ENVIRONMENTAL RESEARCH
LETTERS

Prospective impacts of windstorm risk on carbon sinks and the forestry sector: an integrated assessment with Monte Carlo simulations

IOP Publishing Environ. Res. Lett. 19 (2024) 094008 https://doi.org/10.1088/1748-9326/ad661b

ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
27 February 2024

REVISED
9 July 2024

ACCEPTED FOR PUBLICATION
22 July 2024

PUBLISHED
2 August 2024

LETTER

Prospective impacts of windstorm risk on carbon sinks and the forestry sector: an integrated assessment with Monte Carlo simulations

Félix Bastit[1], **Miguel Riviere**[1,2,*], **Antonello Lobianco**[1] and **Philippe Delacote**[1,3]

[1] Université de Lorraine, Université de Strasbourg, AgroParisTech, CNRS, INRAE, BETA, Nancy 54000, France
[2] Centre d'études et de prospective, ministère de l'Agriculture et de la Souveraineté alimentaire, Paris 75007, France
[3] Chaire d'Economie du Climat, Paris, France
[*] Author to whom any correspondence should be addressed.

E-mail: miguel.riviere@agroparistech.fr

Keywords: windstorm, forest, carbon, economics, resilience

Supplementary material for this article is available online

Abstract

Storms pose a significant threat to economic activities in the forest sector and introduce non-permanence risks for carbon stocks. Following escalating climate ambitions, understanding and addressing these risks becomes imperative. Uncertainties intrinsic to the storm phenomenon render this task complex. This study uses an integrated forest sector model to assess the economic and carbon impacts of storm regimes, emphasizing the importance of uncertainties through Monte Carlo simulation. From an economic perspective, we unravel complex interplays between the salvage and inventory effects of storms that lead to heterogeneous transfers of economic welfare across agents and space. Non-affected forest owners benefit from inflated prices, while affected owners' recovery hinges on the magnitude of storm damage. From a climate perspective, storms significantly impact the forest sector's carbon sink, with a high risk of falling short on mitigation objectives. In 25% of simulations, we observe a substantial 24% decrease in carbon sequestration. Our findings advocate for (1) conservative reliance on natural carbon sinks in national climate mitigation strategies toward net-zero, and (2) tailored risk-sharing insurance mechanisms for forest owners, providing a buffer against economic uncertainties arising from climatic disruptions.

1. Introduction

Commitments to achieve net-zero emissions are becoming widespread and rely on cross-sectoral efforts to reduce emissions and enhance carbon removals (Buck *et al* 2023). The forest sector, from tree planting to wood product manufacturing, plays a crucial role in withdrawing carbon from the atmosphere by storing it in biomass, soils, and long-lived wood products (Fahey *et al* 2010). This potential is widely recognized (Henderson *et al* 2020) and many climate action plans hinge on the forest sector's carbon sink to achieve net-zero emissions (Nabuurs *et al* 2018), making strong hypotheses regarding its size and future evolution.

Reliance on carbon sinks exposes to the risk of non-permanence, i.e. potential releases of carbon stored in non-geologic reservoirs back into the atmosphere. For forests, this can result from wood harvests or natural disturbances such as windstorms, wildfires, and bark beetles. In Europe, disturbances have affected 17% of forest area between 1986 and 2016 (Senf and Seidl 2021), causing 78.5 Mm^3 yr^{-1} of damage between 2001 and 2019, or 16% of annual fellings (Patacca *et al* 2023). Climate change is expected to intensify disturbance events and their regimes (Seidl *et al* 2017). This evolution questions forests' carbon sink's contribution to climate change mitigation, and their resilience (Anderegg *et al* 2020). For instance, Seidl *et al* (2014) projected carbon losses due to natural disturbances, for 2021–2030, of the same order of magnitude as gains from mitigation-based management strategies, offsetting a large part of their effect, and Reyer *et al* (2017) demonstrated that disturbances exacerbate expected climate-induced productivity declines.

Nonetheless, current IPCC guidelines for national inventories (IPCC 2006, 2019) and NDCs guidance reports (e.g. Sato *et al* 2019, Taibi *et al* 2020) provide limited insight on ways to incorporate the risk of non-permanence and its effects on carbon sinks.

Windstorms, the most common forest disturbance in Europe, have accounted for 46% of disturbance damage (28.5 Mm^3 yr^{-1}) over 1951–2020 (Patacca *et al* 2023), and their impact on carbon budgets is 5–10 times higher than that of wildfires (Pilli *et al* 2016). Windstorms are complex weather phenomena influenced by regional and local environmental conditions (e.g. atmospheric pressure and forest structure) (Gardiner *et al* 2013). Damage is driven by extreme storms, which are high-impact, low-probability events (Patacca *et al* 2023). Despite advancements in storm modeling (Gardiner 2021), assessments of impacts on the forest sector remain rare. For instance, Chen *et al* (2022) showed that, without storms, annual carbon storage in Taiwanese forests would double, while Pilli *et al* (2021) showed that storm Vaia caused a 4% decrease in Italian carbon stocks.

While these studies consider wind and vegetation dynamics, they omit economic features (e.g. forest management). Windstorms disturb timber markets through a short-term spike in supply due to salvage, and a longer-term decrease due to losses of growing inventory. This affects prices and economic welfare, leading to discrepancies across affected and non-affected locations, forest owners, and consumers. Conversely, management decisions by economic agents under risk or after a storm may impact forest resources (Prestemon and Holmes 2008, 2010). Research in forest economics has addressed interactions between forest management and hazard risk (Reed 1984, Loisel *et al* 2020). However, carbon has remained a minor concern, and the strong focus on the stand scale hinders establishing a direct link to the sector's overall carbon sink (Montagné-Huck and Brunette 2018).

Forest sector models are integrated models projecting the joint evolution of forest resources, management, and markets (Riviere and Caurla 2021), that bridge the gap between vegetation and economic models. While these models are often used to evaluate climate mitigation policies and project carbon budgets (Honkomp and Schier 2023), risks and uncertainties, including disturbances, have received limited attention (Chudy *et al* 2016). This is attributable to the models' deterministic nature, simplified representation of forest inventories, and focus on timber markets (Riviere *et al* 2022). Storms, in particular, have only been the focus of retrospective assessments (Caurla *et al* 2015, Henderson *et al* 2022).

The main objective of this article is to assess the economic and carbon sequestration consequences of windstorms for the forest sector. An integrated model of the forest sector is used, incorporating a windstorm damage component. We account for uncertainty inherent to the windstorm phenomenon through Monte Carlo simulations, enabling an analysis of carbon stocks' resilience. A secondary objective is to explore the forest sector's response to high-intensity, low-probability disturbance events, a topic mostly studied at the stand scale (Bastit *et al* 2023). Doing so, we underline how stochastic simulations can be used to feed NDCs with crucial information on the risk of non permanence of carbon sinks.

We apply our analysis to France, where forests cover one-third of the country's area, ranging from temperate to mountain to intensive plantation forests (IGN 2023). Forestry is a major stake: 40 Mm^3 of wood is harvested annually, the forest sector represents 416 000 direct jobs, and yields a value added of 27.6 billion euros (VEM 2021). France is exposed to windstorms on its Atlantic side, with storms Martin-Lothar (December 1999) and Klaus (2009), causing losses of 140 Mm^3 and 40 Mm^3 respectively, the prejudice of the latter being estimated at 1.5 billion euros (Costa *et al* 2009, IGN 2009). France has committed to an ambitious net-zero target by 2050 outlined in the National Low-Carbon Strategy (MTECT 2020). Achieving it requires doubling the land carbon sink by 2050, with the forest sector expected to contribute two thirds of the total (55 MtCO2e/year). While current policies aim at increasing harvests, recent observations show a weakening of the carbon sink, questioning the feasibility of carbon targets (Académie des sciences 2023).

2. Material and methods

2.1. The French forest sector model (FFSM)

The FFSM is a bio-economic model that represents forest inventories, forest owners' management decisions and timber markets (Lobianco *et al* 2015, supplementary data online). It provides a systemic description of the forest sector, considers interactions between ecological and economic dynamics, and is well-suited to exploring alternative futures and performing policy analyses (Latta *et al* 2013, Riviere and Caurla 2020). It has previously been used to address bioenergy production (Caurla *et al* 2018), climate change impacts (Riviere *et al* 2022) and pest outbreaks (Petucco *et al* 2020), albeit without considering salvage.

The FFSM is dynamic and comprises three modules exchanging information at an annual time step:

- A matrix-based **forest inventory module** representing growing timber stocks at the level of 8 km pixels, for 6 categories of forests and 13 diameter classes. Both growth and mortality rates are spatially heterogeneous. The model is calibrated

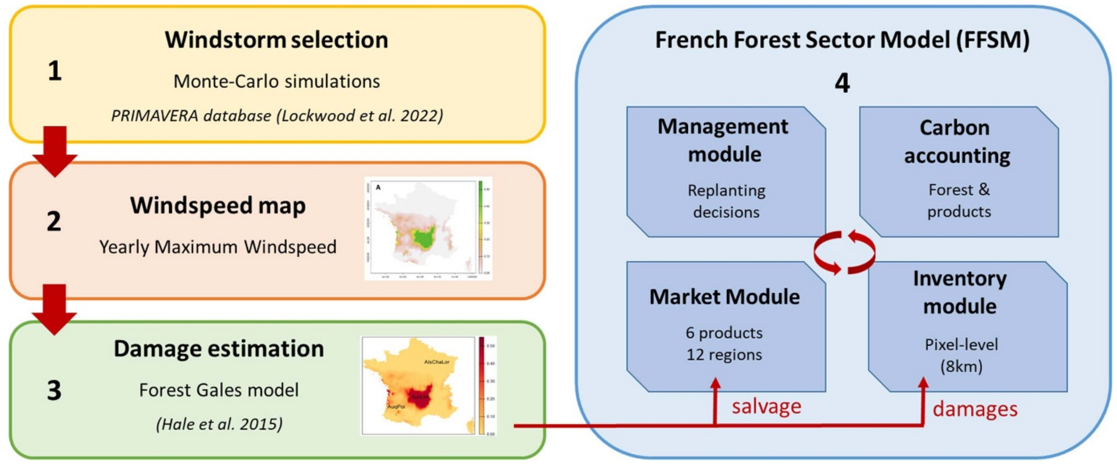

Figure 1. Illustration of the simulation setup.

from national forest inventory data (Lobianco *et al* 2015).

- A partial equilibrium **module of timber markets** combining Samuelson's (1952) spatial price equilibrium framework (i.e. maximization of economic surplus net of transport costs) and Armington's international trade framework (Sauquet *et al* 2011) to endogenously determine the quantities of wood products supplied, traded, and their prices. The module distinguishes 3 primary wood products, 6 transformed products, and manufacturing processes are modeled using input-output matrices. Demand is elastic to price, supply is elastic to price and available growing stocks. The module comprises 12 French regions and one world region (Caurla *et al* 2010).
- A pixel-level **module of forest owners' management decisions**, based on Faustmann's (1849) criterion, i.e. maximization of land expectation value to determine how area harvested should be replanted and/or managed (Lobianco *et al* 2016).

2.2. Introduction of windstorm damage

We introduce windstorm damage into the FFSM (figure 1) following the general approach by Chen *et al* (2018). Damages provoked by windstorms are primarily related to wind speed. We define yearly maximum wind speed YMW as the maximal wind speed observed on an 8 km pixel over a year. France may face several storm events yearly, however years with several events are rare and they usually follow distinct geographical paths. Yearly aggregation also enables compatibility with the FFSM's time step.

We use a sigmoid to represent the relationship between YMW and damages D to timber inventory (equation (1)). CWS corresponds to critical wind speed, i.e. a threshold where damage reaches half its maximum value $D_{\max}$. The slope near CWS is specified by parameter R_f. Following Chen *et al* (2018) and discussions with forest disturbance experts, we set $D_{\max}$ at 70% and R_f at 6 m.s^{-1}, and set a positive value (35m.s^{-1}) under which no damage is caused to filter out low wind speeds

$$D\left(\mathrm{YMW}\right) = D_{\max}\left(\frac{1}{1+e^{\left(\frac{\mathrm{CWS}-\mathrm{YMW}}{R_f}\right)}} - \frac{1}{1+e^{\frac{\mathrm{CWS}}{R_f}}}\right). \quad (1)$$

CWS is obtained using ForestGALES, a mechanistic wind risk model[4] (Hale *et al* 2015). ForestGALES is specified for individual species, while the FFSM uses broader categories (broadleaf, conifer). We respectively used oak (*Quercus robur*) and Norway spruce (*Picea abies*), the most common species in France, to parametrize the model. This procedure was tested on the major Lothar-Martin storms of 1999 (supplementary material).

In the FFSM, in a given year t, timber supply S for a given primary product pp is elastic to product prices P and available timber inventory I(equation (2)). Windstorms fell large amounts of timber, which can be stored or put onto the market before quality deteriorates too much (Prestemon and Holmes 2008). The model's supply function was adapted to consider this possibility, introducing a positive elasticity of supply γ to available damaged timber D. Therefore, when a windstorm occurs, the market enters a new regime where timber can be salvaged before it is spoiled (Prestemon and Holmes 2010). In the current setup, damaged timber can be used for two years to produce roundwood and four years to produce pulpwood and fuelwood

$$S_{\mathrm{pp},t} = S_{\mathrm{pp},t-1}\left(\frac{P_{\mathrm{pp},t}}{P_{\mathrm{pp},t-1}}\right)^{\alpha}\left(\frac{I_{\mathrm{pp},t}}{I_{\mathrm{pp},t-1}}\right)^{\beta}\left(\frac{D_{\mathrm{pp},t}}{D_{\mathrm{pp},t-1}}\right)^{\gamma}. \quad (2)$$

[4] Implemented in the *fgr* package on software R.

2.3. Simulating windstorm regimes

We used a database of YMW maps constructed from the PRIMAVERA project's dataset (Lockwood *et al* 2022), which provides simulated footprints for European windstorm events from 1950 to 2013. We constructed YMW maps by aggregating storms within a given storm season, yielding a set of 1330 maps at the resolution of the FFSM's 8 km pixels. This constitutes the simulation dataset.

We constructed a validation dataset using the ERA5 reanalysis dataset (Lockwood *et al* 2022), i.e. observed data. A loss index was defined to compare storm events, computed as the sum of timber volumes damaged for a given YMW map over all of the FFSM's pixels, using base-year inventory data. Comparison showed that the simulation dataset includes more frequent powerful storms than the validation dataset (supplementary material). To avoid overestimating damages, we split the simulation dataset into three sections based on each YMW map's loss index, with breaks at 10Mm^3 and 50Mm^3 and occurrence probabilities based on observed ERA5 data (29/35, 5/35 and 1/35 respectively).

Monte Carlo simulations until 2050 were performed by drawing random storms (i.e. YMW maps) from this simulation dataset. 300 different simulations were carried out, all yielding different results. Within each simulation, each year, one of the winter seasons in the simulation dataset (1330 in total) is chosen and introduced in the FFSM.

3. Results

Results are presented in two steps. First, we describe how a single storm event affects the forest sector. We focus on one storm event chosen due to its high intensity. Then, we present results from Monte Carlo simulations, focusing on impact distribution.

3.1. Impacts of a single storm event

The demonstration storm followed a west-to-east path and mostly affected the southern half of the country (figure 2(a)), felling a total of 360 $\text{Mm}^{3,}$ (12.67% of growing stocks, table 1). The central *AuvLim* region was the most affected and concentrated half of the damage (154.1 Mm^3). The south-western *AquPoi* region was moderately impacted (54 Mm^3), and *AlsChaLor*, in the north-east, was not affected: they were chosen for comparison purposes.

Immediately after the storm, we observe a strong decrease in forest inventory, which reconstitutes afterwards (figure 2(b)). Forest growth is at first faster than in the counterfactual (no-storm scenario), owing to the preferred use of salvaged timber over regular harvests, which decrease strongly by e.g. 66.8% nationally, up to 100% in the most affected areas (table 2, salvage period). Concomitantly, prices decrease owing to the temporary abundance of salvaged wood.

Once salvaged wood stops being used, harvests increase again, preventing growing stocks to reach their counterfactual levels even after several decades. However, harvest levels remain lower than in the counterfactual, by around 10% nationally.

In non-affected regions, in the medium-to-long term, harvests increase and reach higher levels than in the counterfactual (e.g. +9.11% in *AlsChaLor*), leading to moderate decreases in growing inventory (e.g. −3.64%). Wood harvested this way is exported to meet the demand that cannot be met by affected regions owing to long-term decreases in harvests due to the inventory effect.

Storms provoke two types of welfare transfers:

- **Value-chain transfer**: during the salvage period, wood products prices decrease and supply is abundant due to salvaged wood. Consumer surplus increases while producer surplus sharply decreases, especially in the most affected regions. Later on, salvaged wood cannot be used anymore, and harvest levels remain lower than in the counterfactual, increasing prices and reversing welfare transfers at the expense of consumers.
- **Spatial transfer**: unaffected regions compensate for the decrease in timber supply in affected regions by selling more timber, at a higher price. Long-term effects are ambiguous in affected regions: while significant decreases in timber stocks decrease economic surplus in most affected regions, long-term welfare impacts on moderately impacted regions can either be positive or negative.

The storm does not affect the forest sector's carbon balance immediately, e.g. forest carbon is only 0.47% lower nationally at the end of the salvage period. Indeed, damaged wood is either salvaged or left in the forest, and carbon remains stored. In the medium-to-long term, carbon stored in forests decreases compared to the baseline due to the gradual decomposition of dead wood and to the time needed for forests to regrow. For instance, seven years after the storm, forest carbon is 2.75% lower than in the counterfactual scenario[5].

How economic agents react to storms can affect outcomes. Given the large quantities of salvaged wood after a storm, timber suppliers' behaviors regarding its use is of particular importance. We performed a sensitivity analysis on the elasticity of timber supply to salvaged wood availability (supplementary material). Results reveal that larger elasticity leads to potentially strong increases in the supply of salvaged wood, and a concomitant decrease in timber prices.

[5] Effects on carbon pools in products has been investigated and is minor in comparison (results available upon request).

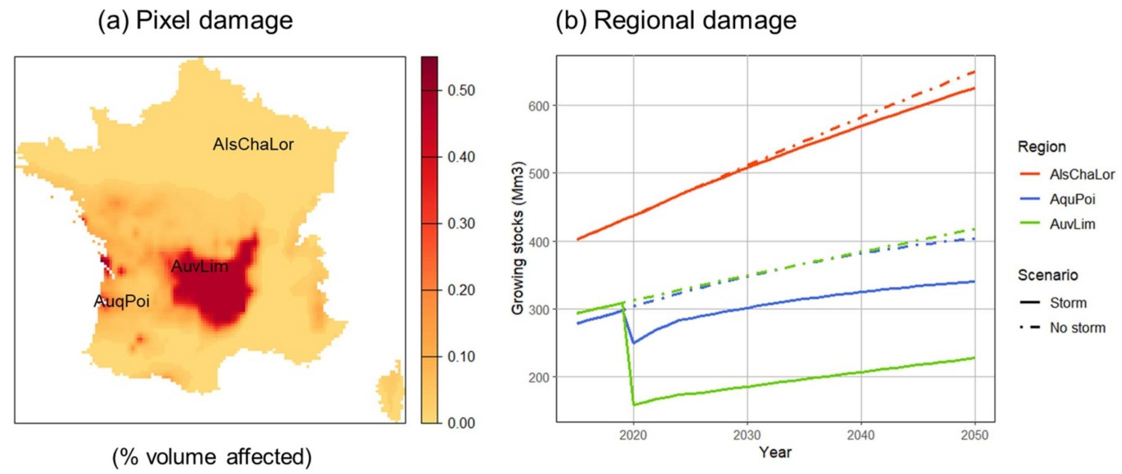

Figure 2. Impacts of a single major storm. Pixel-level damage for coniferous forests (a) and regional evolution of forest inventory (b).

Table 1. Storm damage over France and selected regions.

Region	Storm damage (Mm^3)	% growing stock
France	359.67	−12.67%
AuvLim	154.1	−49.88%
AquPoi	53.99	−18.12%
AlsChaLor	0	0%

However, these dynamics only last for as long as salvaged wood can be used. Elasticities also affect welfare. Larger elasticity increases consumers' surplus (owing to the larger supply). Producers' surplus and sectoral welfare display a concave pattern, suggesting the existence of an overall optimal salvage strategy.

3.2. Impacts of storm regimes

Over 300 simulations, annual storm damage equals 4.82 Mm^3 yr^{-1} (0.19% of growing stocks) and cumulated damages equals 183 Mm^3 on average. Damage distribution is skewed: there are large amounts of small storms and a low number of extreme events (figure 3). For example, there is a 10% chance to reach 320 Mm^3 of cumulative damage, while the median is 164 Mm^3. Damage is unequally distributed geographically, with stronger impacts on the Southern half of the country and in the north-east. Overall, cumulative regional damage ranges between 2% and 11% of growing inventories. By 2050, national forest inventory is on average 4.73% lower than in a no-storm-simulation, with high spatial variability, i.e. from −20% to −0.42%.

Yearly carbon sequestration decreases in all simulations with a mean value of −7.56 MtCO2eq. yr^{-1} (−9.83% compared to the baseline, table 3). The distribution is skewed and shows a high variability: in 25% of simulations, sequestration decreases by at least −12%, and in 10% of cases by more than −24%. Resilience can be assessed through the time needed for an ecosystem to reach its pre-disturbance state (Knoke *et al* 2023). Table 4 shows the distribution of recovery times for growing wood stocks, computed over all individual storms simulated. Two-thirds of the time (72%), recovery time is below two years. However, 23% of the time, the recovery period lasts 3–4 years, and 5% of storms result in recovery periods lasting 5 years or more, highlighting the importance of extreme events.

Harvests decrease in all simulations by up to 14.52%, with an average deviation of −4.6% and, in 10% of cases, decrease by at least 7.7%. Product prices increase for all products, with average changes between +0.66% and +3.9%. The latter value concerns softwood roundwood, which corresponds to the type of resource most exposed and sensitive to storms. In a few simulations, prices do not change or even decrease, although by less than 1%. This corresponds to simulations with few and minor storms, where the salvage effect compensates inventory losses. The positive impact on prices concerns 93%–100% of simulations depending on products. The evolution of product supply mirrors that of prices, albeit with lower relative changes compared to the baseline (−0.06% to −0.7% on average). In 6%–15% of simulations, depending on products, supply increases owing to interplays between the timing and magnitude of storms and the salvage effect.

Consumer surplus decreases on average by −0.27%, showing that decreases in price during the salvage period do not compensate for longer-term impacts. In 13% of simulations, consumer surplus increases to a limited extent (e.g. +0.01% to +0.03%). Producer surplus increases in all simulations (+1.44% on average).

Table 2. Impacts of a single major storm on the forest sector.

	Salvage period		Short-term		Long-term	
	(2020–2022)		(2023–2027)		(2028–2050)	
Growing inventory	−319,5	(−10,78%)	−332,93	(−10,64%)	−519,66	(−13%)
AlsChaLor	−0,25	(−0,06%)	−0,83	(−0,17%)	−23,64	(−3,64%)
AquPoi	−43,15	(−13,78%)	−41,95	(−12,64%)	−63,7	(−15,78%)
AuvLim	−152,9	(−47,74%)	−158,09	(−47,18%)	−189,8	(−45,45%)
Forest carbon	−26,35	(−0,47%)	−165,32	(−2,75%)	−695,12	(−9,15%)
AlsChaLor	−0,36	(−0,04%)	−1,39	(−0,15%)	−31,31	(−2,6%)
AquPoi	−0,53	(−0,09%)	−17,86	(−2,7%)	−86,97	(−10,84%)
AuvLim	−25,81	(−4,25%)	−86,82	(−13,47%)	−255,56	(−32,47%)
Products carbon	+7,53	(+2,1%)	−1,2	(−0,33%)	−17,59	(−4,58%)
AlsChaLor	+0,94	(+1,32%)	+0,08	(+0,1%)	−2,05	(−2,62%)
AquPoi	+2,28	(+3,34%)	−0,5	(−0,72%)	−5,8	(−7,87%)
AuvLim	+0,83	(+2,72%)	−0,37	(−1,19%)	−2,4	(−7,6%)
Harvest levels	−59,9	(−66,8%)	−23,76	(−10,54%)	−37,21	(−3,47%)
AlsChaLor	+0,22	(+1,43%)	+1,21	(+3,1%)	+17,33	(+9,11%)
AquPoi	−15,14	(−100%)	−9,06	(−23,54%)	−18,31	(−9,66%)
AuvLim	−9,2	(−100%)	−12,88	(−56,03%)	−53,8	(−52,7%)
Consumer surplus	+989,04	(+9,08%)	−704,99	(−2,56%)	−6203,13	(−4,8%)
AlsChaLor	+170,67	(+8,31%)	−79,99	(−1,54%)	−950,79	(−3,89%)
AquPoi	+218,31	(+10,09%)	−185,03	(−3,38%)	−1481,31	(−5,77%)
AuvLim	+128,23	(+18,17%)	−106,25	(−5,94%)	−936,53	(−10,91%)
Producer surplus	−1137,31	(−31,08%)	+1832,94	(+20,44%)	+5303,45	(+13,29%)
AlsChaLor	+13,13	(+2,15%)	+215,98	(+14,37%)	+1639,18	(+24,03%)
AquPoi	−242,33	(−42,75%)	+639,77	(+45,61%)	+825,67	(+12,69%)
AuvLim	−569,62	(−166,59%)	+62,22	(+7,51%)	−1265,48	(−36,88%)
Supply	+6,88	(+16,75%)	−5,89	(−5,69%)	−43,61	(−8,86%)
AlsChaLor	−0,41	(−5,21%)	+2,3	(+11,71%)	+10,63	(+11,74%)
AquPoi	+2,98	(+31,68%)	−1,03	(−4,26%)	−14,59	(−11,98%)
AuvLim	+1,37	(+21,67%)	−9,2	(−57,97%)	−42,78	(−57,43%)
Price	−10,44	(−13,21%)	+22,68	(+29,53%)	+21,94	(+31,2%)

Note: values are relative to a no-storm scenario. For growing inventory, forest carbon and products carbon, values are reported for the final year in the period. Prices and supply are given for softwood roundwood.

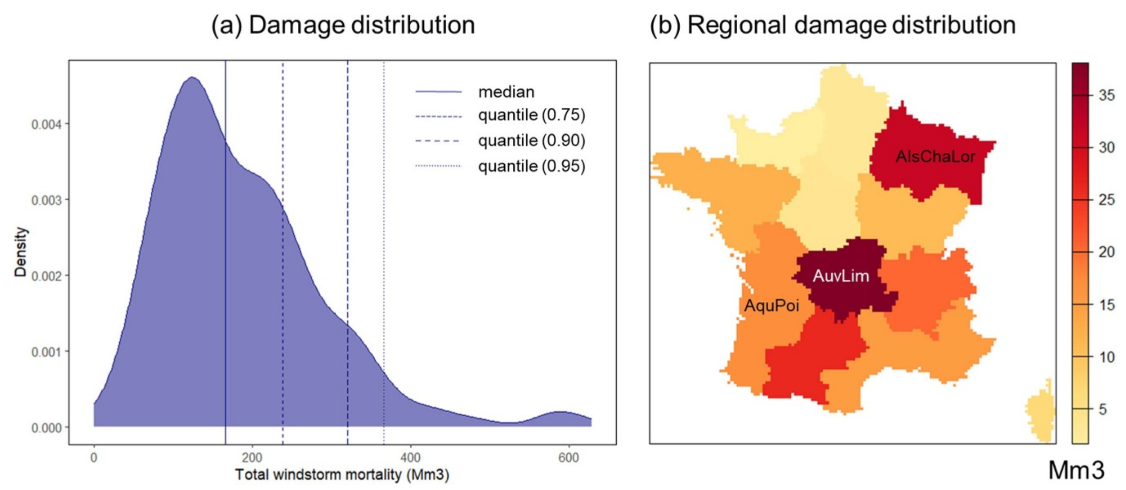

Figure 3. Distribution of storm damages in Monte Carlo simulations. Density function of cumulative damages (a) and regional distribution of annual damage (b).

Table 3. Average impacts of storm regimes in Monte Carlo simulations compared to the baseline. q10 and q90 correspond to the bottom and top deciles. $N \geqslant 0$ shows how many simulations, out of all 300 performed, display a positive change relative to the baseline, for each variable.

Variable	Min		Mean		Max		q10		Median		q90		$N \geqslant 0$
Storm mortality (Mm3)	+0,33	—	+4,82	—	+16,53	—	+1,89	—	+4,32	—	+8,43	—	—
Growing stock (Mm3)	−798,71	(−19,99%)	−189,19	(−4,73%)	−16,73	(−0,42%)	−343,04	(−8,58%)	−160,17	(−4,01%)	−69,89	(−1,75%)	0%
Harvest level (Mm3)	−6,66	(−14,52%)	−2,11	(−4,6%)	−0,09	(−0,21%)	−3,56	(−7,77%)	−1,91	(−4,16%)	−0,88	(−1,91%)	0%
Producer surplus (M€)	+9,03	(+0,02%)	+598,73	(+1,44%)	+3618,66	(+8,72%)	+133,64	(+0,32%)	+441,39	(+1,06%)	+1223,14	(+2,95%)	100%
Consumer surplus (M€)	−2693,82	(−2,11%)	−346,05	(−0,27%)	+378,01	(+0,3%)	−888,25	(−0,7%)	−213,02	(−0,17%)	+13,66	(+0,01%)	13%
Supply—softwood (Mm3)	−1,12	(−5,31%)	−0,15	(−0,7%)	+0,2	(+0,93%)	−0,37	(−1,77%)	−0,09	(−0,43%)	+0,01	(+0,06%)	13%
Prices—softwood (€/Mm3)	+0,07	(+0,1%)	+2,89	(+3,9%)	+17,06	(+23,03%)	+0,74	(+0,99%)	+2,15	(+2,9%)	+5,79	(+7,82%)	100%
Supply—hardwood (Mm3)	−0,04	(−0,76%)	+0	(−0,06%)	+0,01	(+0,24%)	−0,01	(−0,17%)	+0	(−0,04%)	+0	(+0,03%)	15%
Prices—hardwood (€/Mm3)	−0,15	(−0,15%)	+0,66	(+0,66%)	+5,59	(+5,62%)	+0,09	(+0,09%)	+0,42	(+0,42%)	+1,59	(+1,6%)	98%
Supply—fuelwood (Mm3)	−0,44	(−1,15%)	−0,06	(−0,16%)	+0,1	(+0,26%)	−0,12	(−0,33%)	−0,05	(−0,13%)	−0,01	(−0,02%)	6%
Prices—fuelwood (€/Mm3)	−0,24	(−0,84%)	+0,29	(+0,99%)	+2,51	(+8,66%)	+0,01	(+0,04%)	+0,18	(+0,61%)	+0,72	(+2,49%)	93%
Carbon sequestration (MtCO2eq/year)	−58,85	(−76,58%)	−7,56	(−9,83%)	−0,08	(−0,1%)	−18,4	(−23,94%)	−4,54	(−5,91%)	−1,42	(−1,85%)	0%

Table 4. Distribution of recovery times after storms.

Recovery time	⩽2	3	4	5	⩾6	Total
Nb. storms	286	59	33	8	10	396
	72%	15%	8%	2%	3%	100%

4. Discussion

4.1. Resilience of the forest's carbon sink and climate policy

Previous research has shown that storms have impacts on carbon balance of the same order of magnitude as forest-based mitigation efforts, potentially offsetting them (Seidl *et al* 2014, Reyer *et al* 2017). Our results stress the high variability of such impacts. For instance, 25% of simulations displayed a reduction of at least 24% in carbon sequestration. This stresses the importance of taking into account uncertainty in the occurrence and magnitude of storms.

Many policy strategies rely on modeling that either omits disturbances or only considers them deterministically. Upon request from the French Ministry for agriculture, Roux *et al* (2020) produced estimates of the forest sector's potential contribution to mitigation by 2050. Their assessment used several forest inventory, carbon budget and economic models. It considered both disturbances (wildfires, storms, pests) and the impacts of climate change on forest growth. Disturbances were simulated deterministically, and only one disturbance event of each kind was assessed (e.g. one major storm). While this assessment had a wide coverage, it remained an illustrative example of a given disturbance event. Similarly, the French National Low-Carbon Strategy (MTECT 2020) relies on model simulations that take into account climate-induced mortality crises, but fail to explicitly represent disturbance events and the stochasticity of their regimes.

Basing decisions on such results impedes policymakers from appropriately weighing their decisions against potential risks. It omits important pieces of information, such as the probability distribution of impacts, estimates of the risk of deviating from objectives, etc. Having access to them enables one to arbitrate between different levels of ambition and resilience for an objective, e.g. choosing less ambitious sequestration targets (and simultaneously more ambitious emission reduction targets) if the risk of failure is too high. For this reason, we advise that prospective modeling exercises performed to inform policy making be more often based on probabilistic/stochastic modeling when possible.

4.2. Spatial and distributional effect along the value chain

We showed that damage was largely driven by the occurrence of extreme but rare events, in accordance with the specialized literature (Outten and Sobolowski 2021). Damage was spatially heterogeneous and, on average, affected 0.19% of growing stocks yearly in our simulations, a value which is of the same order of magnitude as those observed over the past decades (Patacca *et al* 2023).

From an economic viewpoint, our results highlight the existence of a phase where the abundance of damaged timber prompts forest owners to sell, leading to price decreases. This stresses the importance of salvage, which temporarily substitutes for regular harvests. Besides, how timber suppliers react to the availability of salvaged wood affects prices and welfare. Afterwards, there is a second phase where long-term losses of timber inventory durably inflate product prices. The existence of these temporally adjacent effects has been predicted by economic theory (Prestemon and Holmes 2008) and is corroborated by the few studies that have been performed when post-storm market data was available (e.g. Henderson *et al* 2022). Our study, which uses a large-scale integrated model and performs repeated simulations over a large sample of storms confirms and consolidates the existence of these dynamics.

Two kinds of transfers of economic welfare occur within the forest sector: along the value chain and between impacted and non-impacted regions. Immediately following a storm, consumers of wood products benefit from low prices while forest owners lose welfare. After the salvage phase, only forest owners in the most affected areas incur long-term losses (inventory effect), while owners in moderately affected locations see their economic surplus increase (price effect). Interestingly, we highlight increases in the welfare of forest owners in non-affected regions, who increase harvests to benefit from inflated prices (windfall profits). This result reveals a spatial propagation of storm effects which is enabled by the existence of a spatial price equilibrium. This propagation bears environmental consequences because it indirectly reduces carbon sequestration in non-affected regions in addition to direct losses in affected locations. This fits economic theory (Prestemon and Holmes 2010) but could not be satisfyingly proved empirically (e.g. Prestemon and Holmes 2000), suggesting needs for additional research, even though long data series need to be available.

From a policy perspective, heterogeneous spatial impacts suggest exploring systems of mutual insurance where forest owners contribute to a risk-sharing mechanism. Such a system already exists in some countries (Sacchelli *et al* 2018) and would contribute to reducing welfare transfers by compensating the owners of damaged forests. For a given storm situation, forest owners in regions less commonly affected may have no interest in entering the mechanism. However, uncertainty surrounding storm location and intensity is high, and extreme storm events are expected to become more common (Patacca *et al*

2023). Both reasons suggest a risk-sharing mechanism could be attractive overall. Attractiveness could also be increased through state subsidy to the insurer (Loisel *et al* 2020). In addition, the literature shows that such a scheme tends to extend rotation lengths, leading to co-benefits in terms of carbon storage (Loisel *et al* 2020) and climate change adaptation (Brunette *et al* 2017).

4.3. Modeling shortcomings

Our approach suffers from shortcomings regarding the modeling of storm damage. The use of a process-based approach, while common and suitable for an exploratory assessment, does not align as closely with empirical observations as a statistical model might. Notably, our focus on wind speed overlooked other contributors such as soil composition and landscape structure (Gardiner 2021). Besides, damage estimation was primarily based on the behavior of the most prevalent tree species nationally. This approach may introduce bias in regions where species exhibiting different characteristics are abundant, e.g. pine plantations in the South-West. These decisions were driven by the necessity to align with data available in a large-scale forest sector model. Future enhancements should consider incorporating region-specific or species-level damage modeling.

Storms interact with other disturbances (Seidl *et al* 2017). For instance, susceptibility to pathogens increases following storms. Additionally, while less conclusive than studies on e.g. wildfires, there is growing evidence that climate change will intensify storm regimes, especially extreme event patterns, and interactions between disturbances (Seidl and Rammer 2017, Seidl *et al* 2017, Outten and Sobolowski 2021). Our study, designed as an exploration of the economic and environmental dynamics following storm events in a stochastic setting, omitted these factors and likely underestimated impacts. Future assessments should aim to encompass multiple risks, their interactions, and the influence of climate change, for a more comprehensive analysis. Finally, future work could also investigate how economic agents could coordinate to optimize the use of salvaged wood at the sectoral scale.

5. Conclusion

Our bio-economic analysis sheds light on the intricate interplay between salvage and inventory effects resulting from storms, driving dynamic fluctuations in timber harvests and prices. Directly impacted by storms, timber prices experience a significant initial decrease, followed by a subsequent increase. This pattern induces temporary transfers of economic welfare, disadvantaging producers in the short term and consumers in the long term. Our study further uncovers a spatial propagation of these effects, with forest owners in non-affected regions benefiting from inflated prices. Leveraging Monte Carlo simulations, our research demonstrates the sectoral-scale applicability of these dynamics across a wide range of storm scenarios, emphasizing the pivotal role of extreme event timing. Our research advocates for the development of risk-sharing insurance mechanisms tailored to forest owners, providing a buffer against economic uncertainties arising from climatic disruptions.

From an environmental standpoint, our findings underscore the substantial impact of storm risk on the carbon balance of the forest sector. We showed that a significant 23% of storms modeled induced a loss of forest inventory during 3–4 years while, in 5% of cases, 5 or more years were necessary for forests to reconstitute. More importantly, our model reveals high uncertainties in these dynamics, with 25% of simulations predicting a significant 24% decrease in carbon sequestration.

This work gives useful guidelines for GHG inventories (IPCC 2019) and NDCs (Taibi *et al* 2020), suggesting methodologies to assess the risk of non-permanence of carbon sinks when facing stochastic events. Further, it highlights for policy makers the need for (1) robust risk-management strategies, particularly in the face of a changing climate and escalating disturbance regimes, and (2) conservative reliance on carbon sinks (hence stronger reliance on emission reductions) when countries outline their climate strategies and Intended Nationally Determined Contributions.

Finally, our work prompts researchers to consider stochastic disturbance events in large-scale prospective modeling in order to offer insights for decision-makers grappling with climate resilience targets and the potential consequences of falling short.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.10717009 (Riviere 2024).

Acknowledgments

The UMR BETA is supported by a grant overseen by the French National Research Agency (ANR) as part of the 'Investissements d'Avenir' programme (ANR-11-LABX-0002-01, Lab of Excellence ARBRE). We are also grateful to the french ministry of Agriculture and food Sovereignty that funded the research activities. This research is part of the Agriculture and Forestry research program by the Climate Economics Chair. The authors would like to thank Dr B Gardiner and Dr H Jactel for their insights on disturbance modelling, and Dr C Guivarch and Dr F Clayes.

Author contributions

Félix Bastit: Writing, Investigation, Methodology, Conceptualization. **Miguel Riviere**: Writing, Investigation, Supervision, Conceptualization. **Philippe Delacote**: Supervision, Conceptualization. **Antonello Lobianco**: Software, Methodology.

ORCID iDs

Miguel Riviere https://orcid.org/0000-0003-3469-9588
Antonello Lobianco https://orcid.org/0000-0002-1534-8697
Philippe Delacote https://orcid.org/0000-0002-9888-7193

References

Académie des sciences 2023 Les forêts françaises face au changement climatique *Rapport du Comité des sciences de l'environnement de l'Académie des sciences et points de vue d'Académiciens de l'Académie d'Agriculture de France—juin 2023*

Anderegg W R *et al* 2020 Climate-driven risks to the climate mitigation potential of forests *Science* **368** eaaz7005

Bastit F, Brunette M and Montagné-Huck C 2023 Pests, wind and fire: a multi-hazard risk review for natural disturbances in forests *Ecol. Econ.* **205** 107702

Brunette M, Couture S and Pannequin F 2017 Is forest insurance a relevant vector to induce adaptation efforts to climate change? *Ann. For. Sci.* **74** 1–8

Buck H J, Carton W, Lund J F and Markusson N 2023 Why residual emissions matter right now *Nat. Clim. Change* **13** 351–8

Caurla S, Bertrand V, Delacote P and Le Cadre E 2018 Heat or power: how to increase the use of energy wood at the lowest cost? *Energy Econ.* **75** 85–103

Caurla S, Garcia S and Niedzwiedz A 2015 Store or export? An economic evaluation of financial compensation to forest sector after windstorm. The case of Hurricane Klaus *Forest Policy Econ.* **61** 30–38

Caurla S, Lecocq F, Delacote P and Barkaoui A 2010 The French forest sector model: version 1.0. presentation and theorical foundations (Documents de Travail. INRA, Laboratoire d'Economie Forestière (LEF)) p 41 (available at: https://hal.science/hal-01189498)

Chen Y Y *et al* 2018 Simulating damage for wind storms in the land surface model ORCHIDEE-CAN (revision 4262) *Geosci. Model Dev.* **11** 771–91

Chen Y Y, Huang W, Cheng C T, Hong J S, Yeh F L and Luyssaert S 2022 Simulation of the impact of environmental disturbances on forest biomass in Taiwan *J. Geophys. Res.* **127** e2021JG006519

Chudy R P, Sjølie H K and Solberg B 2016 Incorporating risk in forest sector modeling–state of the art and promising paths for future research *Scand. J. For. Res.* **31** 719–27

Costa S, Lecocq M, Drouineau S and Peyron J L 2009 Evaluation of the pecuniary losses suffered by forest owners as a result of the Klaus storm-damage to the maritime pine *Revue Forestière Française* **61** 49–66

Fahey T J, Woodbury P B, Battles J J, Goodale C L, Hamburg S P, Ollinger S V and Woodall C W 2010 Forest carbon storage: ecology, management, and policy *Front. Ecol. Environ.* **8** 245–52

Faustmann M 1849 Berechnung des Werthes, welchen Waldboden, sowie noch nicht haubare Holzbestande fur die Waldwirthschaft besitzen [Calculation of the value which forest land and immature stands possess for forestry] *Allgemeine Fotst-und Jagd-Zeitung* **25** 441–55

Gardiner B 2021 Wind damage to forests and trees: a review with an emphasis on planted and managed forests *J. For. Res.* **26** 248–66

Gardiner B, Schuck A R T, Schelhaas M J, Orazio C, Blennow K and Nicoll B (eds) 2013 *Living with Storm Damage to Forests* vol 3 (European Forest Institute) p 129

Hale S E, Gardiner B, Peace A, Nicoll B, Taylor P and Pizzirani S 2015 Comparison and validation of three versions of a forest wind risk model *Environ. Model. Softw.* **68** 27–41

Henderson B, Frezal C and Flynn E 2020 A survey of GHG mitigation policies for the agriculture, forestry and other land use sector

Henderson J D, Abt R C, Abt K L, Baker J and Sheffield R 2022 Impacts of hurricanes on forest markets and economic welfare: the case of hurricane Michael *For. Policy Econ.* **140** 102735

Honkomp T and Schier F 2023 Scoping review of carbon pricing systems in forest sector models *Environ. Res. Lett.* **19** 013001

IGN 2009 Tempête Klaus du 24 janvier 2009. L'If, n°21

IGN 2023 Mémento edn (available at: www.ign.fr/files/default/2023-10/memento_oct_2023.pdf)

IPCC 2019 *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories ed E* Calvo Buendia, K Tanabe, A Kranjc, J Baasansuren, M Fukuda, S Ngarize, A Osako, Y Pyrozhenko, P Shermanau and S Federici (IPCC)

IPCC 2006 2006 IPCC guidelines for national greenhouse gas inventories *Prepared by the National Greenhouse Gas Inventories Programme ed H S* Eggleston, L Buendia, K Miwa, T Ngara and K Tanabe(IGES)

Knoke T, Paul C, Gosling E, Jarisch I, Mohr J and Seidl R 2023 Assessing the economic resilience of different management systems to severe forest disturbance *Environ. Resour. Econ.* **84** 343–81

Latta G S, Sjølie H K and Solberg B 2013 A review of recent developments and applications of partial equilibrium models of the forest sector *J. For. Econ.* **19** 350–60

Lobianco A, Delacote P, Caurla S and Barkaoui A 2015 The importance of introducing spatial heterogeneity in bio-economic forest models: insights gleaned from FFSM++ *Ecol. Modell.* **309** 82–92

Lobianco A, Delacote P, Caurla S and Barkaoui A 2016 Accounting for active management and risk attitude in forest sector models: an impact study on French forests *Environ. Model. Assess.* **21** 391–405

Lockwood J F, Guentchev G S, Alabaster A, Brown S J, Palin E J, Roberts M J and Thornton H E 2022 Using high-resolution global climate models from the PRIMAVERA project to create a European winter windstorm event set *Nat. Hazards Earth Syst. Sci.* **22** 3585–606

Loisel P, Brunette M and Couture S 2020 Insurance and forest rotation decisions under storm risk *Environ. Resour. Econ.* **76** 347–67

Miguel R 2024 Data supporting "Prospective impacts of windstorm risk on carbon sinks and the forestry sector: 1 an integrated assessment with Monte-Carlo simulations" (https://doi.org/10.5281/zenodo.10717009)

Montagné-Huck C and Brunette M 2018 Economic analysis of natural forest disturbances: a century of research *J. For. Econ.* **32** 42–71

MTECT 2020 National low carbon strategy. Ministry for the ecological and solidary transition (available at: https://www.ecologie.gouv.fr/sites/default/files/documents/en_SNBC-2_complete.pdf)

Nabuurs G J Arets E J and Schelhaas M J 2018 Understanding the implications of the EU-LULUCF regulation for the wood supply from EU forests to the EU *Carbon Balance Manage.* **13** 1–10

Outten S and Sobolowski S 2021 Extreme wind projections over Europe from the Euro-CORDEX regional climate models *Weather Clim. Extrem.* **33** 100363

Patacca M *et al* 2023 Significant increase in natural disturbance impacts on European forests since 1950 *Glob. Change Biol.* **29** 1359–76

Petucco C, Lobianco A and Caurla S 2020 Economic evaluation of an invasive forest pathogen at a large scale: the case of ash dieback in France *Environ. Model. Assess.* **25** 1–21

Pilli R, Grassi G, Kurz W A, Moris J V and Viñas R A 2016 Modelling forest carbon stock changes as affected by harvest and natural disturbances. II. EU-level analysis *Carbon Balance Manage.* **11** 1–19

Pilli R, Vizzarri M and Chirici G 2021 Combined effects of natural disturbances and management on forest carbon sequestration: the case of Vaia storm in Italy *Ann. For. Sci.* **78** 46

Prestemon J P and Holmes T P 2000 Timber price dynamics following a natural catastrophe *Am. J. Agric. Environ.* **82** 145–60

Prestemon J P and Holmes T P 2010 *Economic Impacts of Hurricanes on Forest Owners ed J M* Pye, H M Rauscher, Y Sands and D C Lee (United States Department of Agriculture (USDA)) pp 207–21

Prestemon J P and Holmes T P 2008 Timber salvage economics *The Economics of Forest Disturbances: Wildfires, Storms and Invasive Species ed T* Holmes, J Prestemon and K Abt (Springer) pp 167–90

Reed W J 1984 The effects of the risk of fire on the optimal rotation of a forest *J. Environ. Econ. Manage.* **11** 180–90

Reyer C P *et al* 2017 Are forest disturbances amplifying or canceling out climate change-induced productivity changes in European forests? *Environ. Res. Lett.* **12** 034027

Rivière M and Caurla S 2020 Representations of the forest sector in economic models *Œconomia Hist. Methodol. Philos.* **10-3** 521–53 (available at: https://journals.openedition.org/oeconomia/9418)

Riviere M and Caurla S 2021 Landscape implications of managing forests for carbon sequestration *Int. J. For. Res.* **94** 70–85

Riviere M, Pimont F, Delacote P, Caurla S, Ruffault J, Lobianco A, Opitz T and Dupuy J L 2022 A bioeconomic projection of climate-induced wildfire risk in the forest sector *Earth's Future* **10** e2021EF002433

Roux A, Colin A, Dhôte J F and Schmitt B, 2020. *The Forestry & Wood Sector and Climate Change Mitigation: From Carbon Sequestration in Forests to the Development of the Bioeconomy* (Quae)

Sacchelli S, Cipollaro M and Fabbrizzi S 2018 A GIS-based model for multiscale forest insurance analysis: the Italian case study *For. Policy Econ.* **92** 106–18

Samuelson P A 1952 Spatial price equilibrium and linear programming *Am. Econ. Rev.* **42** 283–303 (available at: www.jstor.org/stable/1810381)

Sato I, Langer P and Stolle F 2019 Enhancing NDCs: opportunities in the forest and land-use sector *Working Paper* (World Resources Institute and United Nations Development Programme) (available at: www.wri.org/publication/enhancing-ndcs-forest)

Sauquet A, Lecocq F, Delacote P, Caurla S, Barkaoui A and Garcia S 2011 Estimating Armington elasticities for sawnwood and application to the French Forest Sector Model *Resour. Energy Econ.* **33** 771–81

Seidl R *et al* 2017 Forest disturbances under climate change *Nat. Clim. Change* **7** 395–402

Seidl R and Rammer W 2017 Climate change amplifies the interactions between wind and bark beetle disturbances in forest landscapes *Landsc. Ecol.* **32** 1485–98

Seidl R, Schelhaas M J, Rammer W and Verkerk P J 2014 Increasing forest disturbances in Europe and their impact on carbon storage *Nat. Clim. Change* **4** 806–10

Senf C and Seidl R 2021 Mapping the forest disturbance regimes of Europe *Nat. Sustain.* **4** 63–70

Taibi F-Z, Konrad S and Bois von Kursk O 2020 *Pocket Guide to NDCs under the UNFCCC* (European Capacity Building Initiative)

VEM 2021 Veille économique mutualisée (available at: https://vem-fb.fr/)