M€ for the constant climate case). Indeed, the price increase overcompensates the supply decrease, which overall gives a positive impact on producer's surplus. Gains in producer surplus increase to 153–157 M€ with a warming climate. While welfare does go up for softwood producers, it actually decreases for hardwood (−12.7 to −18.2 M€) and industrial wood (−36.5 to −70.2 M€) producers. For the former, increased prices offset decreases in industrial outputs, while this is not the case for latter two. Besides, changes are not homogeneous across regions, and producer surplus remains stable or decreases in regions that are most affected by fires. Due to higher prices, consumer surplus decreases and total economic surplus, that is, economic welfare in the forest sector, is reduced by 210–290 M€.

Expected forestry returns, that is, income forest owners expect in the future, decrease by −1% to −3% for all forest types in the first decades compared to the reference, with limited differences across climate scenarios. In the long-term, expected returns undergo contrasted evolutions across forest types: they decrease for broadleaf forests (−1.27% to −2.23%), reach values similar to the reference for mixed forests (around −0.5%) and increase for coniferous forests (+1.67% to +2%). These long-term changes can be explained by higher products prices, especially for softwood roundwood, which can offset anticipated mortality increases. Changes in expected returns affect replanting decisions, which marginally influences forest composition in the long term. By the end of the century, the area of coniferous forests expands by 7000–8700 ha, while those of broadleaf and mixed forests decrease.

Table 3
FFSM Outputs

	Reference		Constant climate		RCP 4.5		RCP 8.5	
	South	North	South	North	South	North	South	North
Burned areas (ha)	0		205,393		259,086		318,294	
Mortality (Mm3)	229	160	11.8 *(+5.2%)*	−0.3 *(−0.2%)*	20.9 *(+9.1%)*	−0.4 *(−0.3%)*	27.2 *(+11.9%)*	−0.4 *(−0.3%)*
Timber volume[a] **(Mm3)**	2530	2367	−93.8 *(−3.7%)*	−7.9 *(−0.3%)*	−121.8 *(−4.8%)*	−9.9 *(−0.4%)*	−130.3 *(−5.1%)*	−10.2 *(−0.4%)*
Forest carbon[a] **(MtCO2eq)**	4755	4517	−137.4 *(−2.9%)*	−12.1 *(−0.3%)*	−173.2 *(−3.6%)*	−15.0 *(−0.3%)*	−180.7 *(−3.8%)*	−15.3 *(−0.3%)*
Products carbon[a] **(MtCO2eq)**	162	207	−1.0 *(−0.6%)*	−0.6 *(−0.3%)*	−1.3 *(−0.8%)*	−0.7 *(−0.3%)*	−1.4 *(−0.9%)*	−0.7 *(−0.4%)*
Harvests (Mm3)	706	857	−7.9 *(−1.1%)*	3.2 *(+0.4%)*	−10.4 *(−1.5%)*	4.4 *(+0.5%)*	−11.0 *(−1.6%)*	4.8 *(+0.6%)*
Products supply (Mm3)	1004	1006	−10.5 *(−1%)*	4.6 *(+0.5%)*	−14.0 *(−1.4%)*	6.3 *(+0.6%)*	−14.9 *(−1.5%)*	6.8 *(+0.7%)*
Hardwood	51	118	−0.6 *(−1.1%)*	0.5 *(+0.4%)*	−0.8 *(−1.5%)*	0.6 *(+0.5%)*	−0.8 *(−1.6%)*	0.6 *(+0.5%)*
Industrial wood	570	639	−4.8 *(−0.8%)*	2.9 *(+0.5%)*	−6.9 *(−1.2%)*	4.2 *(+0.7%)*	−7.4 *(−1.3%)*	4.5 *(+0.7%)*
Softwood	383	249	−5.1 *(−1.3%)*	1.2 *(+0.5%)*	−6.4 *(−1.7%)*	1.5 *(+0.6%)*	−6.7 *(−1.7%)*	1.6 *(+0.7%)*
Products prices[b] **(€/m3)**								
Hardwood	85		0.4 *(+0.5%)*		0.5 *(+0.6%)*		0.5 *(+0.6%)*	
Industrial wood	27		0.2 *(+0.6%)*		0.2 *(+0.8%)*		0.2 *(+0.9%)*	
Softwood	82		1.8 *(+2.2%)*		2.3 *(+2.8%)*		2.4 *(+3%)*	
Producer surplus (M€)	27,432	27,361	128.4 *(+0.5%)*	391.5 *(+1.4%)*	153.2 *(+0.6%)*	499.4 *(+1.8%)*	157.3 *(+0.6%)*	528.8 *(+1.9%)*
Hardwood	1916	6109	−12.7 *(−0.7%)*	39.0 *(+0.6%)*	−17.1 *(−0.9%)*	50.9 *(+0.8%)*	−18.2 *(−1%)*	53.3 *(+0.9%)*
Industrial wood	8599	9848	−36.5 *(−0.4%)*	110.0 *(+1.1%)*	−62.5 *(−0.7%)*	152.2 *(+1.5%)*	−70.2 *(−0.8%)*	163.6 *(+1.7%)*
Softwood	16,916	11,405	177.6 *(+1%)*	242.5 *(+2.1%)*	232.7 *(+1.4%)*	296.2 *(+2.6%)*	245.8 *(+1.5%)*	311.9 *(+2.7%)*
Consumer surplus (M€)	73,937	97,196	−338.0 *(−0.5%)*	−255.1 *(−0.3%)*	−427.8 *(−0.6%)*	−327.1 *(−0.3%)*	−445.3 *(−0.6%)*	−342.1 *(−0.4%)*
Total surplus (M€)	101,368	124,557	−209.6 *(−0.2%)*	136.4 *(+0.1%)*	−274.6 *(−0.3%)*	172.3 *(+0.1%)*	−288.0 *(−0.3%)*	186.7 *(+0.1%)*
Expected returns (€/ha/year)								
Broadleafs	19	63	−0.2 *(−1.3%)*	0.2 *(+0.4%)*	−0.3 *(−1.6%)*	0.3 *(+0.5%)*	−0.4 *(−2.2%)*	0.3 *(+0.5%)*
Coniferous	84	127	1.4 *(+1.7%)*	2.3 *(+1.8%)*	1.8 *(+2.2%)*	2.9 *(+2.3%)*	1.7 *(+2%)*	3.0 *(+2.4%)*
Mixed	31	65	−0.1 *(−0.2%)*	0.6 *(+1%)*	−0.1 *(−0.3%)*	0.8 *(+1.2%)*	−0.2 *(−0.7%)*	0.8 *(+1.2%)*
Forest area[a] **(ha)**								
Broadleafs	3937,477	3924,214	−5110.7 *(−0.1%)*	−3743.9 *(−0.1%)*	−6294.5 *(−0.2%)*	−4670.2 *(−0.1%)*	−6259.3 *(−0.2%)*	−4804.1 *(−0.1%)*
Coniferous	1836,247	1181,125	6946.0 *(+0.4%)*	4129.4 *(+0.3%)*	8571.3 *(+0.5%)*	5127.1 *(+0.4%)*	8742.4 *(+0.5%)*	5281.6 *(+0.4%)*
Mixed	2334,249	874,378	−1835.4 *(−0.1%)*	−385.3 *(0%)*	−2277.0 *(−0.1%)*	−456.7 *(−0.1%)*	−2483.2 *(−0.1%)*	−477.4 *(−0.1%)*

Note. Values are averaged over sets of 30 replications of each fire history. Metrics are given as cumulated values over the end of century period (2070–2100).
[a]Given for 2100. [b]Prices given as average values over the period.

Differential impacts across products and forest types relate to how fires affect the resource across space. A majority of forest inventories suitable for softwood roundwood production are located in the study area, especially in AQU and MID, both of which are heavily affected by fires in our projections. As a result, nationally, a larger proportion of resources devoted to producing softwood products is affected by fires. Besides, changes in expected returns may affect agriculture/forests land-use change trade-offs, which we do not consider.

3.2.2. Impacts in Northern France

While timber supply decreases in the South, demand remains unaffected nationally, and harvests and supply increase slightly in Northern France, leading to a limited decrease in timber inventories (e.g., −0.3% to −0.4% compared to the reference) and forest carbon (−0.3% to −0.9%) by 2100. Because both prices and supply increase, producer surplus rises in Northern France (+1.4% to +1.9%). This increase is witnessed for all products, but is highest for softwood products (+2.1% to +2.7%) than for other products (+0.64% to +1.5%). Higher timber supply in Northern France partly compensates for losses in Southern France: trade fluxes from the study area to northern France go down (pulpwood and softwood), while they rise in the other direction (hardwood). Because prices increase while no future fire-mortality is expected, expected returns from forestry increase for all forest types in Northern France. Again, impacts are relatively more marked for coniferous forests (+2.3% to +3.1%) than for broadleaf and mixed forests (+0.4% to +1.2%).

3.2.3. Regional Distribution of Impacts

Owing to larger burned areas, the southern PRO and AQU regions undergo the largest relative decreases in standing forest inventory, for example, around −6.5% by 2100 in RCP 8.5 compared to the reference. In these two regions, harvest levels decrease strongly, by for example, 3.1% and 2.5%, while decreases are more moderate in northern regions (−0.4% in RHO, −0.5% in AUV). Industrial output decreases, especially for softwood roundwood in AQU (−3%) and industrial wood in PRO (−3.3%) and, as a result, and contrary to the overall trend, producer surplus respectively stays stable (+0.4%) and decreases (−2%), leading to regional decreases in economic welfare in the forest sector. On the other hand, as a result of the spatial price equilibrium, harvests increase in region MID despite high burned areas, leading to higher industrial output, especially for softwood roundwood (+1.7%), which is exported to other regions and leads to a significant increase in regional producer surplus (+4.8%).

3.3. Uncertainty in Model Projections

Figure 4 illustrates the contribution of the four sources of climate and fire-related uncertainty to total uncertainty in model projections for a fire activity metric (burned areas) and two forest sector metrics (harvests and expected revenues). Uncertainty in the evolution of fire activity is dominated by inter-annual variability, which accounts for more than 75% of uncertainty until 2060. Over time, other sources of uncertainty become more important and total uncertainty increases by 66.6% over the course of the simulation. By 2100, model and scenario uncertainty account for 15.8% and 20.8% of total variance respectively, but, owing to internal climate variability, inter-annual variability still represents 54.7% of total variance. These results are consistent with those highlighted for fire danger by Fargeon et al. (2020), even though the relative importance of inter-annual variability is higher for BA than for FWI and weather metrics. Indeed, the influence of internal climate variability may be amplified due to the non-linearitiy of weather-FWI-BA relationships. Fire uncertainty remains rather stable and only accounts for 2.9%–8.7% of total variance: once inter-annual fluctuations are removed, differences in BA across replications remain limited. Tree mortality directly depends on BA and shows a similar evolution (available as an online supplementary material).

Uncertainty in projections of forest sector metrics displays a different profile. In absolute terms, uncertainty starts at a low level, increases slowly at first but more rapidly later on. Inter-annual variability dominates in the first years, but its relative importance decreases rapidly. It represents more than 50% of total uncertainty until 2036, and only accounts for 0.6% by 2100. Other sources of uncertainty rise strongly after the first decades. Model uncertainty increases first, keeps increasing in absolute value throughout the simulation, and its relative importance peaks at 48.2% in 2069 before decreasing to 42.8% by 2100. Scenario uncertainty expands in absolute and relative terms throughout the simulation, represents 25% of total uncertainty from 2061 onwards and accounts for 50% of total uncertainty in 2100. Fire uncertainty increases steadily in absolute terms throughout the simulation. Its relative importance peaks at 25% between 2040 and 2050 and then decreases to 6.6% by 2100.

10.1029/2021EF002433

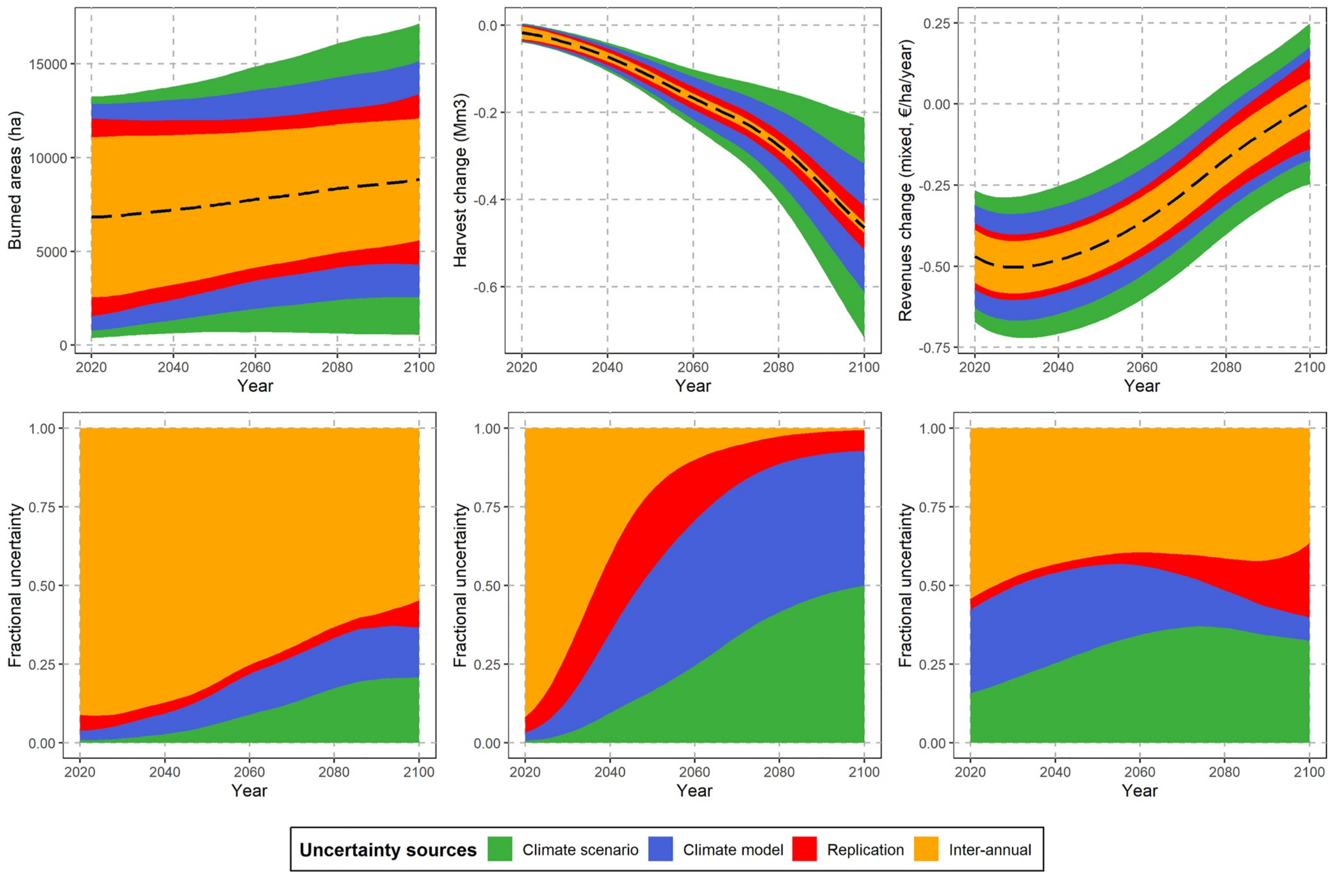

Figure 4. Uncertainty profiles for 3 model outputs: burned areas (left), harvests (middle) and expected revenues for coniferous forests (right). The top row shows average projected values and 90% confidence intervals, while the bottom row shows the relative contribution of each uncertainty source.

Uncertainty in timber supply and prices show profiles similar to harvests, except that fire uncertainty accounts for a moderately higher share of total variance (e.g., up to 38% mid-simulation). Besides, inter-annual variability represents a lower share of total uncertainty for hardwoods than for other products, suggesting that hardwood markets may be more resilient when the resource is submitted to disturbances.

Our simulations prior to the introduction of wildfires are deterministic and start diverging only once fires are introduced. As a result, total uncertainty remains low at first for metrics other than BA and mortality. Fires only affect a small proportion of timber inventories every year, hence inter-annual fluctuations in BA, even though they may be very large, only marginally translate into inter-annual fluctuations in for example, harvests. However, burned inventories are removed from production and growth for several decades (i.e., until a new forest grows): fires thus have a quasi-cumulative impact on forest sector dynamics. Therefore, differences across scenarios (and models) remain negligible in the first decades and then diverge as total uncertainty increases due to model and scenario uncertainty. In the case of multiple replications within a given simulation set, overall BA are of the same order of magnitude, but their spatial distribution is different, as is that of forest resources. As fires affect different areas year after year, impacts on the forest sector also diverge from one replication to another, albeit to a lesser degree than from for example, one climate scenario to another.

Expected returns are annual metrics whose values minimally depend on past values, hence they display uncertainty profiles similar to those of fire activity. For coniferous and mixed forests, trends from various models and climate scenarios intersect in the second half of the simulation, resulting in lower contributions from climate and scenario uncertainties at these moments, and a higher contribution from fire uncertainty (e.g., 30%).

4. Discussion

4.1. Forest Sector Impacts and Policy

We assessed the implications for the forest sector of climate-driven changes in wildfire regimes in Southern France, considering environmental and economic dimensions, as well as the feedbacks between forest resources, forest management and timber industries. Results show a significant increase in forest burned areas by the end of the century, by up to 55% with climate warming corresponding to the RCP 8.5 scenario. This is in line with previous literature, which predicts an aggravation of fire regimes in the Mediterranean and an extension of the fire-prone area at its Northern margins (Chatry, 2010; Dupuy et al., 2020; Fargeon, 2019; Fargeon et al., 2020). This aggravation results in higher tree mortality, losses of standing timber inventory and forest carbon, with cascading market implications such as harvest decreases, concomitant price increases, and welfare implications that showed discrepancies across regions and products categories. However, at the sectoral scale, these implications remain moderate, and we project that only a few metrics will undergo changes higher than 1%–2% compared to a constant climate case. Besides, most of these relate to forest dynamics rather than industrial dynamics, hinting at the relative resilience of the forest-based bioeconomy.

French forest policy puts a strong emphasis on leveraging the forest sector to pursue a double goal of industrial competitiveness and climate change mitigation. With this in mind, several points in our results warrant attention.

1. First, due to the inhomogeneous distribution of forests across France, we expect wildfires to affect coniferous forests relatively more than broadleaf forests. Consequently, the softwood industry, which is the largest in volume, is likely to undergo the largest disruptions, potentially jeopardizing economic competitiveness objectives.
2. Second, results highlight welfare implications that are differentiated across regions and products. While overall welfare in the forest sector decreases following higher wildfire activity, timber producers become better off owing to increased products prices, especially softwood producers. However, producers in the most affected areas suffer losses, while producers in Northern France, contrary to the general trend, are expected to increase their harvests and consequently benefit more than their counterparts in Southern France.
3. Third, we highlighted the cumulative and incremental nature of these impacts. Given the strong inertia in the forest sector, forest stakeholders and policymakers need to anticipate these trends, even though implications may seem distant and limited as of today.

4.2. Uncertainties and Prospective Assessments

Due to the long time scales involved in forest issues, model-based simulation studies can provide valuable information to policymakers (Ohrel, 2019). Given that large uncertainties remain on climate evolution and how it may affect economies and ecosystems, several outlooks need to be considered, and recent sectoral assessments consider several warming and mitigation scenarios (Daigneault & Favero, 2021; Lauri et al., 2019). We assessed the propagation of four different sources of uncertainty in fire activity throughout the forest sector: three climate-induced sources and one related to the intrinsic stochasticity of the fire process. On the one hand and in accordance with previous studies (Fargeon, 2019; Fargeon et al., 2020), wildfire activity displayed an uncertainty profile largely dominated by inter-annual fluctuations. On the other hand, forecasts of forest sector dynamics were dominated by the choice of the warming level and that of the climate model, especially in the long-term, while, on the medium term, uncertainty due to fire stochasticity was significant. These results underline the importance of considering not only several climate outlooks, but also reassert the need to take into account uncertainty related to climate models' responses as suggested by Delacote, Lobianco, et al. (2021) and also stress the relevance of considering variability intrinsic to environmental processes. While these factors are commonly accounted for in environmental sciences (Lehner et al., 2020), their consideration in economic assessments is rarer and needs to become more common.

Integrated simulation models are large and often deterministic models and scenario analysis, where storylines are developed by the operator, remains the standard way of investigating the future (Chudy et al., 2016; Riviere & Caurla, 2020a). A recent but expanding literature (Delacote, Caurla, & Riviere, 2021) uses systematic sensitivity analysis methods to assess the robustness of forest sector model projections, largely focusing on model parameters and market-related metrics (Buongiorno & Johnston, 2018; Kallio, 2010; Sohngen et al., 2019). Through our application to wildfires, we demonstrated that the use of probabilistic frameworks could be extended to not only test model robustness, but also introduce uncertain events. Such probabilistic frameworks offer an interesting option to complement classical scenario-based approaches, in particular when stochastic processes are at stake. From a broader perspective, our work showcases the interest of developing environmental-economics model couplings to perform *integrated assessments* and account for the complex relationships within social-ecological systems. However, their implementation in routine simulation procedures requires larger computing times and increases model complexity: they may therefore be better suited for in-depth analyses focused on one factor, and results (including their statistical distribution) may be later reused in broader assessments.

4.3. Study Limits

We identify three key limitations in this work. First, Firelihood was adjusted in a subregion of the studied area where accurate data was available, and winter fires were ignored. Previous work (Fargeon, 2019) has shown that the extrapolation to the whole Southern France was credible, which we confirm in Supplementary material. Differences with observations in northern areas can arise from overestimation with Firelihood or under-filling of fire observations, but these two effects remain hard to disentangle. Hence, our results can be seen as a worst-case scenario, especially in the northern areas. On the contrary, ignoring winter fires underestimates overall fire activity in specific regions where they are known to be relevant (e.g., Pyrenees Mountains). The development of Firelihood is the subject of active research: the extension to other subregions like the Landes in Aquitaine, where specific datasets are available (GIP ATGeRi), the extension to winter conditions, the development of refined spatio-temporal models (Koh et al., 2021) with land-use and socio-economic data and the representation of extreme fire years are part of our research agenda.

Second, the FFSM model represents forest resources based on inventory data for merchantable timber. Even though it offers a higher degree of fineness compared to other forest sector models, it contains fewer details in resource modeling than for example, a vegetation or landscape model (Ager et al., 2018; Hantson et al., 2016). Some processes were simplified, such as fire effects modeling, where we used mortality coefficients inspired from the empirical literature and expert knowledge. Similarly, vegetation changes in the forest model do not influence fire risk, nor does the fire model include differences in fire susceptibility across forest types, and processes such as wood combustion or lagged mortality were similarly omitted. However, scale mismatch and data requirements preclude sector-level integration with process-based or mechanistic fire effects models.

Third, our work, owing to its methodological focus on uncertainty, focused on wildfires in isolation. Climate change is expected to also affect background tree mortality, growth, species ranges, as well as other forest disturbances, which may in addition interact with wildfires (Lindner et al., 2010b; Seidl et al., 2017). Previous forest sector model-based assessments have been dedicated to such issues, both for France (Caurla et al., 2015; Delacote, Lobianco, et al., 2021; Petucco et al., 2019) and other regions (Hanewinkel et al., 2013; Sohngen & Haynes, 1997; Tian et al., 2016), and a significant future challenge resides in their integration.

5. Conclusion

In this article, we established a soft-link between a probabilistic fire activity model and a bio-economic model of the forest sector and performed multiple stochastic simulations to assess the implications for the forest sector of climate-induced changes in wildfire regimes in Southern France. Results showed that, while burned forest areas were expected to increase by more than 50% in worst-case scenarios, implications for the forest sector remained moderate for the resource and limited for timber markets, which was due to the cumulative manner in which wildfires affect forest resources. However, owing to the strong inertia within the forest sector, such impacts remain significant and already need to be taken into account in policy planning, especially given the high economic and environmental stakes related to industrial competitiveness and climate mitigation. Besides, we showed that implications could be much higher in some regions than others, which underlines the necessity to take into account the local context and the distributional impacts of evolutions in disturbance regimes.

By decomposing variance in results at several points in time and across the forest sector, we highlighted that, while wildfire activity and its direct impacts (e.g., tree mortality) showed high inter-annual variability, forest sector dynamics were more resilient and most uncertainty came from the choice of a climate scenario and model. Besides, uncertainty due to the intrinsically stochastic nature of the wildfire phenomenon accounted for a significant share of total uncertainty in forest sector dynamics in the medium term. These results highlight the necessity to consider several climate outlooks, but also uncertainty intrinsic to environmental processes, especially disturbances, in sectoral assessments to provide policymakers with valuable insight into the future of the forest sector. From a broader perspective, our work constitutes an illustration of how probabilistic frameworks can be used to introduce uncertainty in large deterministic models, where the assessment of issues related to risks remains a marginal topic. The probabilistic setting indeed offers the possibility to generate large numbers of replicated simulations, which is particularly convenient for events with heavy-tailed empirical distributions. While we focused on one type of disturbance event (wildfires) and climate-related uncertainty, the approach can be adapted to other disturbances and categories of uncertainties (e.g., market-related).

Data Availability Statement

Fire observations used to calibrate Firelihood are available from the Prométhée database at https://www.promethee.com/. Land-Use data used for Firelihood simulations and to assign burned areas to land use classes in the study are available from the Corine Landcover database of the Copernicus programme of the European Union by the European Environment Agency at https://land.copernicus.eu/pan-european/corine-land-cover under a full free and open data policy. Weather simulation data from various pairs of Global-Regional simulation models used in this study for Firelihood simulations is available from the EURO-CORDEX initiative at https://www.euro-cordex.net/index.php.en for non-commercial research and educational purposes. The French Forest Sector Model (FFSM) is a bio-economic simulation model of the French forest sector used in this study to simulate the evolution of forest resources, management and industrial activities. The model and its source code are preserved at https://ffsm-project.org/wiki/en/home, under a modified GNU General Public License. Version used in this study is FFSM++ following developments on Wed, 15 Jan 2020 15:04:16 +0100. The software is being developed in a GIT repository at https://github.com/LEFNancy/ffsm_pp, which is private due to third-party proprietary data. Detailed information on each of the model's components can be found in the following publications: Caurla et al. (2010), Lobianco et al. (2015), Lobianco, Caurla, et al. (2016), Lobianco, Delcote, et al. (2016) and Wernsdörfer et al. (2012). Firelihood is a probabilistic model of wildfire activity used in this study to simulate the ignition and spread of wildfires under several radiative forcing scenarios. Detailed information on the model can be found in Fargeon (2019) and Pimont et al. (2016, 2021). Firelihood and FFSM simulation outputs supporting this manuscript can be found at www.zenodo.org in the following repository: Data_support_Riviere_et_al_2021 (10.5281/zenodo.5569671).

Acknowledgments
The UMR BETA is supported by a grant overseen by the French National Research Agency (ANR) as part of the "Investissements d'Avenir" program (ANR-11-LABX-0002-01, Lab of Excellence ARBRE). Authors also want to thank the anonymous reviewers and the French Ministère de l'Agriculture et de l'Alimentation and French Agence de la Transition Ecologique (ADEME) who contributed funding to this work. This research is part of the Agriculture and Forestry research program by the Climate Economics Chair. The authors want to thank the Climate Economics Chair for financial support.

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