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Par **Félix BASTIT**

Sous la direction de Marielle BRUNETTE

An Economic Approach of Multiple Risks in Forests

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Membres du jury :

Directrice de thèse :	**Mme Marielle BRUNETTE**	Directrice de recherche INRAE, BETA, NANCY
Président de jury :	**M. Jean-Philippe TERREAUX**	Ingénieur général des Ponts, des Eaux et des Forêts, INRAE, CESTAS
Rapporteurs :	**Mme Katrin ERDLENBRUCH**	Directrice de Recherche INRAE, CEE-M, MONTPELLIER
	M. Hubert STAHN	Professeur des universités, AMSE, AIX-EN-PROVENCE
Examinateur :	**M. Denis ALLARD**	Directeur de Recherche INRAE, BioSP, AVIGNON

An economic approach of multiple risks in forests

Forests are a major natural resource in Europe. It covers 33% of the territory, accounts for 0.2% of European GDP and provides 3.6 million jobs. European forests are also the source of numerous ecosystem services such as wood production and carbon storage. However, they are subject to numerous hazards: wildfires, windstorms, droughts, insect outbreaks, etc., which threaten the provision of these services. In addition, climate change is increasing the probability and intensity of these hazards, as well as their interactions. From an economic point of view, two main risks arise from the occurrence of natural hazards: a production risk (wood and carbon storage) and a market risk (price volatility).

The literature has focused on wood production risk at stand scale, since this is the relevant scale for forest management decisions. However, this is not the right scale for modeling large-scale natural hazards, nor for modeling the effects of price changes. In this thesis, we have therefore decided to work at several different spatial scales: stand, regional, country and continent. Furthermore, potential interactions between natural hazards have rarely been considered, even though they could lead to phenomena of unprecedented magnitude. Price risk has also been studied extensively in the literature, but generally independently of production risk, even though there is a strong correlation between the two, as demonstrated by price falls after major historical storms. In this thesis, we will try to take this correlation into account.

This work is divided into four parts. Firstly, a review of the forest economics literature shows the current limitations and the most promising avenues of research. The main conclusion of this work is that natural hazards are generally considered independent in forest economics, whereas ecological models are more inclusive.

In response to this, in the second chapter we decided to abandon the classical forest economics model to study the resilience of a self-sufficient regional timber market to generic hazards of catastrophic magnitude. We have studied the levels of hazards and acceptable return times to ensure the stability of long-term market equilibrium.

In the third chapter, we applied this model more precisely to the French forestry sector, using a recursive partial equilibrium model (French Forest Sector Model). A spatially explicit simulation module for windstorms and insect outbreaks was developed. This enabled us to establish results on the strategies of the various economic actors in the sector in the event of the occurrence of interacting natural hazards. We also studied the desirable public policies to be implemented in anticipation of the occurrence of major storms. We then discussed the robustness of public policies to mitigate climate change, such as intended nationally determined contributions from the Paris Agreement, facing natural disturbances.

In the final chapter, the potential cost of climate change based on wood production at European level was estimated, including the four economically significant tree species in Europe. We have shown that losses due to catastrophic natural hazards are likely to increase significantly as a result of climate change, but that some of these losses will be offset by gains in forest productivity. These effects are, however, spatially very heterogeneous, leading to winners and losers, for whom climate change mitigation strategies could prove all the more complicated to implement in the event of a reduction in their forest carbon sink.

Une approche économique des risques multiples en forêt

La forêt est une ressource majeure en Europe. Elle occupe 33% du territoire, représente 0,2% du PIB européen et 3,6 millions d'emplois. La forêt européenne est aussi la source de nombreux services écosystémiques tels que la production de bois et le stockage de carbone. Cependant, elle subit de nombreux aléas : feux, tempêtes, sécheresses, pullulations d'insectes, etc. qui menacent la provision de ces services. De plus, sous l'effet du changement climatique, la probabilité et l'intensité de ces aléas augmentent ainsi que leurs interactions. Du point de vue économique deux risques principaux découlent de l'occurrence des aléas naturels : un risque de production (de bois et de stockage de carbone) et un risque de marché.

La littérature s'est concentrée sur le risque de production de bois à l'échelle de la parcelle, puisque c'est l'échelle pertinente pour la décision de gestion forestière. Ce n'est néanmoins pas la bonne échelle pour modéliser les aléas naturels de grande ampleur, ni pour modéliser des effets de changements de prix. Dans cette thèse, nous avons donc pris le parti de travailler à plusieurs échelles spatiales. Par ailleurs, les interactions potentielles entre aléas naturels sont également jusqu'à maintenant rarement considérées, alors même qu'elles pourraient mener à des phénomènes d'une ampleur inédite. Le risque de prix a aussi été beaucoup étudié dans la littérature, mais généralement indépendamment du risque de production alors même qu'il existe une forte corrélation entre les deux, comme l'ont montré les chutes de prix après les grandes tempêtes historiques. Dans cette thèse, nous tâcherons donc de prendre en compte cette corrélation.

Ce travail s'articule autour de quatre parties. Tout d'abord, une revue de la littérature d'économie forestière a montré quelles étaient les limites actuelles et les pistes de recherche les plus prometteuses. La conclusion principale de ce travail est que les aléas naturels sont généralement considérés comme indépendants en économie forestière, alors que les modèles écologiques sont plus inclusifs.

En réponse à cela, dans le deuxième chapitre, nous avons décidé d'abandonner le modèle classique d'économie forestière pour étudier la résilience d'un marché autarcique de bois à l'échelle régionale face à des aléas génériques d'ampleur catastrophique. Nous avons étudié les niveaux d'aléas et les temps de retour acceptables pour assurer la stabilité des équilibres de long terme du marché.

Ce modèle a, dans le troisième chapitre, été appliqué plus précisément au contexte du secteur forestier français grâce à modèle récursif d'équilibre partiel (French Forest Sector Model). Un module de simulation spatialement explicite de tempêtes et de pullulation d'insectes y a été ajouté. Cela nous a permis d'établir des résultats sur les stratégies des différents acteurs de la filière en cas d'occurrence d'aléas naturels en interaction. Nous avons aussi étudié les politiques publiques souhaitables à mettre en œuvre en prévision des occurrences de grandes tempêtes. Puis, nous avons discuté la robustesse des politiques publiques d'atténuation du changement climatique.

Dans le dernier chapitre, le coût potentiel du changement climatique basé sur la production de bois à l'échelle européenne a été estimé en incluant les quatre essences économiquement significatives en Europe. Nous avons montré que les pertes dues aux aléas naturels catastrophiques devraient significativement augmenter à cause du changement climatique mais qu'une partie serait compensée par des gains de productivité des forêts. Ces effets sont néanmoins spatialement très hétérogènes, ce qui mènera à des gagnants et à des perdants, pour qui la stratégie d'atténuation au changement climatique pourrait s'avérer d'autant plus compliquée à mettre en œuvre en cas de diminution de leur puits forestier de carbone.

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[1]Que j'ai eu la chance de rencontrer au cours de ma thèse en forêt de Chantilly

Future generations are unlikely to condone our lack of prudent concern for the integrity of the natural world that supports all life. There is still very limited awareness of the nature of the threat. This is an era of specialists, each of whom sees his own problem and is unaware of or intolerant of the larger frame into which it fits.

Rachel Carson, Silent Spring (1962)

-Mais il y a tant de choses simples, [...] que c'est l'ensemble qui devient compliqué, et que l'on perd de vue. Il faudrait pouvoir regarder ça de très haut.
-Et alors, dit Lil, on sera effrayé de voir que tout est très simple.

Boris Vian, L'herbe rouge

À mes aïeux.

Publications

Peer-reviewed publication included in this thesis

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Other peer-reviewed publication

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Other publications

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URL: https://theconversation.com/secheresses-incendies-et-maladies-les-risques-en-cascade-qui-menacent-les-forets-francaises-157448

Bastit, F., & Sergent, A. (2023). "Quel rôle pour les politiques publiques dans la gestion des crises ?": synthèse de l'atelier. *Revue forestière française*, 74(2).
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Conferences

Conferences with selection committee

European Association of Environment and Resource Economists, Berlin (Online), 23-25 June 2021. Oral parallel session: *Earth, wind and fire: A multi-hazard risk review for natural disturbances in forest.*

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French Association of Environmental and Resource Economists, Rouen, 8-9 September 2022. Oral parallel session: *Stability and resilience of a forest bio-economic equilibrium under natural disturbances.*

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Other conferences and workshops

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Introduction

0.1 Context

0.1.1 European forests: an endangered resource

European forests are a major resource, representing 227 million hectares (equivalent to 4 times the metropolitan French territory) (FOREST EUROPE, 2020), or 35% of the total European area, storing 35 billion m^3 of timber (FOREST EUROPE, 2020), and accumulating more than 10 billion tonnes of carbon in living biomass (Mauser, 2022). European forests are primarily temperate forests in Western and Central Europe (45% of the total forest surface), boreal forests in Scandinavia (40%), Alpine forests in mountainous regions (10%) and Mediterranean forests (5%) in Southern countries, bordering the Mediterranean Sea (European Environment Agency, 2017). These diverse forests are the source of a large number of ecosystem services, which pertain to the benefits and resources that humans obtain from forests. This includes provisioning services, such as food, water or timber, regulating services, this is the case for floods, climate or water quality, but also cultural services, in particular recreation, landscape aesthetics or spiritual purpose, and supporting services, especially for soil formation and nutrient cycling (Millennium Ecosystem Assessment, 2005). All of these services are significant contributors to human well-being. In particular, the timber sector represent 0.2% of the European GDP and employs at the European scale 560 thousand people in the direct forestry and logging industry and 3.6 million people in all forest-based activities, i.e. manufacture of products, paper, furniture (EUROSTAT, 2022, 2023).

European forests are an important natural resource at the European scale but are also facing several natural disturbances such as windstorms, wildfires, insects outbreaks, ice and snow storms, pathogens, browsing, etc. Natural disturbances are a part of ecosystem dynamic, because each forested ecosystem has evolved under a given regime of disturbance, so that disturbances have shaped forests over long periods of time.[2] But their effects are still important. Patacca et al. (2023) tried to exhaustively measure the impacts of natural disturbances that struck Europe between 1950 and 2019. Their work was based on more than 170,000 records from 600 different sources. The average damages over these decades were estimated at 62.1 Mm^3/yr. During the period 1950-2000, Schelhaas et al. (2003) stated that disturbed volumes represented more than 8% of the total yearly harvest. Windstorms caused 46% of the total damages (24 Mm^3/yr) on the total period but two decades were remarkable (Patacca et al., 2023): the 1990s with 47.8 Mm^3/yr (due to Vivan and Wiebke in 1990 and Lothar and Martin in 1999) and 2000s with 38.8 Mm^3/yr (due to Gudrun in 2005, Kyrill in 2007 and Klaus in 2009). Wildfires were also a significant disturbance in European forests, accounting for 24% of total damage and bark beetles for 17% (Patacca et al., 2023).

Damages due to natural disturbances was high in the past but, more importantly, are currently strongly increasing. The impact of fire has, for example, risen considerably between 1950 and 2019 across Europe with a sharp increase in the 1970s (Patacca et al., 2023). The wildfire regime is characterized by catastrophic fire years at the regional scale due to particularly fire prone climatic conditions. Finally, bark beetles represented only 1/6 of the total damages in the 70-year period, but during the 2010s, bark beetles' damages rose to become comparable to windstorms damages (23 Mm^3/yr). Overall, damages from disturbances rose from 42.6 Mm^3/yr for the period 1970-2000 to 78.5 Mm^3/yr for the period 2000-2019, almost doubling (Patacca et al., 2023). A share of this increase can be explained by the increase of the total European growing stock over the period: if there is more timber in the forest, we can expect the damages to be larger. But even in terms of the share of total growing stock (i.e. the volume damaged divided by the total volume of timber in the forest), damages represented

[2]Some species have, for example, evolved to become fire resistant, such as cork oak (*Quercus suber*), in the Mediterranean fire prone region (Buma and Wessman, 2012).

only 0.23%/yr on the second half of the 20^{th} century, whereas they reached 0.27%/yr during the beginning of the 21^{st} century (i.e., a 17% increase). The trends in these data suggest that the regime of disturbances is currently changing (Seidl and Rammer, 2017). Senf et al. (2021) observed a similar drift from the remote sensing data, citing a significant trend in the increase of canopy mortality in Europe. It is argued that if the increase is maintained in the long term, European forests could stop growing older[3], deeply changing the demographic of the forest, and even jeopardizing the possibility of further carbon storage in the forest. This trend was also observed by Cohen et al. (2016) in the US between 1985 and 2012. They noted that harvest[4] was historically the most important disturbance to forest cover, but that it has been replaced by forest decline due to increase in natural disturbances, leading to a necessary decrease in the harvest intensity. Seidl et al. (2011) stated that there are two main drivers of this trend of increasing natural hazards: changes in forest management (especially in the case of windstorm), and climate change (especially in the case of fire). Interestingly the increase in bark beetles damage was a mix of both effects. Indeed, Seidl and Rammer (2017) stated that the damages due to interactions of natural hazards should increase ten times faster than historical hazards themselves in the context of climate change.

A few years ago, a comment in Nature raised the question of how interactions between natural hazards can lead to disasters (AghaKouchak et al., 2018). They have focused their analysis on a deadly landslide caused by heavy rains one month after a large wildfire in California, which caused losses of forest cover, that previously protected against erosion. In fact, this kind of interaction between hazards was already theorized in forest ecology. Buma (2015) showed that despite the fact that we now know enough about each single natural hazard, the consideration of multiple interacting hazards can lead to at least four changes compared to the consideration of a single hazard: a higher extent (increase in the intensity or severity of the hazard); a change in the hazards likelihoods; a decrease in ecosystem resilience; a global change of the entire risk regime for the ecosystem (emergent type of damages from interactions). These emergent effects induced by considering multiple hazards rather than by dealing with single independent hazards, resonate with the definition of compound risk by IPCC (2022): "arises from the interaction of hazards, which may be characterized by single extreme events or multiple coincident or sequential events that interact with exposed systems or sectors." In more tangible terms, Dale et al. (2001) gave a first review of the different hazards that affect temperate forests, explaining how they could interact with each other in the context of climate change.

Bark beetles outbreaks are a typical example of compound risks. Bark beetles infest and feed on the inner bark of trees. They belong to the family *Scolytidae*. For example, we will focus on *Ips Typographus*, whose host plant is Norway spruce (*Picea Abies*). Bark beetles have co-evolved with their host tree and typically target weakened or stressed trees, tunneling through the bark and disrupting the tree's nutrient and water transport system. This focus on stressed trees can even be beneficial for the rest of the forest stand because it removes the trees that consume the most resources. This is the role of bark beetles at normal level. Under certain conditions, large outbreaks of bark beetles can lead to tree mortality and have significant ecological and economic impacts on forests. For example, if an entire Norway spruce stand sees its level of defense diminished, bark beetles can grow exponentially, reach an epidemic level of population and are capable of killing even healthy trees whose defenses are

[3]The current demographic trend of European forests is aging, because the forests are young and productive so that the harvest and mortality are lower than the biological growth. If the level of mortality continues to strongly increase, this trend could be stopped.

[4]Ecology literature often considers harvest as a human induced disturbance to the ecosystem. From our human-centered forest economics point of view, harvest is considered normal management and only natural hazards are considered disturbing forest management.

outnumbered by the number of attacks (Berryman et al., 1984). The transition between both population levels is a typical case of multi-hazard interaction. Most of the time, bark beetle outbreaks are caused by a windstorm that produces a large amount of windfalls (Wermelinger et al., 1999). If this dead wood is not quickly harvested, it is a great opportunity for the bark beetles to make a first generation on this defenseless timber. In the event of severe drought, the vitality of the trees is also diminished, so it is easier for bark beetles to overwhelm the defense of these trees (Wermelinger, 2004). Windstorms and droughts have thus a direct effect on bark beetle damage. Finally, bark beetle outbreaks can also have an effect on another natural hazard: wildfires. Dupuy et al. (2015) have shown that the effect of bark beetles on fire regime depends on the stage of infestation of the stand. For instance, there is a strong increase in fire risk after a bark beetle outbreak in the "red stage" (i.e., when the tree is dry but still has its needles) and a small antagonist effect in the "gray stage" (when the tree has lost its needles), due to a lack of fuel. Bark beetle outbreaks are thus an interesting case of hazard whose occurrences are linked with several other natural hazards.

0.1.2 From hazard to risk

The previous section discussed the level of natural hazards and the change of hazard regime in Europe, concluding that hazards are playing an important role in the forest dynamic and should play an even more important role in the future. When we look at the definitions in Box 1, it is clear that one step forward needs to be done. For the moment, we have focused on the description of the natural hazards themselves, which is mainly done thanks to ecological tools. But we should also investigate the potential impacts of these natural hazards. To achieve this further step, it is necessary to make use of economic tools. We have previously discussed that European forests provide a tremendous number of ecosystem services. Many of these are threatened by natural hazards: such as tourism (Michalson, 1975), recreation (Monge and McDonald, 2020), landscape aesthetics (Hansen and Naughton, 2013), timber production (Hanewinkel et al., 2013), climate mitigation (Senf et al., 2021), erosion protection (Monge et al., 2018), etc. Natural hazards constitute major risk for the provisioning of ecosystem services.

At this stage, is is necessary to consider the forest as a socio-ecological system (Renaud et al., 2010) made out of two subsystems. The first ecological subsystem is the forest by itself and its ecological dynamic. The second subsystem is a socio-economic one: it corresponds to the human exploitation and use of forests. Both systems are interlinked because the forest brings ecosystem services to society, so that humans strongly manage this ecosystem. For example, a typical socio-ecological systems is for example the forest sector, where forest is the source material for timber products. This typology is especially interesting to make the next necessary step: we have previously discussed the hazards impacting the forest socio-ecological system, but it is still necessary to estimate the risks that the forest socio-ecological system is facing due to hazards occurrences, thanks to economic tools.

Box 1: Definitions (IPCC, 2022)

"Risk" and the rest of its lexical field such as "disturbance", "hazard", "impacts", etc. are very commonly used words and often used indifferently. Some basic definitions are required to establish a universal framework for research (IPCC, 2022).

Hazard[a]	"The potential occurrence of a natural or human-induced physical event or trend that can cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources."
Risk	"The potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems."
Impacts	"The consequences of realized risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather/climate events), exposure, and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Impacts may be referred to as consequences or outcomes and can be adverse or beneficial."
Resilience	"The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure."

[a]Please, note that "natural hazards" and "natural disturbances" will be further used without any distinction.

To remain as generic as possible, natural disturbances can lead to two different types of risks[5] that are traditionally studied in the forest economics literature: timber production risk and market risk. Timber production risk refers to the variability associated with production processes, due weather conditions, pests and diseases and production inputs. Market risk deals with the volatility associated to prices, demand, supply, and trade. This unpredictability can be related to natural disturbances occurrences (Gardiner et al., 2010) but also to shocks in global demand, or volatility in energy prices. Moreover, Komarek et al. (2020) insisted on the fact that both market and production risks should be linked, especially in the case of weather shocks that lead to a contraction of the supply, interfering with the market.

In this thesis, multi-hazard refers to multiple natural hazards impacting simultaneously the same exposed element (Gallina et al., 2016), meaning that several natural hazards are considered at the same time to impact forests. This is, for example, the case if a forest is subject to storms, fires, insects outbreaks or if a forest is facing several possible hazard regimes, such as normal vs. extreme hazards. Whereas multi-risk means that several types of risk are considered at the same time, for instance, production risk and market risk (Gallina et al., 2016). Finally, let us mention that it is possible to consider simultaneously multi-hazard and multi-risks.

For example, increased interactions between natural hazards could be detrimental to the resilience of the forest socio-ecological system. Buma (2015) defined "compound interactions"

[5]Komarek et al. (2020) reviewed different risks to create an interesting typology for agriculture. In addition to production and market risk, health risk, financial risk and institutional risk are also mentioned. These three risks do not seem especially relevant in the context of forest.

as a potential interaction between hazards that disturb the resilience of an ecological system. An interesting example is the introduction of windstorms in a system of serotinous trees (Buma and Wessman, 2012). Some tree species need fire to open their cones and disperse their seeds in the field. This is a strong ecological advantage because competing species are removed by the fire and the fresh seedlings have an important comparative advantage to regrow. This kind of ecosystem has evolved with fire occurrences and can even evolve in the direction of increasing the frequency of fires, making this ecosystem resilient. However, if a storm occurs, grown trees can be removed and breaking this positive cycle of fire/regrowth, because seedlings from grown trees are not dispersed anymore. Buma and Wessman (2012) indeed observed in the western US that landscapes severely impacted by a storm in 1997 and wildfires in 2002 did not regrow as fast as landscapes only impacted by wildfires in 2002. The temporal interaction between both natural hazards thus diminished the resilience of the ecological system. From an economic perspective, we can test the resilience of a forest market to natural hazards. The forest socio-ecological system has indeed faced important impacts from natural disturbances in the past (Patacca et al., 2023), but the impact of natural disturbances, and especially their interactions, will continue to escalate in the future (Seidl et al., 2017). The literature has this far focused on the prominence of direct effects of single disturbances because they are easier to isolate and study (Seidl et al., 2017). However, doing so leads to an underestimation of the potential effect of natural disturbances and potential tipping points in the forest socio-ecological system, especially in the case of climate change. For instance, these increased impacts of natural hazards could impact the resilience of the forest ecosystems.

In parallel to risks increasing as well as their interactions, threatening the European forests, national governments take engagements in terms of carbon sequestration in the forests. Forests are indeed a natural carbon sink (Canadell and Raupach, 2008; Mauser, 2022). The Intergovernmental Panel on Climate Change (IPCC) emphasized in its last report the importance of adhering to the target of carbon neutrality established by the Paris agreement of 2015, which aims to limit global warming below 1.5°C in relation to preindustrial levels (IPCC, 2022). To achieve carbon neutrality, all greenhouse gas (GHG) emissions must be reduced or eliminated from the atmosphere and sequestered in carbon sinks, such as forests or soil. Regarding the French low carbon strategy, with 35 $MtC0_2$/yr stored in the forest biomass and 20 $MtC0_2$/yr in forest products, it is expected to store 55 $MtC0_2$/yr in French forests to reach carbon neutrality in 2050 (Ministry for the ecological and solidary transition, 2020). Natural disturbances could be detrimental to this strategy and reduce the resilience of the forest carbon sink. Roux et al. (2020) led an analysis of the potential for climate mitigation through the use of the French forest sector, under several management scenarios (more or less harvest intensity). This report included an interesting sensitivity analysis of these different scenarios under three natural hazards: an exceptional wildfire year, an exceptional windstorm and post-windstorm bark beetles' damages. Their analysis was very exogeneous and not fully satisfactory because they have focused on single occurrence of hypothetical events. It is, however, a first attempt to test the resilience of the French low carbon strategy with respect to natural hazards.

This thesis aims to understand the environmental and economic impacts of multi-risks and multi-hazards on the forest sector and their potential public policy implications. Before going deeper in the presentation of the chapters and arrive to more precise research questions, it is still necessary to present how production and market risks have been included in the literature so far.

0.1.3 Linking production and market risks

Forest economics literature has traditionally focused on the forest owners' decisions, decisions which are taken at the stand scale. The question is: how should forest owners manage their forest stand under different circumstances? To answer this question, the literature has a long tradition of working within the Faustmann framework, especially to evaluate the impact of natural disturbances (Yousefpour et al., 2012). The elegance of Faustmann's equation (Samuelson, 1976) lies in its simplicity. To answer the question "when should a forest owner harvest his forest?" it is only required to find the rotation period that optimizes the forest value, which is the discounted sum of revenues corresponding to infinite repetition of a single rotation. This optimal rotation period corresponds to the time when the growth of the harvest value equals the discount rate. The intuition of this result is the following: if the growth harvest value is larger than the discount rate, it would be detrimental to harvest and not to wait more. On the contrary, if the growth of the harvest value is lower than the discount rate, it is detrimental to pursue growing the stock. It should stop at the moment where the growth of the harvest value equals the discount rate.

This classical model has several drawbacks, one of which being the absence of stochasticity regarding the future production of wood. Reed (1984) was the first to incorporate stochasticity with a generic risk into the Faustmann rotation period. Under the assumption hazards' occurrences following an exponential distribution[6], he showed that the optimal rotation was the same as considering an increased discount rate by the probability of the hazard. Later, Xu et al. (2016) complexified Reed's paper by introducing a second hazard that can occur after the first one. They showed that the optimal sylvicultural strategy[7] depends on the share that is destroyed at each hazard occurrence. All these classical Faustmann-based models are, however, generally doing an implicit, but rather strong hypothesis: price is fixed forever to a constant. This means that market risk is not included in this type of models.

A large body of literature has focused on market risk, exploring different pathways of relaxing the hypothesis of eternal fixed prices in the classical Faustmann framework. For example, instead of constant prices, several studies have considered random prices. Prices follow independent identical distributions, such as normal distributions (Knoke et al., 2005; Roessiger et al., 2013) or first-order auto-regressive walk (Yin and Newman, 1996; Knoke and Wurm, 2006), such as a Wiener process. This means that there can exist a long-term trend for prices (a drift) and a short-term volatility from this trend. Price volatility is however completely exogenous from the natural disturbance dynamic. Price variations and natural disturbance occurrences are however not independent.

To go further, it should be acknowledged that timber production is strongly dependent on the price of the timber. Prestemon and Holmes (2000) explained that natural disturbances have two effects to the market. In the short term, it can bring an excess of dead timber on the market, whereas in the long term, it reduces the quantity of available timber in the forest. In the case of a windstorm, Gardiner et al. (2010) noted that storm damage can cause an unexpected and abrupt increase in timber supply, which frequently affects timber prices and consequently the financial gains of both producers and consumers. A notable illustration of this is the aftermath of the Gudrun storm in 2005, which resulted in a reduction of 63% and 86% in the prices of spruce and pine sawlogs, respectively, in southern and central Sweden, compared to the previous year. Going back to the bark beetle dynamic depicted in the previous section, an interesting example is the 2018 European drought and the following bark beetle crisis, where prices for coniferous industrial round wood experienced a decline in the European subregion, particularly in central Europe (WRI, 2020). Initially, this situation was restricted to areas only physically affected by beetles, but it eventually spread to non-affected

[6] This distribution is a memoryless probability distribution. Without this assumption, Reeds calculus does not hold anymore.

[7] Three different strategies are tested in the paper: harvest and replant after the first hazard occurrence, harvest and replant after the second hazard occurrence, or do nothing (i.e., wait until the forecasted end of the rotation).

areas because many countries that experienced bark-beetle outbreaks became net exporters of round wood. In some instances, this even resulted in a reversal of the typical trade flows of coniferous industrial round wood. For example, Germany, which had been a significant net importer of coniferous round wood for several years, became a net exporter (UNECE/FAO, 2020). Therefore, the link between natural hazards and market risk is key to understand the timber market dynamic.

Both literatures on production and market risks are quite developed. However, most often, the forest economics literature considers market and production risks as independent. To mimic the effect of a price drop after the occurrence of an hazard, many papers assume that there exists an effective price at which the timber should be sold if it is damaged by a hazard (Knoke et al., 2022). Dieter et al. (2001) was the first to include this effect, citing three motivations: a price drop due to the excess of timber on the market, higher harvesting costs due to greater demand for harvesting, and loss of value due to direct hazard damage. All in all, Dieter et al. (2001) estimated that the price should be reduced by 50%. This strategy does however not take any stochasticity into account; this means that whatever the intensity of the hazard, the market effect remains the same.

Scale is in fact a major factor in forest economics, especially in the case of risk assessment. The traditional scale is indeed the stand. Because forest economics has essentially focused on forest owners decisions, it is relevant to work at the stand scale, which is the scale at which the decisions must be taken. But the pertinent scale for natural hazard interactions is the landscape scale, and for the market risk, it is at least regional and maybe national or even global. Furthermore, as presented in Figure 0.1, these scales interact with each other. For example, if a natural disturbance occurs at the landscape scale, there will be a strong influx of timber on the market on a larger scale, but this will also have impacts on the perceptions of forest owners, who can can change their management decisions to reduce the vulnerability of their forest in the future.

The choice of scale also has important implications from a technical point of view. Due to a focus on small geographical scales (i.e., the forest stand), most forest economics models are based on the assumption that a hazard, when it occurs, destroys the entire stand. This assumption is often justified by examples such as fire and storms, which are frequently large-scale hazards happening at the landscape scale. This raises two problems. First, some risks may have other impacts than mortality, such as a reduction in annual growth, e.g. defoliating insects or drought. Moreover, even if a hazard has an impact on mortality, only partial stand destruction can be expected, so that it can be reasonable to let the stand continue. This was, for instance, studied by Xu et al. (2016): they allowed for the destruction of only a share of the stand. Doing so raises however several problems in terms of forest dynamics. If the damage are expressed only in terms of destroyed stems, it can be beneficial for forest owners to have natural disturbances in young stands, because it acts as a free thinning. If it acts to destroy a share of the stand (expressed as an area), then one can argue that it is then possible to split the stand into smaller stands that are fully destroyed or intact. Nevertheless, the local stand scale is not a relevant scale to include interactions between natural hazards, which usually have larger-scale effects.

Finally, considering only the stand scale does not allow for market risk's considerations, because prices are defined at larger spatial scales (Prestemon and Holmes, 2000). Rakotoarison and Loisel (2017) attempted to conciliate damages at the stand scale and local price dynamic. They used the stand scale but implicitly supposed that the windstorm damages on the studied stand were representative of the damages of the region so that the timber price directly depended on the damages of the stand. One could, however, argue that local stand damages are not really consistent with the damages at the region scale. Indeed, there exists a body of literature disentangling the effects of large scale natural disturbances between the

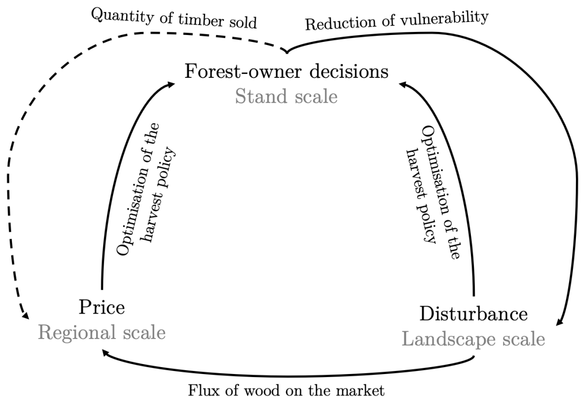

Figure 0.1: Interaction of the different spatial scales to assess the impact of natural disturbances.

forest owners that are affected (who lose producer surplus) and not affected (who take over producer surplus). For example, the country scale was used by Petucco et al. (2020) to assess the impact of ash dieback[8] on the French forest sector. Caurla et al. (2015) investigated the potential benefits of logging or export subsidies after a severe windstorm in the south-west of France. To be consistent, it is thus necessary to study several different scales at the same time to assess the effects of natural hazards on the forest.

0.1.4 A broad typology of methods

Zhai and Ning (2022) recently reviewed the different types of models used to assess the economic impacts of forest disturbances. They restricted their study to 25 highly relevant papers and divided them into four categories.

The first type of models uses the “with and without” method. This technique is based on the estimation of an economic indicator under two different scenarios: one where a risk occurs and a complementary scenario where no risk is assumed. The difference between both estimates corresponds to the cost of the risk. For example, Knoke et al. (2021) estimated the cost of natural disturbances on spruce by measuring the difference in land expected value between a scenario with natural disturbances and a scenario without natural disturbances. Haight et al. (2011) used the same method to predict the potential losses due to the development of oak wilt in the US and argued that society would be better off preventing invasion.

Second, “partial and computable general equilibrium” models are used to design policies for regional development. Computable General Equilibrium (CGE) model has been used to analyze the economic effects of timber supply shocks from forest disturbances on the local gross domestic product. For example, Boccanfuso et al. (2018) stated with a CGE model that natural disturbances potentially reduce the total GDP of Quebec (Canada) by 0.12%. The partial equilibrium framework is essentially used in two models: the French Forest Sector Model (FFSM) and the Global Forest Products Model.

Third, the “intervention” model allows for an examination of the long-term effects of various disturbances on an intervention’s impact. This model offers two key advantages over the traditional damage appraisal approach. First, a damage appraisal approach only takes into account the difference with and without the damage, without considering salvage logging or its impact on market equilibrium prices. Second, it does not distinguish between producers with damaged and preserved forests. This literature especially flourished after 1989 following hurricane Hugo in the US (Yin and Newman, 1996).

[8] Ash dieback is a disease that has been spreading from Eastern Europe and kills most of ash trees.

Finally, economists have shown great concern for economic surplus. Economic surplus is defined as the difference between the costs and benefits of producing goods and services, corresponding to one of the most significant aspects of human welfare. The "social welfare" model can be used to measure the welfare impacts of salvage logging on different market participants and timber markets. In particular, the market distributional consequences of salvaging can be specified among forest landowners with damaged forests, forest landowners with undamaged forests, and consumers. Therefore, the application of the social welfare model could significantly affect governments' efforts to mitigate economic losses through salvage logging. Prestemon and Holmes (2010) is an interesting example that estimated the impact of six hurricanes on timber producers and consumers.

These complementary methods will be used in this thesis to answer different research questions raised by multi-hazards and multi-risks in European forests. Specifically, is the timber market resilient to catastrophic damages? How are the effects of natural hazards distributed in the forest sector? How should different actors of the forest sector behave if a large windstorm occurs? What is the cost of natural hazards? What is the effect of climate change on the evolution of this cost? The next section is dedicated to motivating these different questions, presenting the methods used and a summary of the main results.

0.2 Thesis objectives and chapters description

Previously mentioned literature has highlighted three complementary conceptual gradients: a gradient of type of risks, a gradient of hazards and a spatial scale gradient. Each of my chapters[9] can be placed on these conceptual gradients (see Figure 0.2).[10]

First, a gradient of type of risks: the first and last chapters of this thesis only consider production risk, whereas the second and third chapters focus on both production and market risks. This has strong implications in terms of possible indicators to study. If we focus solely on production, the key parameter is the value of the forest. In contrast, if the whole market is considered, we can focus on other parameters such as social welfare, price dynamics, etc.

Second, a gradient of hazards types included in the models is crucial. From very generic damages to spatially explicit multi-hazard models, a large gradient of hazards types can be treated. The first chapter aims at reviewing the state of this particular conceptual gradient in the literature. The second chapter considers a generic hazard. The fourth chapter tries to disentangle the effect of basic vs. catastrophic natural hazards, whereas the third chapter focuses on the modeling of two spatially explicit interacting hazards.

Finally, a gradient of spatial scales. A large range of scales are relevant to study the effect of natural disturbances on the forest, including the stand scale (where the managers takes forestry decisions) to the global scale (where trades flow are taking place). The second chapter relies on a regional study to estimate market effects. The third chapter includes three spatial layers: the forest management layer (8km pixels), a regional layer (with 12 layers over France) and a country layer.[11] The fourth chapter takes into account two different spatial layers: a pixel scale (15km pixels) for forest management and the European scale to aggregate the results.

[9] The first chapter is a literature review, so that is does not focus on any specific level of these complementary gradients. It should however be noted that this review mainly focuses on multi-hazard.

[10] Please, note that each chapter focuses on a different level of each gradient. It would be presumptuous to believe that one single model could answer all the questions, so that each chapter has required some compromises (that should be mentioned and motivated) to be able to answer very different questions.

[11] In fact, there is even a fourth layer because the model includes the rest of the world to trade some products. However, this is completely exogeneous.

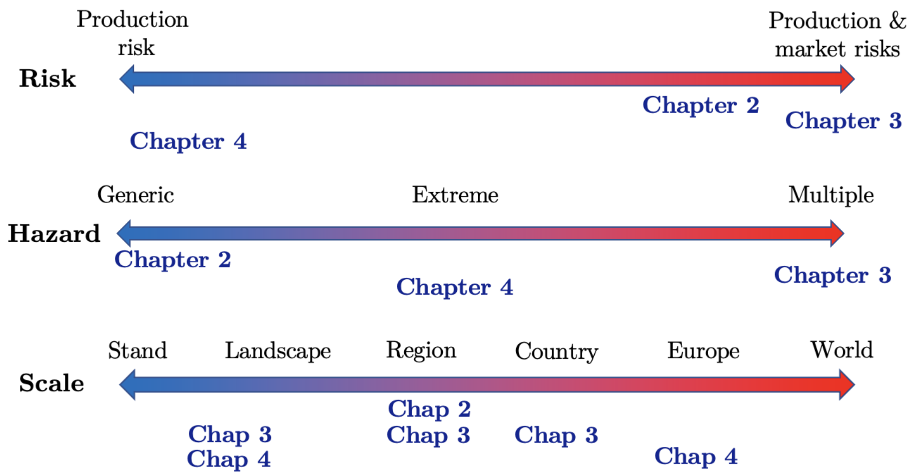

Figure 0.2: Graphics of the conceptual gradients driving the chapters of this thesis.

0.2.1 First chapter: Literature review of multiple hazards

The context section has exhibited the importance of considering multiple natural hazards to properly assess the full potential impact of natural hazards on the forest sector. My first research question is thus to understand how the different natural hazards are included in the forest economics literature: are multiple hazards already included in the literature? If yes, with which methods?

To our knowledge, Yousefpour et al. (2012) was the first review paper focusing on the question of risks and uncertainties in forest economics. Indeed, their work, under the context of climate change, investigated the literature on forest owners' adaptation decisions. A few years later, Montagné-Huck and Brunette (2018) reviewed more than three hundred articles focusing on single natural hazards such as wildfires, pests, pathogens, storms, browsing, snow/ice storms.

There is, to the best of our knowledge, no contribution reviewing the forest economics literature dealing with multiple natural hazards. This is why we conducted a systematic literature review of forest economics papers including several hazards. Moreover, we have broadened the literature to articles dealing more generally with optimal forest management assuming several hazards.

This literature review led to several conclusions: the most studied hazard couples are storms/ insects (mainly in Europe, where bark beetles outbreaks have regularly a significant economic impact) and fire/insects (mainly in the US). The pure economic literature does not really consider any interactions between hazards for the moment and even consider more often generic hazards[12] than explicit hazards modelling, in the contrary to the ecologically oriented literature. We showed that there are some exchanges between both literatures but they are still poorly connected. From perspective of methodology, the Faustmann framework is the most commonly used framework, especially at the stand scale.

0.2.2 Second chapter: Production and market risks, regional scale, generic hazard

The goals of this chapter are twofold: first, it is an attempt to bridge the market risk with the production risk. Contrary to existing literature (Rakotoarison and Loisel, 2017), we anchor our

[12]See for example (Xu et al., 2016) that considers two generic, non interacting hazards and looks for the optimal management strategy in the long term.

method at the regional scale, which seems more consistent to properly assess market effects. Second, it tries to evaluate the resilience of a timber market to extreme disturbances. It incorporates the resilience theory from ecological systems to socio-ecological systems, defined here as a system composed of the forest as the ecological subsystem and the timber market as the socio-economic one. Knoke et al. (2022) investigated the resilience of the value of a forest stand, expressed at the time that is required to go back to its value before the occurrence of the natural hazard (Perrings, 1998). We extended this work to a larger geographical scale in order to include the market effect of natural disturbance. We went further by also considering another possible definition of resilience, which is the potential shift of the forest timber market to an undesirable (defined as unsustainable) state.

In order to do so, we developed a macro-stylized model that establishes an equilibrium between forest inventory and growth, as well as a timber market, facing natural hazards. Our approach involves linking a simple forest growth model and a market model, which respectively accounts for the management of the forest by owners. We incorporated an equilibrium-displacement model into the forest growth model to investigate how the market responds to natural disturbances. Equilibrium-displacement models are commonly employed to explain short-term fluctuations in timber markets caused by natural hazards, such as the decrease in timber prices following hurricane Hugo in Florida in 1989. This chapter tries to link this intervention model (third methodology in Zhai and Ning (2022) typology) with the notion of resilient timber market under extreme natural hazards.

We determined the critical inventory required to ensure the long-term sustainability of the forest inventory and maintain its stability in the presence of stochastic natural disturbances. We also showed that whatever the volume of timber in the forest, there can exist a large enough disturbance that leads to exhaustion of the timber inventory. However, the level of disturbance must generally be very high to destabilize the market and put in on an exhaustion pathway. Moreover, we tried to estimate admissible return times for the disturbances that ensure the resilience of the forest dynamic. Moreover, we showed that increasing the mean or the standard deviation of disturbances have negative effects on the resilience of the forest. Climate change is expected to increase both: there will be more events and more intense events.

0.2.3 Third chapter: Production and market risks, France scale, spatially explicit interacting hazards

The framework of the second chapter of this thesis is rather simple but fits quite well to the regional market model of FFSM. Indeed, the equations to derive demand and supply from prices and inventories (through elasticities) are similar. An important limit of the second chapter is that the framework is abstract and theoretical. On the other hand, FFSM framework is very concrete because it represents the French forest sector dynamic. This is thus a way to logically extend the second chapter work to a particulary applied and explicit case.

The metropolitan forests of France span over 17 million hectares, with a growing stock volume of 2.8 billion m^3 (IGN, 2022). These forests currently serve as a net carbon sink, sequestrating approximately 1.3 billion tons of carbon. Furthermore, the growth of this resource has been significant, with French forest area expanding by over 20% since 1985 and growing stock increasing by roughly 50% (IGN, 2022). For this reason, the French forest is at the center of the national low carbon strategy, targeting net-zero emissions in 2050 (Ministry for the ecological and solidary transition, 2020). In order to achieve this goal, French forests should sequestrate 35 $MtCO_2$/yr in the forest biomass and store 20 $MtCO_2$/yr in timber products, representing more than two thirds of the total French carbon sink. French forests, however, have faced many large disturbances: the Martin and Lothar windstorms in December

1999, the Klaus storm in 2009 and more recently spruce bark beetle outbreaks in the East of France. These severe disturbances globally impact the French forest sector and could prevent the achievement of French climate commitments. A bio-economic model such as FFSM is necessary to evaluate the impacts of natural hazards on the French forest sector because it simultaneously captures the ecological dynamics of the forest as well as the dynamics of the market, forest management and their interactions.

This chapter thus aims at several objectives. First, from a methodological perspective, it is a first attempt to include a windstorm hazard regime into a forest sector model, which is the most important natural hazard at the French national level. Second, we try to create a conceptual framework to link insects outbreaks with windstorm occurrences in a partial equilibrium model. Third, we test the French low carbon strategy by evaluating the potential effect of carbon storage in forest inventory, carbon sequestration into timber products and emission substitution from wood-sourced products.

The French Forest Sector Model (FFSM) is a recursive partial equilibrium model. Several modules are coupled to get the dynamic of the forest sector: resource module, management module, market module, carbon module and our new hazard module. We included two spatially explicit natural hazards in the model: windstorms and bark beetles. We focus on the main hazard in France, windstorms, and we have also included bark beetles because it is the hazard that is the most correlated to windstorms. The temporal dynamic of windstorms was modelled based on a recent set of windstorms derived from a large set of climate models under historical past climate (Lockwood et al., 2022). Spatial damage from windstorms were based on the mechanistic model ForestGALES (Hale et al., 2015; Chen et al., 2018), deducing the share of damage on each FFSM pixel from local windspeed, diameter and forest type. Concerning the dynamics of bark beetles, we used a simple Markov process with two states: normal population, without any damage and epidemic population, where damages occur. The probability of moving from normal to epidemic population was mainly driven by local windstorm damage (Schelhaas et al., 2002; Roux et al., 2020). This papers satisfies three categories of Zhai and Ning (2022) typology of methods. First, it is a partial equilibrium model. It also enters the "economic surplus analysis" category, because we focused on the effects of natural hazards on the different actors of the sector. To a lesser extent, it touches the "with and without" category, because we compared the scenarios where windstorms occur to a counterfactual scenario without storms.

Our results are threefold: first, we illustrated the effects of a single windstorm on the French forest sector at the national scale. Our model confirmed that there is a transfer of economic welfare between producers and consumers, always facing a loss of welfare due to an increase of price. Moreover, there exists a transfer of welfare between the regions impacted by the windstorm and the regions that are not, which could motivate the creation of a mutual fund between the different French regions to redistribute these effects. Second, concerning the welfare transfer between the upstream and the downstream sectors, it seems that the decisions of the forest owner could be detrimental to society because it is in their interest to sell less timber than socially optimal during the crisis. Third, Monte Carlo simulations showed that the distribution of damages from storm are very volatile among the different scenarios and that interacting natural hazards could jeopardize the potential for carbon storage in French forests.

0.2.4 Fourth chapter: Production risk, European scale, basic and extreme disturbances

Previous chapters have focused on resilience and the forest sector, orienting the discussion in the direction of market effects. In this last chapter, we change our view point and focus on the upstream part of the sector, i.e. the economic value of forest stand, seen from the perspective of an individual forest owner. This means that we essentially focus on the value that can be extracted by the forest owners from their forests. We restrict our analysis to production risk because we extend the spatial scale of the study to the European continent. The cost that needs to be paid for this broadening is thus to drop the notion of market risk, to model natural hazards in a very concise way and to use only generic hazards. However, it enables to include two different types of hazards: background and catastrophic level of hazard.

European forests are diverse and can be split in at least three different biomes: temperate, boreal and Mediterranean forests, each with different natural hazards regime. The European scale is quite relevant from a forest economic point of view because the number of major timber species is relatively low (spruce, pine, oak and beech represent 61% of the total forest) and because it is an appropriate geographical scale to apprehend the European common market and environmental policies.

To our knowledge, Schelhaas et al. (2003) were pioneers to review past forest disturbances in Europe over the second half of 20$^{\text{th}}$ century. An update of this study was done by Patacca et al. (2023), including a larger set of records. They focused on the trend of natural hazards over the period 1950-2019. However, Hanewinkel et al. (2011) has explained that there are four steps to include effect of climate change in forest management (framework analysis, hazard modelling, cost estimation and choice of action). Reviews of natural hazards stop at the second step: they analyze the framework and assess the probability of hazard, but do not estimate the costs if any action is taken or not.

An interesting question is thus to evaluate the cost of natural hazards at the European scale and to evaluate the potential effects of climate change on this cost. This evaluation could incentivize the decision makers to adapt European Forests to climate change. Hanewinkel et al. (2013) attempted to estimate the costs of climate change by estimating the change in forest economic productivity in the case where the geographical ecological niche of each species changes due to climatic parameters modifications. Interestingly, this estimate relies on a model at the border between process-based and statistical analyses. Also on the estimation of climate change cost assessment, Callahan and Mankin (2023) recently estimated the extra losses due to the increased probability of El Niño events on the world economy.

In the previous chapter of this PhD, we modelled spatially explicitly three natural hazards. In this last chapter, we alter our perspective. Instead of explicitly simulating the dynamic of natural hazards and trying to observe emergent patterns from interactions, we rely on a purely statistical approach to natural hazards. This is enabled by the recent contribution of Brandl et al. (2020), who estimated survival functions for four different timber species (Norway spruce, Scots pine, oak, and common beech) at the European scale. These survival functions enabled us to compute the value of the European forests in a “with and without framework” (Zhai and Ning, 2022). Recent pulses of mortality have been observed in Europe, such as the 1990s windstorms and a severe spruce bark beetle outbreak at the end of the 2010s due to a high level of drought. The cost of these pulses events are estimated in our model (Patacca et al., 2023).

To estimate these costs, we separated European forest into a large number of pixels. On each pixel, the natural growth of four economically productive timber species was simulated. A standard matrix-based model was used to allocate the forest area to a given species/age-class at each time period. To predict the dynamics of the volume of the different pixels, we used standard yield tables and we assigned to each pixel a given yield using Net Primary Productivity (NPP) estimates based on climate scenarios. We obtained the European Forest Value under three different climate models and four climate scenarios in order to obtain a panel of results, sensitive to global warming intensity.

Several conclusions can be drawn from this work. First, the total cost of natural disturbances at the European scale should increase in the context of climate change. Second, we showed that this result was based on several effects playing in opposite directions. The result must indeed be separated into a gain of productivity and greater losses due to a higher level of background hazard and more intense and frequent catastrophic events. Aggregating costs and benefits at the European scale hid important spatial heterogeneities. For example, a large gain of forest value was expected in some regions (especially in Scandinavia and Alps mountains), where large forests were facing low levels of mortality and gains of productivity, whereas some other regions (Mediterranean and Central European regions) should lose value due to strong reductions in forest survival.

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Chapter 1

Pests, Wind and Fire: A Multi-Hazard Risk Review for Natural Disturbances in Forests

Pests, Wind and Fire: A Multi-Hazard Risk Review for Natural Disturbances in Forests

Félix Bastit[a] , Marielle Brunette[a,b] and Claire Montagné-Huck[a]

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[a] Université de Lorraine, Université de Strasbourg, AgroParisTech, CNRS, INRAE, BETA, 54000 Nancy, France
[b] Associate researcher at the Climate Economics Chair (CEC), Paris, France

Abstract Natural disturbances are paramount in the development of ecosystems but may jeopardise the provision of forest ecosystem services. Climate change exacerbates this threat and favours interactions between disturbances. Our objective was thus to capture this dimension of multiple disturbances in forest economics through a literature review. We built a database that encompasses 101 English peer-reviewed articles published between 1916 and 2020. We looked at the relationships between six main natural hazards: fire, windstorm, drought, ice/snow, insects and pathogens/disease. Our results indicate that the most frequent pairs of hazards analysed together are "Wind-Insects" in Europe and "Fire-Insects" in North America. We show that most economic studies assume that natural hazards are independent of each other and could thus miss some of the effects of changing hazard regimes, contrary to ecology-oriented articles. Finally, we suggest creating bridges between the ecology and economics of forest disturbances in order to refine current models of each discipline with the tools provided by the other discipline, especially in the critical context of climate change.

Keywords Multi-hazard risk, Interaction, Economics, Management, Ecology, Review, Forest.

JEL codes D81 (Criteria for Decision-Making under Risk and Uncertainty); Q23 (Forestry); Q54 (Climate • Natural Disasters and Their Management • Global Warming)

1.1 Introduction

Natural hazards play a key role in the shaping of ecosystems and are especially beneficial to biodiversity. However, they may also represent serious threats to forests worldwide. Natural hazard is defined as "a natural process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage" (UNISDR, 2009). Indeed, natural hazards are responsible for several economic disturbances. In the case of timber production, natural hazards account for the loss of forest cover, leading to a share of the production that is merely lost and to an eventual reduction of marketability for the salvaged timber driven by a market overwhelmed by the supply of timber. Natural hazards also jeopardise long-term forest management and lead to supplementary costs of forest restoration, reducing the future stand value (Birot and Gollier, 2001). In addition, natural hazards threaten the provision of ecosystem services such as the carbon stored in forests and, to a lesser extent, the sequestration capacity of forests (Thürig et al., 2005). Impacts on biodiversity and recreation (Thom and Seidl, 2016) as well as the loss of hunting or other income (Birot and Gollier, 2001) are also common. In other words, natural hazards jeopardise timber production as well as the provision of other ecosystem services.

At the global scale, van Lierop et al. (2015) estimated that over the period 2002-2013, 67 million hectares of forest burned annually, 85 million hectares (period: 2002-2013) were affected by insects, 38 million hectares (period: 2002-2013) by severe weather conditions (e.g., storm, hurricane, drought, etc.) and 12.5 million hectares (period: 2002-2013) by disease. At the European scale, Schelhaas et al. (2003) showed that over the period 1950-2000, an average of 35 million $m^3.yr^{-1}$ of wood were damaged by natural events, representing 8.1% of the annual harvest. Storm was responsible for 53% of this damage, fire for 16%, and biotic factors for 16% (half of them due to bark beetles). On a smaller scale, Dale et al. (2001) estimated the economic impact of insects and pathogens for the United States at $2 billion per year. In Canada, spruce budworm (*Choristoneura fumiferana*) impacted 38.6 million hectares between 1941 and 1996 (Fleming et al., 2002). Mega-fires in Australia during the 2019/2020 fire season destroyed almost 19 million hectares and cost 33 human lives (Filkov et al., 2020). These examples show the relevance of natural hazards for forests.

According to the Fifth Assessment Report of the IPCC, the magnitude and frequency of most of these natural events is expected to increase due to climate change. This intensification is already observed and tends to be accentuated (Seidl et al., 2011b). An example is Schelhaas et al. (2003) who show that the damage caused by wind, fire and insects drastically increased over the period 1958-2001: on average, by +2.59% yr^{-1} for wind, +4.23% yr^{-1} for wildfire, and +5.31% yr^{-1} for bark beetles (Seidl et al., 2011b; Thom et al., 2013).

Forest economics and management have considered the issue of timber production risk for a long time (Lovejoy, 1916), but Reed (1984) was the first to integrate risk into standard forest economics models (i.e., the Faustmann (1849) model). He showed that considering fire hazard reduces the optimal rotation length. This seminal paper was followed by a flourishing literature on natural hazard impacts in forest economics, considering both the impact measurement and the forest management aspects (Seidl et al., 2011a). This literature is reviewed in Montagné-Huck and Brunette (2018) who analysed 340 economics articles dealing with natural forest disturbances and the way in which economic analysis deals with such an issue. In the same vein, Yousefpour et al. (2012) proposed a review of the different methods used in forest economics to study risks and uncertainties induced by climate change. These two literature reviews reveal that the traditional economic approach is to consider one hazard at a time. The possible interactions between hazards are not usually considered, whereas their effects could be major due to climate change.

In addition to these changes in the regime of natural disturbances, climate change also favours the interactions between disturbances (Seidl et al., 2011b; Susaeta et al., 2014; Gallina et al., 2016; Seidl et al., 2017). For example, the increase in temperature due to climate change increases the drought risk in some regions, which, in turn, increases vulnerability to insect attacks as well as to the direct growth rate of insect populations. This makes it necessary to consider interactions between types of hazards as an emergent and non-linear phenomenon, separate from the study of individual hazards (Buma, 2015; Agne et al., 2018). As such, Seidl and Rammer (2017) expect to see the interactions between risks increase ten times more than the risks themselves.

In this context, our literature review proposes to address the following research questions: Are the interactions between hazards already considered in the literature and how? What are the most commonly studied hazard interactions? What are the methods used in the literature to assess multi-natural hazard risks? What are the relevant perspectives for future research?

Considering several hazards[1] can have major impacts from an economic perspective. First, different interactions between hazards can lead to over-additive or under-additive damage, depending on the sign of the interaction (Petucco and Andrés-Domenech, 2018). Second, at the forest owner scale, the optimal adaptation strategy is often hazard-dependent. The owner decides to plant a more well adapted tree species that is less vulnerable to drought, but this species may be more vulnerable to another hazard like storm for example. Considering several hazards at the same time improves the decision-making process of forest owners by considering potential arbitrage. Third, the opportunities to reduce the aftereffects of hazards can vary from one hazard to another, so that trade-offs have to be investigated to find more optimal silvilcultural systems. It can, for example, be beneficial to increase thinning intensity to reduce drought effects, but may be detrimental to the resistance of forests to windstorms for a short period. Moreover, at the sector scale, interacting hazards can lead to major crises, creating fluctuations on the timber market and changes in strategies for the forest owner, especially in terms of reservation prices. For example, the 2009 Klaus windstorm in the Landes de Gascogne (France) destroyed 30% of the standing timber volume, leading to an estimated price drop of between 45 and 85% (Peyron et al., 2009). Finally, on the long term, interacting hazards can create uncertainty on the timber supply, questioning the viability of the sector.

Our objective was therefore to identify publications in forest economics that deal with multiple hazard interactions in order to review the different methods for assessing tree mortality and economic impacts induced by natural hazards, as well as the different practices used to reduce risk impact under climate change. We adhere to the concept of Gallina et al. (2016) that considers that the risk induced by multiple hazards falls within the "multi-hazard risk" category. We built a database that consists of 101 English peer-reviewed articles published between 1916 and 2020. After a short description of the main characteristics (author(s), year, journal, keywords, country) of the paper, we explore the relationships between six main natural hazards (fire, windstorm, drought, ice/snow, insects and pathogens/disease) and the disciplinary orientation of the publications. Our results indicate that most of the publications are from North America (with emphasis on fire and insects) and Europe (dealing primarily with windstorm and insects). In addition, when several risks are considered, most of the economic studies consider them as being independent. Finally, we investigate the links between the ecology and economics of forest disturbances. This could make it possible to refine both disciplines by sharing state-of-the-art results to improve final forest decision-making in order to address climate change challenges.

The rest of the paper is organised as follows. Section 1.2 describes the material and methods. Section 1.3 presents the main results. Section 1.4 is devoted to a discussion of the

[1]We focus here on the economic effects of multiple natural hazards in the case of forestry, but this problem is extendable to other fields of ecological economics, such as agriculture, food security, housing, fisheries, etc.

potential collinearities between the ecology and economics of forest disturbances.

1.2 Material and methods

1.2.1 Concepts and definitions

Hanewinkel et al. (2011) propose two conditions to define a natural hazard: first, the singularity of the event, which must be unexpected, uncontrollable and of an unusual magnitude; and second, it must have a direct consequence on the activities or the people themselves (welfare loss, health problems, mortality, etc.). A natural disturbance may be broken down into three main parts (IPCC, 2012): first, hazard likelihood, which includes the return rate of the hazard at a certain intensity level; second, exposure, which represents the value of the ecosystem that can be subject to the hazard; and third, vulnerability, which is the predisposition of the ecosystem to be damaged by the hazard.

The risk emanating from the occurrence of a hazard corresponds to the intersection between exposure and vulnerability for a given hazard intensity. The consequences of a natural hazard can take the form of several risks: firstly, a risk to timber production or any other ecosystem service directly related to the impact on forest cover. An eventual large-scale market risk is also possible, from which may arise a financial risk for private owners.

To address the question of the integration of risk assessment into forest management, a four-step approach has been suggested by Hanewinkel et al. (2011):

1. Framework analysis: type of extreme events, climate scenario, etc.
2. Hazard modelling: likelihood, exposure and vulnerability within a given framework.
3. Cost estimation.
4. Choice of action: choice of optimal strategy to tackle the risk.

This typology was initially created to address single hazard risk, typical of the literature of the 1980s, but should necessarily be extended to multi-hazard risk. This means that several hazards, eventually interacting, must be included in the framework analysis and the hazard modelling to more accurately assess their effect.

Gallina et al. (2016) review the different methods to assess multi-hazard risk (i.e., the risk resulting from multiple interacting hazards), and propose a systematic methodology that can be reproduced here to extend Step 2 from single to multi-hazard risks. Considering only single hazards and neglecting the eventual interactions between natural hazards could lead to poor assessments of the different risks and to sub-optimal decisions.

Steps 1 and 2 are further regrouped in a "hazard modelling" framework because both deal with the description of the hazard. Step 3 is expanded in a broader "impact assessment" framework to make sure that it includes all of the socio-economic consequences resulting from a hazard occurrence.

1.2.2 Eligibility criteria

We conducted screening of the literature to identify peer-reviewed English-language publications up to 2020. This screening consisted of four steps.

In the first step, we defined a list of relevant keywords linked to multiple hazard risk lexicon: catastroph* (catastrophe, catastrophic), damage, mortality, disturbance, hazard, risk, stochastic, uncertainty, interaction, cascad* (cascade, cascading), multi-risk.

In the second step, in order to restrict the research to papers dealing with forest economics, we created the following query: forest AND economic AND "a risk-related keyword" (i.e., catastroph*, damage, mortality, etc.).

In the third step, these queries were systematically entered in four well-known databases: ScienceDirect, JSTOR, Ingentaconnect and NRC Research Press. The co-occurrence of the keywords was looked for throughout the full paper, including title, keywords and text.

In the last step, papers whose abstracts were relevant were included in this study. The exhaustive reading of these papers led to the discovery of relevant complementary references, which were then added to the initial list.

We ended with a list of 101 papers published in English between 1916 and 2020.

1.2.3 Description of the database

To review our list of papers, we applied a common systematic analysis scheme and created a database, containing the attributes listed in Table 1.1.

Attribute	**Describing**
Bibliometric indicators	
Author	Name of all the authors
Year	Year of publication
Journal	Journal in which the article was published
Keywords	Keywords indicated by the authors on the title page of the article and index keywords chosen by content suppliers (standardised based on publically available vocabularies)
Country	Country of the first author
Investigated parameters	
Orientation	Economics/Ecology/Both
Group	$\text{Group}_{\text{Ind}}$ if independence; $\text{Group}_{\text{Dep}}$ if dependence
Hazard	Wind: 0/1 (N_W); Fire: 0/1 (N_F); Drought: 0/1 (N_D); Insects: 0/1 (N_I) Ice & Snow: 0/1 (N_{IS}); Pathogens & disease: 0/1 (N_{PD})
Category	Hazard modelling/Impact assessment

Table 1.1: Variables included in the database.

The bibliometric indicators include the names of the different authors, the year of publication, the journal in which the article was published, the keywords indicated on the title page of the article (and also those chosen by content suppliers) and the country. The geographical origin of the papers ("Country" variable) was taken into account by using the available data on the first author of each paper. This data was aggregated at the scale of the continent.

We also created and collected attributes related to the core of this study. They are detailed below.

Disciplinary orientation

The screening of the literature focused on economic studies. However, during the article selection process, some ecology-oriented papers[2] turned out to be interesting for our topic. Indeed, many ecology-oriented papers fully anticipate the effects of multi-hazards that have not yet been included in economics publications. We think that this difference - between economics-oriented and ecology-oriented - may be important to better understand the literature on inter-

[2]The authors do not claim to make an exhaustive overview of the publications in ecology on multi-hazard risks.

actions between natural hazards. Consequently, we propose to classify the articles according to their disciplinary orientation ("Orientation" variable in Table 1.1), as follows. First, economics: these papers use economic methods. This includes maximising a utility-related criterion (land expected value, timber stock, sequestrated carbon, other ecosystem services, etc.), assessing costs and benefits, insuring against worst-case scenarios, etc. Second, Ecology: these papers study the effects of disturbances on the forest ecosystem. This includes niche-based models, dynamic global vegetation models, forest diversity, study of past climate, etc.

The last category, "Both", consists of articles that often propose optimal forest management solutions, controlling several parameters to minimise the effect of natural disturbances: rotation length, tree species and diversity, thinning path, density of trees, height-over-diameter ratio, etc.

Multi-hazard group

The list of papers is divided into two exclusive groups: in the first group ("$\text{Group}_{\text{Ind}}$"), the papers consider several hazards but no correlation between the different hazards. In the second group ("$\text{Group}_{\text{Dep}}$"), several hazards interact with each other (at least two-by-two).

This variable allows us to determine if the article simply considers several risks independently from each other and then provides no information on the way to consider the interaction, or if the article attempts to consider the dependency between the risks.

Hazard types

Six main natural disturbances were explicitly retained in our review (Seidl et al., 2017; Montagné-Huck and Brunette, 2018). Four are abiotic hazards: fire, wind, drought and ice/snow; and two are biotic ones: insects and pathogens/disease.

If a paper deals with (respectively, does not deal with) the hazard H (fire, wind, etc.), then the value corresponding to this hazard H in the database is 1 (resp. 0). To assess this value, we proceeded in two steps. First, we took the studied hazards declared in the abstract and in the core of the paper into account. Second, we read the pdf files with R software and looked at the number of occurrences of each hazard in the text (we denote this number of occurrences by N_H in Table 1.1 for hazard H). To avoid papers that claim to study a given hazard but that are not relevant, we set a minimum threshold of occurrences in the full papers at $\text{N}_H = 10$. Under this threshold, declared hazards were double-checked and modified when applicable.

Other hazards exist and can be crucial in particular ecosystems (mammals, game species, gravitational hazards, etc.) but occur less often than the six others mentioned above. Moreover, particularly in theoretical economics papers, a single general risk can also be considered to simultaneously represent several hazards (fire and windstorm, for example). To solve both issues, we added a seventh category of risk: *unspecified hazards*.

Categories

In keeping with Section 1.2.1, we adopted a typology that includes two categories. The first category is thus hazard modelling: this includes two sub-categories of methods to design the hazard parameters, the first one encompassing papers that use statistical methods, and the second one, papers that use vegetation process-based models. The second category is impact assessment: we assume three sub-categories in terms of impact: impact on individual preferences, value assessment and uncertainty management. The first sub-category contains articles dealing with the impact of natural hazards on individuals, such as on their houses or on their financial assets. The second sub-category captures the effect of natural hazards on the forest value. The last category tackles the way to manage these natural hazards in a context of risk and uncertainty.

Note that it is possible for a paper to be in both categories: by modelling a new hazard parameter, it is possible to assess its ecological or economic impact. Note that each sub-category can also be studied by several methods. For example, it is possible to assess the value of a forest stand and to measure its land expected value using Faustmann's or Hartman's formula, but it is also possible to consider the internal rate of return.

1.3 Results

To present the results of this systematic literature review, we suggest beginning with the analysis of the bibliometric indicators and investigated parameters that reveal an increasing interest on the part of both the ecology and economics communities, but still denote a high degree of heterogeneity. We then go deeper into the question of interactions between hazards and take a look at the methodologies used. Finally, we expand our research from a strict production risk point of view to other risks, including market risk.

1.3.1 Descriptive analysis

Bibliometric indicators

Our review contains 101 articles published between 1916 and 2020 (see section 1.6.1 in Appendix for a full list of the references). Figure 1.1 shows that until the 2000s, multi-hazard studies were mostly concentrated in North America but have recently considerably increased in Europe, particularly during the 2010s. This figure also reveals that, regardless of the geographical area, the multi-risk issue has increased over time. This result is in line with the literature reviews of Yousefpour et al. (2012) and Montagné-Huck and Brunette (2018) that highlight the focus of economics literature on one risk at a time, at least until recently.

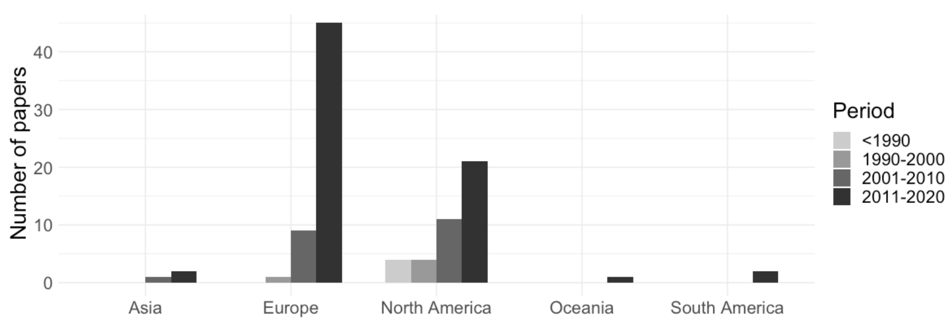

Figure 1.1: Evolution of the number of studies per decade for the five continents represented.

Figure 1.2 is obtained by looking at the "index keywords" indicated by the journals to sort articles[3]. The size of the circle is proportional to the number of occurrences of the keyword. Only keywords that appear at least five times are printed, restricting the network from 983 to 65 keywords. The keywords are linked together if they appear at least once in the same publication, and the thickness of the link between keywords is proportional to their number of co-occurrences. The most frequently cited keywords are "Forestry" (51 times), "Climate change" (28 times), "Forest management" (25 times) and "Risk assessment" (24 times).

[3]Note that among the 101 articles, only 96 contained "index keywords".

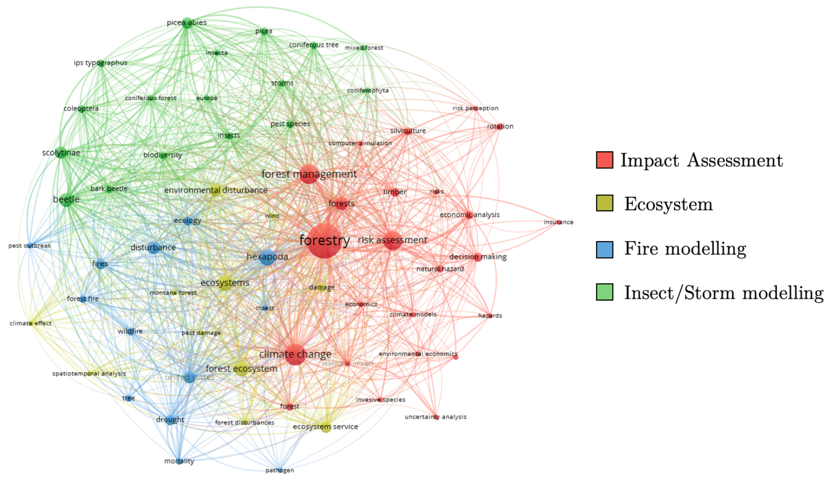

Figure 1.2: Index keyword co-occurrence network for 96 articles, created with VOSViewer software.

Figure 1.2 has been divided into four clusters with VOSViewer software. The first red cluster consists of impact assessment topics, depicting our "Impact Assessment" category. The second blue and third green clusters deal with fire hazard modelling contributions and insect/storm modelling contributions, constituting our "Hazard modelling" category. Finally, a last yellow cluster is devoted to generic ecosystem issues. The analysis of the keywords thus validates the category used to characterise the different methods in the literature.

The total number of authors involved in at least one paper in the review is 381. Among these, eight have more than three contributions, 27 have two, and 346 only one. This shows that the literature is not concentrated because many authors contribute, and generally only once. Moreover, 57 papers in the review were exclusively written by authors with only one article. The biggest co-contribution network (i.e., authors sharing at least one publication) consists of 66 authors, 17% of the total number of authors. We can thus conclude that the different networks of authors are poorly connected in terms of the co-construction of articles.

To further extend this analysis, we represented the citation network of 251 authors in Figure 1.3. The size of the circle is proportional to the number of contributions of the author (between 1 and 6), and the thickness of the link between two authors is proportional to the number of times they cite each other (the links are undirected, i.e., no distinction is made between a citation from author A to author B, or vice versa).

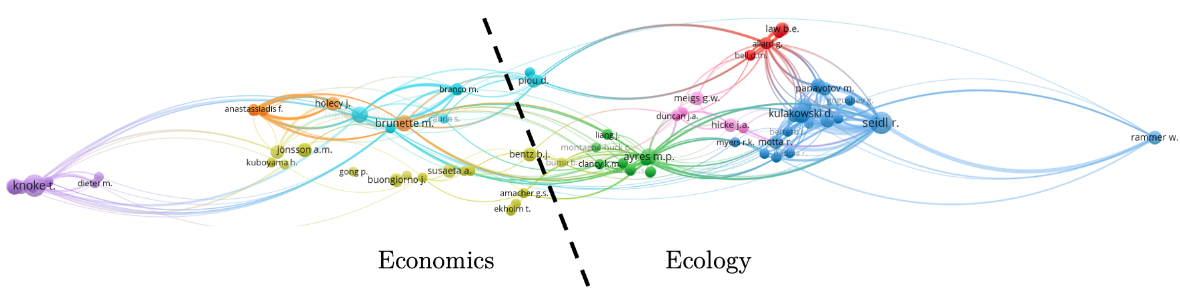

Figure 1.3: Citation network of contributing authors, created with VOSViewer software.

The network in Figure 1.3 links 251 authors (66% of the total number of authors) with each other, meaning that even if authors have only a few co-publications, they do cite each other. This means that even if there are few connections in the creation of the publications, there is still some dissemination between authors. Moreover, even if several clusters appear, we can see that the network can be split into two parts: contributing economics authors on the left and ecologists on the right. This network, exhibits a certain interesting level of permeability between both disciplines.

Table 1.2 summarises the main scientific journals (a total of 41) contributing to this review. The diversity of the scientific journals is thus high, which is in agreement with the diversity of orientations, hazard types and methods used to model, assess and manage multi-hazard forest risk.

Journal title	**No. of articles**
Forest Ecology and Management	28
Forest Policy and Economics	13
Journal of Forest Economics	6
Ecological Economics	5
Ecological Modelling	5
Forest Science	3
Other	42
Total	**101**

Table 1.2: Overview of the main scientific journals.

These results show that multi-hazard research is an issue of increasing interest in the ecology and economics communities, but that it remains quite heterogeneous in terms of authors, journals and topics, even if there are still links between both disciplines. The next section will thus attempt to provide a deeper understanding of these links in light of our parameters.

Investigated parameters

The following table presents the number of articles, among the 101 articles of our database, for each parameter investigated in this study presented in Table 1.1.

Orientation	**Group**	**Hazard**	**Category & sub-categ.**
Economics: 52	$\text{Group}_{\text{Ind}}$: 62	Wind: 45	Hazard modelling: 38
Ecology: 44	$\text{Group}_{\text{Dep}}$: 39	Fire: 43	- Statistical method: 28
Both: 5		Drought: 17	- Vegetation process: 10
		Ice & snow: 18	Impact assessment: 54
		Insects: 44	- Individual preferences: 15
		Pathogens & disease: 21	- Value ass.: 39
		Unspecified hazards: 23	- Uncertainty manag.: 17

Table 1.3: Number of articles for each investigated parameter.

The sample is almost equally divided between economics-oriented and ecology-oriented articles. Although the papers consider several hazards in their analysis, most of them consider these hazards as independent ("$\text{Group}_{\text{Ind}}$"). In terms of hazard types, the most highly represented are "Wind", "Insects" and "Fire", with more than 40 articles dealing with each one of them.

Figure 1.4 shows that European publications have mainly focused on wind and insects, whereas North American ones primarily deal with fire and insects, confirming the results of

Montagné-Huck and Brunette (2018). Insects and drought (and wind, to a lesser degree) have the particularity to be treated more in $\text{Group}_{\text{Dep}}$ than in $\text{Group}_{\text{Ind}}$, which reflects how important their interactions with other hazards can be.

Figure 1.4 also allows us to conclude that most of the articles deal with temperate, Mediterranean and boreal forests in North America and Europe. This means that tropical forests are practically absent from this literature review. They are, however, exposed to the same risks, as revealed by Seidl et al. (2017) in their review with an ecological perspective that focused on regions of the world like Asia, Africa and Oceania. This means that, at that time, economics had not yet dealt with the problem of multiple natural hazards in tropical forests.

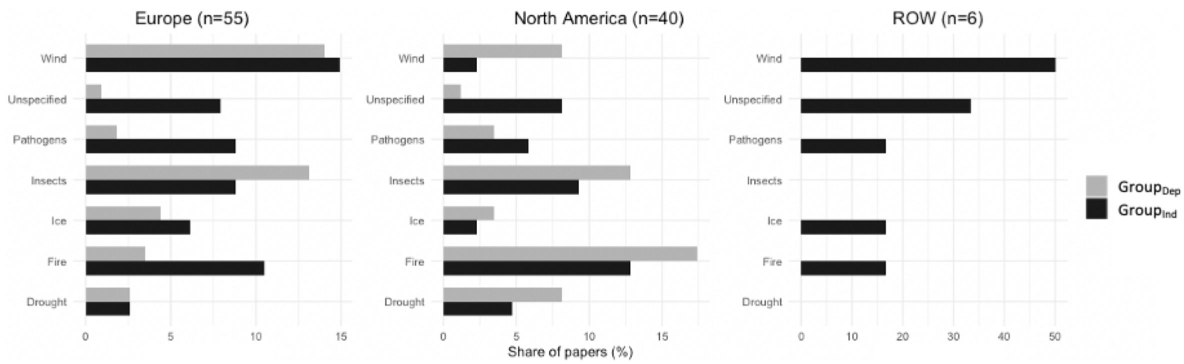

Figure 1.4: Prevalence (%) of each of the six + unspecified hazards per continent (ROW = Rest Of the World = Asia + Oceania + South America) for both groups.

1.3.2 Interactions between hazards

To analyse the relationship between the six hazards, we began with our classification of articles into "$\text{Group}_{\text{Ind}}$" and "$\text{Group}_{\text{Dep}}$", and we determined if the hazards interacted and how (Section 1.3.2), and if there was an eventual correlation with disciplinary orientation (Section 1.3.2). Finally, we made a more in-depth analysis of the categories ("Hazard modelling" and "Impact assessment") and the proposed sub-categories in order to identify relevant methods to address the interactions between hazards (Section 1.3.2).

Study of interactions

To study if and how the seven categories of hazard types considered interact with each other, a Venn diagram is shown in Figure 1.5. This diagram includes two dimensions. The position of the label on the diagram gives the hazards considered, and both numbers on the label "X;Y", with X (resp. Y) give the total of the number of $\text{Group}_{\text{Ind}}$ (resp. $\text{Group}_{\text{Dep}}$) studies. Among the 64 possible interactions, 33 are represented in this review, with mainly two-by-two or three-by-three interactions.

The most frequently represented association of hazards is "Wind-Insects" (13 articles). In addition, the interaction between the two hazard types is considered, i.e., ten articles in "$\text{Group}_{\text{Dep}}$" as compared to three in "$\text{Group}_{\text{Ind}}$". "Wind" and "Insects" are also the most highly represented hazard types in our database, as indicated in Table 1.3. During some years after a storm occurrence, the likelihood of insect infestations increases the impact of the initial storm damage (Gardiner et al., 2010). This "Wind-Insects" interaction is thus of primary importance to ecologists concerned by a possible severe impact of climate change on this interaction, and by economists because of the importance of the area of productive European forests concerned

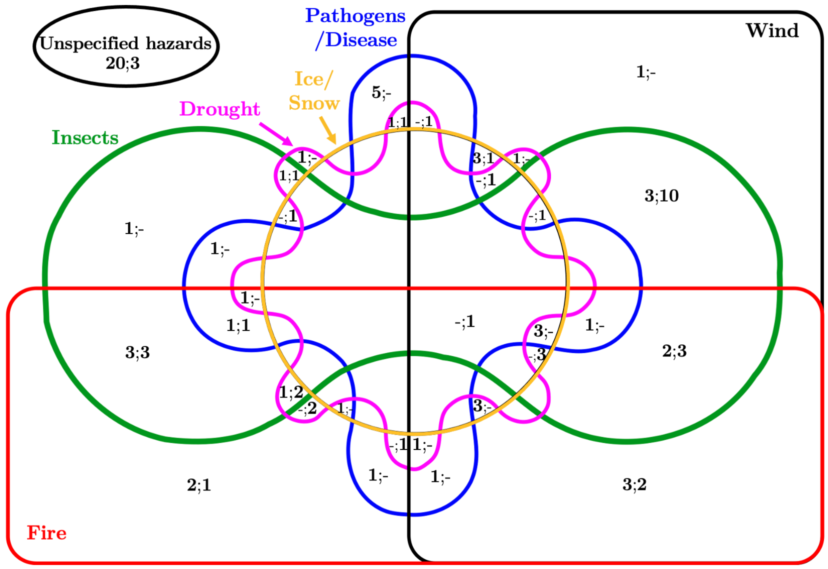

Figure 1.5: Venn diagram for distribution of the number of articles across six types of natural hazard. Key: "X;Y" with X (resp. Y), counting the number of $\text{Group}_{\text{Ind}}$ (resp. $\text{Group}_{\text{Dep}}$) studies. *Key: two (resp. three) papers of the Group_{Ind} (resp. Group_{Dep}) are exclusively devoted to fire, wind and insect hazards.*

by this issue (Seidl and Rammer, 2017). For example, in 2018 and 2019, wind and insects together damaged at least 68.1 Mm^3 of German forests, representing 51% of the total timber harvest (Destatis, 2020).

The next association that is the most frequently analysed is "Fire-Insects" with as many articles in both groups (three articles in "$\text{Group}_{\text{Ind}}$" and three articles in "$\text{Group}_{\text{Dep}}$"). Once again, "Fire" and "Insects" are also among the most highly represented hazard types in the database (see Table 1.3). This interaction is particularly studied in western North America where wildfires and native bark beetle outbreaks are considered as the two primary conifer forest disturbances (Jenkins et al., 2014). The cascading effect of fire on insect populations seems to depend on the type of insect. Reciprocally, insect outbreaks seem to favour wildfires by increasing available fuel (Jenkins et al., 2014), regardless of the direction of the interaction, "Fire-Insects" or "Insects-Fire".

These two interactions ("Wind-Insects" and "Fire-Insects") are also among the rare associations where the number of $\text{Group}_{\text{Dep}}$ articles is greater than the number of articles in $\text{Group}_{\text{Ind}}$, meaning that the interaction between the two hazard types is considered.

We can observe that only one publication studied the six hazard types simultaneously and, in addition, the article considers the interaction between the hazards (Dale et al., 2001). This article reviews the existing knowledge about the effects of eight natural disturbances and their expected modifications under climate change, proposes strategies to deal with natural disturbances in the future, and concludes with future research requirements necessary to fully understand the impact of natural disturbances.

It is quite surprising to note that "Drought" has not yet been much studied. There are only two papers on the "Drought-Insects" association and two on the "Fire-Drought" association, mainly ecology-oriented. Drought can trigger direct forest mortality but more often favours secondary mortality agents through combined effects, leading to much larger levels of mortality (Senf et al., 2020). Kolb et al. (2016) suggested, for example, a positive correlation between drought intensity and opportunistic biotic disturbances (bark beetle and secondary fungal pathogens like cankers and root rot), but a negative correlation with primary pathogens (rust) or sap feeders. This small number of articles dealing with drought is in accordance with Montagné-Huck and Brunette (2018) since drought is not part of their literature review because it is not tackled in the forest economics literature, even as a single risk. The literature is just emerging on that point, as revealed by the recent publication of Brèteau-Amores et al. (2019, 2022) dealing with the drought-induced risk of forest decline from an economic perspective. In addition, the effect of drought is expected to be highly non-linear with climate change and thus have a strong impact in the future (Seidl et al., 2017).

Disciplinary orientation as a key determinant

Table 1.4 presents the distribution of the articles as a function of their disciplinary orientation and of the group.

	Group$_{\text{Ind}}$	**Group$_{\text{Dep}}$**	**Total**
Economics	46	6	52
Ecology	13	31	44
Both	3	2	5
Total	62	39	101

Table 1.4: Overview of the orientation and group.

The main result is that in economics, the articles mainly consider the hazards as being independent, whereas in ecology, they generally consider interactions. Table 1.4 thus reveals that 88% of the 52 economics-oriented papers belong to Group$_{\text{Ind}}$. Only five studies take both economic and ecological orientations into account at the same time. We found only two types of studies that fit into this category. The first strategy is to use multi-criteria analysis that incorporates ecological and economic criteria (Lin and Buongiorno, 1998; Waring et al., 2009; Jactel et al., 2012; Knoke et al., 2020). The alternative, less common, is to incorporate an economic framework into an ecological process-based model (Jönsson et al., 2015).

Diversity of methods employed in the literature

Several methods exist and have been used to manage multiple natural hazards, as indicated in Figure 1.6. In this figure, we extended the list of methods proposed by Yousefpour et al. (2012) in their literature review of risk and uncertainty assessment in the context of climate change in forests. To build this mind map, we started from both categories ("Hazard modelling" and "Impact assessment") presented in Section 1.2.3 and the corresponding sub-categories. Finally, we allocated the different methods used in each publication to a sub-category.

Figure 1.6 shows that, like Yousefpour et al. (2012), Faustmann's method is the most commonly used to assess the land expected value of a forest, but other methods are also mobilised. Note that many publications use several methods simultaneously. For example, Sacchelli et al. (2018) use a GIS-based model to assess key risk parameters and can thus develop an insurance risk premium model in Italy at the same time.

It can be noted that the standard approach in the articles in our database is to consider that timber production losses are consecutive to a natural disturbance occurrence.[4]. However, Figure 1.6 shows that among the other ecosystem services considered, carbon loss also plays a role (at least, in seven articles) and has an impact on tourism-recreation (in two articles). It

[4]For the reader who would like to know more about the methodology used to fix the hazard parameters in the risk assessment, we propose another mind map that summarises the literature in section 1.6.2 in Appendix. Methods are separated into two approaches: empirical and theoretical models.

seems that, with the exception of timber and carbon losses, other services are rarely integrated.

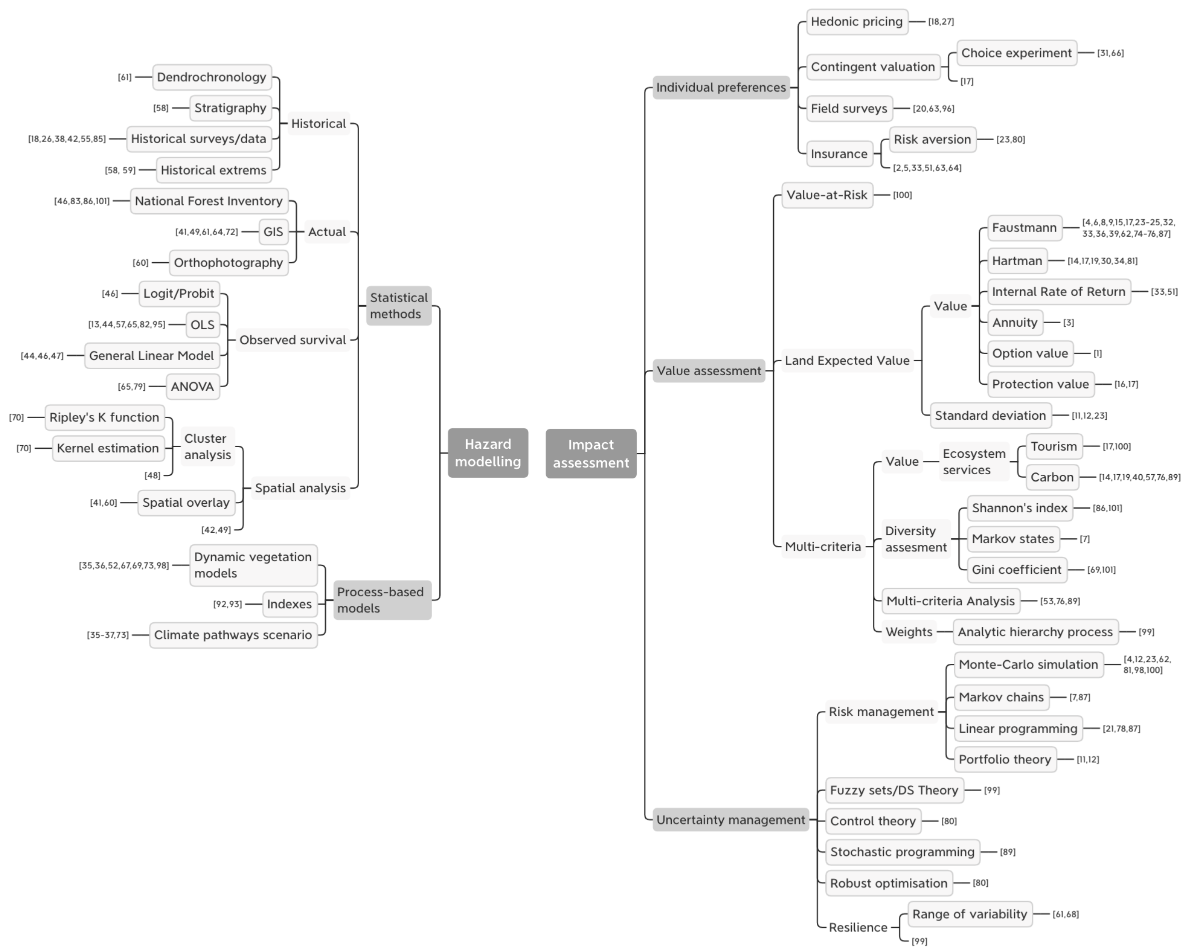

Figure 1.6: Mind map representing the panel of methods used to model hazards, determine parameters and assess hazard impacts. *Key: Dark grey = category; light grey = sub-category; framed = method; [...] = references of the papers using the method mentioned, listed in section 1.6.1 in Appendix.*

1.3.3 Other economic risks

Our study is focused on the timber production risk due to natural hazards, but other risks could have been investigated as well. Komarek et al. (2020) suggest a review of several risks studies in agriculture. The following five risks are studied: production risk, personal risk, financial risk, institutional risk and market risk.

The effects of natural disturbances on human health (i.e., personal risk) are particularly present. For example, Lin and Buongiorno (1998) show that vegetation feedbacks during drought exacerbate ozone air pollution extremes in Europe, strongly impacting human health. The impact of fire is also often expressed in terms of human lives (Halbritter et al., 2020). Finally, some forest economics papers (Notaro and Paletto, 2012; Vacchiano et al., 2016) have focused on pricing protective forests, whose main value is the reduction of personal risk.

Concerning financial risk, Dai et al. (2015) measure the effect of forest insurance on the income of Chinese households and how this avoids ruin for the impacted households. The literature on the portfolio theory applied to forest diversification to reduce financial risk is also flourishing at this time (Knoke et al., 2005; Knoke, 2008).

In this review, we did not find any contributions to the assessment of institutional risk. Indeed, this topic is very relevant for agriculture, where agricultural policies often change with immediate and large impacts on the farmers and the agricultural sector. However, this is less true for forestry, which is characterised by a greater degree of inertia. This difference is linked to the temporal horizon of each sector, with several months to a year for agriculture, allowing flexibility in the implementation of new policies, whereas several decades to a century are necessary for forestry because of the inertia.

Finally, concerning market risk, when a natural disturbance occurs, a large quantity of unexpected wood enters the timber market. As a direct consequence, the price of timber decreases. Thus, the co-effect of natural hazard and market risk can be considerable. Indeed, Rakotoarison and Loisel (2017) expect the market risk to be as great as the production risk if we are to obtain an accurate idea of the land expected value of a forest, arguing that forest owners need to be certain of the profitability of their forest in order to reinvest in silviculture, particularly in a context of climate change. For example, price risk and wind have been studied by Rakotoarison and Loisel (2017), and price risk and fire by Susaeta and Gong (2019). Several methods are commonly used to integrate price risk into an economic analysis:

- deterministic: timber price is diminished and extraction costs are increased due to the unexpected quantity of timber on the market. The price variation can be fixed for any hazard (Knoke et al., 2005) or can vary depending on the intensity of the hazard (Rakotoarison and Loisel, 2017).

- i.i.d. stochastic: prices at each time are assumed to be independent and identically distributed random variables, often following a normal distribution (Knoke et al., 2005; Roessiger et al., 2013).

- autoregressive stochastic: price is a random variable following a Wiener process, determined by a linear drift and a noise (Yin and Newman, 1996; Knoke and Wurm, 2006).

Moreover, the market risk induced by fluctuations of the interest rate is also common in the forest economics literature. For example, Buongiorno and Zhou (2011) propose a generalisation of Faustmann's formula that takes account of stochastic interest rates, using a Markov decision process.

To our knowledge, no publication has yet studied the effect of market risk in a "$\text{Group}_{\text{Dep}}$" hazard framework, i.e., that considers interactions between several natural disturbances. This lack offers interesting avenues for future research.

1.4 Discussion

Ecology and economics literature raises different research questions. Ecology literature considers the existence of natural hazards and their effect on the forest ecosystem. The issue is thus to model the natural hazard. To tackle this hazard, many papers then propose optimal management strategies from an ecosystem point of view, which is why ecology literature leans to the left side of Figure 1.7. It often focuses on two scales: the tree or the region. On the other hand, economics literature assumes that hazard parameters are fixed (such as likelihood or severity) and proposes the impact assessment of such a hazard. This makes it possible to propose explicit optimal management strategies with respect to forest value. It often focuses on the scale of the forest stand, especially beneficial for assessing the impact of natural disturbances on a forest owner.

Our results showed that the literature is quite heterogeneous in terms of the hazards studied, the interactions considered and the approaches, especially when comparing economic and ecological literature. For instance, ecology papers often suggest that the effect of multiple interacting hazards can be major (Seidl and Rammer, 2017). This raises several questions: In what respect can hazard interaction considerations give food for thought to forest economics? Could forest disturbance ecology be influenced by economic results? What are the motivations to aspire to more interdisciplinary projects? It is precisely these questions that we propose to answer in this section.

1.4.1 What can hazard interactions consideration contribute to forest economics?

When facing hazards, a major economic question is to understand how forest owners decide on the optimal management strategy. For example, on the theoretical economics side, Xu et al. (2016) proposed a generalisation of the results of Reed (1984) to several risks. The occurrences of these risks are independent but correlation between damage levels is possible. This enables the authors to find the best forest management among three possibilities: harvesting after the occurrence of the first hazard, after the second hazard or waiting until the end of the rotation. The optimal strategy strongly depends on the hazard parameters (probability of each hazard and severity). This shows that the decision of the forest owner is strongly impacted by the interaction of the hazards so that it would be useful to better understand multiple hazards to assess forest owners' decisions.

Xu et al. (2016) do not consider the forest owner's expected utility but, instead, the land expected value. Using a generic risk economic approach, Courbage et al. (2017) show that under the assumption of risk aversion, the level of optimal prevention between two hazards depends on the fact that these hazards are correlated or not (independent of the sign of the correlation). This suggests that a better understanding of how risk interact can lead to different results, in particular in the field of insurance. The papers related to insurance included in this review consider single or independent hazards (Holecy and Hanewinkel, 2006). It seems that the case of insurance for multiple hazard could be interesting and also relevant for fields other than forest economics.

In addition, Buma (2015) defines two types of hazard interactions based on their temporal effects: first, simultaneous, referred to as "concurrent" or "compound" events (same place and time). An example of this type of interaction is the effect of drought on insect populations: during a drought, the intensity of an insect outbreak is generally greater because of the stress caused by drought, reducing the defence capacities of the trees; second, sequential, referred to as "cascading" events (same place but later). An example is storm and insects: if a storm occurs, many fallen trees will be targeted by the insects, whose population will increase and then reach epidemic proportions, capable of overwhelming the defences of healthy trees. Consequently, the time during which the effect of the preliminary event persists must be defined. These effects can modify the hazard likelihood (i.e., the time of return of the hazard) and/or the vulnerability of the forest. A basic economic question would be to investigate if the optimal strategy of the forest owner should be different if events are concurrent or sequential, with the same respective level of damage. This kind of study has, to the best of our knowledge, not yet been investigated.

At the macro scale, the aftereffects of multiple natural hazards are diverse. The first effect is the timber price volatility due to the volatility of timber supply after the occurrence of natural disturbances (Prestemon and Holmes, 2000). This effect is major but is still not perfectly understood. Rakotoarison and Loisel (2017) investigated this price risk after windstorm at a micro-scale. Although this paper is a first step to equating price with storm severity, it is not representative of what happens at the regional scale. To the best of our knowledge, the question of the effect of hazard correlations on price dynamics has not yet been investigated in the literature. Hazard correlation could still be very significant on price dynamics because it would increase the volatility of timber supply and, consequently, price volatility.

1.4.2 What can forest economics bring to forest ecology?

Human behaviours are the ground of all decision-making processes, including those involving forest management. Economics makes it possible to understand, represent and quantify the different individuals' behaviours. In this sense, economics brings heterogeneity in terms of forest owners' behaviours, and ecology could benefit from these advances. For example, a part of the literature shows that private forest owners are risk-averse and that these preferences towards risk have an impact on forestry decisions like insurance (Brunette et al., 2013; Sauter et al., 2016), timber harvesting (Brunette et al., 2017), forest rotation (Loisel et al., 2020) and adaptation to climate change (Brunette et al., 2020). This means that the forest owner's behaviours should be represented through a concave utility function, and s/he should be considered as a utility maximiser, whereas s/he is again too often assumed to be a simple profit maximiser who is neutral towards risk. The literature goes even further by computing average risk-aversion coefficients for forest owners that may be helpful to calibrate models. Authors use experimental economics and, in particular, elicitation methods like the Multiple Price List (Holt and Laury, 2002) to compute average coefficients. Brunette et al. (2017) thus obtained an average relative risk aversion coefficient of around 1 for French private forest owners. Brunette et al. (2020) also quantified the preferences of forestry professionals from France and Germany, and they show that in France, they are generally more risk-averse than in Germany. This last article pushes the thinking even further by considering forest owners' preferences towards uncertainty in addition to those towards risk. The authors reported that forestry professionals are generally uncertainty-averse, with no real difference between the coefficient of uncertainty aversion of French and German forestry professionals. Considering uncertainty is of utmost importance in a context of climate change.

Economics also makes it possible to identify the determinants of decisions, especially using surveys. For example, Dai et al. (2015) reported that the education of forest producers, participation in producers' organizations in the local area, and the incidence of forest fires in the local counties are significant determinants of participation in the forest disaster insurance in Fujian province in China. Qin et al. (2016) show that in Zhejiang province in China, the forest owner's insurance demand is influenced by variables like the proportion of forestry revenues in the total household income, forest size, forest disaster frequency, forest insurance liability, insurance cost, and farmer satisfaction regarding the premium subsidy policy. Brunette et al. (2017) identified relevant determinants of harvesting decisions among French private forest owners, such as gender, age, location, delegation of the management and being certified. This way of collecting data about individuals improves the understanding and the knowledge of forest owners' decisions. Forest ecology modelling can benefit from the advances made by forest economics in this field.

The management of certain hazards requires large-scale decisions (Jönsson et al., 2015). For example, in the case of fire or bark beetle prevention, all the local forest managers have to coordinate their management to achieve an effective reduction of exposure. The diversity of the forest at different scales, from the tree to the landscape, can also have a major impact on the risk regime (Sebald et al., 2021). For this type of problem, it is often in the interest of the forest owner to under-invest, but also for the others to invest more in prevention. To deal with these types of issues, game theory is a useful tool to predict which strategy each participant will follow. The same kinds of questions can apply to the role of carbon storage in the forest

(Lewandrowski et al., 2014): agents have to coordinate at a large scale to be efficient. Public policies are usually necessary to promote this type of forest management.

1.4.3 Conjoint optimisation

As clarified in both previous sections, economics and ecology complement each other but there has been little cooperation between these two disciplines until now, whereas this interdisciplinary collaboration is crucial to the improvement of the understanding and modelling of multiple natural hazards in forests. Figure 1.7 shows that "Risk modelling", "Impact assessment" and "Optimal management" are strongly connected in a closed loop. Forest owners' decisions to go toward optimal private strategy, and optimal public policies are strongly influenced by the hazard regime, but the hazard regime also depends on the decisions taken by the forest owners (Stritih et al., 2021).

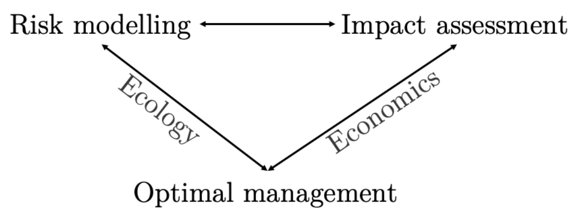

Figure 1.7: Theoretical loop between "Risk modelling", "Impact assessment" and "Optimal management".

A way to introduce more hazard interactions into economics studies would be to capitalise on the competences developed in the ecological literature on hazard interactions. Indeed, it is possible to use process-based models (examples: Jönsson et al. (2012) and Jönsson et al. (2015)) and to incorporate economic packages. This option is however often considered "weak" because risk is not completely endogenous: there should indeed be a feedback of economic results on silviculture, but, to our knowledge, this has not yet been developed.

Reciprocally, ecology-oriented papers can also benefit from collaboration with economists since the future path of human-managed forests mainly depends on forest owners' decisions, which can be described using microeconomics tools. Forest management could thus become endogenous rather than exogenous, as in most cases in ecology-oriented articles.

Climate change is a particular situation where this interdisciplinary framework could be especially meaningful to tackle future complex challenges. More than one quarter of the articles in this review (28 out of 101) consider the effects of climate change on the hazard and attempt to quantify the induced modification of the hazard likelihood or intensity. Most of these papers are ecology-oriented (18 articles out of 28), such as Dale et al. (2001) who attempt to understand the implication of climate change on forest ecosystems for eight major production hazards.

Multidisciplinary studies are relevant in the context of climate change for two main reasons. First, climate change modifies hazards and their interactions (Seidl and Rammer, 2017), directly impacting forest stands and requiring an adaptation of existing forest stands (Yousefpour et al., 2012). However, there is also a retro-action of forests on the world climate through carbon storage (Lewandrowski et al., 2014), which attenuates climate change. Forests are therefore key drivers on the pathway to reduce CO2 emissions in several countries. Forests are thus part of the problem but also part of the solution. Consequently, the future management of forest stands is of utmost importance.

This makes the optimal management strategy of forest ecosystems a major issue that must be dealt with in terms of economics and ecology. Only a few economics articles focus on climate change and its impact (seven articles out of 28). This research gap will require further exploration to find these optimal paths and should be based on ecology literature that has already modelled the risk due to climate change. Different scales are relevant to study this question, from forest owners' decisions to macro-scale effects, but only multidisciplinary studies can grasp the global picture.

1.5 Conclusion

In this article, we review the literature that considers multiple hazards in forests. We built a database on the basis of 101 articles that include variables related to the characteristics of the article (author(s), year, journal, keywords, country) and to the characteristics of the study such as the disciplinary orientation, if interaction is considered or not, the type of hazard and if the paper deals with hazard modelling or impact assessment.

Our key messages are the following. First, the most frequent pairs of hazards analysed together are "Wind-Insects" in Europe and "Fire-Insects" in North America. Then, categorising articles as economics-oriented or ecology-oriented allows us to emphasise that interactions rarely considered in economics are commonly taken into account in ecology. Finally, we suggested some avenues for future research, especially on possible ways economics could benefit from the introduction of interacting multiple hazards and how these results could also be a benefit to advances in ecology.

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1.6 Appendix of chapter 1

1.6.1 List of references included in the database (n=101)

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1.6.2 Summary of the approaches in the literature to describe natural hazards

The different approaches are divided into two exclusive groups:

- Empirical models: they are based on empirical observations. These methods rely on the central limit theorem, expected to rebuild the true density function of the hazard parameters thanks to sufficiently long observations. Mean time of return and damages can thus be proposed. These models have the advantage of accurately representing past data but have at least two limits: they often do not offer the possibility to consider a changing trend (climate change, for example), and their calibration is highly dependent on the length of the considered period.

- Theoretical models: they are based on theoretical hypotheses and can be calibrated thanks to real observations and Kolmogorov-Smirnov tests, or use multiple hypothetical values to carry out sensitivity analyses. An example of this would be to expect the probability density function of the yearly maximum wind speed to follow a Gumbel distribution, or the occurrence of a storm to depend on a time-dependent Weibull distribution. The limit of these models is knowledge of how well they fit with reality.

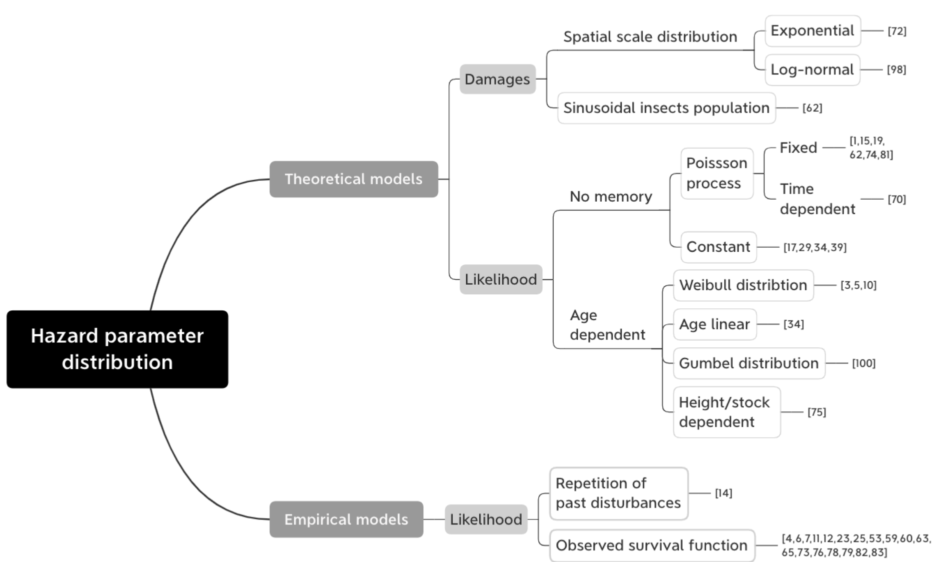

Figure 1.8: Mind map of the diversity of methods used to implement hazard likelihood in a model.

Figure 1.8 shows that most of the articles that use the "Theoretical models" approach consider Poisson processes to represent risk distribution (mainly fire and windstorm), while articles classified as "Empirical models" exclusively consider observed survival functions (for all types of risks).

Chapter 2

Stability and Resilience of a Forest Bio-Economic Equilibrium under Natural Disturbances

Stability and Resilience of a Forest Bio-Economic Equilibrium under Natural Disturbances

Félix BASTIT[a], David SHANAFELT[a] and Marielle BRUNETTE[a,b]

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[a] Université de Lorraine, Université de Strasbourg, AgroParisTech, CNRS, INRAE, BETA, 54000 NANCY, FRANCE
[b] Associate researcher at the Climate Economics Chair (CEC), PARIS, FRANCE

Abstract Natural disturbances play a key role in the long-term evolution of a forest but are by essence unforeseeable. If a sustainable management is fixed in a forest, where the harvest is equal to the forest growth (such as at maximal sustainable yield), natural disturbances could jeopardise the established equilibrium by modifying the future forest growth and possibility to harvest timber. This paper aims at studying the stability of a bio-economic equilibrium, where a forest is first managed in a sustainable way and has reached an equilibrium between the timber market and biological timber production. So far in forestry, sustainable management schemes do not appropriately integrate disturbance regimes. To overcome this issue, we describe a bio-economic equilibrium that includes a forest inventory, a local unregulated timber market (whose variations are defined by an equilibrium-displacement model), and natural disturbances. The paper investigates the short- and long-term effects following a disturbances. For reasonable descriptions of both forest evolution and timber market equilibrium, we show that there exists a critical forest inventory under which it is impossible to find a stable state where the forest inventory persists in the long term. For a forest inventory larger than this critical level, the equilibrium is what we call "meta-stable", because while the forest inventory does often persist in the long term, there always exists a certain level of natural disturbance able to destabilize the equilibrium and, ultimately, exhaust the forest inventory. However, this threshold is often too large to threaten real forests. Finally, we derive the maximum frequency between hazards that ensures the long-term sustainability of the forest.

Keywords Keywords: multi-risk, sustainable management, economics, local timber market, forest.

JEL codes JEL codes: D81 (Criteria for Decision-Making under Risk and Uncertainty); Q23 (Forestry); Q54 (Climate • Natural Disasters and Their Management • Global Warming)

2.1 Introduction

The long-term sustainability of forest resources - defined as the maintainable harvest of timber (Hahn and Knoke, 2010) - is one of the driving problems of the forest sector, now and into the future (FAO, 2020). Indeed, forests are a key source of ecosystem services such as carbon storage, timber and non-timber products, biodiversity or water protection (FAO, 2020) and their continued maintenance is a real challenge. In this context, forest management, specifically timber harvest, constitutes a delicate bio-economic equilibrium between the renewable resource sold on a market and its natural production (Conrad and Clark, 1987; Conrad, 1999; Clark, 2010).

Such a bio-economic equilibrium is brittle because it is often disturbed by natural hazards such as windstorms, wildfires, or pest outbreaks. For instance, van Lierop et al. (2015) suggested that natural disturbances impact a mean surface area of 7.9 10^7 ha of forest each year worldwide, representing 1.9% of the 4.06 10^9 ha of the world's forests (FAO, 2020). At the European scale, Schelhaas et al. (2003) estimated that damages due to natural disturbances amounted to roughly 8% of harvested volumes during the second half of the 20^{th} century. Moreover, in a context of climate change, natural disturbances are expected to become more intense and more frequent (IPCC, 2012). Natural disturbances thus represent a threat for the permanence of the forest cover that can jeopardise the provisioning of ecosystem services, especially timber production. Moreover, occurrences of natural hazards can lead to increased volatility in timber markets (Gardiner et al., 2010), which can cause volatility in timber production as the quantity sold depends on its price (Brazee and Mendelsohn, 1988).

In this paper, we investigate how the quantity of timber in a forest evolves through time if timber is harvested and sold on a market, where hazards can have direct major impact on the level of the resource. We study the dynamics of a timber market, based on an equilibrium-displacement model including endogenous timber prices, facing large scale natural disturbance. Specifically, we address the following research questions. First, what are the conditions for a stable bio-economic equilibrium that balances timber demand and forest inventory growth, what are the main drivers of this equilibrium, and how sensitive is it to variations in these drivers? Next, if such an equilibrium is stable, what level of damages can a forest cope with and still maintain timber production? Finally, what is the impact of the frequency of natural hazards on the existence of such equilibrium?

This article is at the border of three branches of economics literature: first, empirical case studies from forest economics, especially developed after hurricane Hugo; second, the classical environmental economics literature; and lastly, theoretical forest economics linking the effect of price volatility on forest owners' decisions. First, on the empirical side, Prestemon and Holmes (2000) suggested that the main economic effect of a natural disturbance is a transfer of welfare between different forest owners. For example, forest owners impacted by storm hazards are forced to sell their timber at a reduced price because of the influx of wood on the market. After hurricane Hugo (USA), the timber price dropped by 49% in Florida while the inventory shock was as high as 21% (Kinnucan, 2016). This means that impacted forest owners sold their timber at a lower-than-expected price in the short term. However, in the long term, a higher price would be expected, because the quantity of timber in the forest is reduced, e.g. a scarcity of the resource (Conrad and Clark, 1987; Conrad, 1999; Clark, 2010). For hurricane Hugo, Prestemon and Holmes (2000) estimated this long-term effect to increase timber price by 15%. This means that forest owners who were not directly impacted could sell their timber at a higher price than expected in the long term, leading to a transfer of welfare between impacted and not impacted forest owners (Prestemon and Holmes, 2000). It is possible to calibrate a model from these econometrics analyses, but to the best of our knowledge, the question of the long-term dynamics of a forest facing natural disturbances from a theoretical point of view has yet not been tackled by the literature.

Second, the environmental economics literature includes examples of the management of natural resources under price volatility and natural disturbances, but seldom considers forests. Traditionally, the focus of this literature is optimal extraction of non-renewable resources (Hotelling, 1931; Coase, 1960) or the optimal management of renewable species stocks (Clark, 1973; Clark and Munro, 1975), as opposed to the forest. (See, for example, Reed (1988), who considered the optimal fishing policy in the case where the fish resource can randomly collapse.) A notable exception is the body of work centering around the Faustmann rotation model (Faustmann, 1849; Samuelson, 1976; Conrad, 1999). Natural hazards where first introduced in the Faustmann context to derive the optimal harvesting strategy in the case of fire occurrence (Routledge, 1980; Reed, 1984), but we know of no study that does so in the context of endogenous prices.

Third, in theoretical forest economics, the long-term stability of forest stocks in the face of natural hazards with endogenous prices has yet to be investigated. Forest economics literature most often considers timber prices as constant in time (Reed, 1984). Even when assuming stochastic prices, prices are often independent from natural hazards (Yin and Newman, 1996; Loisel, 2011). One approach to capturing the price effects of natural disturbances - such as increased market supply, diminished quality of damaged timber, and higher costs of harvest due to increased demand - assumes that the price of timber diminishes by a given percentage following a crisis (Dieter, 2001), independent from the intensity of the natural hazard. In contrast, Knoke et al. (2021) separated cases of "local disturbance" and "extreme events", where damages are higher in the latter case. Another strategy is to consider price variations as random and independent from natural hazards. For example, Brazee and Mendelsohn (1988) suggested that wood prices followed independent and identically distributed processes, which can be Brownian (Yin and Newman, 1996; Knoke and Wurm, 2006) or normally distributed (Roessiger et al., 2013). Rakotoarison and Loisel (2017) assumed that timber price diminished several years after a storm. This approach enabled them to derive expected losses within a Faustmann framework. Their model is based on the stand scale (i.e. few hectares), which is much smaller than that at which timber prices are defined. We suggest to study the price volatility at a regional scale, where both price and timber quantity should be better defined. It must be noted that Rakotoarison and Loisel (2017) estimated the effect of price drop on the land expected value, making the assumption that the damages on a given stand are a good proxy for the local timber price variation. Like Rakotoarison and Loisel (2017), we consider two interdependent risks (Bastit et al., 2023): price risk and a long-term timber production risk which follows from it. This means that the price risk and the production are directly linked in our model.

We create a macro-stylised model that describes an equilibrium between forest inventory and growth and a timber market in the face of natural hazards. Specifically, we connect a forest model, which describes the biological growth of a forest inventory over time, to a market model, which describes the management (in our case, harvest) of the forest by forest owners. We nest an equilibrium-displacement model into the forest growth model to analyze the market response to natural disturbances (Kinnucan, 2016). Equilibrium-displacement models have often been used to explain short-term variations of timber markets to natural disturbances (Kinnucan, 2016; Sun, 2020), such as the drop in timber prices following hurricane Hugo in Florida in 1989. However, as suggested by Prestemon and Holmes (2000), they can be also used for long-term predictions. This enables to derive the critical inventory necessary to ensure the long-term existence of the forest inventory and the stability of the inventory in the face of stochastic natural disturbances.

We study the resilience of a social-ecological system in the sense that we consider a model with societal (timber market) and ecological (forest) subsystems (Renaud et al., 2010), the interactions of which lead to dynamics that would be unexpected without those interactions (Costanza et al., 1993). Measurements of resilience and stability have been particularly developed in ecology (Holling, 1973; Pimm, 1984; Gunderson and Holling, 2002; Arnoldi et al., 2016; Donohue et al., 2013). These include Holling's resilience of multiple equilibria (the maximum size of perturbation that a system can absorb and still return to its original state) (Holling, 1973), persistence (the time spent in a given equilibria) (Perrings, 1998), return time (time elapsed between two occurrences of a given natural hazard, corresponding to the inverse of the frequency of natural hazards) (Holmes et al., 2008) and variability (quantifies how far a parameter evolves from its mean) (Carpenter and Brock, 2006).

These methods have found their way into a large body of work measuring the resilience of coupled social-ecological systems (Perrings, 1998). For example, Reed (1988) derived the optimal management strategy for a fishery that can disappear due to a random natural catastrophic collapse. Anderies et al. (2002) developed a model to assess the resilience of grasslands subject to pressures of grazing and wildfires. Perrings and Walker (2004) suggested that the optimal use of rangeland is in fact not constant through time and should dynamically evolve. Kinzig et al. (2006) even went further by suggesting that resilience should not be defined by the evolution of a single parameter but by the co-evolution of several systems, acting at different scales, interacting with each other, creating highly nonlinear regimes. The contribution of Knoke et al. (2022) to assess the resilience of a temperate forest stand facing natural hazards is, to our knowledge, the only publication dealing with forest resilience in the forest economics literature. They estimated the time needed for a forest stand to return to its original value following a natural hazard, e.g. return time (Pimm, 1984). They evaluated different forest management strategies such as clear-cuts and harvesting to preserve continuous forest cover, focusing on the stand scale with constant prices. In contrast, we indirectly compute Holling's stability of multiple equilibria by measuring how the traits of the coupled forest-market can move the system from a state of long-term existence of the forest inventory to collapse. We then measure the return time of the system to equilibrium following a natural hazard.

In the contrast to the classical resource economics literature (Conrad and Clark, 1987; Conrad, 1999), we do not pursue an optimal policy, maximizing the profit of an individual forest owner or maximizing the welfare of society. We suggest a harvest policy in which harvest is elastic to price and the available volume of timber in the forest, which corresponds to an equilibrium that balances supply of timber by forest owners and timber demand by buyers. We assume a single decision maker who manages the entire forest inventory at a regional scale, with harvest levels adjusting to the stock of forest and market price of timber (both of which can change over time). We further assume that the market is not regulated by a policy maker and that the timber market smoothly responds to fluctuations in the forest stock and the harvest regime. The aim of our model is not to find optimal forest management policies, but to describe the conditions for the stability of our bio-economic equilibrium in the face of natural hazards.

The rest of our paper is organized as follows. Section 2 describes the theoretical model in two essential parts: forest inventory growth and the timber market. Section 3 presents the main results in the case of a small natural disturbance, and conditions to maintain the existence of a meta-stable equilibrium. The long-term dynamic of the timber market is then investigated. Section 4 is devoted to a discussion of the results. Finally, a brief conclusion and perspective is provided in Section 5.

2.2 Methods

2.2.1 The model

Figure 2.1 summarises the different blocks of our model, illustrating the feedbacks between natural forest growth, forest management, the timber market model, and natural disturbances.

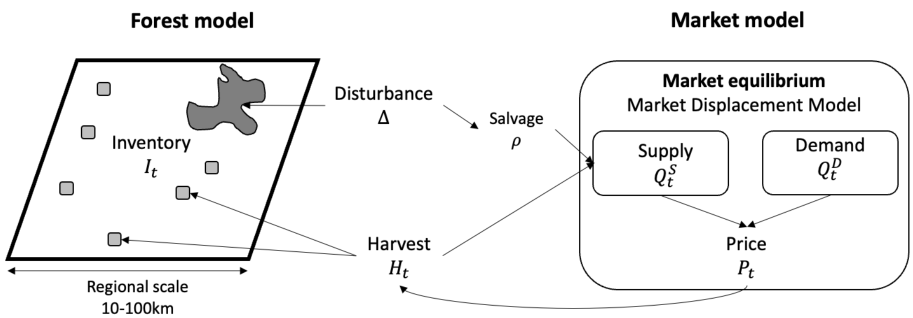

Figure 2.1: Graphical representation of the theoretical model.

The forest model We consider a forest inventory consisting of multiple stands (Figure 2.1, left), representing the aggregate standing volume of timber available in a region independent from any age or diameter class[1]. We use a basic logistic function to describe the evolution of the forest standing timber in the absence of forest management and natural disturbance (Berryman et al., 1984), such that

$$I_{t+1} - I_t = g(I_t) = \frac{I_t}{\tau} \cdot \left(1 - \frac{I_t}{K_I}\right) \tag{2.1}$$

where τ corresponds to a characteristic time scale for the forest inventory evolution. It corresponds to the inverse of the traditional growth rate typical to logistic growth models. Forest growth is proportional to the inverse of τ. The greater its value, the slower the rate of timber growth. While our use of τ is contrary to a normal growth rate, as we will show below, this formulation will prove especially relevant when describing the return time to equilibrium following a disturbance. The parameter K_I represents the maximum carrying capacity of the forest, or the maximum amount of available timber in the region if there were neither harvest nor natural hazard. We further generalize Eq. (2.1) such that K_I, and by extension I_t, is normalized to 1 and $0 < I_t < 1$.

This shape of the logistic function implies that if there is neither harvest nor natural disturbance, the size of the forest inventory is increasing as long as $I_t < K_I$. As we normalize Eq. (2.1), growth reaches a maximum when $I_t = 0.5$, i.e. when the inventory is at half its maximum. Moreover, the shape of the curve is symmetrical with respect to 0.5. Albeit using a logistic function is less precise than yield tables, it captures well the phases of forest inventory growth: a slow initial phase (young forest), fast growth at intermediate volumes, and then decreasing growth until inventory reaches its carrying capacity (Berryman et al., 1984).

Forest management The forest inventory is managed by a single decision-maker who decides in each period to harvest a quantity H_t of the inventory I_t, which is sold on the timber

[1]It is possible to specify age classes and fix the evolution of each class separately (*sensu* Kuusela and Lintunen (2020)). However, this introduces more complexity to the model and is not central piece of this article.

market at price P_t. The quantity of timber harvested at a period t depends on the timber price P_t and the total inventory I_t such that,

$$H_t = h \cdot P_t^{\varepsilon_{PH}} \cdot I_t^{\varepsilon_{IH}} \tag{2.2}$$

where h is a constant describing the harvest intensity, and ε_{PH} and ε_{IH} are constant elasticities of harvest with respect to price and inventory respectively (Sun, 2020). The last two represent the percent change in harvest for changes in price or inventory size (e.g., if price increases by 1%, then harvest will increase by ε_{PH}%). We would expect $\varepsilon_{PH} > 0$, as harvest should increase with price (Kinnucan, 2016). Similarly, we would also expect $\varepsilon_{IH} > 0$, as harvest should scale with forest inventory size (Prestemon and Holmes, 2004). The multiplicative shape of H_t is commonly used in equilibrium-displacement models (Prestemon and Holmes, 2004; Kinnucan, 2016; Sun, 2020). For instance, this is this non zero harvest elasticity to price that enables to consider endogenous timber price.

Natural disturbance To quantify the effect of natural disturbance, we introduce a generic natural hazard and quantify its effects as a share Δ of the forest that is affected. It corresponds to the damage of a single event such as a fire or a windstorm, but - as damage is expressed in terms of generic volume loss (Reed, 1984) - it can depict more generally all the possible damages that can impact timber stocks in a forest. Multiple natural hazards could also be considered in the single distribution of damage.

Market equilibrium The supply of timber to the market consists of harvested timber and the quantity of salvageable timber brought to the market by a natural disturbance,

$$Q_t^S = \begin{cases} H_t + \rho \cdot \Delta \cdot I_t & \text{if a hazard occurs} \\ H_t & \text{otherwise} \end{cases} \tag{2.3}$$

where, when a natural disturbance occurs, a fraction ρ of the fallen timber is salvaged and sold on the market[2]. We assume that all harvested timber is sent to the market, i.e. there is no self-consumption, timber black market, or timber production via natural mortality.

Market demand for timber depends only on price such that:

$$Q_t^D = q \cdot P_t^{\varepsilon_{PD}} \tag{2.4}$$

where ε_{PD} is a constant elasticity of demand to price, and q is a constant. As per the classic supply and demand curves, we expect ε_{PD} to be negative. Moreover, we suppose that the market reaches an equilibrium between supply and demand at each moment in time, or more formally,

$$Q_t^D(P_t) = Q_t^S(P_t, I_t) \tag{2.5}$$

That is, in each period, supply Q_t^S and demand Q_t^D instantaneously adjust to their market equilibrium price P_t and quantity, the latter of which is determined by harvest and natural disturbance (if it occurs). There are no delays between the forest being harvested (or damaged), brought to the market, and then the market adjusting to the new supply.

[2] Several effects lead to ρ being less than 1 (imperfect efficiency). We would expect a fraction of fallen timber to be too damaged to be sold on the market. Furthermore, as greater amounts of stock are downed, forest owners are not able to properly salvage it and it may become unusable. Thus we would expect ρ to decrease with the intensity of damages.

The full coupled social-ecological system The dynamics of the full social-ecological system can be written as,

$$I_{t+1} - I_t = \begin{cases} g(I_t) - H_t - \Delta \cdot I_t & \text{if a hazard occurs} \\ g(I_t) - H_t & \text{otherwise} \end{cases} \tag{2.6}$$

$$H_t = h \cdot P_t^{\varepsilon_{PH}} \cdot I_t^{\varepsilon_{IH}} \tag{2.7}$$

$$P_t = \begin{cases} \left[\frac{H_t}{q} + \frac{\varrho}{q} \cdot \Delta \cdot I_t\right]^{\frac{1}{\varepsilon_{PD}}} & \text{if a hazard occurs} \\ \left[\frac{H_t}{q}\right]^{\frac{1}{\varepsilon_{PD}}} & \text{otherwise} \end{cases} \tag{2.8}$$

which is a system of three equations and three unknowns and, given an initial level of forest inventory, can be solved for values of I_t, H_t, and P_t over time.

In the absence of disturbance, the long-term steady-state is reached when the natural growth (left side of Eq. (2.9), see Figure 2.2 black line) equals the quantity that is harvested (left side of Eq. (2.9). To estimate this, we re-inject the price in case of no hazard (Eq. (2.8)) into Eq. (2.4). All in all, long-term steady forest inventory (I^*) verifies of the following equation:

$$\frac{I^*}{\tau} \cdot (1 - \frac{I^*}{K_I}) = q\left(\frac{h}{q} \cdot (I^*)^{\varepsilon_{IH}}\right)^{\frac{\varepsilon_{PD}}{\varepsilon_{PD} - \varepsilon_{PH}}} \tag{2.9}$$

which can have one, two, or three possible steady-state values, depending on parameter values of τ, h, q and different elasticities (Figure 2.2). I^* corresponds to the largest solution of the set of possible solutions. Equilibrium values for harvest (H^*) and price (P^*) can be solved using the equilibrium forest inventory in Eq. (2.9) and equations (2.7) and (2.8).

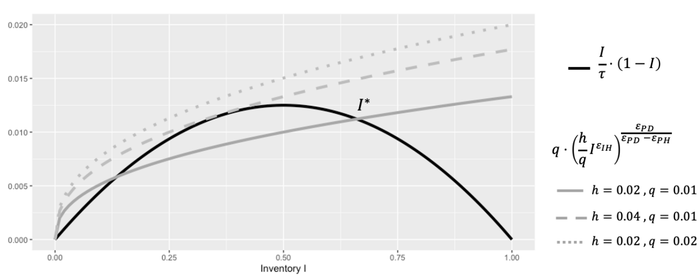

Figure 2.2: Graphic summing up the equilibrium states for different parameterizations. The black line corresponds to the left side of Eq. (2.9), whereas the grey lines correspond to the right side of Eq. (2.9) for different values of h and q. The solid line has three solutions, the long-dashed line has only two solutions, and the dashed line only accepts the trivial solution.

Model analysis We analyze the model by first determining the short and long-term effects of a single disturbance. We then focus on the recovery of the system following a natural disturbance and the long-term survival of the forest inventory in the face of multiple disturbances. For the former, we treat the initial state of the forest as free and evaluate the relationship between the magnitude of the disturbance and the critical inventory necessary to prevent inventory collapse. For the latter, we set the initial state of the system at equilibrium, measure the time it takes for the system to return to its previous level following a disturbance, and determine the return time between disturbances needed to prevent collapse. We derive analytical results when possible, but as the system of equations in (2.6)-(2.8) has no closed-form solution, we rely on numerical simulations when analytical results are not feasible. Parameter values for numerical simulations were calibrated from the forest literature. Baseline values can be found in Table 2.1.

Symbol	Description	Value [Variation range]
ε_{IH}	Elasticity of harvest to inventory	1^a [0.2 ; 1.46]
ε_{PH}	Elasticity of harvest to price	0.5^b [0.25 ; 0.55]
ε_{PD}	Elasticity of demand to price	-0.35^b [-0.43 ; -0.57]
ε	Elasticity of harvest to damages (Eq. (2.11))	0.41 [0.35 ; 0.83]
ρ	Salvageable share	0.3
τ	Time of evolution of our system	55
K_I	Maximum carrying capacity	1
h	Harvest intensity	0.01
q	Level of demand for timber products	0.02

Table 2.1: Baseline values for the main parameters used in the study. Approximated from: [a]Binkley (1993), [b]Newman (1987).

2.3 Results

2.3.1 General effects of a single disturbance

We will first look at the effects of a single disturbance (Δ) on the social-ecological system at time t_Δ. We can separate the effects of a natural disturbance into two categories: a short-term price drop effect due to an influx of timber supplied to the market, and a long-term existence effect of the forest inventory (Prestemon and Holmes, 2000).

In the short term, the quantity of timber on the market is larger than that with no disturbance. Foresters must sell their salvageable timber, which, in accordance with the supply curve in Eq. (2.3), leads to excess supply in the market and a drop in price. In other words, when foresters sell their timber following a disturbance, they do so at a lower price than they would with no disturbance.

It is important to note that this drop in price is strongly correlated with the proportion of fallen timber that can be salvaged and sold on the market (ρ), the scalar (q), and the elasticity of the demand function (ε_{PD}). In particular, as foresters lose efficiency in salvaging fallen timber or natural hazards are more damaging, there is less excess timber supplied to the market and the short-term effects of the hazard are felt less in changes in price and more by changes in the forest inventory. Indeed, by taking the partial derivative of Eq. (2.2) with respect to the forest inventory (I_t), it is straightforward to show that a decline in inventory size leads to a decrease in harvest rates (all else held equal).

In addition to the short-term effects, which only last through the salvage period (a few quarters), disturbances can affect the long-term existence of the forest inventory (Figure 2.3). Define $I_{t_\Delta^+}$ as the level of forest inventory following a disturbance. Several trajectories, beginning from $I_{t_\Delta^+}$, are possible. The inventory can either follow a track going toward its previous target value I^*, but a long-term exhaustion of the inventory can also be undertaken.

From Eq. (2.1), in the absence of harvest or disturbance, the forest inventory would always tend to its long-term carrying capacity (K) as long as $I_t > 0$ (Gotelli, 1995). Therefore, the existence or collapse of the forest inventory depends on the market effects following a natural hazard.

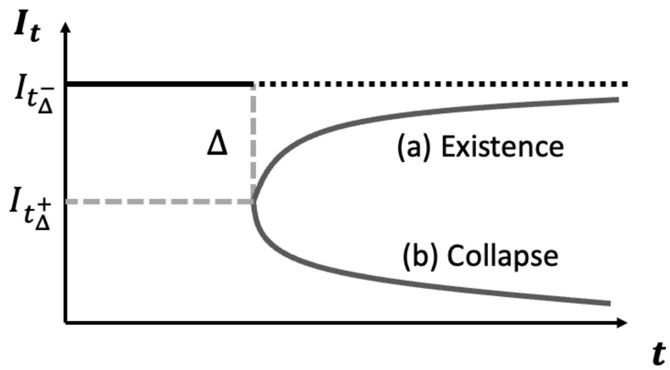

Figure 2.3: Criterion to define stability: if the inventory goes back up (resp. goes to 0) after a disturbance Δ, the equilibrium is Δ-stable (resp. Δ-unstable) as in case (a) (resp. case (b)).

The market effect In the absence of natural disturbance, the market price and harvest rates are tied directly to the level of the forest inventory. Disturbances, through the market effect, decouple this one-to-one linkage and can lead to the over-exploitation of the forest inventory to depletion.

Let us suppose that a disturbance occurs at time t_Δ. We call t_Δ^-, the time just before the hazard, i.e. not yet affected by the hazard, and t_Δ^+, the time just after the disturbance where the short-term effects (such as the short-term price drop) are not playing a major role anymore: the market is back on its long-term trajectory. The new price $P_{t_\Delta^+}$ is defined by the market equilibrium between demand $Q^D(P_{t_\Delta^+})$ and supply $Q^S(P_{t_\Delta^+}, I_{t_\Delta^+})$, where[3]

$$P_{t_\Delta^+} = \left(\frac{h}{q} \cdot I_{t_\Delta^-} \cdot (1-\Delta)\right)^{\frac{\varepsilon_{IH}}{\varepsilon_{PD}-\varepsilon_{PH}}} = P_{t_\Delta^-} \cdot (1-\Delta)^{\frac{\varepsilon_{IH}}{\varepsilon_{PD}-\varepsilon_{PH}}} > P_{t_\Delta^-} \tag{2.10}$$

After the initial short-term price drop to the influx of timber to the market (see above), timber prices rise over time as expected due to scarcity in the resource ($\frac{\varepsilon_{IH}}{\varepsilon_{PD}-\varepsilon_{PH}} < 0$). The new price being known, it follows from Eq. (2.7) that harvest can be expressed as,

$$H_{t_\Delta^+} = H_{t_\Delta^-} \cdot (1-\Delta)^{\varepsilon} < H_{t_\Delta^-} \quad \text{where} \quad \varepsilon = \frac{\varepsilon_{IH} \cdot \varepsilon_{PD}}{\varepsilon_{PD} - \varepsilon_{PH}} = \frac{\varepsilon_{IH}}{1 + |\frac{\varepsilon_{PH}}{\varepsilon_{PD}}|} \tag{2.11}$$

where ε can be interpreted as the harvest elasticity to disturbance. In other words, if the inventory is diminished by 1%, i.e. $\Delta = 0.01$, harvest is reduced by ε%. The elegance of this aggregated parameter is that it summarizes the three elasticities into a single parameter that takes into account the long-term effect of natural hazard on harvest.

If a disturbance is sufficiently large, the market decouples from the forest inventory and the forest is not able to biologically produce what is demanded from the timber market. Harvest exceeds forest growth, a trend which, because of constant elasticities of harvest, price, and demand, continues until the depletion of the forest inventory. Reductions in harvest in response to lower inventories still exceed forest regeneration. It is clear that the parameter Δ, the level of damage from a natural hazard, is the key parameter of our study. In the following section, we investigate the level of Δ required to destabilize the timber market equilibrium and lead to the collapse of the forest inventory.

[3]To see this, note that $I_{t_\Delta^+} = (1-\Delta) \cdot I_{t_\Delta^-}$, substitute it into Eqs. (2.7) and (2.8), and solve for $P_{t_\Delta^+}$.

2.3.2 The minimal inventory of equilibrium

In this section, we study the size of a single disturbance necessary to induce the collapse of the forest inventory. As the system of equations in (2.6)-(2.8) has no closed-form solution and depends on parameter values (see Eq. (2.9) and Figure 2.2), analytical results are difficult to obtain and we rely on numerical simulations. However, if we assume that the disturbance is small, we can obtain analytical results by focusing on the dynamics of the system around its equilibrium.

Supposing that Δ is small, it is possible to linearize the system by taking a first-order Taylor approximation in Δ to study the response of the system to disturbance in the vicinity of its equilibrium I^*. This manipulation is equivalent to calculating the eigenvalue of the problem near its equilibrium (Clark, 2010). Doing so allows us to derive an inequality that holds if the forest inventory moves towards collapse,

$$\frac{I^*}{\tau} \cdot (1-\Delta) \cdot (1 - I^* \cdot (1-\Delta)) < q \cdot \left(\left(\frac{h}{q} \right)^{\frac{1}{\varepsilon_{IH}}} \cdot I^* \right)^{\varepsilon} \cdot (1 - \varepsilon \cdot \Delta) \tag{2.12}$$

where the inequality (2.12) is first-order in I^*. Re-arranging allows us to define a critical threshold $\mathcal{I}_\varepsilon^*$ under which there cannot exist any inventory of equilibrium $I^* > 0$.

$$I^* < \mathcal{I}_\varepsilon^* = \frac{1-\varepsilon}{2-\varepsilon} \tag{2.13}$$

Even though the disturbance is "small", it is possible for the disturbance to move the system from a state of persistence to that of collapse. There exists a nonlinear relationship between the size of the natural disturbance necessary to collapse the forest inventory and the elasticity of harvest to disturbance, which is due to the nonlinear growth of the forest inventory (Figure 2.2). In general we would expect $I_\varepsilon^* > 0.5$, which is where the growth of the forest inventory is at its maximum. Indeed, regardless of changes in price and adjustments in harvest, harvest must outpace forest growth in order for the inventory to go to collapse - which is less likely if the inventory stock is at its inflection point. We plot the relationship between $\mathcal{I}_\varepsilon^*$ and ε in Figure 2.4. Calibrating the individual elasticities of ε from the literature (see Eq. (2.11) and Table 2.1) suggests that range of ε varies between 0.35 and 0.83. Within this range of ε, I_ε^* varies between 0.4 and 0.15.

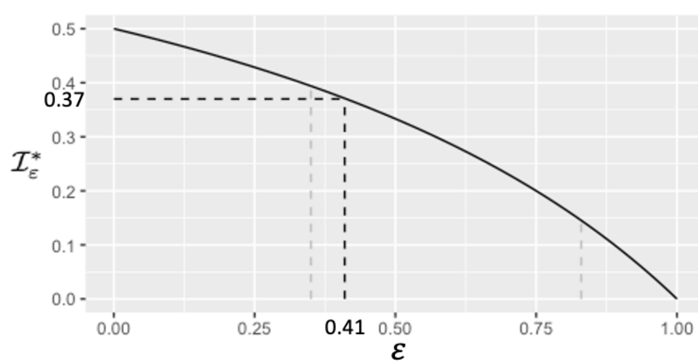

Figure 2.4: Critical inventory $\mathcal{I}_\varepsilon^*$ with respect to ε. The literature suggests $\varepsilon \sim 0.41$ (black dotted line), giving $\mathcal{I}_{\varepsilon=0.41}^* = 0.37$. Grey dotted lines represent the expected range of values of ε from the literature. Values of $\varepsilon < 0$ or $\varepsilon > 1$ lead to either inventory collapse (former) or infeasible levels of the inventory (latter, $\mathcal{I}_\varepsilon^* > 1$).

We extend our results via numerical simulations in Figure 2.5, which depicts the long-term persistence of the forest inventory for all levels of disturbances (not only small ones). For all

$I^* \leq \mathcal{I}^*_\varepsilon$, the forest collapses, regardless of the initial inventory before the disturbance. An interesting corollary is that if $I^* > \mathcal{I}^*_\varepsilon$, then there exists some level of disturbance that the market can support and come back to its equilibrium. We will now concentrate on the case where $I^* > \mathcal{I}^*_\varepsilon$ and find thresholds over Δ and $I^+_{t_\Delta}$ that ensure the sustainability of the forest inventory.

2.3.3 Critical inventory for collapse

To do so, we generalize our results for all possible values of Δ to determine the minimum level of inventory I^Δ, ensuring that if $I_t > I^{\Delta^*}$, the dynamic of the system remains in the existence domain. This problem is strictly equivalent to looking for the level of disturbance $\Delta^*_{I^*}$ required to destabilize the system at equilibrium I^* and lead to the collapse of the forest inventory. In another words, I^{Δ^*} corresponds to the minimum level of inventory required to stay on the existence path and $\Delta^*_{I^*}$ is the maximum disturbance that the inventory can cope with. The link between both variables is given by $I^{\Delta^*} = (1 - \Delta^*_{I^*}) \cdot I^*$.

$\Delta^*_{I^*}$ is indeed the solution of Eq. (2.14). This equation cannot be analytically solved, so we rely on numerics for its solution. Figure 2.5A exhibits the solutions of the problem in terms of $\Delta^*_{I^*}$, whereas Figure 2.5B focuses on the response in the forest inventory.

$$\frac{1 - I^* \, . \, (1 - \Delta^*_{I^*})}{1 - I^*} = (1 - \Delta^*_{I^*})^{\varepsilon - 1} \tag{2.14}$$

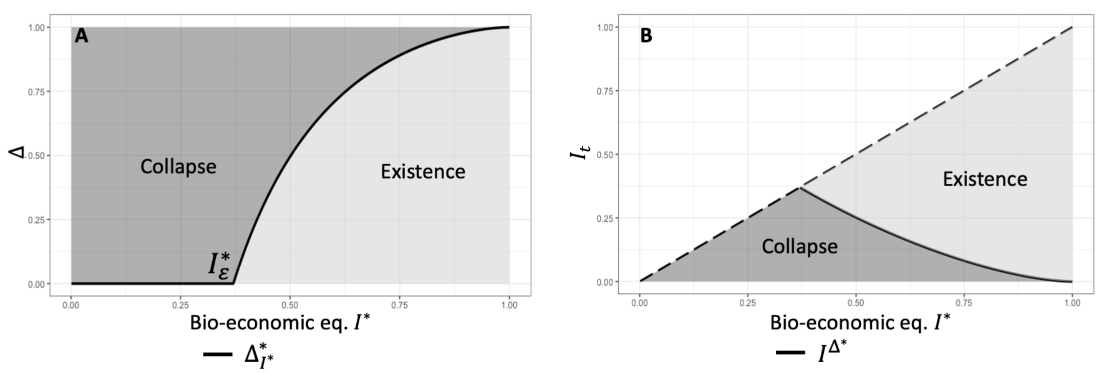

Figure 2.5: Stability of the equilibrium for every possible bio-economic equilibrium I^* depending on the level of damage Δ (left) and inventory after disturbance (right). The grey part is stable (inventory goes back to equilibrium I^*) whereas the red one is unstable (inventory is depleted).

To conclude, even if the inventory of equilibrium I^* is larger than $\mathcal{I}^*_\varepsilon$, if a disturbance of severity $\Delta > \Delta^*_{I^*}$ occurs, it still leads to a dynamic of inventory depletion. For the interested reader, section 2.6.1 in Appendix extends Figure 2.3 (left) to every possible ε values.

2.3.4 Minimum return time from natural hazard

In the previous section, we considered how large a single disturbance must be to destabilize the forest inventory and lead to its collapse. Now we focus on another perspective of the problem: the relevant time scale for the forest inventory to recover following a disturbance. To do so, it is useful to have a reference point by which to compare numerical simulations. Therefore, we start each simulation at equilibrium using our baseline parameter values, apply a disturbance, and measure the time it takes for the system to return to its equilibrium or collapse.

Unfortunately, the differential equation describing I_t has no closed-form analytical solution. However, as suggested on Figure 2.6 (left) we can define a time θ, as a function of I^* and Δ, that characterizes the time scale needed to come back to equilibrium. If the inventory grows at a rate $g(I_{t_\Delta^+}) - H_{t_\Delta^+}$ following a disturbance Δ, then the link between θ, I^* and Δ can be written as,

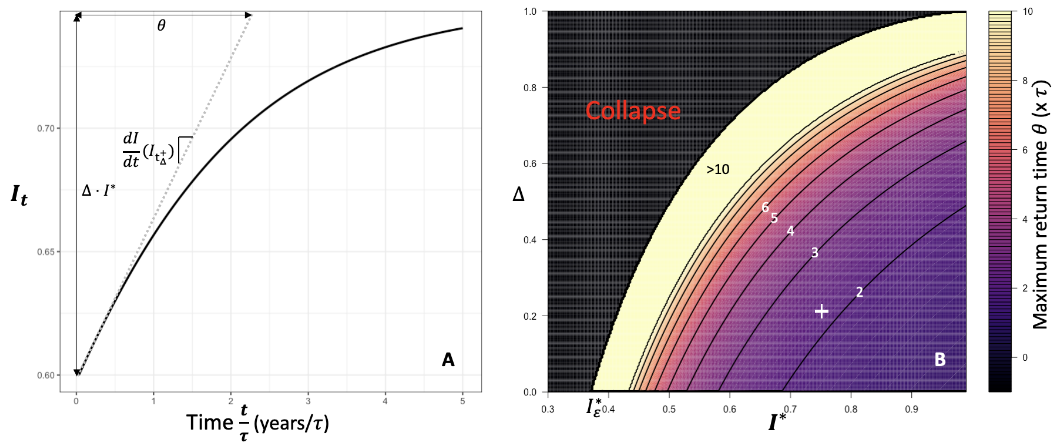

Figure 2.6: (A) Evolution of the forest inventory I_t in the case of $I^* = 0.75$, $\Delta = 0.2$. (B) Graphic of the normalized maximum return time of disturbance $\frac{\theta}{\tau}$ for the different values of I^* and Δ. Note that the white cross corresponds to the left example.

$$\theta = \frac{\Delta \cdot I^*}{\frac{dI}{dt}} \tag{2.15}$$

where θ approximates the minimum mean return time of the natural hazard to its former equilibrium, assuming that multiple disturbances follow each other and have the same intensity. If disturbances are spaced further apart in time than θ, the inventory will persist. Figure 2.6 shows how θ varies for the different combinations of I^* and Δ. For example, in the case where the equilibrium forest inventory is $I^* = 0.75$ and the disturbance has a strength $\Delta = 20\%$, the maximum return time of the disturbance is $\theta = 2.2\,\tau$ (see the white cross on Figure 2.6, right). In our baseline parameter values, τ would be around 50 years. This means that a major disturbance should not occur more than every 110 years.

In addition, Figure 2.6 shows that for small inventories (lower than 0.5), whatever the disturbance, the time between two disturbances should be at least 5τ (i.e. more than 250 years). This result moderates the fact that the market helps to stabilise the forest inventory. Even if this can help the stabilization, it also strongly slows down the dynamic of the system such that the frequency of disturbances should stay low. This result also suggests that the effects of a disturbance on both timber market and forest inventory can linger for a very long time (several decades).

2.3.5 Persistence of the forest inventory in the face of multiple natural disturbances

The previous sections gave us intuition regarding the effects of a single disturbance (happening regularly with the same level of damages) on the forest inventory and the relevant timescale of its recovery. However, at the timescale of the life of a forest inventory, natural disturbances are likely to come in spades. Here we assign a distribution to Δ and evaluate the time spent at its long-term persistent equilibrium I^* as a function of the mean and standard deviation of the distribution of Δ.

Suppose that the yearly damages from natural disturbances $\Delta_{p,d}$ is a random variable, following a Bernoulli distribution with the parameters p (probability of occurrence) and d (magnitude of damages),

$$\Delta_{p,d} = \begin{cases} d & \text{with probability } p \\ 0 & \text{with probability } 1-p \end{cases} \tag{2.16}$$

which has a mean and standard deviation of $p \cdot d$ and $(1-p) \cdot p \cdot d^2$ respectively. We assume that the distribution of $\Delta_{p,d}$ does not vary over time. The advantage of a Bernoulli are threefold: first, it is simple and intuitive; second, it lines up well with traditional definitions of risk (Knight, 1921); third, by fine-tuning the parameters p and d, it can be calibrated to a diversity of natural hazards which can vary in frequency and/or damages.

As before, we set the parameters at their baseline values, initialize the model at equilibrium, and measure the average time the forest inventory spends at its long-term equilibrium value. Using Monte Carlo simulations, we estimate the average time t that is needed to move from the I^* equilibrium to the minimum level of inventory ensuring existence ($I_t < I^{\Delta^*}$). t can be seen as a mean survival time, because it corresponds to the mean time during which the inventory stays on the existence track. We ran 500 simulations for each combination of mean and standard deviations 500 simulations with a temporal horizon of 1000 years.

Figure 2.7 shows that mean survival time is reduced when the mean of the damage is increasing but also when the standard deviation is increasing. It is quite straightforward to understand why the time elapsed before changing the equilibrium is negatively correlated with the mean damages: the more damage there are, the more quickly the minimal threshold of inventory is reached. However, the effect of standard deviation is a bit more complicated: when standard deviation increases, the mean being fixed, this time is also diminished. This means that rare and large natural hazards are more harmful to the long-term resilience of the equilibrium than small and regular events. Note that this effect disappears above the orange line, because this would correspond to events with damages larger than 100%, which is not possible.[4]

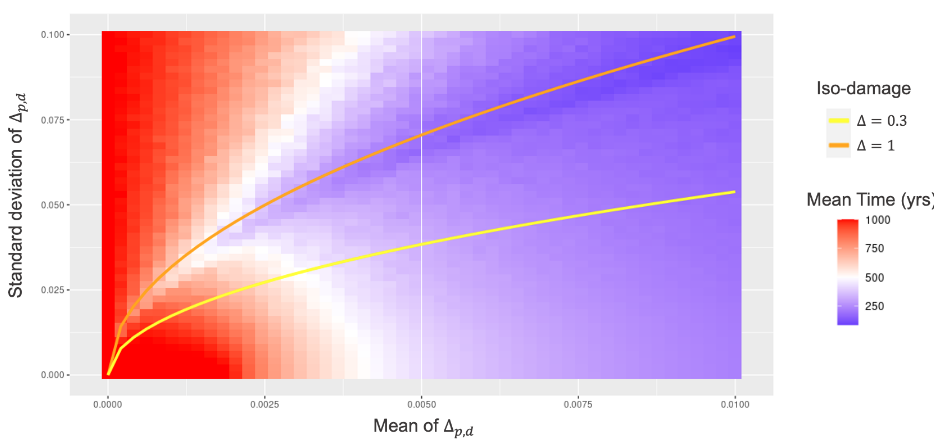

Figure 2.7: Heatmap showing the mean time spent needed to go from equilibrium I^* to a level where the market is collapsing. All points above the orange curve cannot be reached because they represent damages larger than 100% of the stand. The yellow curve represents constant 30% expected damages. (Parameters: $I^* = 0.75$, and $\tau = 55$ years, maximum time limit is set to 1000 years).

[4]The reason for this effect is that the substitution of probability to get larger damages is useless when damages are larger than one.

2.4 Discussion

One of our key findings is that natural disturbances can break the linkage between harvest and the forest inventory, leading to the over-exploitation of the forest stock and its eventual depletion. This resonates well with the classic findings in resource economics of the Tragedy of the Commons (Hardin, 1968), Easter Island (Brander and Taylor, 1998; Good and Reuveny, 2006), and the exploitation of fisheries (Clark, 1973). In these cases, even with forward-looking behavior, in the case of absence of property rights, limited foresight or high discount rate, it is possible to over-exploit the resource and drive it to depletion.

In our case, the destabilization of the forest inventory comes as a result of the market effect (as opposed to forest growth - in the absence of harvest, a logistic growth function will always return to its carrying capacity if the inventory is greater than zero). Assuming effective monitory of the forest inventory following a disturbance or disturbances, a public policy could be implemented if the inventory falls below the critical threshold I_{ε}^{*} to prevent the over-exploitation of the resource. Harvest is determined by price (Eq. (2.8)). Therefore, we could imagine an intervention such as a timber tax to reduce demand and subsequently deforestation. Alternatively, we could envision policies designed to increase the resilience of the inventory to natural disturbances, such as subsidies for plantations (aid in the recovery following a disturbance) or adaptive strategies (decrease the magnitude of damages). For example, the EU Commission has framed some conditions under which a member state can "aid to prevent and repair damage to forests caused by forest fires, natural disasters, adverse climatic events which can be assimilated to natural disasters, other adverse climatic events, plant pests and catastrophic events" (European Union (EU), 2014). This enables the European member states to subsidy several actions reducing the risk of wildfires, for example.

Both the frequency and intensity of natural disturbances are expected to increase in the future as a result of climate change (IPCC, 2012; Machado Nunes Romeiro et al., 2022). Furthermore, the interactions between different types of natural hazards (e.g., storms, fires, and pest outbreaks) is expected to increase as well (Buma, 2015; Seidl et al., 2017; Ridder et al., 2022), leading to multi-risk situations and cascade effects that stress the forest inventory. In the same way, Buma (2015) claims that natural hazard can interact with each other and lead to cascades of hazards, concentrated around few main events. Ridder et al. (2022) demonstrated that the occurrence of compound events should increase in the the future due to climate change. We could use our model to assess some impacts of climate change on timber market. Additionally, climate change is linked to increased timber demand (Cowie et al., 2021). Biomass sourced products, such as fuel wood (Favero et al., 2020), produce less carbon dioxide than their fossil fuel counterparts, making them potential favourable options in the future. On the demand side, this would decrease ε_{PD} and subsequently decrease ε, leading to an overall increase in $\mathcal{I}_{\varepsilon}^{*}$. In other words, we would require a higher level of forest inventory to prevent its long-term collapse.

Interestingly, in our model with endogenous prices, the forest inventory is more resistant to collapse than inventories in similar models with constant prices. With constant prices, demand and supply are constant, so that a sustainable trajectory requires $I_t > 0.5$. In our model, endogenous prices decrease demand when the resource becomes more scarce. Harvest being reduced is a stabilizing effect of the market and enables us to have an equilibrium I^* smaller than 0.5 (even if it should remain larger than $\mathcal{I}_{\varepsilon}^{*}$, which is smaller than 0.5).

While our framework is simple, we believe that it effectively captures the effective dynamic of the forest inventory, the market, and natural disturbances. Certainly incorporating greater complexity in the model could add a deeper touch of reality, but doing so quickly complicates the analysis. Even in our simple setting, general analytical results are not always feasible. Nonetheless, our approach is not without its limitations. We discuss several of these in turn.

Myopic harvest agents One of our strongest assumptions in the model is that agents are myopic and consider only the present in their management decisions. Implementing forward-looking behavior - not necessarily dynamic optimization, but discounting or a "sustainability" or preservation threshold - would likely stabilize the forest inventory and minimize the market effect following a natural hazard. Nor is our model optimal, either in a static (maximize benefits today) or dynamic sense (maximize benefits for a set time period). Indeed, in optimal control problems in resource economics, seldom is it optimal to completely exhaust the resource (Conrad and Clark, 1987; Clark, 2010). In forestry terms, as the resource becomes scarce, its "shadow value" or the value of an extra unit of forest increases and prevents its complete depletion.[5] We can partially account for this behavior by adjusting the elasticity of harvest to the forest inventory, ε_{IH}. Increasing ε_{IH} leads to a more cautious harvester that responds to declines in the inventory by more strongly reducing their harvest rates. It can be shown that increasing ε_{IH} lowers the critical inventory threshold $\mathcal{I}^*_\varepsilon$.

An autartic economy In this paper we consider a regional timber market that operates with perfect efficiency. Supply and demand are governed locally by the dynamics of the forest inventory without imports or exports of raw wood materials. However, the timber market is global. Implementing trade could affect the stability of the forest inventory. In the short term, we would expect our price drop in the regional market to cause a jump in exportation, as the global price would likely remain constant following a regional-scale disturbance. This has been discussed by Kinnucan (2016) and Sun (2020), especially on the relevant time scales to consider to modify the local trade habits. In the long term, we might expect trade to limit the increase in timber price following a disturbance - local demand could be satisfied by importation of timber - which would provide a strong stabilizing effect to the system.

Constant parameter values We treat our baseline parameter values as constant over time. Relaxing these assumptions could shift the value of our critical threshold $\mathcal{I}^*_\varepsilon$, return time, and resilience of the inventory in the face of multiple hazards. For instance, with rising temperatures and carbon dioxide concentrations, mean forest growth is expected to increase (Pretzsch et al., 2014) in the future, at least in the short term. This would reduce the value of τ, thereby increasing the growth rate and the ability of the forest inventory to recover following a disturbance. Similarly, the equilibrium-displacement model supposes constant market elasticities even when $\Delta > 20\%$, which is exceedingly large (Sun, 2020). We could also, for example, expect forest owners to change their harvesting behavior if the forest inventory is nearing collapse.

2.5 Conclusion

In this article, we suggest to assess the stability of a timber bio-economic equilibrium. To do so, an equilibrium between the timber produced by a forest and a timber market is disturbed by a natural hazard. Our key findings are that, with reasonable assumptions, there should always exist a minimal forest inventory to have a stable, equilibrium of the forest inventory. Over this minimal inventory, the equilibrium is always "meta-stable" and can always be lost if a large enough disturbance occurs. Such a severe disturbance is however unlikely, even if this could change in the future due to climate change.

[5] A notable exception is Clark and Munro (1975), who illustrated that if the benefits of harvesting a fishery can be re-invested in natural capital, then it can be optimal to drive the stock to extinction. Similar behaviors can be observed when the value of the resource at the end of the management time horizon or scrap value is zero, or when a manager places zero value on future benefits (e.g., the discount rate approaches infinity) (Conrad and Clark, 1987).

We have assessed the stability of the market equilibrium but it would be very interesting to dig further in this model by calibrating it to specific types of disturbances or events and see the effective evolution of the forest inventory, timber price and quantities sold over time. For example, a model linking storm effects and bark beetle damage could be introduced in order to model explicitly an interaction between these hazards and understand the different processes at work when a major disturbance hits a forest at a large scale.

The model may also be used to analyze the coverage of both the production and price risks considered. For example, timber storage is a measure that is encouraged and funded by public authorities after extreme windstorms in order to prevent the price decreases. Such storage areas were implemented after windstorms Lothar and Martin in France and Germany in 1999. This public policy tool may be simulated in the model. In the same way, the model may serve to determine floor price under which the bio-economic equilibrium become unstable. Finally, insurance may be studied to cover production risk.

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2.6 Appendix of chapter 2

2.6.1 Sensitivity to ε

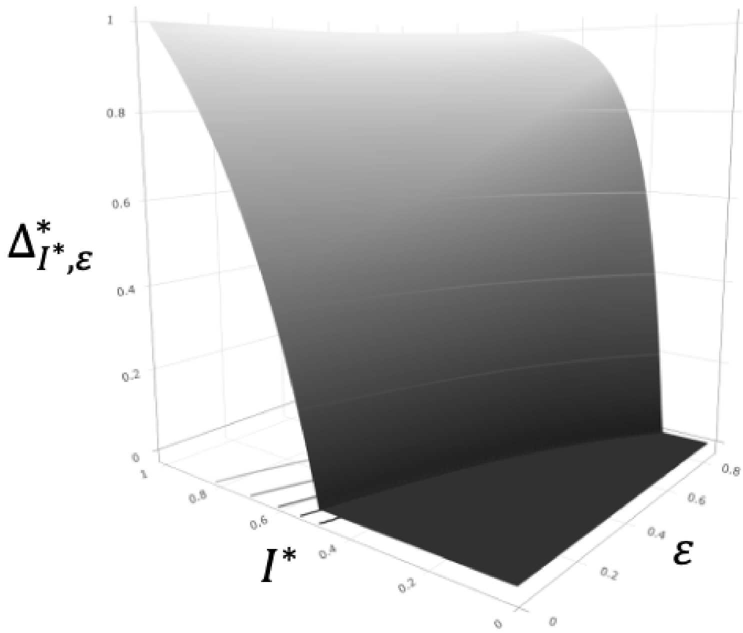

Figure 2.8: Maximum disturbance to stay in the I^* stable equilibrium for every possible bio-economic equilibrium I^* and every possible levels of elasticity ε.

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2.6.2 Calculation details

By definition, at the equilibrium, the forest is growing at the speed it is harvested (with H^* the equilibrium harvest). This means that the equation of the equilibrium is:

$$\frac{I^*}{\tau} \cdot (1 - I^*) = H^*$$

Let's suppose that a disturbance Δ impacts this equilibrium. The new forest growth corresponds to:

$$\frac{I^* \cdot (1-\Delta)}{\tau} \cdot (1 - I^* \cdot (1-\Delta)) = g(I^* \cdot (1-\Delta))$$

Whereas the harvest level is given by Eq. (2.11):

$$H = H^* \cdot (1-\Delta)^{\varepsilon}$$

The inventory is on the existence path if the natural growth exceeds the harvest level, i.e. if:

$$\frac{I^* \cdot (1-\Delta)}{\tau} \cdot (1 - I^* \cdot (1-\Delta)) = H^* \cdot (1-\Delta)^{\varepsilon}$$

By replacing H^* we find Eq. (2.14). This equation has no analytical solution in the general case. We can however linearize it in the case where Δ is small with respect to 1. To do this, we make a Taylor expansion of $(1-\Delta)^{\varepsilon}$.

This leads to the following equation that can be re-injected in the previous one and thus leads to Eq. (2.13).

$$(1-\Delta)^{\varepsilon} \approx 1 - \varepsilon \cdot \Delta \quad \textbf{if} \quad \Delta << 1$$

Chapter 3

Estimating the Economic Impact of Multiple Natural Hazards on the French Forest Sector

Estimating the Economic Impact of Multiple Natural Hazards on the French Forest Sector

Félix BASTIT[a], Antonello LOBIANCO[a], Philippe DELACOTE[a,b] and Miguel RIVIERE[a,c]

[a] Université de Lorraine, Université de Strasbourg, AgroParisTech, CNRS, INRAE, BETA, 54000 NANCY, FRANCE
[b] Chaire d'Économie du Climat, PARIS, FRANCE
[c] Université Paris-Saclay, CNRS, Ecole des Ponts ParisTech, CIRAD, EHESS, UMR CIRED, NOGENT-SUR-MARNE, FRANCE

Abstract French forests are a source of numerous ecosystem services and, in particular, provide timber for industrial processes and store carbon to contribute to mitigating climate change. However, natural hazards such as windstorms (e.g. Lothar and Martin 1999 , Klaus 2009) or end-of-2010s European bark beetle outbreaks can represent a major threat to French forests and their services to society.

This article aims to understand the large-scale effects of windstorms and insect outbreaks and their potential interactions on the French forest sector. The objective of the paper is to evaluate mortality rates during the period 2011-2050 due to natural hazards in terms of economic outputs such as changes in timber price, transfer and loss of social welfare, changes in the productions of the French wood industry, and loss of carbon storage.

A bioeconomic recursive partial equilibrium timber market model (French Forest Sector Model, FFSM) is for the first time coupled with a spatially explicit model of windstorms (process-based using an original wind gust data set) and bark beetles (stylized dynamic probabilistic model, linked to windstorm occurrences). To assess the full distribution of impacts, we run Monte Carlo simulations with different scenarios of hazards.

First, our model succeeds in reproducing the regional damage observed from the 1999 Martin and Lothar windstorms. This enables us to study the possible distribution of damages from windstorms in France. Second, we estimate the effect of windstorms on the different actors of forest sector and look for optimal salvage harvest from the different perspectives. Third, in a more prospective way, we try to estimate the possible effects of interactions between natural hazards and the resilience of the French low carbon strategy under such regime of hazard.

Keywords Keywords: Forest sector; Social surplus; Natural hazards; France; Carbon.

JEL codes JEL codes: Q23 (Forestry); Q54 (Climate • Natural Disasters and Their Management • Global Warming)

3.1 Introduction

French metropolitan forests cover more than 17 million ha for a growing stock volume of 2.8 billion m^3 (IGN, 2022). French forests currently store 1.3 billion tons of carbon and constitute a net carbon sink. This resource is currently growing fast: since 1985, French forest area has grown by more than 20% and the growing stock by around 50%. Moreover, French forests are managed under the paradigm of multi-functionality and, even if timber production is a major objective, there is a strong ambition to mitigate French national CO_2 emissions through forestry. This mitigation strategy is essentially based on two levers: to increase the carbon directly stocked in forests, and to increase the carbon stocked in long-living timber products, such as lumber. Moreover, it is also possible to substitute fossil fuel based products and energy with timber products or wood energy. These objectives are summarized in the French National Low-Carbon Strategy (SNBC) (Ministry for the ecological and solidary transition, 2020), which aims at storing 35 million tCO_2 per year in French forests and 20 million tCO_2 in timber products by 2050.

(IGN, 2022) remarks that despite the general tendency of increasing timber stock between 1985 and 2022, two French departments did not see their timber stock increase on the period because they faced especially intense damages from the Martin, Lothar (December 1999) and Klaus (January 2009) windstorms. These storms have caused, respectively, the loss of more than 140 million m^3 (IGN, 2003) and 40 million m^3 (Costa et al., 2009). The prejudice of Klaus on forest owners was estimated at 1.5 billion € (Costa et al., 2009). Windstorms are thus a major threat to French forests. Wildfires are the second source of damages at the French scale, but wildfires damages only represented one third of windstorms damages over the period 1986-2016 (Senf and Seidl, 2021b). French forests are also facing other natural hazards such as bark beetles or pathogens. Senf et al. (2021) have for instance estimated an increase in French canopy mortality by 1.5% per year between 1985 and 2018.

Such disturbances have two major effects through the timber stocks they affect: first, an effect on the volume of timber available and thus a direct impact on forest carbon stocks. Second, a cascading effect on wood production for the downstream industry. There are indeed two major market effects after the occurrence of a disturbance (Prestemon and Holmes, 2004). On the short term, harvest increases during the period of deadwood salvage, leading to lower prices, which can be beneficial to the industry but detrimental to forest owners. On the longer term, the price increases because there is a shortage in wood resources due to the destruction of a share of the stock.

Natural disturbances also interact with climate change. Under the influence of climate change, temperate oceanic European forests such as those found in France are expected to be more exposed to extreme events, especially storms, floods, and droughts (Lindner et al., 2010). Seidl et al. (2014) estimated that climate change will have a strong impact on disturbance regimes, reducing the forest carbon budget and possibly leading to a saturation of the carbon sink in Europe's forests. Besides, Senf and Seidl (2021a) suggested that a climate-induced worsening of hazard regimes across Europe may have a significant impact on the demographics of the European forest, ultimately leading to their rejuvenation. Such a development could potentially exert a strong influence on the downstream timber sector.

Furthermore, Dale et al. (2001) expected interactions between natural hazards to increase under the influence of climate change. For example, interactions between repeated droughts and spruce bark beetles (*Ips Typographus*) explain a large part of the increase in forest mortality in France in the recent period (Seidl and Rammer, 2017; IGN, 2021). Seidl et al. (2017) estimated that the potential effect of such increased interactions could lead to a higher increase in total damage compared to a case where such interactions are not accounted for.

Within this context, this paper aims to assess the economic and environmental effects of windstorms on the French forest sector, in particular those related to welfare distribution across agents, the sector's climate mitigation potential and its long-term alignment with policy objectives, and the interactions between several natural hazards.

This paper is at the crossroads of two literatures: studies evaluating the impacts of disturbances on forest inventories (Seidl et al., 2011) and integrated bio-economic modeling for prospective analysis. Firstly, several studies have aimed to quantify the economic or environmental impacts of worsening disturbance regimes in Europe in the context of climate change. Schelhaas et al. (2002) estimated the effect of windstorms, wildfires, and insect outbreaks in the context of climate change in Switzerland and evaluated the dynamic of the growing stock volume in different scenarios. They concluded that stimulated growth induced by climate change outperformed the effect of increasing natural disturbances. The management of forests was, however, assumed to be completely exogenous from any economic perspective. Venäläinen et al. (2020) reviewed the impacts of several natural hazards (windstorms, snow loading, drought, forest fires, pests and pathogens) on Finnish forests under current and future climate. They concluded that the probability of cascading events such as windstorms and the outbreak of major bark beetles is expected to increase strongly in the future and lead to much greater damages. This study is very exhaustive on the resource side but does not review any effect on the downstream parts of the timber market.

At the French scale, Roux et al. (2020) reviewed the potential of the French forest sector to act as a carbon sink and included a sensitivity analysis to natural catastrophes. They showed that the forest carbon stock is always reduced due to disturbance occurrences, but that the substitution effect with products from dead wood can be increased and partially offset the loss. In addition, they mentioned that severe windstorms can have an impact on forest carbon stock that could require two decades to restore. However, they focused on the occurrence of a single hazard: a single windstorm or an especially severe fire year. Thus, their study consisted in a worst-case scenario sensitivity analysis. Our perspective is very different because we want to create credible hazard regime each year of our simulations.

This paper is indeed a natural follow-up of several papers studying the effect of natural disturbances into the French Forest Sector Model (FFSM, Lobianco et al. (2016a)). First, Caurla et al. (2015) compared several scenarios of public subsidies after Klaus storm (2009) in the French Landes de Gascogne to optimize social welfare. They showed that the actual plan was beneficial but that additional subsidies to store more timber would have resulted in an even more advantageous strategy. Petucco et al. (2020) estimated the cost of ash dieback over the French forest sector by simulating the spatial dispersal of a pathogen in FFSM. This filled a gap in the literature by integrating the effects of invasive pathogens into a forest model. They showed that the impacts are very heterogeneous among the different regions and that the long-term effects strongly depended on the management decisions after the invasion. More recently, Riviere et al. (2022) focused on wildfires and how climate change could influence burned areas in FFSM. They concluded that there was a welfare transfer from fire-prone areas to the other regions. Furthermore, they investigated cascading uncertainties in the model and argued that including such uncertainties can be beneficial in assessing the global potential effect of climate change on the timber resource.

This paper seeks to address the following research question: what are the economic and environmental impacts of catastrophic events, storms in particular, on the French forest sector? This general topic will be tackled through three more focused objectives:

1. To quantify the short and long-term impacts of a storm on the different actors in the forest sector in terms of welfare, and on forest resources and carbon stocks, including in terms of spatial and temporal distributions.

2. To explore the behaviors of different categories of economic agents when submitted to

a regime of realistic random storm disturbances, and the potential implications of these behaviors for public policy.

3. To evaluate the robustness of climate mitigation objectives assigned to the forest sector in ecological planning strategies.

These questions will be answered using an integrated model of the forest sector (FFSM) expanded to explicitly account for storm and pest hazards using both mechanistic and probabilistic modelling. This is, to our knowledge, a novel methodological contribution to the field of forest sector modelling. Another contribution of our work comes from the consideration of interactions between two natural hazards with significantly different spatial and temporal patterns.

3.2 Study area and the French Forest Sector Model

Our study includes all forests of the French metropolitan territory, covering more than 17Mha. The most present tree species are oak (27%) and common beech (10%) for broadleaf and silver fir (8%), Norway spruce (7%), Douglas fir (5%), maritime pine (5%) and Scots pine (5%) regarding conifers. Nevertheless, FFSM does not take the timber species into account but only includes six different "forest types". These forest types link a forest structure with a tree type: broadleaf (793 Mm^3), coniferous (684 Mm^3) and mix (248 Mm^3) high forest, broadleaf (610 Mm^3) and mix (74 Mm^3) intermediate forests and broadleaf coppice (112 Mm^3). The spatial distribution of these six forest types is shown in Figure 3.1.

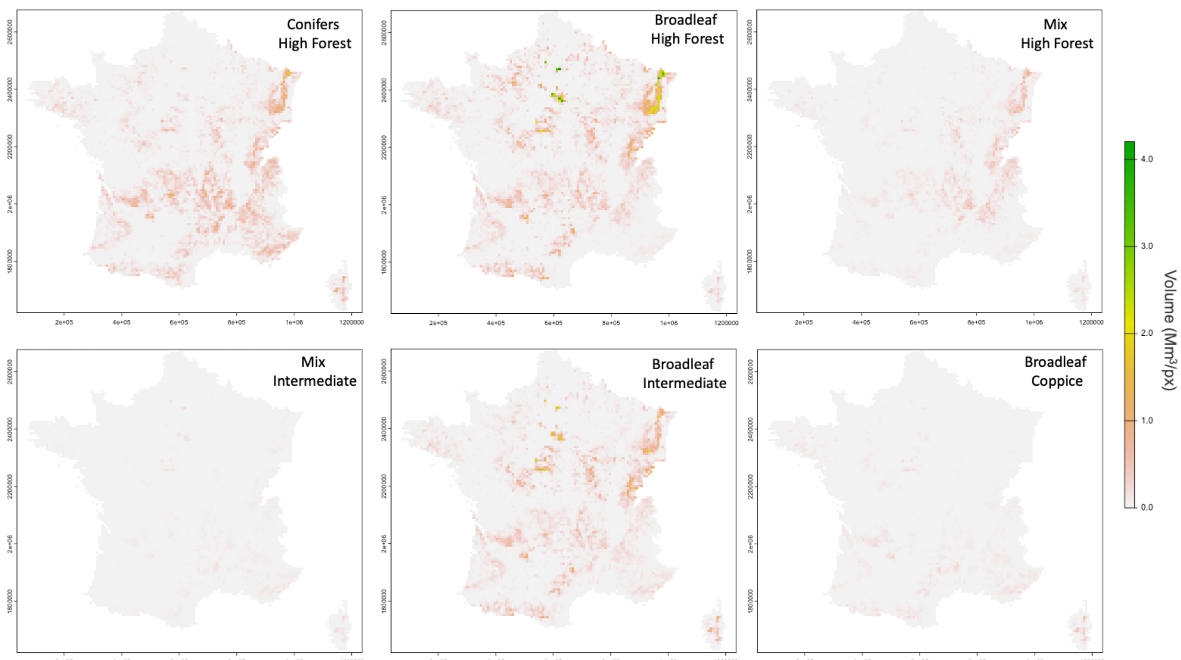

Figure 3.1: Volume of timber per pixel (Mm^3/px) for the different forest types in FFSM in year 2011 (first year of FFSM simulation).

FFSM (Caurla et al., 2010) is a bio-economic model that allows one to simulate the evolution of the French forest resource and timber industries over time. It is a yearly recursive model that encompasses four complementary modules (see Figure 3.2):

1. Resource module (Lobianco et al., 2015): the French territory is divided into 8588 pixels of 8km side (which can be seen on Figure 3.1). On each pixel, a matrix-based model is used to distribute the forest inventory in timber volumes for 6 forest types and 13 diameter classes (from 10cm to 130 cm). At each period, some share[1] of each diameter class is moved to a larger diameter class and some share faces mortality or harvest. Natural disturbances module will be coupled with this resource module, by exogenously increasing the level of mortality due to windstorms or insect outbreaks.

2. Market module (Caurla et al., 2010): at each period, timber volumes are aggregated across pixels at the regional level. A share of the regional level is harvested to create some primary timber products. The transformation of primary products into final products is

[1]FFSM allocates share of surfaces to each forest forest type/diameter.

represented as Leontief's input-output processes.[2] Primary and final products are traded across the 12 French regions as perfect substitutes within a spatial price equilibrium framework (Samuelson, 1952) or with the 'rest of the world' region. In this latter case, Armington elasticities (Armington, 1969) are used to take into account the fact that domestic and imported products are not perfect substitutes. The equilibrium is achieved at the regional scale by optimizing the overall financial surplus, deducting transportation and manipulation expenses, according to a set of constraints, which is formulated as a programming problem. The regional demand is then redistributed at the pixel level proportionally to the available volume for each product.

3. Management module (Lobianco et al., 2016b): when the market equilibrium is solved, the regional timber harvest is distributed among pixels in the region.[3] Forest owners are considered as rational risk-averse[4] decision markers, who can decide on the way to reallocate the harvested surface by maximizing the Faustmann Land Expectation Value over the different forest types (Samuelson, 1976).

4. Carbon module (Lobianco et al., 2016a): this module estimates the quantity of carbon sequestrated in the forest biomass (i.e., in the standing volume of timber but also into dead timber, extra biomass and soils) and timber products (considering an exponential decay of the products once produced, their half-life depends on product type) and finally the carbon that is spared by avoiding to use fossil fuel-based products(in the case of fuelwood and materials substitution). The carbon module thus includes six different carbon effects in the global carbon balance of the forest sector, see Table 3.1 for the descriptions for the different effects.

Type	**Variable**	**Description**
Sequestration	STOCK_INV	Carbon in forest inventory (live and dead tree logs)
Sequestration	STOCK_EXTRA	Carbon in extra biomass (soils, branches, etc.)
Stock	STOCK_PROD	Carbon stored in forest products
Substitution	EM_ENSUB	Energy substitution
Substitution	EM_MATSUB	Material substitution
Emissions	EM_FOROP	Emissions from forest operations

Table 3.1: List of carbon effects taken into account in FFSM.

To consider the effect of natural disturbances on the market, a positive elasticity of supply to the available dead timber has been included in the equation estimating the supply $s_{pp,t}$ for each product pp at each time t (see Eq. 3.1). $I_{pp,t}$ is the total forest inventory available at time t to produce a given primary product pp. For example, conifer high forests with $\geq$30cm diameter can be harvested to produce either some soft round wood or some pulp wood and fuel wood. $P_{pp,t}$ is the price of this product and is taken into account with an elasticity σ. The third term in Eq. 3.1 was not included in FFSM and has been implemented to take into account the market effects of windstorms. $\delta_{pp,t}$ is the dead timber volume at time t that can be used to produce the primary product pp. As long as $\delta_{pp,t}$ remains lower than a fixed threshold δ^*_{pp}, the factor is fixed to one and has no effect. However, when a disturbance leads to a large

[2]This means that there is only one way to produce a certain level of product from different inputs: inputs cannot be substituted.

[3]The harvest dedicated to a certain product is proportional to the volume of timber available for this specific product on the pixel.

[4]The risk aversion is heterogeneous among pixels.

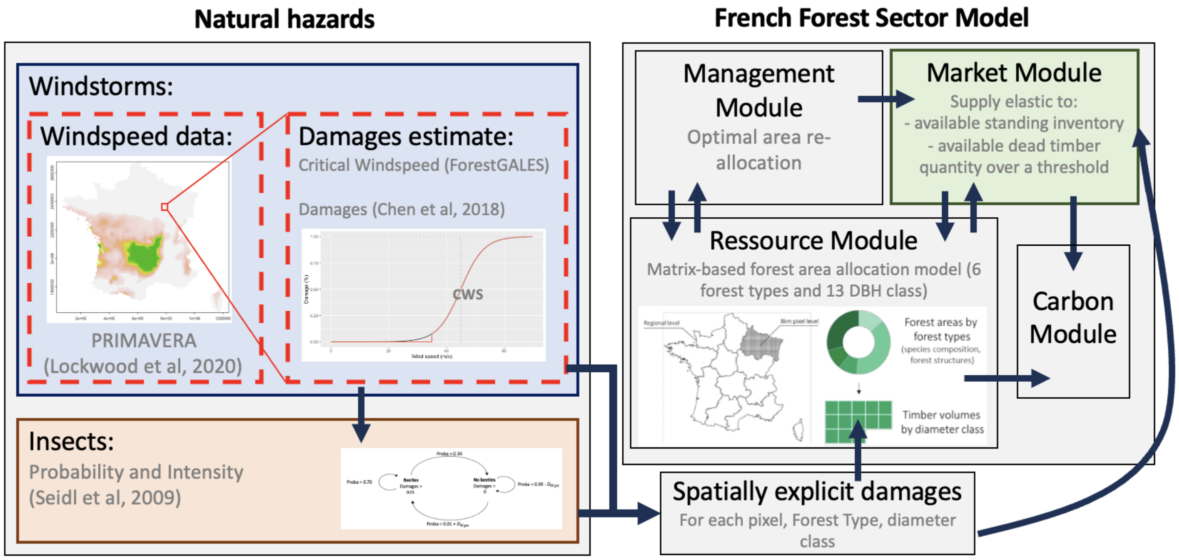

Figure 3.2: Graphical summary of the coupling of FFSM modules with natural hazards.

amount of dead timber[5] that is usable for primary products, the market enters a new regime in which forest owners will try to sell their dead timber before it is spoiled, so that the supply increases significantly. Dead timber can be used two years to produce some round wood and four years to produce pulp and fuel wood. After these periods, timber cannot be used anymore because of quality degradation, it is thus simply considered as unusable dead wood decaying at a given rate (with a certain half life).

$$s_{pp,t} = s_{pp,t-1} \cdot \left(\frac{I_{pp,t}}{I_{pp,t-1}}\right)^{\gamma} \cdot \left(\frac{P_{pp,t}}{P_{pp,t-1}}\right)^{\sigma} \cdot \left(\frac{\max(\delta^*_{pp}, \delta_{pp,t})}{\max(\delta^*_{pp}, \delta_{pp,t-1})}\right)^{\gamma_d} \tag{3.1}$$

We integrate a fifth module to FFSM for natural hazards. We make a soft coupling of this module with the resource module (see Figure 3.2). Two natural hazards are modelled in this paper: winter windstorms and eruptive insect outbreaks. Having presented briefly FFSM, we split this chapter into three complementary parts:

1. We focus on a single windstorm and analyze the different ways in which it affects the forest sector from an economic point of view.

2. We estimate the potential optimal supply elasticity to quantity of dead timber γ_d from several different points of view: the producers' perspective, the forest sector perspective and the global society perspective.

3. Eventually, we quantify the forest sector impacts of interacting windstorms and pest outbreaks. We implement successions of different windstorm events drawn from a statistical distribution and we build a model to link these damages with insect outbreaks. In particular, we present the potential carbon implications of a large number of Monte Carlo simulations and challenge the possibility to follow carbon neutral path with the consideration of natural hazards.

[5]The threshold δ^*_{pp} was fixed at 5% of the forest inventory because it corresponds to the minimum level of damages that you would expect from a large windstorm. See the minimum windspeed threshold in the next section.

3.3 Effects of a single windstorm in FFSM

3.3.1 Research question

In the first part of this chapter, we model the effect of a single large windstorm on the French forest sector. We will more specifically focus on three points: understand the short and long-term effects of a windstorm in FFSM, concentrate on the distribution of effects among the different actors (consumers vs. producers) in the sector and look at the spatial dissemination of these effects. Finally, we will investigate the impact of windstorms on the forest sector carbon balance.

3.3.2 Materials and Method

A windstorm is a complex meteorological phenomenon (Gardiner et al., 2013) and can refer to different objects, with different properties: tropical cyclone, extra-tropical cyclone, bomb cyclone, etc. Europe is mainly affected by extra-tropical cyclones that are associated to the track of low-pressure events and most often occur between the extended winter period (i.e., from October to March).

Windstorm spatial evolution is generally described by one of these parameters: the track of the minimum atmospheric pressure or the track of the maximum of wind vorticity. The literature to statistically create windstorms from past observed patterns is flourishing (Sharkey et al., 2019). This statistical way of tracking windstorms is however not relevant in our context, because we are only interested in the windspeeds the forests are facing and these cannot be simply deduced from the parametrization of these two parameters. To avoid this problem, we define the Yearly Maximum Windspeed (YMW) as the maximum windspeed over each pixel in France during a given winter (from October of the year y to March of the year $y+1$). YMW is more meaningful than focusing on particular windstorms because the relevant time period in FFSM is the year, corresponding to one time step of the recursive model. In fact, there are a large number of storms each year, so that aggregating every windstorms in a single map including only the yearly maximum windspeed is very efficient.

Damage estimate

From the knowledge of YMW, it is possible to deduce the level of timber damage. Chen et al. (2018) recommended using a sigmoid function (Eq. 3.2) to estimate the level of damage $D(\text{YMW})$ (expressed as a share of surface damaged) for a given yearly maximum windspeed YMW.

$$D(\text{YMW}) = D_{max}\left(\frac{1}{1+e^{\frac{(\text{CWS}-\text{YMW})}{R_f}}} - \frac{1}{1+e^{\frac{\text{CWS}}{R_f}}}\right) \tag{3.2}$$

CWS corresponds to the Critical Wind Speed. It describes the windspeed threshold at which the damages share reaches half its maximum D_{max} ($D_{max} = 0.7$ from Chen et al. (2018)). R_f is a parameter describing the rate of change of the damages near CWS, it is set to 6 m.s^{-1} for all tree species and age (Chen et al., 2018).

We have set a minimum threshold of wind speed to have damages at 35m/s. This has several advantages: first, in the absence of such a threshold each pixel would face strictly positive (even if very low) damages every year, so that we would have damages everywhere in France every year. Second, it is expected in the literature that there exists a minimum level of windspeed to observe real damages (Chen et al., 2018). Figure 3.3 shows the influence of the different parameters on damage estimates.

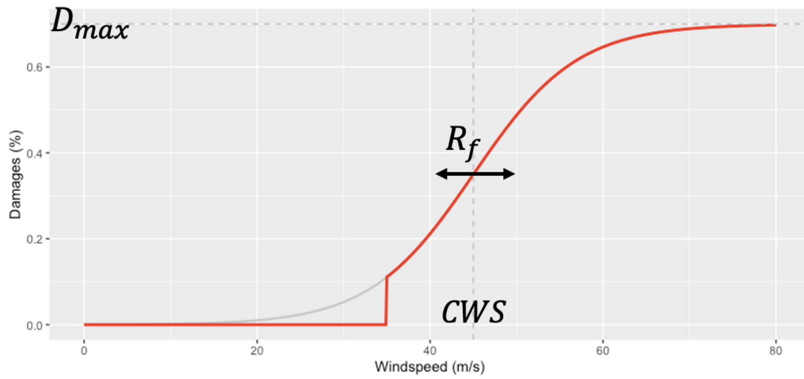

Figure 3.3: Graph of the damages (%) function of the yearly maximum wind gust speed on a given pixel for a given diameter class and forest type.

Critical windspeed estimate

To compute CWS, we use the process-based wind risk model ForestGALES (Hale et al., 2015) and its implementation in the `fgr` package (Locatelli et al., 2022) developed on `R` software (R Core Team, 2013).

Minimal `fgr` requirements to provide CWS are: forest specie, diameter and tree spacing. Because FFSM only provides data on the structure of the forest (high, intermediate or coppice) and on the specie type (broadleaf, conifer or mix) and not the exact specie, we only focused on Oak and Spruce, because they are respectively the most common broadleaf and conifer in France. The data to compute the different CWS for each forest type and diameter class from `fgr` is available in section 3.8.2 in Appendix.

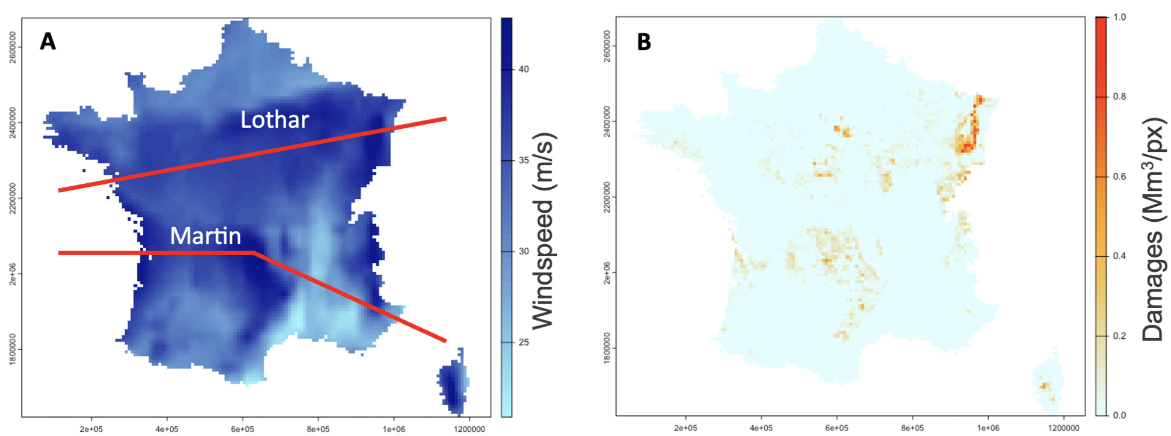

Figure 3.4: Map of (A) 3-second maximum windgust (m/s) for each pixel in France for the winter 1999. The red lines show the footprints of Lothar and Martin windstorms and (B) the volume of damages per pixel (in Mm^3/px) induced by this YMW summed over each forest type and diameter class.

Validation from Lothar and Martin storms

To validate the damages predicted with our model, we suggest relying on past damage observations of a windstorm at the French level and compare observed damages with the damages predicted with our model. Damage estimates for storm Lothar (25^{th} and 26^{th} December 1999) and Martin (28^{th} and 29^{th} December 1999) were available in IGN (2003). These estimates are aggregated at the level of the region and only consists in absolute volumes of damages, without any specifications of forest type. This is however an interesting opportunity to validate our data. Even if the storm model does not fit perfectly with reality at the pixel level, the coherent level of aggregation for the timber market in FFSM is the region. This means that if we have consistent estimates at the level of the region, it is already a first good and efficient estimates for further computations.

To get the windspeed from 1999, we rely on ERA5 dataset (see Figure 3.4A). This consists in a reanalysis of all historical observations of meteorologial parameters and is thus considered as a reference for past historical climate, including windspeeds. More specifically, we used ERA5 data (which has been transformed by Lockwood et al. (2022) with the same methodology as the rest of the PRIMAVERA[6] data) to get the YMW field of winter 1999, during which both storms have happened. $D_{R,\text{IGN}}$ are the damage observed by the French Forest National Inventory for each region R and $D_{\text{R,Model}}$ are the damage that our model predicts for winter 1999 (see Figure 3.4B) aggregated at the level of each region R.

$$D_{R,\text{IGN}} = \beta_0 + \beta_W \cdot D_{R,\text{Model}} \tag{3.3}$$

Figure 3.5 represents the graphical expression of Eq. 3.3. We estimate $\beta_0 = -1.3 \pm 4.8$, meaning that the intercept is not significantly different from 0 and $\beta_W = 0.98 \pm 0.27$. This shows a good fit between predicted and observed damages. The model still over-predicts in BouFra and in all the regions where there are only few damages.[7] It under-predicts in AquPoi but the general behavior of the windstorms seems to be reproduced. This validates our modeling process.

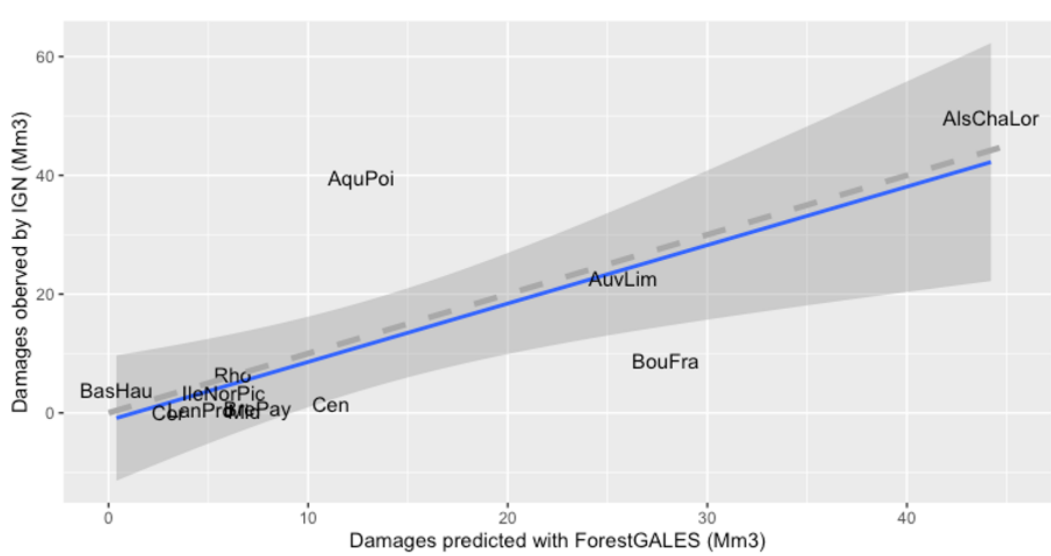

Figure 3.5: Volume of damages (Mm^3) predicted with ForesGALES aggregated at the regional level vs. observed by the French National Inventory (IGN, 2003).

[6]This dataset will be later used and is presented in section 3.4.2.

[7]This could indicate that it would be meaningful to have a higher threshold of windspeed under which there is no damage.

Simulation of a unique windstorm in FFSM

To study the effect of windstorm on the forest sector, we peak one of the stormiest year available in PRIMAVERA dataset and implement it to impact the French forest on year 2020. Figure 3.6A depicts the damages of the windstorm (as share of each pixel surface destroyed for a given diameter class and forest type) and Figure 3.6B shows the total volume of damages aggregated at the regional level. The distribution of the damages for each Forest Type by region is available in Table 3.2. Auvergne Limousin (AuvLim) is the most impacted region with more than 140 Mm^3 damaged. On the opposite, Alsace Champagne Lorraine (AlsChaLor) remains unaffected, whereas Aquitaine Poitou (AquPoi) experiences a moderate level of impact. Studying these three regions gives us a large gradient of damages. Moreover, the focus of the study will be on the conifers because it is the most impacted specie.

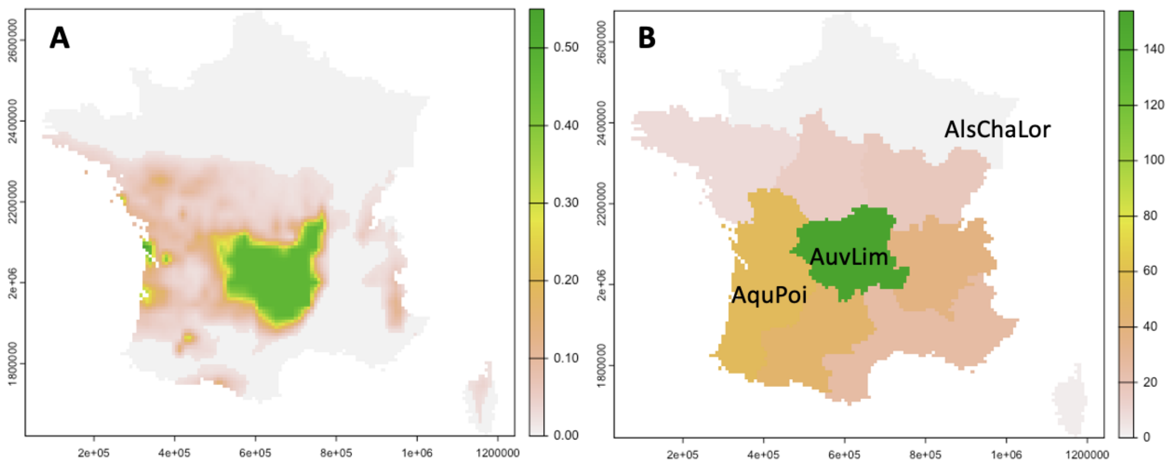

Figure 3.6: (A) Share of surface (%) per pixel impacted by the storm (for diameter class 10cm, conifer High Forest) , (B) Volume (Mm^3) of dead timber per region.

Region	High Forest			Intermediate		Coppice
	Conif	Broadl	Mix	Broadl	Mix	Broadl
AlsChaLor	0	0	0	0	0	0
AquPoi	24	11.3	3	11	1	4
AuvLim	65	32	19	29	5	4
France	144	73	41	71	13	17

Table 3.2: Volume of damaged timber (Mm^3) per region and at the national scale.

3.3.3 Results

Stock effects

Several effects of the windstorm can already be discussed from Figure 3.7, depicting the dynamic of the volume of high forest conifer in the three regions of interest. These effects happen with different temporal dynamics.

The first short term effect is a large drop in 2020 for AquPoi (orange) and AuvLim (red) curves. This represents the direct impact of the windstorms on the forest inventories, as depicted in Table 3.2. The available volume of conifer high forest is diminished because a large share is damaged in both regions. Moreover, it can be noted that the volumes of timber

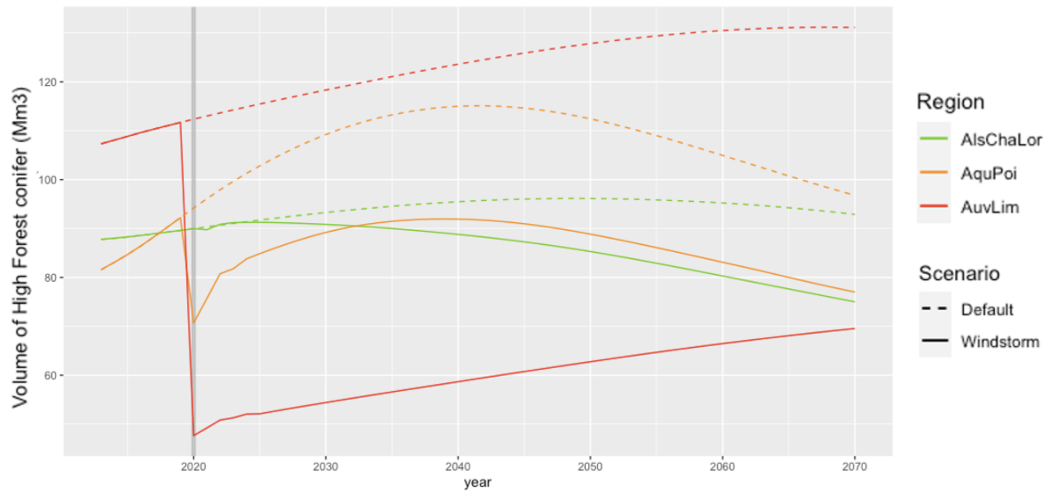

Figure 3.7: Temporal dynamic of the conifer high forest volume (Mm^3). The color indicates the region that is concerned. Dashed lines show the counterfactual without any storm.

in these two regions are growing much faster than their counterfactual during few years (2 to 4 years). This can be explained by the fact that FFSM is coded to use first the dead timber to satisfy the demand, so that there is a strong decrease in the harvest from living forest, which leads to a faster accumulation of timber as long as there is still some dead timber available. This effect is especially clear on Figure 3.8: during 2 years, the total harvest of conifers strongly increases (but the harvest of living conifers is reduced to zero) and then diminishes in the long term. In fact, timber can be used 2 years to produce round wood and 4 years to produce pulp and fuel wood. This will have an important effect for the resilience estimate in the third section of results.

In the preserved region AlsChaLor, the behavior differs relatively largely from the counterfactual scenario in the long term. The quantity of timber indeed diminishes in the forest. This is due to the fact that the price in the affected regions becomes larger in the long term, because the timber resource is more scarce (see Figure 3.9 red and orange curves). Because timber from the different French regions are perfect substitutes, this leads to an increase in price in the unaffected region (see Figure 3.9 green curve). Because the supply is elastic to price, a higher price means a larger supply, as long as the inventory does not change, which is the case in the unaffected region. Because the supply is increased, the stock is diminished in the long term.

There are also important long term effects in the impacted regions: the general behavior of the curves remain more or less the same but they do not seem to reach back their pre-disturbance level. Damages are so large that ensuring the demand prevents from reaching back to the counterfactual scenario. If we focus on the red line of Figure 3.7, we see that the level of harvest remains much smaller in the windstorm scenario than in the counterfactual scenario. Two effects play here adverse roles. The first effect is simply that if the total volume of timber is smaller, the supply is also reduced (see Eq. 3.1). There is however a second effect coming from the coding of FFSM. In the model, the elasticity of supply to living inventory noted γ in Eq. 3.1 is not symmetrical if the inventory is increasing or decreasing. Indeed, γ is set to 0.7 if the inventory is increasing and to 1.5 if the inventory is decreasing. This is motivated by the fact that the reactions of the forest owners are not symmetrical if their forests are growing or declining. If the timber volume is growing, they want to sell a bit more timber but if their timber inventory is decreasing they want to reduce strongly their sells. Such a behavior has a tendency to avoid selling too much timber if the stock decreases. However,

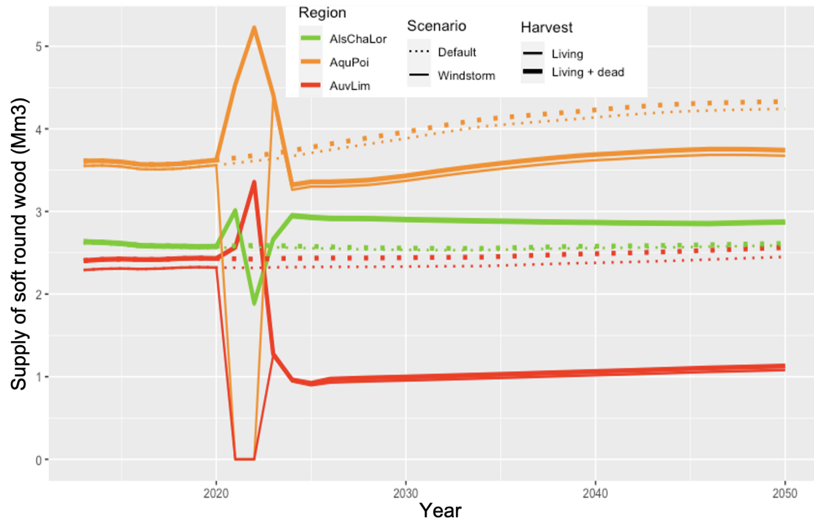

Figure 3.8: Volume of timber harvested per region. The thick line shows the sum of dead and leaving biomass that is harvested each year and the thinner line only shows the living biomass. The color indicates the region that is concerned. Dotted lines show the counterfactual without any storm.

this makes the supply function strongly dependent on its past path. In fact, if they lose some timber, the forest owners decide to sell less but when the forest is growing back toward its past value, the elasticity of supply is lower (0.7 in stead of 1.5). The consequence is that when the same inventory as before the disturbance is reached, the supply is much smaller than before. More precisely, if a share δ of the inventory is lost, the supply remains $(1-\delta)^{0.8}$ times lower. This means that the effect is more important when δ increases. For $\delta = 0.5$ (which is the case for the high forest of conifer in AuvLim in our simulation), the effect is to reduce the supply by 33% in the very long term. This is far from being negligible. All in all, this adds up to having a lower harvest in both impacted regions, but the harvest is twice more impacted in AuvLim than in AquPoi.

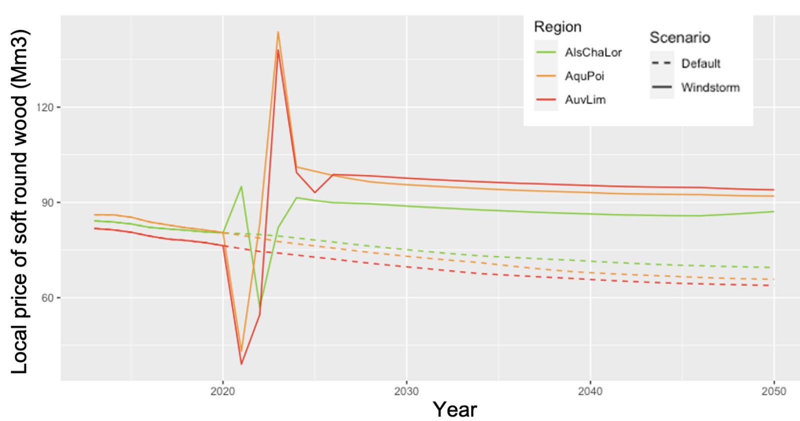

Figure 3.9: Temporal dynamic of the price (€/m^3) of round wood (soft wood). The color indicates the region that is concerned. Dashed lines show the counterfactuals without storm.

Welfare transfers

From the perspective of the surplus distribution in the forest sector, several welfare transfers happen after the occurrence of the windstorm. First, there is an important transfer of welfare between the upstream and the downstream of the forest sector. The direction of this transfer depends on the time period that we are looking for. In the short term, the price is decreased and the supply is very high so that the consumer surplus is increased and the producer surplus is strongly decreased (see the very strong drop in producer surplus on Figure 3.10B right after the storm and the temporary gain of consumer surplus on Figure 3.10A). Whereas in the long term, the effect is globally opposite. Because there is a lack of harvest (see Figure 3.8), the price increases (see Figure 3.9) so that the forest owners are better off: they sell less timber but at a higher price, enhancing their surplus. The increase of the producer surplus is made at the cost of the consumer surplus, so that the downstream of the sector is negatively impacted (see Figures 3.10 A and B).

A second welfare transfer takes place between most impacted and less impacted regions. As mentioned earlier, the unaffected regions sell more timber at a higher price (see the green line on Figure 3.8), so that their producer surplus is clearly increasing (see the green line on Figure 3.10A). Nonetheless, the effect on the affected regions is ambiguous. On the one hand, they sell timber at a higher price but the harvest is reduced due to a higher scarcity of their timber resource. For the most impacted region (AuvLim, red line) the net effect is negative because the loss of quantity supplied is really large (red line on Figure 3.8). For the less affected AquPoi region, the net effect is slightly positive because they sell a few less timber but at a much higher price. Eventually, we see that windstorms occurrences lead to spatially heterogeneous effects and to welfare transfers between producers and consumers.

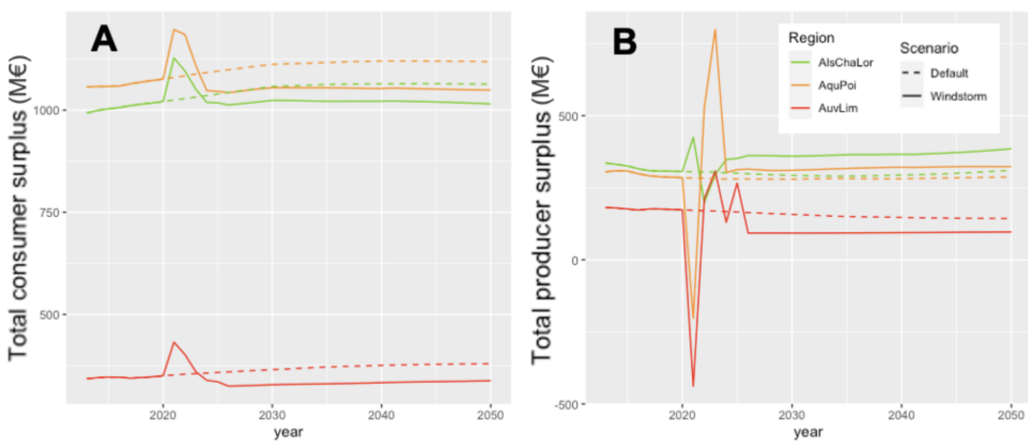

Figure 3.10: Temporal dynamic of the (A) consumer and (B) producer surpluses (€/yr). The color indicates the region that is concerned. Dashed lines show the counterfactual without storm.

Carbon balance

To get a complete picture of the effects of windstorms on the forest sector, it is still necessary to examine the outcome on the sector's carbon footprint, which is depicted in Figure 3.11. Two main points should be observed. The main effect is long-term loss of carbon sequestration in the forest inventory and in the extra biomass. The sequestration is lower in the long term because there is an important loss of timber volume. The effect is however very smooth because the timber that is damaged and not consumed is assumed to remain in the forest and to follow a exponential decay. This is why we do not observe a drop in the quantity of carbon sequestrated in the forest. In the long term, the forest is however less productive because younger, so that the sequestration effect is lowered.

The second point is that there is almost no effect on the four other carbon variables. The storage in long leaving products is almost not affected: in the very short term, we observe a very small increase compared to the counterfactual because there is more timber sold on the market. In the opposite, in the long term, there is a small decrease in this storage effect because less timber is sold. The substitution effect (of both materials and energy) is modified in the same way. This means that further carbon analyses should essentially focus on the carbon stock in the inventory and in the extra forest biomass, because these capture most of the effect.

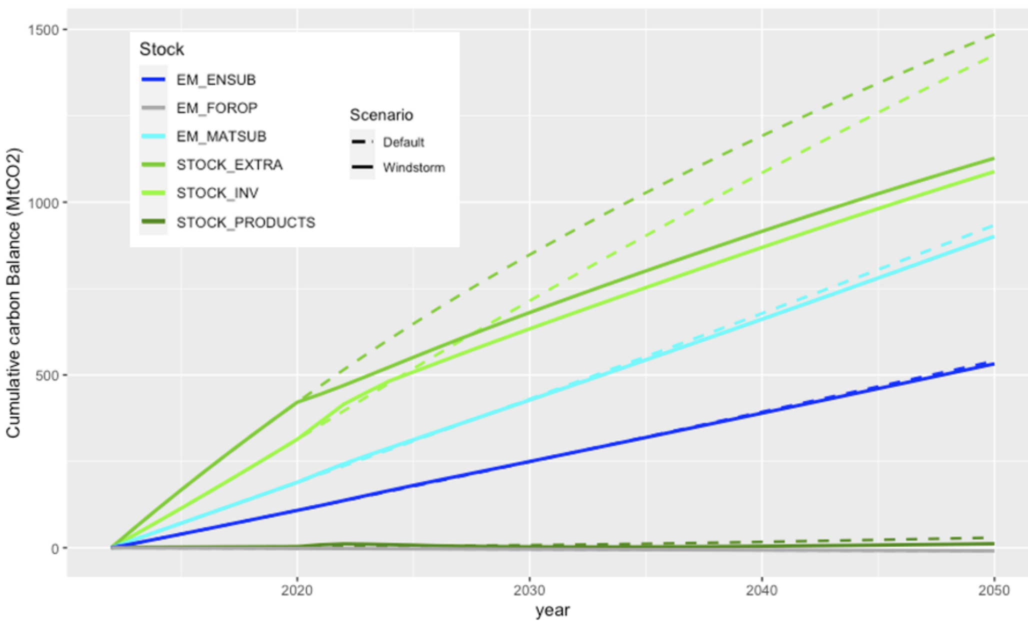

Figure 3.11: Evolution of three different carbon stocks and cumulative substitution effects from 2011 to 2050. For the description of each stock, see Table 3.1.

3.3.4 Discussion

Model of windstorms

We have made the choice to base windstorms damage estimates on a process-based model, linking windspeed to damages for the different forest types and tree diameters. The model is not expected to fit perfectly with past data, essentially because it is a process-based model and not a statistical based one. For example, Schmidt et al. (2010) mentioned that wind speed is not a very powerful predictor of wind damages. The most efficient predictors being tree species, topographic exposure or soil water content. This data is however not available in FFSM and would lead to a too complex model because it requires very fine scale data. Moreover, this kind of statistical estimates does not tell us anything about the occurrence of the windstorms, so that we would need another stochastic predictor of windstorm occurrence. This is why it was especially convenient to directly use yearly maximum windspeed maps, that are available as outputs of climate models, as predictor of damages.

An important extension to improve our work could be to calibrate critical windspeeds at a finer scale than France. Indeed, the forest inventory data (that is used to calibrate some parameters to estimate the CWS with `fgr`) is available at a fine scale so that we could fit the CWS at the regional level and take the most present coniferous and broadleaf specie in the given region. This kind of estimate could enable to have more realistic estimates of windstorm damages. Moreover, the values of R_f and D_{max} (Eq. 3.2) could also be fitted at the regional level to fit better with past observations. In this sense, it could also be very beneficial to have more than Lothar and Martin windstorms to calibrate more parameters.

From the results point of view, our results fits quite well with what is suggested in the literature (Prestemon and Holmes, 2000). There are several phases in the windstorm mechanism: a phase with large quantities of dead wood and therefore low prices, then a phase with a reduced stock of wood and therefore a period of high prices. There is a transfer of harvested volume from highly impacted regions to less impacted regions, leading to a transfer of economic welfare between the different French regions.

Policy implications

From a public policy point of view, these welfare transfers between the producers lead to suggest a system of mutual insurance against windstorm at a large scale because it could correspond to a win-win scenario. In fact, the impacted regions would strongly benefit from an insurance in the case where they face a windstorm because they loose a large share of their producer surplus. There is in fact a transfer from the most impacted regions to the least impacted ones, as can be seen on Figure 3.10B. This Figure shows that most of the regions are gaining in terms of producer surplus in the long term, except the most impacted one (AuvLim). This means that the unaffected regions are in fact largely benefiting from the occurrence of a windstorm, so that it is probably possible to redistribute a share of these gains between the different regions, especially in the case where these regions do not know which will be impacted by the different storms. This spatial distribution of windstorms will be further discussed in the last section of this chapter, where multiple scenarios are analyzed.

3.4 Estimate of the elasticity of supply to dead timber quantity

3.4.1 Research question

Previous section 3.3 exhibited that the windstorm model was reproducing several effects expected by the literature at the French scale and clarified windstorm aftermath on the French forest sector. In the second part of this chapter, we focus on the welfare of the different actors in the forest sector: the consumers, the producers and the global society. Our question is to understand how the dead timber supply behavior could influence sectoral surpluses and carbon outcomes, under different management strategies.

3.4.2 Materials and Method

The elasticity of supply to dead timber quantity

To include a short term effect of windstorms on the timber market, we have included in Eq. 3.1 an elasticity of supply to dead timber quantity, noted γ_d. The effect of modifying γ_d on timber price is shown on Figure 3.12A and on the quantity of timber supplied on Figure 3.12B. Both estimated correspond to the most impacted region AuvLim and the storm implemented is the same as in the previous section in 2020. A larger value of γ_d leads to a larger quantity of timber supplied so that the price is dropping stronger. In fact, the value of γ_d reflects how intensely timber supply should be increased in the case of a large disturbance: when there is more dead timber in the forest, how much more primary products should be supplied to use this available timber?

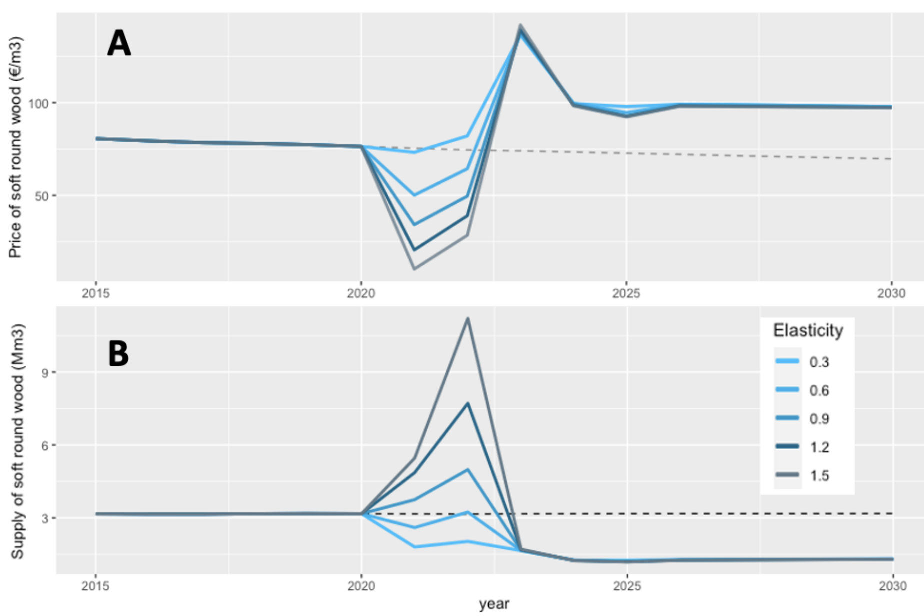

Figure 3.12: Timber price dynamic after a storm in 2020 for different values of elasticity in the most affected region. The dashed line corresponds to the counterfactual without storm.

The literature does not seem to suggest any precise answer to this question. We will thus try to use FFSM to provide an estimate and look at the effects on the different agents in the sector. Indeed, three possible hypothesis could be made. On the one hand, we could suppose that there exists a single forest owner taking the decisions at the French scale, such as a large national cooperative. In this case, we could expect that she would act in order to optimize the global producer surplus, i.e. the total French producer surplus over the whole period of interest (2011-2050). On the other side, it is possible to consider that there exists a social planner, whose interest is to maximize the total social surplus, i.e., the sum of producer and consumer surplus. Finally, we could imagine that the social planner is also taking some carbon aspects into account, leading to another cost estimate internalising the carbon externality. We will thus estimate the elasticity values of γ_d under each assumptions.

Concretely, we will look at the values of γ_d that are optimizing the different surpluses. But to give some more economic perspective, we should consider that γ_d simply traduces the behavior of the producers in front of a certain quantity of dead timber. Looking for the values of γ_d optimizing the different surpluses is thus equivalent to look at the harvest strategies that each actor of the sector would like to observe.

From a methodological perspective, in order to find the values of γ_d that optimize these surpluses, a sensitivity analysis of the parameter γ_d is performed. More precisely, we run $\mathcal{N}$ Monte Carlo simulations of the period 2011-2050 and we try to estimate the mean consumer and producer surpluses. The convergence rate is expected[8] to be in $\frac{\sigma}{\sqrt{\mathcal{N}}}$, where σ is the standard deviation of the surplus. By lack of computational power, we restrict ourselves to $\mathcal{N} = 100$ simulations.[9] The method to create a YMW map for each year in the Monte Carlo simulations is described in the next section.

Monte Carlo simulations of windstorms

PRIMAVERA dataset PRIMAVERA project was originally created to assess the European insurance needs with respect to windstorm occurrences by creating a large set of reliable windstorms over Europe (Lockwood et al., 2022). PRIMAVERA dataset provides the maximum 3s gusts for each windstorms during extended winter (October of year Y to March of year Y+1) over Europe for several climate models, at different resolution (see section 3.8.1 in Appendix). Storms are clustered using TRACK algorithm (Hodges, 1995), separating the different storms from each other by considering only pixels at a smaller distance than 1000 km from the maximum vorticity. TRACK algorithm enables to create a list of storms for each winter and associates maximum windspeeds over 72 hours. 3 hours mean windspeeds are then converted into 3 seconds gusts by extrapolating from ERA5 observed 3 seconds gusts vs. ERA5 observed 3 hours mean windspeeds for each pixel. This method leads to the production of 268 620 storm footprints.

Instead of focusing on each windstorm separately, we have already suggested aggregating all the storms of a given winter by considering for each pixel of our maps the maximum windspeed over all windstorms on the aggregated winter. This leads to creating a map called Yearly Maximum Windspeed (YMW). PRIMAVERA dataset offers a large set of possible Yearly Maximum Windspeed: they have produced 1332 winters. It is thus possible to incorporate some stochasticity in the model by randomly picking each year a YMW from the list of simulated winters. This large dataset enables us to understand the full potential effect of windstorms on the French forest by enlarging greatly the set of possible windstorms with respect to the sole few past windstorms.

Validation of the dataset We create a Loss Index function $\mathcal{L}(\cdot)$, that evaluates the potential damages produced by a given YMW on the French forest.[10] There are two purposes for this index. First, it enables us to validate that the model is consistent with observed past

[8]This is a direct consequence of central limit theorem.

[9]Each simulation takes 35 minutes. There are 100 simulations for 8 values of γ_d. Moreover, each simulation requires to store 100 Mo of data.

[10]The forest that is used is the one used to initiate FFSM simulation, corresponding to the French forest in 2011.

data. Second, it will later offer the possibility to quantify the impact level of each YMW and compare the expected losses of storms from other datasets to past data and ensure that both distributions are similar.

$$\mathcal{L}(\mathrm{YMW}) = \sum_{px}\sum_{ft}\sum_{dc} FV_{px,ft,dc} \cdot D_{px,ft,dc}(u_{px}(\mathrm{YMW})) \tag{3.4}$$

$FV_{px,ft,dc}$ corresponds to the forest volume of pixel px, forest type ft and diameter class dc for the year 2011. $D_{px,ft,dc}(u_{px}(YMW))$ evaluates the damage (as a percentage) of pixel px, forest type ft caused by a windspeed $u_{px}(YMW)$. The loss index (Eq. 3.4) aggregates the damages for all forest types and all pixels.

To validate our dataset, we estimated the Loss Indexes for two different datasets: PRIMAVERA, including 1332 winters from 21 different climate models (historical climate) and ERA5 data, which consists in a reanalysis of all historical observations and is thus considered as a reference for the past period.

To compare the distribution of both samples (see Figure 3.13), a Kolmogorov-Smirnov test was performed. Both samples do not seem to share the same probability distribution: PRIMAVERA data does include more powerful windstorms than ERA5 (p-value = 0.07322).

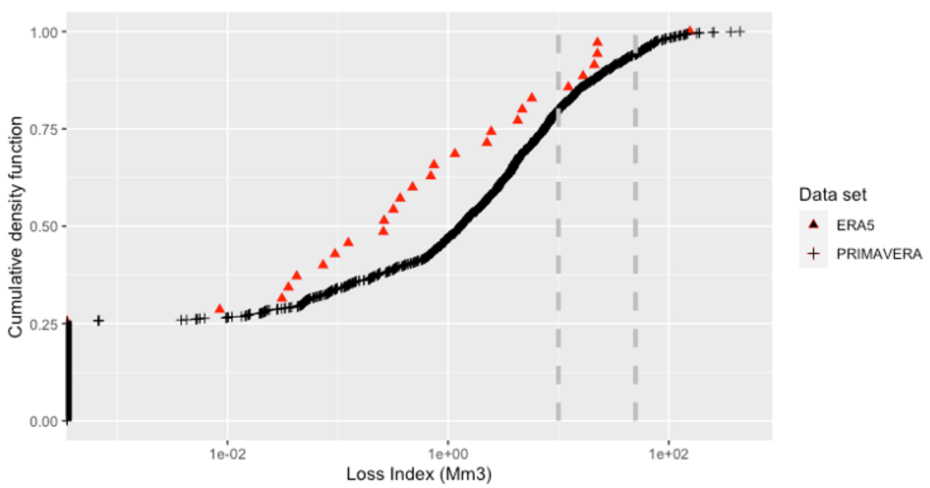

Figure 3.13: Distributions of ERA5 (corrected, past observed windspeeds) and PRIMAVERA Loss Index.

To deal with this problem, we give a certain probability of occurrence of each storm in PRIMAVERA, depending on its Loss Index. More precisely, we suggest splitting PRIMAVERA data into 3 pieces, to make both samples comparable. First, all the storms with a Loss Index lower than 10 Mm^3 are set to 0 damages. Moreover, there is a probability 5/35 to pick a storm with a Loss Index between 10 and 50 Mm^3 and a probability 1/35 to pick a storm with damage larger than 50 Mm^3 (see Figure 3.13). This means that there is a probability of 29/35 to have no damaging storm at all during the winter.

3.4.3 Results

Figure 3.14 shows the value of producer surplus, consumer surplus and overall sector surplus for different values of elasticity γ_d ranging from 0.5 to 1.5. To establish these values, we have taken the same 100 simulations of windstorms from 2011 to 2050, changed the value of elasticity and taken the mean value of the variable over these 100 simulations. Consumer surplus, producer surplus and carbon storage (in both forest and timber products) are summed for the entire 2011-2050 period, results are shown on Figure 3.14.

Producer surplus

The monopolistic hypothesis would lead the decision maker to choose the supply elasticity to dead timber to be set at 1 (see the orange square on Figure 3.14). When the elasticity γ_d becomes larger than 1, it is detrimental to producer surplus for two reasons. Both effects rely on the fact that too much timber on the market leads to lower price, as mentioned in the previous section. If the price is going down, the producers in the unaffected regions sell less timber so that their surplus is reduced in the short term. Secondly, in the affected regions, it is optimal to abandon some of the timber because selling too much timber also leads to very little prices and thus to negative producer surplus because even if a large quantity of timber is sold, the price does not cover the cost function.

Sectoral surplus

The choice $\gamma_d = 1$ is however not optimal from the consumer point of view. The consumers are always better off with a larger elasticity γ_d, implying more timber on the market leading to lower prices. If we take the sectoral surplus as the sum of both consumer and producer surpluses, it is found (see the green square on Figure 3.14) that an elasticity of 1.3 would be better. After this threshold, the loss in producer surplus exceeds the gain in consumer surplus. Moreover, we see that if the elasticity γ_d is larger than 0.5, the sectoral surplus is larger than in the counterfactual scenario because the difference of sectoral surplus with the counterfactual is positive. This means that if enough timber is sold, short-term and long-term effects lead to an overall increase in the social surplus: consumers are gaining in the short period and producers are gaining in the longer period.

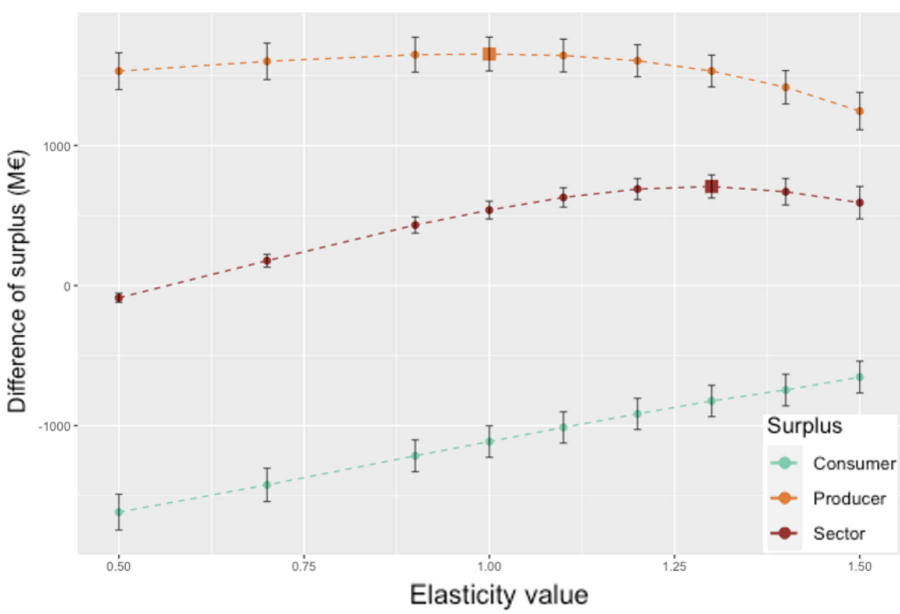

Figure 3.14: Mean difference of surplus (M€) between stormy scenarios and a counterfactual without storm function of γ_d elasticity. The orange line corresponds to producer surplus, the blue line to consumer surplus, the brown to the sector (producer + consumer) surplus. Error bars correspond to the mean $\pm \frac{\sigma}{\sqrt{N}}$.

3.4.4 Social surplus

To get the full picture of the social surplus, it is necessary to add the effect of carbon balance changes[11] to the sectoral surplus. Social cost of carbon is estimated from different values of carbon shadow prices (Quinet et al., 2019). Different values (with different time horizons) have been estimated to achieve the French carbon commitments at 2050 time horizon. Table 3.3 shows a sensitivity analysis of the carbon cost with respect to different values of carbon shadow prices. We see that the social cost of carbon is at least 8 times larger than the consumer surplus loss. This means that the real social cost of windstorms corresponds to carbon sequestration losses.

Indeed, the cost of carbon is relatively flat with respect to elasticity γ_d[12], meaning that carbon balance is relatively independent from γ_d estimate. This is explained by the fact that the amount of carbon stored during the short term period thanks to the higher quantity of timber on the market is not very important in front of the effect of having an important long-term gap in the resource[13]. Ultimately, this means that the optimal social scenario is the same as the optimal sectoral scenario, so that the socially optimal elasticity is also $\gamma_d = 1.3$.

Carbon shadow price (€/tCO_2)	30	150	300
Social cost (G€)	-8.7 ± 1	-43.5 ± 5	-87 ± 10

Table 3.3: Social cost of carbon for different carbon shadow prices (Quinet et al., 2019).

3.4.5 Discussion

Choosing an elasticity γ_d that maximizes the producer surplus is largely detrimental to the consumers because a lot of wood is never sold but also detrimental to carbon storage in wood products, as a large quantity of wood will not be exploited and will simply disappear from the system after its decay.

For the moment, there is no significant link between γ_d and the carbon balance. However, with more Monte Carlo simulations, we could probably get a small positive significant effect of supplying more dead timber after a windstorm because this would lead to use more timber which is leading to carbon substitution. So that with a large value of carbon shadow price, this small differential effect in terms of carbon stored could have a large carbon value effect. In this case, it is clear that an action of the public power to stimulate the supply in case of windstorms could thus be beneficial for both the consumers and the rest of society due to the gains in carbon stored. There could therefore be a strong convergence of interests between consumers and carbon storage, and a divergence of interests between producers and carbon storage. From the point of view of overall social welfare, the producer and socially optimal elasticities are different, so that we expect the need to resort to public power to regulate the market when a windstorm occurs. This can for example take the form of supporting storage or subsidizing the transport of timber between the different regions.

To go further in this analysis, we could explore two different directions. The first is simply to relax the hypothesis of prohibitive storage price. This is the classical policy that has been studied for a long time in forest economics (Prestemon and Holmes, 2004; Caurla et al., 2015; Zhai and Ning, 2022). This would be equivalent to look for the optimal behavior in two

[11] Carbon balance change is expressed as the difference between the mean carbon balance for the 100 Monte Carlo simulations with for a given γ_d value and the carbon balance in the counterfactual scenario without windstorm over the period 2011-2050.

[12] More precisely, the number of Monte Carlo simulations is not enough to distinguish any effect of γ_d on the social cost of carbon.

[13] As depicted in the previous section (Figure 3.11).

dimensions: elasticity and storage time. The net effect of storage is not necessarily clear. Forest owners have more time to sell their dead wood, meaning that prices remain low for longer but that could avoid to go as low for the same dead timber quantity sold. What is sure is that this will have a positive effect on affected forest owners and consumers but a negative effect on the un-affected forest owners. We expect the sector optimal elasticity to decrease but it is not obvious how sensitive this would be. In fact, we have run some very preliminary studies on this topic. We included 5 years storage instead of 2 years. In this case, the sectoral surplus was slightly increased (the producer surplus decreased and the consumer surplus increased). To lead properly this analysis, it would be necessary to split the producers into two groups: affected and preserved. This seems an interesting research avenue.

The second interesting direction would be to estimate some optimal elasticities depending on the loss index of the storm. This can unfortunately not be easily included in FFSM but we could expect that the market answer should be profoundly different if the storm impacts $50Mm^3$ or $200Mm^3$. Another research avenue would be to focus on damages concentration estimates (such as a Gini Index of damages over France). We have indeed observed that there was some strong spatially heterogeneous effects so that concentration of the damages could have an effect on the optimal behavior of the different actors.

3.5 Interacting natural hazards

In this last part, we run a large set of Monte Carlo simulations to understand the full potential impact of natural hazards at the French forest sector scale[14]. We include bark beetles interacting with windstorm hazard and make a particular focus on the variations of carbon balance of the forest sector. Two main questions are risen in this section: what is the distribution of the damages in the forest sector? How is the resilience of the French low carbon strategy affected by natural hazards?

3.5.1 Materials and Method

Windstorms

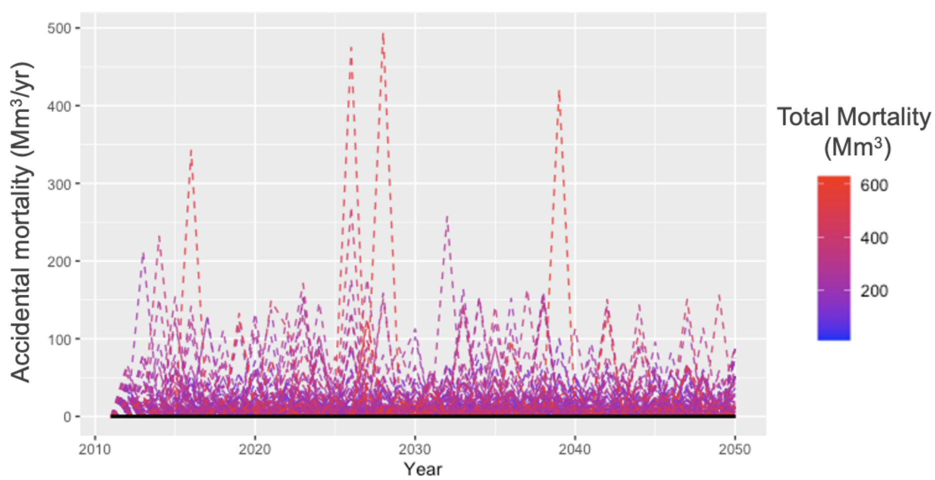

Figure 3.15: Annual volume (Mm^3) of timber affected by windstorms. 300 scenarios for the period 2011-2050 are included.

Figure 3.15 shows the distribution of damaged timber per year for 300 Monte Carlo simulations. It can be observed that most of the storms lead to rather small damages (<50 Mm^3 of damages) and that there are only few events with very large damages (>200 Mm^3). This shows that the variability of damages between the different scenarios is large. From a purely methodological point of view, this also means that the variance of the results will probably be large, so that many Monte Carlo simulations are required to evaluate the mean effects of natural hazards but also the be sure to explore the entire distribution of possible effects. Figure 3.16 exhibits the distribution of volume of timber damaged by storm in the different Monte Carlo scenarios. Median damages correspond to 165 Mm^3 but there is 5% probability to have more than 365 Mm^3 damaged. This shows again the strong variability of windstorm potential effects.

Bark beetle outbreak model

In the contrary to windstorms models, relying on solid backgrounds from disturbances literature, we create a hypothetical stylized model of insects' outbreaks. We focus on crises like bark beetles' outbreaks, regularly infesting the temperate forests. More precisely, we look at primary behavior insects such as *Ips Typographus* responsible for the recent large insects' outbreak over Norway spruce in Europe (Senf and Seidl, 2020). Brázdil et al. (2022) reviewed

[14]The supply elasticity to dead timber quantity is assumed to be set at 0.8 in the entire section.

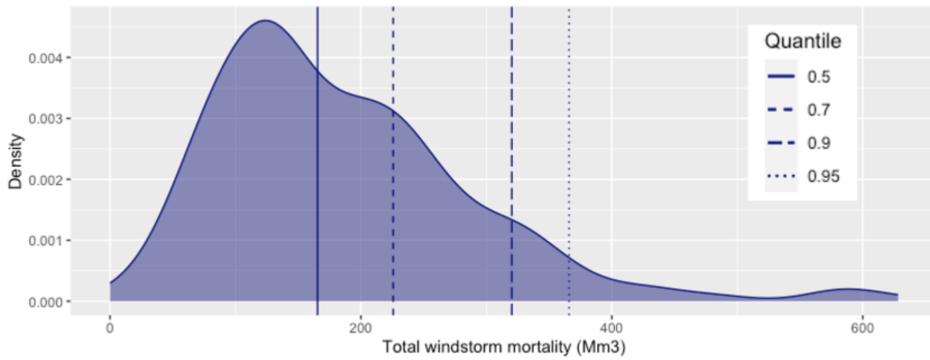

Figure 3.16: Distribution of windstorm damages (Mm^3) summed over the period 2011-2050 for 300 Monte Carlo scenarios. Vertical lines exhibit different quantiles of the distribution.

several crises in the Czech Republic since the 18$^{\text{th}}$ century: there have been several historical bark beetles' outbreaks in the 1800s, 1820s, 1830s, 1870s, 1900s, 1920s and 1940s.

Bark beetles can exist at two levels of population: a normal (or endemic) level, where their attacks are very scarce, sparse and focused on the most stressed trees (Wermelinger et al., 1999). During a crisis, the population grows very fast and eventually reach an epidemic level, such that they become able to attack healthy trees by overwhelming their defenses. This generally happens after the occurrence of a windstorm that produces a large quantity of defenseless timber that can be used as primary host or in the case of strong repeated droughts, heavily stressing the trees (Brázdil et al., 2022).

Our model is inspired by several papers trying to simulate large scale outbreaks of bark beetles. Just as in the case of windstorms, we build the modeling of outbreaks around two complementary stages. These steps are suggested by Seidl et al. (2009): first, a probability of occurrence of an outbreak, that can last for a few years and second, the level of damages in the case of an outbreak.

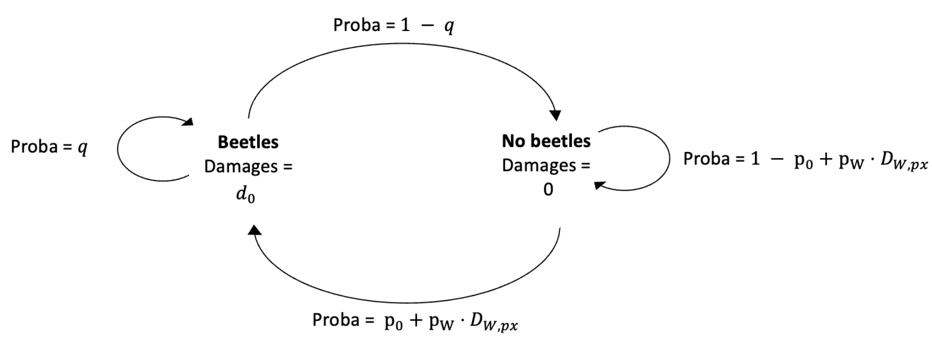

Figure 3.17: Graph summarizing the probability and damages due to insects' outbreaks.

Schelhaas et al. (2002) suggested that a storm occurrence increases the probability of reaching an epidemic level of population. The probability of a pixel to move from an endemic level to an epidemic level of beetles is $p_0 + p_W \cdot D_{W,px}$, with $D_{W,px}$ being the level of windstorm damages on the pixel. This means that the background probability of reaching an epidemic level is p_0 and if there is a storm on a given pixel, this probability increases proportionally to the level of damages $D_{W,px}$ with a coefficient p_W.

Wermelinger et al. (1999) estimated that insects' outbreaks often last few years but generally less than 8 years. For this reason, we chose a yearly probability of survival of 70%. This means that the mean duration of an outbreak is 3.33 years[15] and the probability to exceed 8 years is 5%. This fits well with Wermelinger et al. (1999) observations.

In the absence of windstorms, the mean damages $D_{BB,\text{No interaction}}$ of an outbreak at the pixel level is given by the product of the probability of outbreak by the damages over the mean time of survival of the outbreak. This gives:

$$D_{BB,\text{No interaction}} = p_0 \cdot d_0 \cdot \frac{1}{1-q} \sim 3.10^{-4}$$

From past observations (Patacca et al., 2023; Schelhaas et al., 2003), we expect the mean damages of insects to be between 3 and 4 times smaller than the winsdstorm, i.e. around 3.10^{-4}. Moreover, Roux et al. (2020) estimated that the mean damages of bark beetles after a windstorm (in the case where regular weather conditions have happened) are around 10% (between 6 and 12%) of the total windstorm damages.

$$D_{BB,\text{Wind Interaction}} = p_W \cdot D_{W,px} \cdot d_0 \cdot \frac{1}{1-q} \sim 0.1 \cdot D_{W,px}$$

We expect p_W to be large because windstorm occurrence is the main driver of bark beetles outbreaks, however, it should be constrained in order that the total probability never goes over 1. This is why, for the sake of simplicity and by lack of other data, we estimate $p_W = 1$. From there, we have two equations to define both variables d_0 and p_0. The values of the different parameters are summarized in Table 3.4

Variable	Value	Description
q	0.7	Probability that an outbreak persists
p_0	0.003	Background probability of outbreak
p_W	1	Marginal excess probability of outbreak with respect to windstorm damages
d_0	0.03	Background damages if an outbreak occurs

Table 3.4: Summary of the parameters describing bark beetles oubreaks.

The reader could be surprised that no spatial dispersion is included in this model of outbreak. It should be mentioned that pathogen dispersal has already been implemented in FFSM to evaluate the economic impact of the ash dieback (Petucco et al., 2020). In the contrary to this model, we have decided not to consider any dispersion of bark beetles because the typical range of yearly dispersal does generally not exceed 500m (Wermelinger, 2004) and the pixels of FFSM are 8km wide, much larger than this typical scale. In the contrary to ash dieback, bark beetle's crises do not correspond to a large-scale epidemic dispersal but can lead to large scale events. In fact, this large-scale pattern is often due to similar ecological conditions at a large spatial scale (such as droughts and windstorms damages) and not to insects' dispersal.

3.5.2 Results

Spatial distribution of damages in France

Figure 3.18A shows the mean[16] expected damage, expressed in volume of timber (in Mm^3) over the period 2011-2050 for each region. The variation of impacted volumes varies over a relatively large range among the regions, from few million cubic meters in the North of France (IleNorPic and BasHau) to almost 40 Mm^3 in the AuvLim region.

[15]The mean duration of an outbreak equals $\sum_{n=0}^{+\infty} q^n = 1/(1-q)$.

[16]The mean is taken over the set of 300 simulations.

Different French regions have however a very heterogeneous forest cover. This is why Figure 3.18B shows the mean expected damaged volume, expressed in damaged share of total growing stock volume. The results are smoother on the territory, varying on a range of 2% to 11% of growing stock damaged over the period. AlsChaLor region seems for example way less impacted because it has a large forest stock, whereas Corsica (Cor) is much largely impacted. Most impacted regions are the regions with a cover with more conifer than broadleaf (see Figure 3.1). This is explained by the fact that critical windspeeds for conifer are smaller than for broadleaf (see Table 3.6 in Appendix).

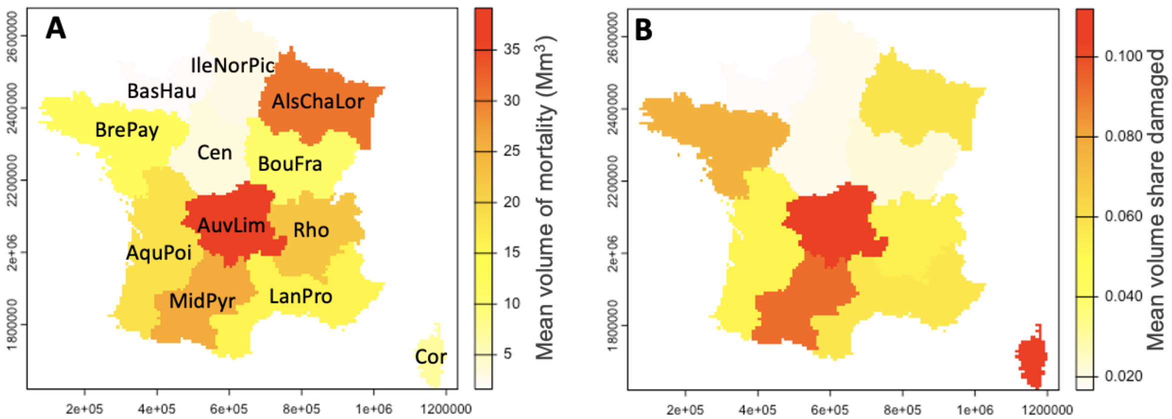

Figure 3.18: Mean damaged volumes expressed in (A) raw volumes (Mm^3) and (B) share of the total growing stock volume in the 12 regions.

Distribution of carbon stored during the 2011-2050 period

We have previously seen on Figure 3.11 that the impact of a windstorm on the forest sector carbon balance can be large, but that most of the effect was concentrated on the carbon that is stored in the forest (both in the timber inventory and in the extra biomass). Figure 3.19 exhibits the distribution of the mean quantity of carbon ($MtCO_2$/yr) stored per year in the forest biomass.[17]

The French low carbon strategy (SNBC) set a goal of 35 $MtCO_2$/yr stored in the forests.[18] Our estimates in Figure 3.19 (solid red and green vertical lines) are not in line with SNBC objectives and are around twice larger, with median carbon stored in the forest biomass is 72 $MtCO_2$/yr. This is explained by the fact that the French low-carbon strategy assumed that the harvest would be very strongly increased in the future to store much more carbon (20 $MtCO_2$/yr) in timber products, so that the forest stock should grow more slowly. With FFSM current parametrization, the storage in timber products is low and constant over time, only varying between 0 and 0.6 $MtCO_2$/yr in the different scenarios. This explains the large difference between both estimates.

It it thus not possible to directly compare the carbon balances estimated from FFSM and the French low carbon strategy. Nevertheless, we can still look at the trajectories in the different Monte Carlo simulations. Indeed, we see that the distribution of carbon stored in the forest biomass is very variable in the different scenarios. For example, we see that there is a 10% probability to store less than 55 $MtCO_2$/yr and 5% probability less than 51 $MtCO_2$/yr.

[17]This corresponds to the total variation of the stock of carbon sequestrated in the global forest biomass (tree logs, extra biomass and soils) between 2011 and 2050 has been divided by 40 years.

[18]This does not take the carbon stored in the soils into account, which is estimated to be around 6 $MtCO_2$/yr (Roux et al., 2020).

This distribution clearly has a fat tail, meaning that most of the time, the scenario is not too far from the median value but some large outliers can occur. It is also noteworthy to acknowledge that our estimates are relatively optimistic because the forest dynamic is not modified with respect to climate change and that we do not include other natural hazards. Fire is, for example, absent of the simulations.

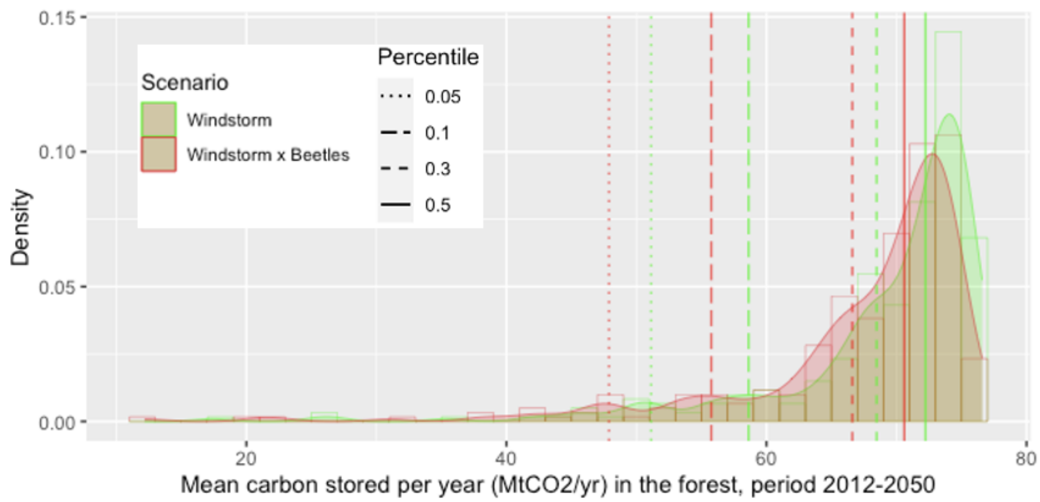

Figure 3.19: Distribution of the mean annual quantity of carbon ($MtCO_2$/yr) stored in the forest inventory.

Interestingly, the effect of bark beetles on the median effect is rather small (compare green and red lines on Figure 3.19). The effect of interactions on the outliers is however more pronounced, which can be seen through the shift in the 5^{th} and 10^{th} percentiles between both scenarios. This is due to the fact that the bark beetles really play a role when storms occur because their occurrence is greatly enhanced. For example, when an extreme storm occurs, bark beetles put a second large layer of damages and stress once again the carbon stock. The effect of interactions between hazards could thus be especially detrimental to the carbon sequestration in the forest biomass.

Resilience

The measurement of resilience in forest science is commonly done through the concept of recovery time. This particular approach utilizes the time it takes for a system to return to equilibrium after a disturbance, as suggested by Pimm (1984). This quantitative method stands out as the most frequently employed concept to evaluate resilience in this field: for example, a recent study by Knoke et al. (2022) assessed the resilience of a forest stand to natural disturbances. To do that, they computed the time needed for a stand to reach back the volume that it had reached before a disturbance occurred. We propose to extend this definition to the global French forest. Let us suppose that the French forest volume is at a level FV_t at a time t and reaches a level $FV_{t+1} < FV_t$, meaning that the forest inventory is decreasing due to a large storm a time $t+1$. Then we look for the time that is needed to reach the previous level of inventory FV_t. More precisely, we are looking for the minimum τ such that $FV_{t+\tau} > FV_t$. The smaller τ remains, the faster the forest is going back to its pre-disturbance level, the more resilient is the forest.

Figure 3.20 shows the distribution of times τ in the 300 Monte Carlo simulations. First of all, it must be noted that it is relatively scarce to have a decreasing forest inventory. This can be easily explained: if a disturbance occurs, this creates a share of dead timber that can be used during a maximum of two years. FFSM is built in order that dead timber is used before living timber. After a crisis, even if there is a loss in the inventory, there is an accumulation of timber due to the substituability of living and dead timber. In fact, only the largest storms (with a loss index larger than 50Mm^3) lead to a decreasing forest inventory and their probability of occurrence is only 1/35. This means that there is a mean of around one large enough storm for each Monte Carlo simulation, because each simulation only lasts 40 years.

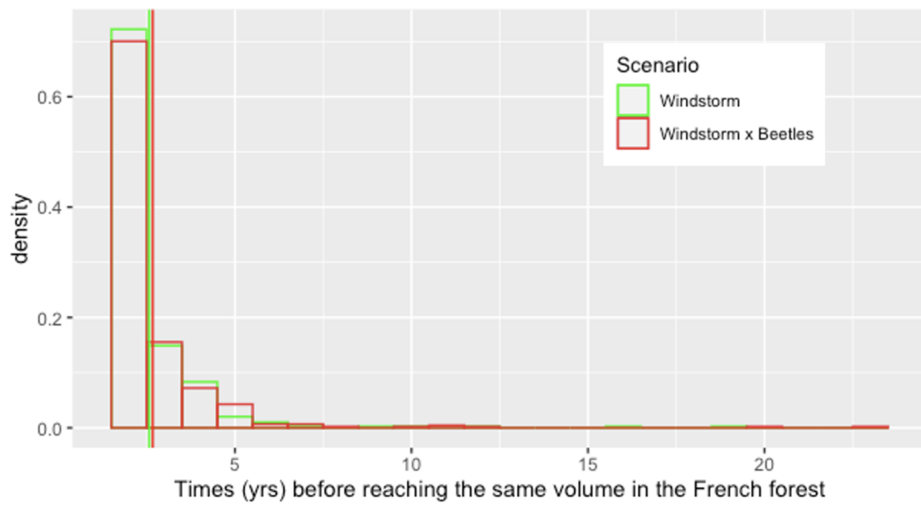

Figure 3.20: Estimation of the time τ (yrs) needed to recover the forest inventory after the occurrence of a large storm.

Figure 3.20 shows that for more than two thirds of the cases, τ equals two years. This means that there is only one year during which the forest volume is lowered. However, 5 percent of the time, τ is larger than 4 years if we consider only storms and larger than 5 years if bark beetles are also included. Figure 3.20 also depicts a classical fat tail distribution: there is a low probability of observing extreme values. Concretely, this means that if such major storms happen, there should be a special forest policy that enables to reach back the previous path. This could for example be a strong reduction of harvest during a certain period.

3.5.3 Discussion

Consistence of spatially explicit damage estimates

Our damages estimates seem to fit relatively well with the past observed damage trends. Indeed, Patacca et al. (2023) estimated that the mean annual damage corresponded to 0.23-0.27% of the growing stock. The French forest inventory observed a mortality of around 0.4% per year over the two last decades (IGN, 2022). Summing these damages over simulation duration leads to expected damages around 8 to 15% of the total growing stock. However, we only included windstorms and bark beetles in the model, which are expected to represent around two thirds of the total damages. An estimate of 2 to 11% of damages in the different regions fits well with past observations.

An important bias in our results is that we have supposed that conifers were equivalent to spruce to estimate windstorm damages and all other forest types equivalent to oak (as explained in section 3.8.2 in Appendix). In the the case of conifers, for species like silver fir and Douglas fir, this hypothesis could be relatively meaningful.[19] However, in the case of

[19]Even if these different tree species do not have the same root system.

pines, we expect a very different behavior. This assumption could be relaxed by considering in each region the most present conifer and broadleaf species and estimate the critical windspeed at a regional scale with these two dominant species. In this way, it would also be possible to make finer estimates of spacing and height with respect to tree diameter. This could also create some more interesting spatial heterogeneity in the model.

Robust projections of the carbon stock in French forests

Countries have taken strong commitments with Intended Nationally Determined Contributions (INDC) setting out in the Paris Agreement their GHG emissions targets for future decades. Paris Agreement required all participating countries to submit their INDCs, which became an integral part of the agreement. These last serve as the basis for global climate action and are expected to be updated and enhanced over time to reflect increased ambition in combating climate change. For example, the French Low Carbon Strategy (Ministry for the ecological and solidary transition, 2020) states that even if GHG emissions should be drastically reduced, 80 $MtCO_2$/yr should still be emitted in 2050, essentially due to agriculture and manufacturing industry. To offset these residual emissions, it is necessary to have carbon sinks that can be exploited. The French strategy is to store 35$MtCO_2$/yr in the forest, 20 $MtCO_2$/yr in timber products and the rest with Carbon Capture and Storage technologies and carbon capture from other lands. French forest sector represent more than two thirds of this low carbon strategy, with 44% in the sole forest biomass. Our results suggest that these estimates could be too optimistic and should include the potential effects of natural disturbances. Moreover, the French low carbon strategy sets some goals to the different sectors with 5-year time steps. We have shown that the typical time for resilience could potentially be larger than 5 years, so that there could be periods during which the French forest sector could miss its carbon storage objectives. Our results show that the robustness and resilience of these estimates with respect to large natural hazards occurrences should be further tested.

An advantage of our model compared to previous studies (Roux et al., 2020) is indeed to provide the distribution of potential losses of carbon storage in the forest sector due to natural disturbances. Previous studies only focused on sensitivity analysis with "worst-case" estimates. We have developed here a method that suggests what could be the different quantiles of the distribution of carbon storage in 2050.

Moreover, it seems that the effect of interacting hazards is essentially to make even worse the bad scenarios. Indeed, because the effect of bark beetles are linked with windstorm damages, when a large windstorm hits France, bark beetles have a strong cumulative effect. This motivates the fact to continue to include other interacting risks such as drought and fire in these studies to assess properly the robustness of a strategy that is at the core of the French 2050 carbon neutrality.

3.6 Discussion

3.6.1 Insurance possibilities

There exists a potentiality for the sharing of risk among the producers: each storm directly affects a particular geographical area, however, other geographical zones may be preserved and thus possess a vested interest in providing assistance due to the fact that, over an extended period of time, every individual region is susceptible to face windstorms. This particular phenomenon complements the effect of redistribution between regions that have been impacted and those that have not been affected: a mechanism for ensuring the provision of insurance between geographical regions, therefore, appears to be doubly pertinent.

Firstly, we could imagine a system of mutual insurance fund among the forest owners in France. This already exists for farmers in France and is called the "Agricultural Disaster Fund". It is financed by contributions from the government, local authorities, and farmers. These lasts contribute to the fund through mandatory contributions levied on crop insurance premiums. We could imagine the exact same kind of mechanism for the forest owners, except that the contribution could probably not depend on forest insurance premiums because most of the forest owners are not insured against natural hazards (Brunette et al., 2017). Moreover, the level of contribution should also vary among the different regions because we have seen that the impact of natural hazards were spatially heterogeneous in Figure 3.15.

Secondly, Figure 3.14 has shown that if γ_d is large enough, the total surplus of the sector is positive (even the global surplus is negative due to loss in carbon sequestration). This should remain the case even if forest owners try to optimize their surplus, disregarding the effects on the downstream sector. This means that there are social gains from the occurrence of windstorms and we could imagine some tools to redistribute the value in the sector.

Finally, because forest owners are facing a risky context, it could be rationally optimal to get a forest insurance or to take part in a fund, as suggested above. It is however necessary to remember that the main effect of windstorm from a social point of view is the loss of carbon sequestration in the long term. We discuss in the next section that forest management decisions can modify the windstorm resistance of a forest stand. It is thus necessary to take into account the potential moral hazard in this context. In this sense, public subsidies for insurances against natural hazards could have a negative impact on the type of management that the forest owners chose to avoid windstorm damages. This could thus be detrimental to the whole society and misalign the incentives given to the forest producers and the social welfare goals. Such insurance subsidies should lead to be even more careful to potential moral hazards.

3.6.2 Adaptative strategies of the forest owners

The level of damage is a function of several parameters of the forest, more precisely, the critical windspeed estimated by ForestGALES depends essentially on diameter, spacing between trees and tree species. This means that there are some parameters on which the forest owner could play to reduce the effect of windstorms.[20] Concerning the diameters, the model is not build to really select preferred diameters.[21]

It is, however, possible to replant the economically optimal forest type when forest is harvested. Because there are heterogeneous effects of windstorms on the different forest types,

[20]Let us mention that we cannot modify in FFSM the spacing between trees.

[21]More precisely, every timber that can be used to produce a certain primary product is aggregated to get the total volume available for a given product. This was called $I_{pp,t}$ in Eq. 3.1. The total harvested volume is estimated and distributes proportionally to the volume of each pixel/diameter class. There is no real selection of diameter in the model. This could however be changed by giving the priority to certain diameter classes.

forest owners can expect the revenues from certain forest types to be lower. We could thus look at the strategies that forest owners might adopt to minimize the impact of storms. This was for example done by Petucco et al. (2020), that gave foresight to the forest owners in FFSM, in order that they took into account the possibility of being hit by ash die back. We could thus compare anticipatory and non-anticipatory behaviors. The time needed to see an effect of such parametrization is however long because it needs a relative long time to harvest a significant share of the French forest so that the species distribution can significantly change.

Moreover, we have seen that the effect of combined natural hazards could be particularly salient on the forest sector. It is generally mentioned by the ecologists that mixed forests are more resistant to such combined natural hazards (Jactel et al., 2017). Furthermore, incorporating broadleaved trees into coniferous forests was found to diminish the damages in case of windstorm or wildfire (Jactel et al., 2017). Moreover, Knoke et al. (2005) showed that risk averse forest owners should rationally diversify their forests to optimize their expected utility. Diversifying as a management decision is particularly interesting in our context because it could be included in FFSM through tuning the level of hazard that mixed forests are facing with respect to other forest types. This is thus an interesting research avenue.

3.6.3 Why it is necessary to use an economic model coupled with a biological model

On a more conceptual perspective, this work has proven – if it was still needed – that bio-economic models have a lot to say about public policies. On the one side, it is relatively clear that it necessary to have a solid ecological framework to model the forest dynamic in order to have a good appreciation of the evolution of the resource. But on the other side, it is also necessary to have a solid economic model taking into account the human decisions over this resource: change of trade, due to price variability, the dynamic of the harvest, the short-term and long-term effects of natural disturbances. First, if we only had an ecological or an economical model we would probably miss a large part of the effects depicted in this chapter. Second, and maybe more importantly, there would also be research questions that could only be asked because of this ecological economic modeling. For example, this is the case for risk sharing among the producers, the adverse effects among the different actors in the sector or the harvest path dependency in the long term. All these issues are nonetheless crucial in terms of public policy.

Indeed, without an endogenous timber demand, the effect on the carbon sequestration would be very different because the harvest would not adapt to the new price equilibrium. This shows that such partial equilibrium models, which are based on a small scale for the dynamic of the resource, can indeed be very beneficial to evaluate several public policies among which: the optimal storage policies after a windstorm, the optimal management of the forest (for example specie diversification) to ensure the resilience of the forest to natural disturbances and to estimate the resilience of the low carbon strategy at the country level.

To be fully consistent, the ecological model describing the natural hazards should even be endogenous to the other modules. For example, bark beetles intensity depends on several biological parameters (like the local concentration of conifers), which can vary during the simulations due to the choices of the forest owners. This would require further development of FFSM to dynamically estimate the level of damages at each time period.

3.6.4 Perspectives

Wildfires represent the second natural hazard at the European level, with 16% of the total damage (Schelhaas et al., 2003). Moreover, the Mediterranean region is a region especially prone to wildfires (Senf and Seidl, 2021b). It could thus be particularly interesting to also include wildfire damages in FFSM. Indeed, Riviere et al. (2022) already included wildfires in FFSM to investigate the effect of the different climate uncertainties in the estimates of the model.

Even more interesting would be to link wildfires with the other hazards. Indeed, we have seen that interacting hazards generally lead to more intense crisis. Interestingly, Schelhaas et al. (2002) have suggested considering that the yearly mean fire activity is a good proxy to estimate the level of damages of bark beetles. Indeed, warm and dry weather, which corresponds to favorable conditions for a high fire activity, also stimulates the development of insects and increases the level of stress for the spruce. No precise function is however defined by Schelhaas et al. (2002).

Fire activity $D_{F,t}$ of year t is defined[22] as the mean damages due to fire over France during the year. The idea of the model would be the following: if $D_{F,t}$ is greater than the historical mean $\mathcal{A}_F$[23], this means that the yearly weather is favorable to fire occurrences and thus that the weather is dry and warm. But such weather is also favoring bark beetles damages because they can develop faster and because the trees will be more stressed. This means that the damage of bark beetles should also be increased. To take this into account, we create a yearly fire damage coefficient $C_{F,t}$. If the yearly activity is smaller than this mean, there is no effect of fire, and the coefficient equals 1. If the activity exceeds this threshold, the coefficient could increase like the square of the yearly activity to have non linear effects.

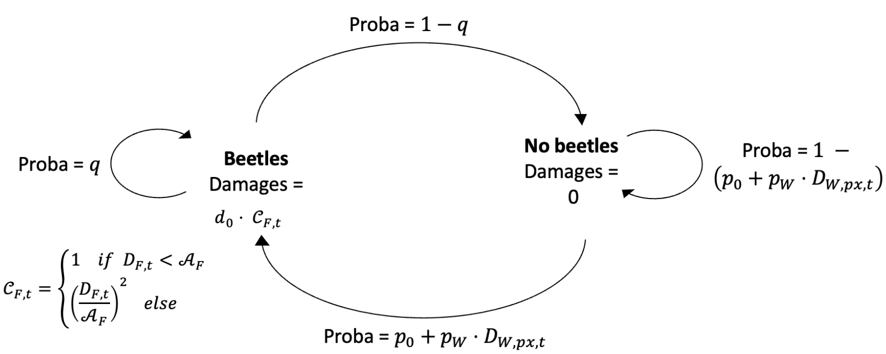

Figure 3.21: Graph summarizing the probability and damages due to insects' outbreaks with fire taken as a proxy for drought level.

Moreover, Fargeon et al. (2020) expected the French wildfire activity to increase with climate change, because fire prone conditions will be more likely. Several pathogens and insects' outbreaks are also driven by such dry and warm climate conditions. The original goal of PRIMAVERA project was also to provide windstorms simulations in future climate to assess the potential future demand for windstorms insurance under the different climate scenarios. It could thus be interesting to include climate scenarios into FFSM and include the potential growth effect of climate change.

3.7 Conclusion

This paper was a first attempt to include windstorms regime as a routine in a partial equilibrium framework. Moreover, it is the first time that two interacting natural hazards are

[22] $D_{F,t} = \frac{1}{N_{px}} \sum_{px \in \text{France}} D_{F,px,t}$ where $D_{F,px,t}$ corresponds to fire damages on pixel px, year t and N_{px} is the number of pixels in France.

[23] $\mathcal{A}_F$ is the mean over time and over all simulations of yearly fire activity $D_{F,t}$.

included in such economic model. We have shown that the we were able to reproduce the basic effects of natural hazards depicted in the literature but we are able to go further because we have several regions at the same time, some being impacted, other being spared. Moreover, we could study the effect of the natural hazard occurrences on the different actors of the French sector.

We have shown that the there is a possibility of creating a fund among the forest owners to insure against the windstorms. Moreover, we have shown that the objectives of the forest owners are logically not in line with the producers objectives but also not with the carbon sequestration objectives. Finally, our results show that the French low carbon strategy might not be resilient to natural hazards occurrences, especially in the case of interacting hazards.

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3.8 Appendix of chapter 3

3.8.1 PRIMAVERA data

Model	Resolution (km)	Mesh at 50°N (km)	Member	Missing data
HadGEM3-GC3.1	LM	135	r1i1p1f1	
			r1i2p1f1	
			r1i3p1f1	
			r1i14p1f1	
			r1i15p1f1	
	MM	60	r1i1p1f1	
			r1i2p1f1	
			r1i3p1f1	
	HM	25	r1i1p1f1	
			r1i2p1f1	
			r1i3p1f1	2006
EC-Earth3P		71	r1i1p1f1	1950, 1951
			r3i1p1f1	1962, 1963, 1970, 1971
	HR	36	r1i1p1f1	
			r3i1p1f1	1966, 1967, 1982, 1983
CNRM-CM6		142	r1i1p1f2	
	HR	50	r1i1p1f2	1
CMCC-CM2	HR4	64	r1i1p1f1	1993
	VHR4	18	r1i1p1f1	1
MPI-ESM1-2	HR	67	r1i1p1f1	1993
	XR	34	r1i1p1f1	1

Table 3.5: List of models available in PRIMAVERA dataset (Lockwood et al., 2022). Data is available from winter 1950 to winter 2013 (i.e. 64 winters for each ensemble) and we have 21 ensembles. This adds up to 1332 simulated winters, because 12 winters are absent from the data.

Data is given from winter 1950 to winter 2013 (i.e. 64 winters for each ensemble) and there are 21 ensembles included in the study. This adds up to 1332 simulated winters, because 12 winters are absent from the data. We use 38 winters per simulation and we make up to 300 simulations, amounting to 11,400 winters required.

3.8.2 `fgr` input data

The requirements to run `fgr` (and its function `fg_rou`) are the following: diameter (m), mean height of the stand (m), spacing between trees and specie. Because FFSM does not include the forest specie, we only considered one broadleaved specie (oak) and one coniferous specie (spruce) and calibrated CWS for both species.

Specie For conifers, we considered Norway spruce (*Picea Abies*) data, whereas we used oak (*Quercus Petraea*) for the broadleafs estimation.

Mean height To assess the height of the forest, we used the French Forest National Inventory (FNI) dataset[24] for spruce and oak. To estimate the height of a given diameter class, the mean of all trees whose diameter was included in the range [Diameter-5cm ;Diameter+5 cm] is taken. Except for the first diameter class (10cm), where the range was reduced to [7.5cm; 12.5cm] because only trees with a DBH larger than 7 cm are included in the study, so that considering a larger diameter range would have biased up the estimate.

Spacing Spacing between trees is unfortunately not specified in the French NFI. We have thus used functions from the literature linking spacing to height. For conifers, we have used an allometric function from Pardé (1984), suggesting that Spacing $= 0.137 \cdot$ Height in the case of spruce. For broadleaf, we have used Oswald (1981), that suggests for oak the following allometric relationship:
Spacing $= \sqrt{\frac{10000}{16372 \cdot exp(-0.136 \cdot \text{Height})}}$.

With these specifications, it is possible to run ForestGALES and establish critical Windspeeds (CWS), that are available in Table 3.6. We used the function `fg_rou` of the package `fgr`. Please, note that the function returns windspeeds at height 10m over land.

	Broadleaf			**Conifers**		
Diameter (cm)	Height (m)	Spacing (m)	CWS (m/s)	Height (m)	Spacing (m)	CWS (m/s)
10	9.7	1.5	47	8.2	1.1	56
20	16.4	2.4	50	16.1	2.2	42
30	20.1	3.1	52	21.1	2.9	42
40	23.1	3.8	50	25.0	3.4	43
50	25.4	4.4	50	27.9	3.8	46
60	27.3	5.0	49	30.3	4.2	48
70	28.6	5.5	49	31.8	4.4	53
80	29.7	5.9	50	33.2	4.5	58
90	30.0	6.0	56	32.8	4.5	68
100	30.5	6.2	59	33*	4.5	77
110	31.1	6.5	61	33*	4.5	86
120	30.8	6.3	70	33*	4.5	95
130	32.1	6.9	66	33*	4.5	104

Table 3.6: Critical Windspeed (CWS) estimates from `fgr`. *For these diameters, there were too few observations in the data to assess the mean height. We extrapolated from the previous stagnation tendancy. This corresponds to less than 0.5% of the total volume of conifers.

There are six forest types in FFSM: Conifer High Forest, Broadleaf High Forest, Mixed High Forest, Broadleaf Intermediate Structure, Mixed Intermediate Structure and Broadleaf Coppice. Conifer High Forest was considered as spruce, the five remaining forest types were considered as oak. Indeed, mix species and mixed structures are expected to be more resistant, so that it seemed reasonable to use Broadleaf parametrization.

[24] Available at https://inventaire-forestier.ign.fr/dataIFN/

Chapter 4

The Market-Based Cost of Natural Disturbances in European forests

The Market-Based Cost of Natural Disturbances in European Forests

Félix Bastit[a], Johannes Mohr[b], Rupert Seidl[b,c], Werner Rammer[b], Dominik Thom[b,d] and Thomas Knoke[e]

[a] Université de Lorraine, Université de Strasbourg, AgroParisTech, CNRS, INRAE, BETA, 54000 Nancy, France
[b] Ecosystem Dynamics and Forest Management Group, TUM School of Life Sciences Weihenstephan, Department of Life Science Systems, Technical University of Munich, Hans-Carl-von-Carlowitz-Platz 2, 85354 Freising, Germany
[b] Berchtesgaden National Park, Doktorberg 6, 83471 Berchtesgaden, Germany
[d] Gund Institute for Environment, University of Vermont, 617 Main Street, Burlington, Vermont 05405, USA
[e] Institute of Forest Management, TUM School of Life Sciences Weihenstephan, Department of Life Science Systems, Technical University of Munich, Hans-Carl-von-Carlowitz-Platz 2, 85354 Freising, Germany

Abstract European forests have recently experienced dramatic disturbances threatening their services to society, especially timber production. However, the economic costs of natural disturbance occurrences in European forests are still poorly understood. This paper aims to evaluate the historical and future market-based costs of natural disturbances from four major economic forest species (Norwegian spruce, Scots pine, common beech, and oak) on the European scale, under the assumption of constant forest management.

To do so, we assess the forest value (provided by current and future tree generations), initiating existing forests with data extrapolated from European national forest inventories, enabling one to grasp European forest diversity while remaining parsimonious in the parameters required by the model. Forest dynamic is simulated on a local scale (0.133° squares) using new predictions of the local growth potential for each species. To assess the costs of natural disturbances, we calculated the European forest value with and without any natural disturbances, also considering climate change dependent disturbances.

To our knowledge, this study is the first to provide explicit market-based costs of natural disturbances accounting for the contribution of the current forest age distribution, evaluated for two different disturbance regimes: a background level of hazard and a regime accounting for catastrophic pulses of mortality causing major forest crises.

We find that the economic loss due to natural disturbances could currently decrease the welfare of forest owners by around 33%, representing 180 billion euros. The effect of climate change could still exceed this estimate by more than double in the most pessimistic climate scenario, showing that climate change may lead to a large increase in economic losses in European forests.

Keywords Natural Hazard; Risk Assessment; Forest; Europe; Pulse Mortality.

JEL codes Q23 (Forestry); Q54 (Climate • Natural Disasters and Their Management • Global Warming)

4.1 Introduction

After three decades of steady increases, European forests cover roughly 227 million hectares (without Russian Federation), accounting for nearly 35% of the European total land area and representing an estimated growing stock of 35 billion m^3 (FOREST EUROPE, 2020). In 2020, forestry generated 0.2% of the total European GDP (EUROSTAT, 2022), but this share was greater than 1% in three European countries (Estonia, Finland, and Latvia), showing the varying economic importance of forestry at a country level. In addition to market goods like timber, Europe's forests provide a wide array of valuable ecosystem services, ranging from recreation to carbon storage and air purification (Millennium Ecosystem Assessment, 2005). The timber industry's contribution to GDP is in stark contrast to the total economic value of forests, including non-market ecosystem services like water purification, recreation, and particularly climate regulation. The value of these ecosystem services has been estimated to be greater than the value of the world's stock market (Kappen et al., 2020). However, a market-based perspective is of particular interest to European forest owners, who rarely receive an emolument for ecosystem services other than timber provisioning.

Natural disturbances are part of ecosystems and play an important role in their long-term development (Seidl et al., 2017). European forests are vulnerable to several natural disturbances and 58% of the total area faces a risk of biomass loss (Forzieri et al., 2021). The main natural disturbances are windstorms, drought, bark beetles, wildfires, root rot, and snow and ice damage; the main drivers of these hazards are management choices and climate change (Seidl et al., 2011; Agne et al., 2018). Patacca et al. (2023) suggested that on average 43 million m^3 were affected by disturbances each year in Europe from 1950-2019 (46% due to windstorms, 24% to fire, and 17% to bark beetles), representing 0.23% p.a. of the average growing stock volume and about 15% of the mean annual harvest for the period 1950-2000. However, these statistics increased significantly in the period 2000-2019: the mean annual damage reached 79 million m^3 (0.27% p.a. of the average growing stock), and bark beetles doubled their share of the total damages.

Although natural disturbance regimes have received increasing scientific interest (Seidl et al., 2017) and recent economic losses have attracted much public attention (UNECE/FAO, 2020), we have limited scientific knowledge about the future economic losses forests will face. For example, a previous European-level estimate of the costs of climate change ignored not only disturbances, but also the current generation of trees in European forests (Hanewinkel et al., 2013). To close this gap, we provide the first estimates of the market cost of disturbance-related damages with respect to current and future climate scenarios including observed inital forest stocks.

Previous assessments of the economic cost of forest disturbances have mostly focused on historical events like hurricanes, forest fires, or large bark beetle outbreaks (Zhai and Ning, 2022). While some prospective studies are available, they tend to focus on a single type of disturbance, such as Butry et al. (2001) that estimated the cost of wildfires in Florida (USA). At the stand scale, some studies have tried to capture the potential effect of multiple risks at once: e.g., Venäläinen et al. (2020) reviewed a wide range of the potential effects of natural hazards on Finnish forests in the context of climate change, although they do not provide any economic assessments. Jönsson et al. (2015) included some economic evaluations of different forest management strategies under climate change in Sweden based on the dynamic vegetation model LPJ-GUESS, but these estimates were used to compare different management strategies and not to compute the cost of natural hazards at the national or supranational level. Economic assessments at this scale do exist outside the forest context: for instance, a recent large-scale study by Callahan and Mankin (2023) estimated that climate-change-driven increases of El Niño-Southern Oscillation events over the 21st century could lead to global discounted losses over the worldwide economy of $374T. However, comparable large-scale estimates of the costs of natural disturbances for European forests specifically is still lacking.

One exception is Hanewinkel et al. (2013) often-cited study suggesting economic losses from climate change correspond to moderate annual values ranging between -9 and -33 €/ha. This would represent a loss of 14 - 50% (mean 28%) of the total present European forest value. These losses resulted from a comparison of the forests' land expectation value under the current distribution of tree species with the land expectation value under the anticipated future distribution of tree species. Therefore, this estimate is based on niche-based models and focuses more on the mean effect of climate change on forest species distribution than on the cost of natural disturbances.

Here, we calculate the market value of EU-wide forest losses due to natural disturbances under historical climate conditions and multiple future climate scenarios, assuming a constant species distribution. To do so, we:

- consider newly established forests (bare soil), but also currently existing European forest stock;
- model two parallel disturbance regimes, including background mortality and catastrophic mortality, fitting better with current observations;
- provide estimates of both forest growth and mortality depending on climate scenarios.

The resulting expected loss estimates shed light on the costs that forest owners will likely bear moving forward and provide a first quantitative estimate of the economic dimension of forest disturbances at the continental scale.

To process the European Forest Value, we exploit a classical deterministic forest economics framework (Samuelson, 1976), which we expand by integrating stochastic occurrences of hazards across time (Knoke et al., 2021a) using survival probabilities computed from an Accelerated Failure Time model (Brandl et al., 2020). These survival probabilities were estimated from historical data depending on long-term mean climatic variables (related to temperature and precipitation) for four European commercial tree species that account for two-thirds of Europe's forest area and three-fourths of its growing stock: Norway spruce (*Picea abies (L.) H.Karst.*), Scots pine (*Pinus sylvestris L.*), common beech (*Fagus sylvatica L.*) and oak (*Quercus robur L. & Quercus petraea Matt. Liebl.*). Finally, we constructed a matrix-based forest growth model that allocates the available forest area to different age classes for each species to obtain local estimates for timber volume and diameter class distributions. Climate change is included at two different levels: it changes forest productivity but also the level of mortality.

4.2 Material and methods

Monte Carlo Simulations (MCS) represent an increasingly popular technique in the climate economics literature, because it offers a versatile and powerful tool for understanding complex systems, analyzing uncertainty, validating models, optimizing decisions, and conducting sensitivity analyses. For instance, Rennert et al. (2022) recently suggested using MCS to revise the social cost of CO_2, in order to better account for the high uncertainties related to climatic, socioeconomic, and damage functions in the context of climate change. A similar MCS methodology has also been used by governments to estimate the social cost of other greenhouse gases (United States Government, 2021).

In the forest context, Knoke et al. (2021a) recently used MCS to calculate the Forest Value of Norway spruce stands in southern Germany exposed to different natural disturbances under various climatic scenarios. To include stochasticity, which is inherent to natural hazards, they conducted a large set of Monte Carlo simulations based on Brandl et al. (2020) estimation of hazards. In this way, they estimate entire distribution of likely future Forest Values. From the Bavarian spruce age distribution, they could extend the value computed at the stand stand scale to the entire Bavarian region cost estimate.

Here, we adopt a similar strategy, but focus exclusively on expected values. This means that instead of considering the complete distribution of potential damages, we restrict ourselves to the analysis of mean damages, which can be explicitly derived because simple probability distributions are used. The lack of information is important[1] but very interesting effects are already captured with this preliminary framework. Indeed, the computational requirements to analyze all different possible effects of natural hazards at the European scale were too large to be handled in the restricted time period of this Ph.D.[2]

The core of the model is built around five main modules (see Figure 4.1): forest growth, climate, natural hazards, forest management, and economic revenues. The first part of the method focuses on the design of the economic model: the focus is set on the variables and parameters that are required within our framework to be able to properly compute the European Forest Value. The second part presents the different sources of data to initiate the dynamic simulations. The third part concentrates on the disturbance computations. Finally, the fourth part deals with the mandatory economic parameters to evaluate the losses.

4.2.1 General framework

European forests are discretized in a large number of pixels (noted px).[3] The pixels are squares (in World Geodetic System) of 0.133°, which corresponds to around 15km in latitude and 9.5km in longitude at a latitude of 50°N. Figure 4.2 shows the area that is included in our study, which covers the majority of the European forest, excluding Russia, Belarus, Ukraine, Moldavia, and Turkey.

This discretization of space enables us to employ a methodology very similar to Knoke et al. (2021a) by treating each pixel as a stand. Although each stand can contain multiple species and age classes, we neglect interactions between them, as such interactions are determined by spatial relationships that occur well below the pixel scale.[4] We also assume that pixels are

[1] Especially in terms of deviation from the mean value.

[2] Complete simulations would have required several dozens of days, due to limited computation powers and a code that has not been optimized yet. However, the paper written from this chapter will be based on MCS.

[3] Europe is paved with 37208 pixels.

[4] This means that there is no positive/negative effect from diversity (in both species and age distribution), i.e. each age class of each specie behaves as if it was alone on the area it has been endowed. More concretely, on each pixel, we consider that for a given age class/specie behaves as a pure even-age stand at each time period.

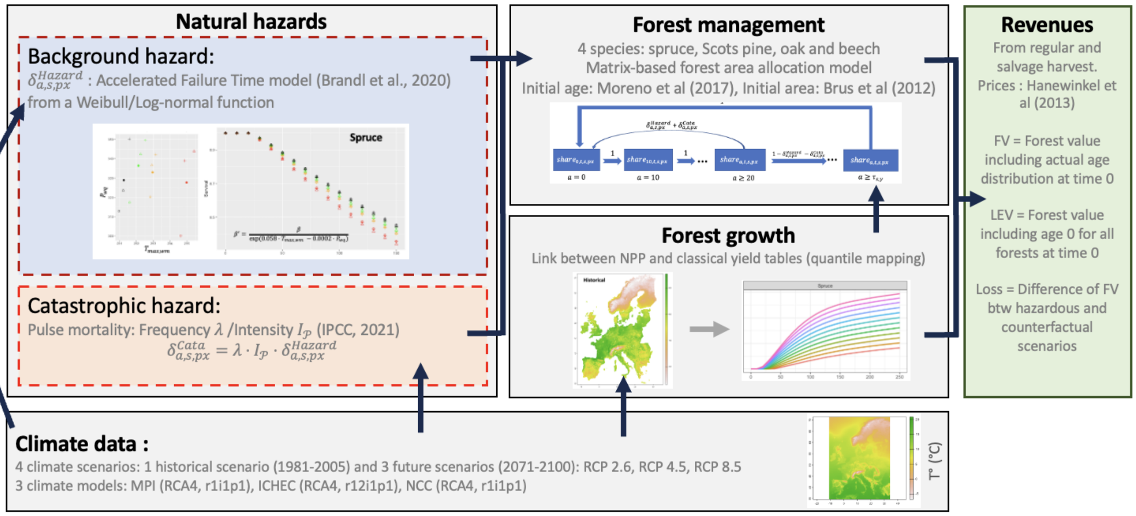

Figure 4.1: Graphic summarizing the different modules that build the model.

independent and do not influence one another, rendering the underlying simulation process strictly linear with respect to spatial extent.

Thus, the European Forest Value (EFV) is thus equal to the sum of local forest values ($\mathrm{FV}_{s,px}$) for each specie s over all pixels (See Eq. 4.1) multiplied by the corresponding forest area $\mathcal{A}_{s,px}$ of species s in pixel px.

$$\mathrm{EFV} = \sum_{px \in Europe} \sum_{s \in species} \mathcal{A}_{s,px} \cdot \mathrm{FV}_{s,px} \tag{4.1}$$

From Eq. 4.1, we see that our assessment problem (finding EFV) is equivalent to calculate $\mathrm{FV}_{s,px}$ for four main tree species and for all European pixels. An important assumption is made here: $\mathcal{A}_{s,px}$ is assumed to be fixed, i.e. it does not change over time and scenario[5]. In other words, the European forest cover maintains the same spatial distribution of forest species in each scenario: 1 ha of spruce always persists as 1 ha of spruce.

To model disturbance dynamics in each pixel, we use a methodology similar to Knoke et al. (2021a), extended to address four commercial tree species (Norway spruce, Scots pine, common beech, and oak) representing 74% of European growing stock of timber (FOREST EUROPE, 2020). These species disproportionately account for the economic value of temperate forests in Europe: Hanewinkel et al. (2013) estimated, for example, that the economic value of Norway spruce alone accounts for 45% of the total market value of European forests. Other species such as silver fir and Douglas fir are also profitable, but currently account for a small share of the European forest portfolio, each accounting for less than 2% of the total European forest area. On the other hand, birch is the fifth most present specie (representing 7% of the European growing stock), but its economic performance on a per-hectare basis is currently marginal. This is why these three species are not included in this study.

The framework we used to estimate the Forest Value of pixel px corresponds to the sum over infinite time of discounted cashflows $\mathrm{CF}_{t,px}$ at each time t (Eq. 4.2).[6] For practical application, the overall sum is restricted to times smaller than T, which is not detrimental if T is large enough and δ_t tends quickly enough towards zero.[7]

[5] This assumption is made even if forest area is currently increasing at the European level and that it could be economically optimal to modify the share of the different species in the different scenarios.

[6] Please, note that no difference is generally made between time t and the associated decade from t to $t+10$.

[7] See discounting section 4.2.4. We will take $T = 500$ years.

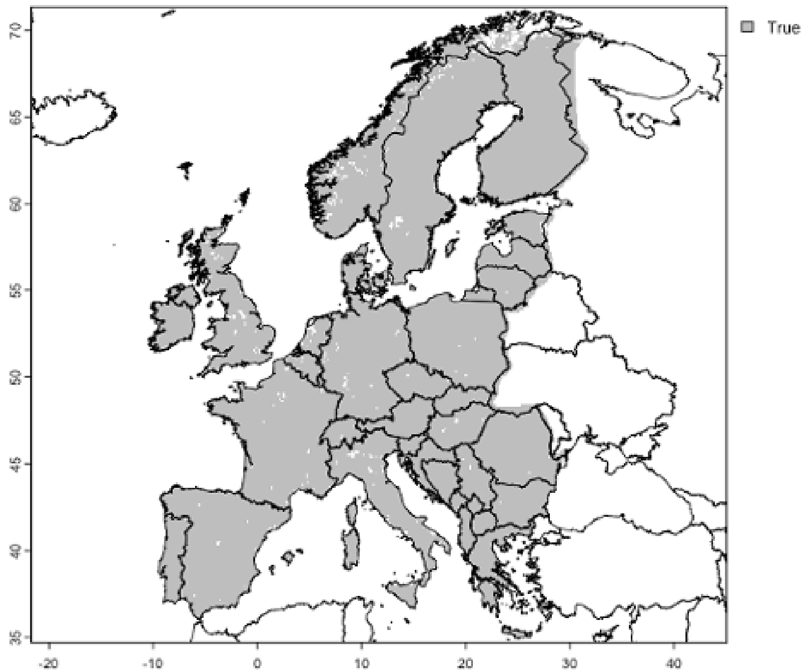

Figure 4.2: Spatial extent of our study: gray pixels are included in the study, white pixels are excluded due to missing data (Moreno et al., 2017).

$$\mathrm{FV}_{s,px} = \lim_{T \to +\infty} \sum_{t=0}^{T} \mathrm{CF}_{t,s,px} \cdot \delta_t \tag{4.2}$$

There are two different sources[8] for the cashflow $\mathrm{CF}_{t,s,px}$ at each period t, specie s, pixel px (Eq. 4.3): regular harvest $\mathrm{RH}_{t,s,px}$ and salvage harvest $\mathrm{SH}_{t,s,px}$ due to the occurrence of a natural disturbance.

$$\mathrm{CF}_{t,s,px} = \mathrm{RH}_{t,s,px} + \mathrm{SH}_{t,s,px} \tag{4.3}$$

Regular harvest occurs when a share of the pixel px has reached its rotation period[9] $\tau_{s,y}$. The cashflow is thus the difference between timber sale revenues (i.e. stumpage price $p_{a,s,y}$ multiplied by volume $v_{a,s,y}$) and planting costs PC_s. These revenues are summed over all ages larger than the rotation period (Eq. 4.4).

$$\mathrm{RH}_{t,s,px} = \sum_{a=\tau_{s,y}}^{250} \mathcal{S}_{a,t,s,px} \cdot (p_{a,s,y} \cdot v_{a,s,y} - PC_s) \tag{4.4}$$

The second source of revenue concerns the expected share of timber affected by natural hazards. This share does not survive until the end of its rotation due to the occurrence of disturbance before reaching age $\tau_{s,y}$. This leads to salvage harvest. The area is then re-established with the same tree species.

[8]Thinning is not included in this study because thinning is very irregularly applied in Europe and methods are very diverse at the European scale so that it did not seem sound to consider them this at this scale. In addition, thinning did not influence the results concerning the economic damages strongly in a sensitivity study carried out by Knoke et al. (2021a).

[9]$\tau_{s,y}$ essentially depends on the timber specie and the productivity of the pixel. It has been set has the rotation period maximizing the land expected value of the pixel in the case where there is no hazard.

Variable	**Unit**	**Description**
EFV	€	Expected European Forest Value
$\text{FV}_{s,px}$	€/ha	Expected Forest Value for specie s of pixel px
$\mathcal{A}_{s,px}$	ha	Forest area of specie s on pixel px
T	years	Duration of the simulations
δ_t	Ø	Discount factor at time t
$\text{CF}_{t,px}$	€/ha	Expected cashflow at time t for pixel px
$\text{RH}_{t,px}$	€/ha	Expected revenues from regular harvest at time t for pixel px
$\text{SH}_{t,px}$	€/ha	Expected revenues from unforeseen (due to hazard occurrence) harvest at time t for pixel px
$\mathcal{S}_{a,t,s,px}$	%	Share of area of specie s on pixel px in age class a at time t
$v_{a,s,y}$	m^3/ha	Timber volume at age a for specie s, yield y
$p_{a,s,y}$	€/m^3	Price of timber at age a for specie s, yield y
PC_s	€/ha	Planting costs for specie s
ρ	%	Apparent share price of timber affected by a natural hazard
$\delta^{\text{Hazard}}_{a,s,px}$	%	Expected share of pixel px, age a, specie s that faces natural hazard
$\delta^{\text{Pulse}}_{a,s,px}$	%	Expected share of pixel px, age a, specie s that faces catastrophic pulse
c_{cata}	€/m^3	Extraction over cost when a stand is impacted by a catastrophic event
$\tau_{s,y}$	years	Rotation period for specie s, yield y

Table 4.1: List of variables in the model.

Two different types of disturbance are included in our study: background and catastrophic. First, a background disturbance occurs (Knoke et al., 2021a), in which case the value of the timber sold is decreased to a share ρ of its regular harvest value. There are three main reasons (Gardiner et al., 2010) for this apparent price reduction: first, when damaged, timber often loses quality and thus value. Second, the harvesting costs can increase because the demand for harvest increases. Finally, a local excess of timber supply can lead to a decrease in timber prices. We assume $\rho = 0.5$ (Dieter et al., 2001) to represent these cumulated effects. This is equivalent to having an apparent price of $\rho \cdot p_{a,s,y}$ in Eq. 4.5 and it is still necessary to pay the planting costs.

In the case of catastrophic disturbance, by contrast, timber can no longer be sold, and it even becomes costly to extract this timber from forests, leading to an over-cost c_{cata} (Eq. 4.5) to remove this wood from the forest. Planting costs are also doubled (Knoke et al., 2021b) due to cleaning costs and potentially a larger demand for plantings in a region where the supply cannot be easily scaled. Catastrophic disturbance can occur in each period.

$\delta^{\text{Hazard}}_{a,s,px}$ and $\delta^{\text{Cata}}_{a,s,px}$ indicate the expected share of the pixel px facing a natural or catastrophic hazard at time t for age class a and species s, where age a must be at least 20 years since we do not expect younger stands to be affected by hazards (Brandl et al., 2020). With this function, we can rewrite the cashflow equation for the salvaged harvest revenues $\text{SH}_{t,s,px}$ as:

$$\mathrm{SH}_{t,s,px} = \sum_{a=20}^{\tau_{px}-10} \mathcal{S}_{a,t,s,px} \cdot \left[\delta^{\mathrm{Hazard}}_{a,s,px} \cdot (\rho \cdot p_{a,s,y} \cdot v_{a,s,y} - PC_s) - \left(\delta^{\mathrm{Cata}}_{a,s,px} \cdot c_{\mathrm{cata}} \cdot v_{a,s,y} + 2 \cdot PC_s\right)\right] \tag{4.5}$$

This enables us to estimate expected revenues for each time period. To close the loop, we need to capture the dynamic between the different age classes, i.e., how the forest area moves from one age class to another at each period. To accomplish this, we use a standard matrix-based model, re-allocating forest area at each time step. At the end of each period t, the part of $\mathcal{S}_{a,t,s,px}$ (i.e. the share of pixel px and species s with age a) that is damaged or harvested is transferred to $\mathcal{S}_{0,t+10,s,px}$ at the next period, meaning that it returns to its initial state, with the same specie s replanted. The remaining part of $\mathcal{S}_{a,t,s,px}$, that is not impacted is moved to the next age class, i.e. $\mathcal{S}_{a+10,t+10,s,px}$ for the following period. This dynamic is summarized in the diagram in Figure 4.3.

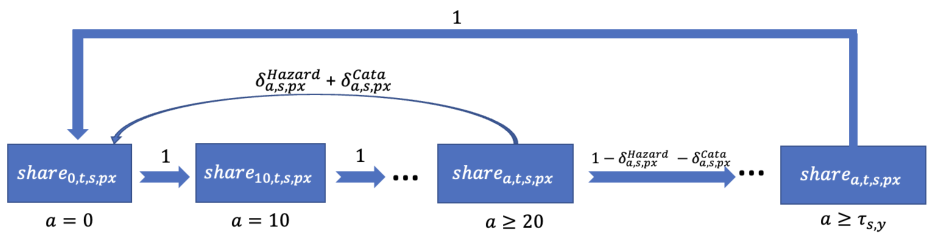

Figure 4.3: Dynamic implementation in the model.

Several indicators are used in the paper (see Table 4.2). First, the European Forest Expected Value (FV) is defined as the value of the European forests for the current age distribution of the European forests (see Figure 4.5). The European Land Expected Value (LEV) is expressed as the value of European Forests but considering that the age of all European forests is 0 at the beginning of the simulation. Concretely, this means that there is no stock in the forest at the beginning of the simulation. Finally, Loss is defined by the difference between a theoretical scenario where natural disturbances occur and a scenario where there are no natural disturbances. This definition aligns with a well-developed body of literature to assess forest disturbance costs, called "with and without" method. This method is used to compare a scenario including natural hazards and a counterfactual without disturbance (Zhai and Ning, 2022).

Estimator	Definition
Forest Value	The cumulative sum of discounted cashflow with the current timber stock in the forest at the beginning of the simulation.
Land Expected Value	The cumulative sum of discounted cashflow without any timber in the forest at the start of the simulation.
Loss	The difference between a scenario including a certain level of hazard and a scenario without any hazard.

Table 4.2: Summary of the three different indicators used in the study.

4.2.2 Ecological input data

Forest area and tree species

Brus et al. (2012) performed a statistical mapping of tree species throughout Europe at a 1x1km level. They have mapped the distribution of twenty tree species in 29 European countries. Their study is based on the national forest inventory (NFI) of 13 countries and extended to the remaining 16 with ICP Level-I data using small-scale predictors such as soil, biogeographical maps and bioindicators through a multinomial multiple logistic regression model. We aggregated these data to obtain the forest area for each species and pixel of the European grid (see Figure 4.4 and Table 4.3).

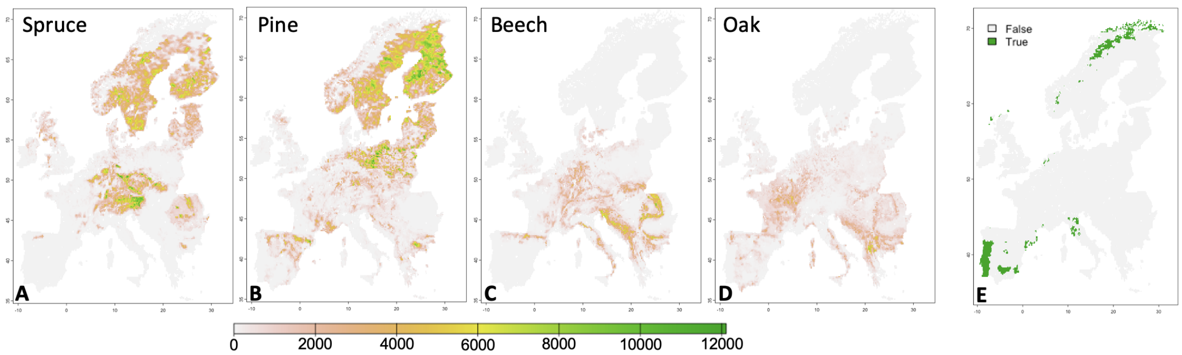

Figure 4.4: Forest area per pixel (ha/px) for spruce (A), pine (B), beech (C) and oak (D). List of pixels (E) where none of the four species is present.

Scots pine and spruce represent more than 50% of the entire European forest area (Table 4.3). Because we focus on four commercially important tree species, only 34% of the total European forest area – corresponding to the 16 other tree species – is excluded. However, there are some pixels in which none of the four species are present (see Figure 4.4E). This is especially the case in Portugal, Spain, Italy and Scandinavia, where the Mediterranean or Arctic biomes are predominant (European Environment Agency, 2017).

Specie	Forest Area (Mha)	Forest Area (%)
Spruce	34.7	22
Scots Pine	48.3	30
Beech	11.7	7
Oak	11.0	7
Total	105.7	66
Other species	54.2	34

Table 4.3: Forest area aggregated at the European level for the different species (Brus et al., 2012).

Forest age

We used a European data set (Moreno et al., 2017) based on several national forest inventories, to obtain the age-class distribution of the existing forests on each pixel (see Figure 4.5). The age-class distribution is represented by height age classes: 0-20, 20-40, 40-60, 60-80, 80-100, 100-120, 120-140, $>$ 140 years. We use this dataset to assign an initial value to $\mathcal{S}_{a,t=0,s,px}$ to each age class a. Because Moreno et al. (2017) use 20-year age classes, we obtain 10-year classes as follows: for each age class [a - 10; a + 10] of Moreno et al. (2017), 25% of the value is assigned to the class a - 10 (being [a - 15; a - 5] of Moreno et al. (2017)), 50% is attributed to the class a ([a - 5; a + 5] of Moreno et al. (2017)), and the remaining 25% to the class a + 10 ([a + 5; a + 15]).

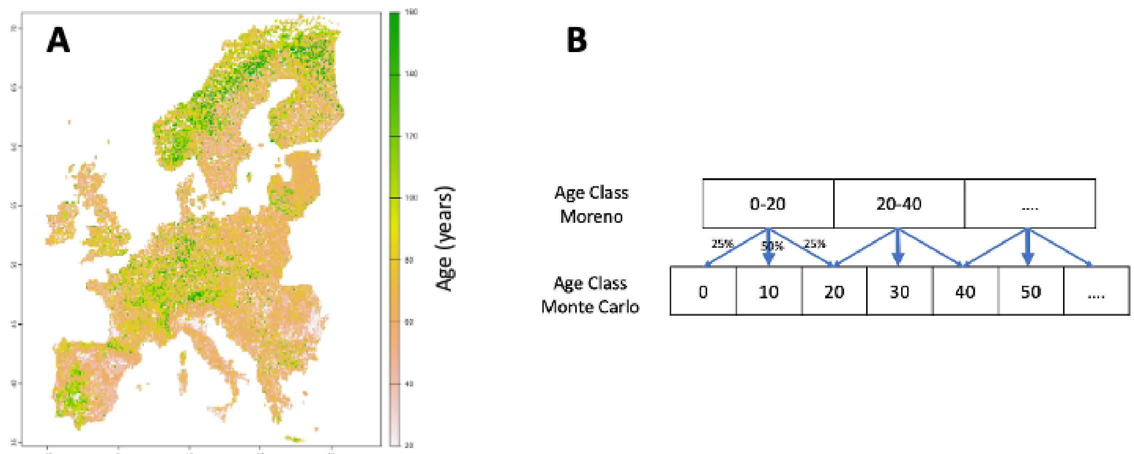

Figure 4.5: (A) Mean forest age (years) of European forests (Moreno et al., 2017), (B) graphic explaining the allocation of shares of the different age classes.

Productivity classes & growing stock volume

Net Primary Productivity (NPP) is a measure of the rate at which plants and other primary producers convert solar energy into organic compounds through photosynthesis, minus the rate at which they consume some of those compounds through respiration. To estimate the variability of forest growth, we use recent climate-sensitive species-dependent predictions of NPP across Europe from Grünig et al. (in preparation).[10] Their data are built from the same climatic scenarios as ours and have been averaged over the same periods.

These NPP estimates translate the potential carbon accumulation in the forest with respect to local conditions but do not provide direct growth estimates of the forest that we can include in a model. This is why we have used traditional yield tables. A yield table is a tool that estimates the growth and dynamic of a forest stand, depending on its level of productivity. For each species, we consider yield tables with a large yield gradient to take into account the full productivity diversity of European forests. In fact, each yield class of each specie leads to a given volume, price, and rotation period. The method for linking yield classes and NPP estimates is described in section 4.6.1 in Appendix. From Grünig et al. (in preparation), we obtain a potential NPP estimate for each species in each pixel for each climate scenario and thus different yield classes in historical and future climate scenarios.

Finally, for each pixel px, we compute in Eq. 4.6 the volume of timber $\mathcal{V}_{px}$ present on the pixel to implement the simulations.[11] This simply corresponds to the sum of the contributions of each species and each age class to the total, where the volume for a given age class is given in Appendix (Figure 4.14) for the four different species and yields.

$$\mathcal{V}_{px} = \sum_{a=0}^{250} \sum_{s} \mathcal{A}_{s,px} \cdot \mathcal{S}_{a,t=0,s,px} \cdot v_{a,s,y} \tag{4.6}$$

[10]Note that these NPP estimates also depend on the soil type but due to a lack of data, we averaged the results over the type of soil.

[11]Table 4.9 shows how $\mathcal{V}_{px}$ depends on the climate scenario.

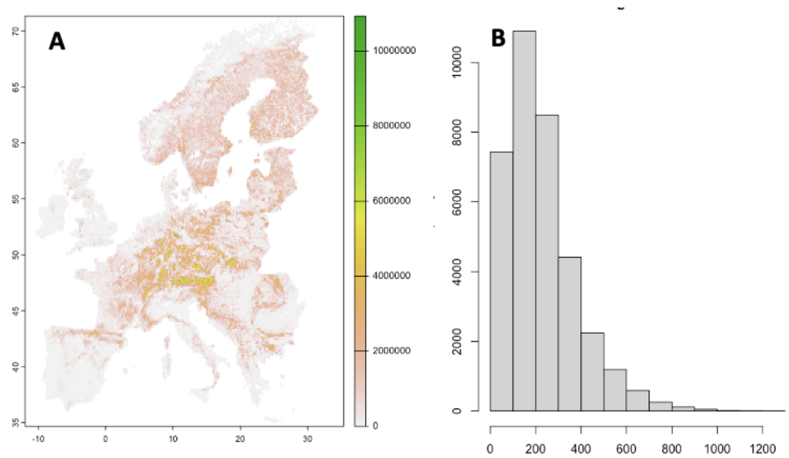

Figure 4.6: Volume of timber per pixel $\mathcal{V}_{px}$ (m^3/px), (B): histogram of forest density (m^3/ha).

4.2.3 Hazard computations data

Hazard probability: $\delta^{\mathbf{Hazard}}_{a,s,px}$

The core of the study relies on the estimates of the probability of hazard and how these depend on climatic data. Brandl et al. (2020) provided Accelerated Failure Time models (AFT), which offers a parsimonious parametric model to predict mortality of our four species. They linked the different species' mortality levels to simple climatic data (see Table 4.4). Their study was based on surveys of the German and pan-European crown condition and linked with 30-year local climate averages. Survival probability functions $S_s(a)$ for each specie s, function of age a, were established as Weibull functions (see Eq. 4.7 and 4.8), except for Scots Pine, where a log-normal distribution showed a better fit. Survival probabilities as function of age can be seen in Figure 4.18 in Appendix for the different climate scenarios and for each of the four species.

$$S_s(a) = exp\left[\left(\frac{a}{\beta_{climate,s}}\right)^{\alpha_s}\right] \tag{4.7}$$

$$\beta_{climate,s} = \frac{\beta_s}{exp(\sum b_i \cdot x_i)} \quad \text{with} \;\; x_i \in \{T_{max,wm}, T_{min,cm}, P_{wq}, share\} \tag{4.8}$$

		Beech	**Spruce**	**Scots Pine**	**Oak**
	Distribution	Weibull	Weibull	Log-normal	Weibull
$T_{max,wm}$	Daily maximum temperature of the warmest month	0.108	0.058	0.077	0.095
$T_{min,cm}$	Daily minimum temperature of the coldest month	-0.050			
P_{wq}	Total precipitation of the warmest quarter		-0.0002	-0.002	
share	Specie share		0.653		

Table 4.4: Table of b_i (see Eq. 4.8) for the different climatic parameters (Brandl et al., 2020).

From survival functions, we calculate the hazard rate $h_s(a)$ for each age class (from a to $a+10$) from Eq. 4.9. $h_s(a)$ thus, corresponds to the expected damage due to natural disturbances during a decade, so we can write: $\delta^{\text{Hazard}}_{a,s,px} = 1 - h_s(a)$.

$$h_s(a) = \frac{S_s(a) - S_s(a+10)}{S_s(a)} \tag{4.9}$$

Climate data

To implement hazard probabilities, some local climate data is required. Representative Concentration Pathway (RCP) scenarios depict a set of greenhouse gas concentration trajectories used by the Intergovernmental Panel on Climate Change (IPCC) to model and project different levels of future climate and monitor their potential effects. These were designed to represent possible pathways for future greenhouse gas emissions based on assumptions about future economic and population growth, energy use, and technological change. RCP 2.6 (the lowest greenhouse gas emissions scenario) is the most optimistic, while RCP 8.5 (the highest emissions scenario) is the most pessimistic scenario. This provides a useful and powerful framework for understanding the potential gradient of impacts of different levels of greenhouse gas emissions.

We compare four climate scenarios: historical climate, RCP 2.6, RCP 4.5, and RCP 8.5. The historical climate corresponds to the mean climate of 1985-2001. We use this as the baseline to assess the historical hazard level. For future climate, the mean was taken over the 2071-2100 period.

Because climate predictions are sensitive to climate model selection, three different climate models[12] are included in our study (see Table 4.5). Estimates of the survival function $S_s(.)$ for the various climate models and climate scenarios are available in Figure 4.18 in Appendix.

Global Climate Model (GCM)	Regional Climate Model (RCM)	Member
MPI-M-MPI-ESM-LR	SMHI-RCA4	r1i1p1
ICHEC-EC-EARTH	SMHI-RCA4	r12i1p1
NCC-NorSM1-M	SMHI-RCA4	r1i1p1

Table 4.5: List of global climate models, regional climate models and members used in our simulations.

Catastrophic pulse risk: $\delta^{\textbf{Cata}}_{a,s,px}$

Brandl et al. (2020) procures statistical hazards from empirical observations of European forest stands. They reflect the long-term expected damages, given historical climatic conditions, and thus provide some background effects of natural disturbances (Knoke et al., 2021a). However, several studies show that the damage level is quite volatile over time. For instance, Patacca et al. (2023) reviewed the different sources of natural disturbances in Europe between 1950 and 2017. The mean level of damages is 62.1 Mm^3 p.a. but some years have registered much greater damage. For example, 1999 windstorms Lothar and Martin have caused 250 Mm^3 of damage in Europe quadrupling the mean value. The recent drought and the induced bark beetle's crisis also caused damages much greater than the historical mean. Senf et al. (2020) stated that the mortality following the 2018 European drought led to a annual mortality five times higher than historical values in affected regions.

[12] The data has been downloaded from Copernicus Climate Data Store. See: https://cds.climate.copernicus.eu/cdsapp#!/dataset/projections-cordex-domains-single-levels?tab=form

Thus, estimates using Brandl et al. (2020) cannot predict extreme events like catastrophic pulses of natural disturbances, which rarely occur but have significant impacts. To integrate extreme events into our simulations, we use a random variable $\mathcal{P}_t$, representing the number of catastrophic pulses per decade at time t. $\mathcal{P}_t$ is assumed to follow a Poisson distribution with parameter λ. The Poisson distribution is commonly used in probability theory to model the number of times an event occurs in a fixed time interval, given the average rate of occurrence of that event. The Poisson distribution is used in situations where the events being counted are rare but occur randomly over time. It is particularly useful when the events are independent of each other (i.e., the occurrence of one event does not affect the probability of another event occurring). The mean number of events per period is equal to λ. The probability of having k pulses during a decade is given by:

$$\mathbb{P}\left[\mathcal{P}_t = k\right] = \frac{\lambda^k \cdot e^{-\lambda}}{k!}$$

If a pulse happens during a given decade, background damages, from Brandl et al. (2020), are multiplied by a given pulse intensity $I_{\mathcal{P}}$. We assume this pulse intensity is fixed to a constant for the entire simulation.

The elegance of using an expected value model (instead of the complete Monte Carlo simulation framework) lies in the simplicity brought to the calculation. Indeed, because pulses follow a Poisson distribution of parameter λ, we expect to have a mean number λ of pulses per period. The intensity coefficient of this pulse is fixed to $I_{\mathcal{P}}$, meaning that the expected damages multiplicator corresponds to $\lambda \cdot I_{\mathcal{P}}$. More specifically, this means that if λ is divided by 2 and that $I_{\mathcal{P}}$ is multiplied by 2, the expected value remains the same. Thus, we exclusively use the product $\lambda \cdot I_{\mathcal{P}}$ from now on. The evolution of both parameters in warmer climate is therefore the key to understanding the potential effect of climate change on expected losses due to extreme forest disturbances. The expected pulse damages $\delta^{\text{Cata}}_{a,s,px}$ for age class a, species s, and pixel px is given in Eq. 4.10.

$$\delta^{\text{Cata}}_{a,s,px} = \lambda \cdot I_{\mathcal{P}} \cdot \delta^{\text{Hazard}}_{a,s,px} \tag{4.10}$$

We estimate from past data that, in the case of historical climate, λ should be around $1/5$ (i.e. one event every 50 years). Indeed, over the last century, we have observed only two types of major events striking European forests: large windstorms during the 1990s (Patacca et al., 2020) and the major bark beetle crisis of 2018-2021 (Schuldt et al., 2020). The damages of these events lead to an increase of around 100% of the harvest over the decade. This means that a quantity of timber that should be harvested in 20 years is harvested in 10 years. Thus, we estimate that in historical climate: $\lambda \cdot I_{\mathcal{P}} = 0.2$.

Senf et al. (2020) suggested that drought has been an interesting proxy to evaluate forest mortality over the period 1986-2016 on the European scale. Thus, estimates of future drought intensities and frequencies could be especially relevant to assess the evolution of our parameters λ and $I_{\mathcal{P}}$.

IPCC (2021) projected[13] the change in frequency and intensity of droughts in the context of global warming (see Table 4.6). The change in frequency is a measure of how often the historical (defined as the 1850-1900 period) decadal[14] drought level is exceeded. The change in intensity evaluates[15] how the first decile of the drought index changes between the different scenarios. Both estimates should be exclusive because depicting both sides of the same coin (increase in frequency vs. increase in intensity). We will, however, multiply their effect because

[13]See chapter 11, especially Figure 11.18 (p. 1581).

[14]The decadal level corresponding to the first decile of the distribution of the z-score of a drought index.

[15]In terms of standard deviation of historical data.

catastrophic pulses are rare events on a very discontinuous scale. Moreover, we expect both intensities and frequencies of catastrophic pulses to increase in the future (Lindner et al., 2010; Seidl and Rammer, 2017; Senf et al., 2021).

Global Warming[16]		Intensity (x $I_{\mathcal{P},Hist}$)	Frequency (x λ_{Hist})	$\lambda \cdot I_{\mathcal{P}}$
1°C (Historical)		1	1	1
2°C (RCP 2.6)	Lower	0.8	0.81	0.65
	Median	1.12	1.40	1.57
	Upper	1.38	2.38	3.28
3°C (RCP 4.5)	Lower	0.87	1.21	1.05
	Median	1.22	1.90	2.31
	Upper	1.54	3.19	4.91
4°C (RCP 8.5)	Lower	1.09	1.40	1.53
	Median	1.41	2.39	3.36
	Upper	1.83	3.69	6.76

Table 4.6: IPCC (2021) estimates of the expected increase in intensity/frequency of droughts in different future climates. Values are expressed as share of historical values. “Lower” and “upper” refer to the bounds of the 66% uncertainty range, whereas “median” refers to the average value across the different climate models used by IPCC (2021). Note that the expected temperature increase under scenario RCP 8.5 is 5.5°C with respect to the 1850-1900 baseline. However, IPCC data did not provide any data for such extremes. We thus decided to attribute the data from the most significant available warming (which corresponds to +4°C, nearer to RCP 6.0 scenario warming in 2100) to the RCP 8.5 scenario, even if it is a quite conservative assumption.

4.2.4 Economic data

Timber price

To compute the net timber prices (i.e. the stumpage prices), we used the prices suggested by Hanewinkel et al. (2013) in their pan-European study. These prices vary by tree species and diameter. We linearized the price between each diameter. Diameter estimates of each species depend on the productivity class of each pixel and are picked from the yield tables. Prices are summarized in Table 4.7 and are available for the different yield classes in Figure 4.16 in Appendix.

	Price (€/m^3)			
DBH (cm)	**Beech**	**Spruce**	**Pine**	**Oak**
5	0	0	0	0
15	5	5	5	5
25	10	25	20	15
35	25	40	35	25
45	40	45	40	40
> 55	50	45	45	60

Table 4.7: Price (€/m^3) of timber for different diameters (Hanewinkel et al., 2013).

Discount rate

Considerations in forest economics have a very long-term character: a tree grows slowly, so two centuries could be required before the optimal rotation period is reached. For this reason, classical exponential discounting can have the effect of discounting the far future too strongly (Weitzman, 1998). Moreover, in the context of large uncertainties, especially when dealing with climate change issues, it can be interesting to use discount rates that vary over time.[17] Gollier et al. (2008) suggested using a balance of two discount factors associated with two different growth projections and thus two different discount rates. For example, Rennert et al. (2022) used such a discounting framework to assess the social value of carbon, which is another typical long-term issue.

We will use the mean of a discount factor estimated from a 2% discount rate and another discount factor estimated from a 1% discount rate for each timepoint t. For times near to the present, this estimate is very close to the discount factor from a traditional discount rate of 1.5% (which is used by Knoke et al. (2021a), for instance). For far future time horizons, the mean discount factor converges to the discount factor associated with the low discount rate (Weitzman, 1998), meaning that the future obtains more weight in the estimates of the Forest Value than under conventional discounting with a constant rate. Figure 4.17 in Appendix shows the discount factor in the case of 1.5% traditional discounting and in the case where both 1% and 2% discount factors are averaged, which correspond to our declining discount rate scenario.

Rotation period

We assume that forest stands starting from bare land are managed according to the optimal rotation period that maximizes their expected net present value. This rotation period ensures the maximum Forest Value is achieved when no natural hazard is assumed. We estimated the optimal rotation period for each species and yield class. Table 4.8 shows that the estimate of the rotation period in historical climate for each specie is more than double of the mean age of each specie, suggesting that large proportions of European forests have not yet reached their equilibrium age (Senf et al., 2021). Moreover, rotation periods differ between climate scenarios because climate influences NPP, which impacts stand volumes, diameter growth, and therefore timber prices.

	Beech	**Spruce**	**Pine**	**Oak**
Rotation period (yrs)	130	134	170	127
Double of mean age (yrs)	115	122	109	104

Table 4.8: Comparison of rotation period estimated from the data with historical climate (mean of the 3 climate models), weighted by species area on each pixel and the double of mean age also weighted by species area on each pixel.

In summary, we integrated four forest species (spruce, pine, beech and oak), several yield classes, four climate scenarios (historical, RCP 2.6, RCP 4.5, RCP 8.5), and three climate models (MPI, ICHEC, NCC) into the forest age matrix-based allocation model. Table 4.9 lists important climate sensitive parameters. For example, we observe that the rotation period is reduced and the volume at time 0 is increased with the intensity of the RCP scenario because the yield is increased. The survival probability up to age 100 years is decreased, due to higher temperature.

[17] It is often argued that if there are uncertainties on the future growth, this means uncertainty on the future discount rate, because both are linked by Ramsey equation.

	Rotation period (yrs)				Survival at age 100 yrs (%)				Yield				Volume at t = 0 ($.10^9$ m^3)			
	B	***S***	***P***	***O***	***B***	***S***	***P***	***O***	***B***	***S***	***P***	***O***	***B***	***S***	***P***	***O***
hist	130	134	170	127	0.70	0.65	0.76	0.69	5.8	4.9	3.3	4.7	3.1	10	8.2	2.1
2.6	127	130	158	126	0.69	0.63	0.75	0.66	6.2	5.6	3.6	5.1	3.3	11	8.9	2.3
4.5	126	129	152	126	0.66	0.61	0.74	0.61	6.4	5.9	3.8	5.3	3.3	12	9.2	2.3
8.5	124	125	136	125	0.60	0.56	0.71	0.52	6.7	6.6	4.2	5.5	3.4	13	10	2.4

Table 4.9: Summary of parameters (rotation period, survival share at age 100yrs, Yield Class, Volume at the beginning of simulation) for the different species and climate scenarios (the mean of the 3 climate models), the mean is weighted with the area of the species on each pixel.

4.3 Results

The results are divided into three parts. The first part concerns the pure estimation of the cost of natural disturbances and the second part focuses on Forest Value and Land Expectation Value (for definitions, see Table 4.2). The last part appraises the redistributional effects of climate change.

4.3.1 Loss of European Forest Value

The cost of disturbances is estimated as the loss of European Forest Value, i.e., the difference between expected Forest Values of a scenario including hazard and a hypothetical scenario where no hazard at all would occur (neither catastrophic pulses, nor background hazard). The results are presented in Figure 4.7.

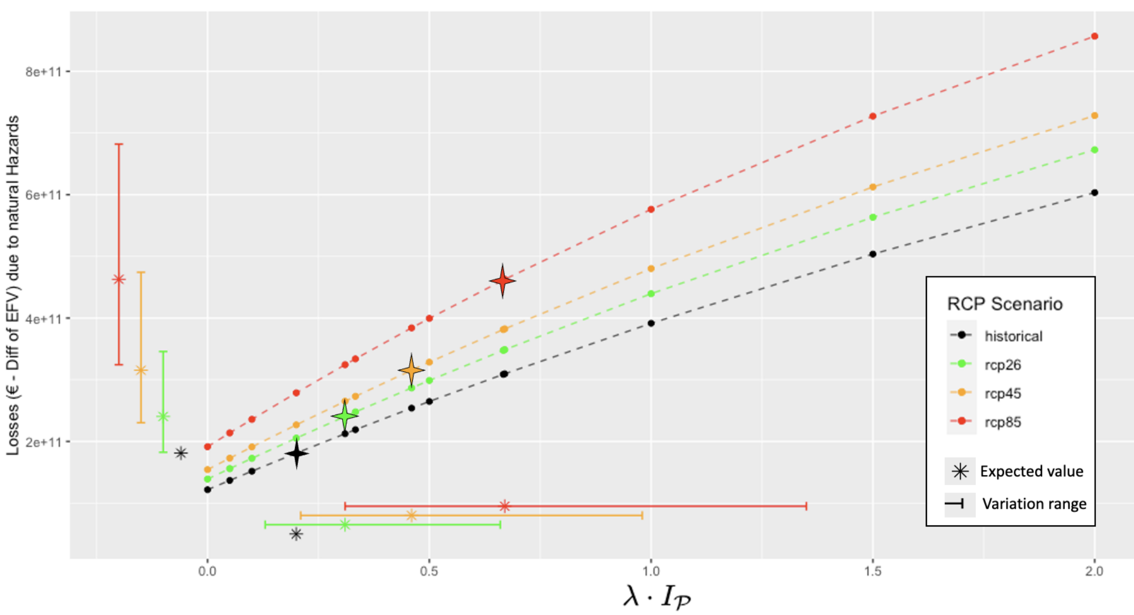

Figure 4.7: Cost (€) of natural hazards on European forests. Cost is averaged over 3 climate models for different probabilities and intensities of catastrophic pulses. The stars (segments) show the expected values (potential ranges of variation) for $\lambda \cdot I_{\mathcal{P}}$.

The cost of natural disturbances under historical climate is estimated at €181 billion, or roughly 1,724 €/ha at the European level. This represents a loss of one third of the total Forest

Value in the event that no risk would occur (5,174 €/ha). The cost of natural hazards rises with increasingly pessimistic emission pathways and the growing importance of catastrophic events, potentially exceeding €500 billion under RCP 8.5.

Three drivers underpin this increasing climate cost. The first driver is that a warmer climate leads to a higher level of background hazards by negatively influencing survival functions (see Table 4.9 and Figure 4.18). Even if some models predict an increase in rainfalls during the warmest quarter (Figure 4.18, right), the driving effect of temperature is more prominent for all species. Because the level of damage is higher, the expected cost of disturbances is logically increased. The second driver is that the mean forest productivity increases when the climate is warmer, particularly in countries with cooler climates and in the mountains, so that the total production of timber also increases. This means that more timber is affected by natural hazards, even for a fixed $\lambda \cdot I_{\mathcal{P}}$. The last (and possibly most important) driver is that the pulses of catastrophic events are expected to dramatically increase in frequency/intensity under warmer climate scenarios, resulting in a significant increase in expected losses.

4.3.2 Effect of climate change on the total European Forest Value and the European Land Value

In this "with and without" framework (Zhai and Kuusela, 2020), loss estimates are particularly relevant to value climate-impacted disturbances. However, we previously saw that three drivers increase the cost of disturbances in the case of a warmer climate, one being the gain of productivity. A consequence of higher productivity is increased Forest Value driven by faster stand growth. This is indeed what is observed in Figure 4.8: for a given level of pulse (i.e. $\lambda \cdot I_{\mathcal{P}}$ fixed) the European Forest Value is increasing with the climate scenario. However, because $\lambda \cdot I_{\mathcal{P}}$ is also expected to increase with the climate scenario, the Forest Value stays relatively constant for RCP 2.6 and RCP 4.5, although it slightly decreases in RCP 8.5 scenario (even if this decrease seems to be only small with respect to the large range of possible trajectories).

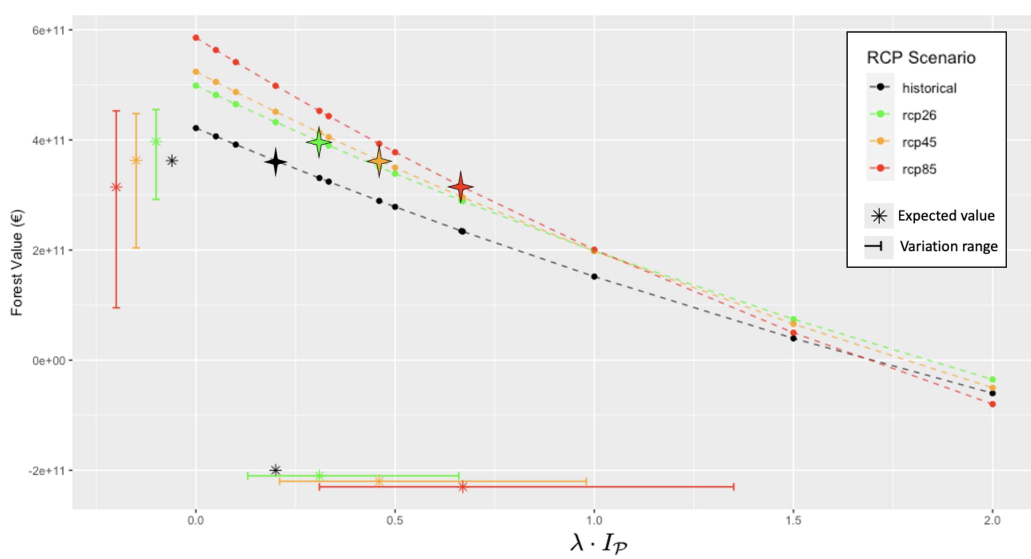

Figure 4.8: Expected European Forest Value (€) for four climate scenarios (average of 3 climate models) and different pulse parameters $\lambda \cdot I_{\mathcal{P}}$.

To estimate the European Forest Value, a given age distribution is required to initiate the simulation. We used age distributions from Moreno et al. (2017) for all climate scenarios. This leads to two major phenomena. First, because the model provides a matrix-based allocation of the forest area to different age classes, the timber volume depends on the yield estimates.

As can be observed from Table 4.9, the volume at time 0 increases by around 10-20% between the historical and RCP 8.5 scenarios. This means that the value of the existing stand is much larger in RCP 8.5 than in the historical scenario[18]. Moreover, the mean rotation period diminishes between the historical scenario and RCP 8.5 (between 2 and 25 years, depending on the specie). This also means that a larger share of forests has directly reached the rotation period before the simulation begins.

Both effects lead to the fact that the first year is very peculiar in the simulation: much more timber is harvested than in the decades following. Thus, the revenue of the first year has a disproportionate influence on our results. One way to overcome this bias is to initiate the simulation with all forests set to an age of 0, meaning that we look at LEV rather than Forest Value. Figure 4.9 depicts the European Land Expected Value under different climate scenarios. Because the effect of the initial volume is removed in the LEV, it appears that the LEV declines slightly in warmer scenarios.

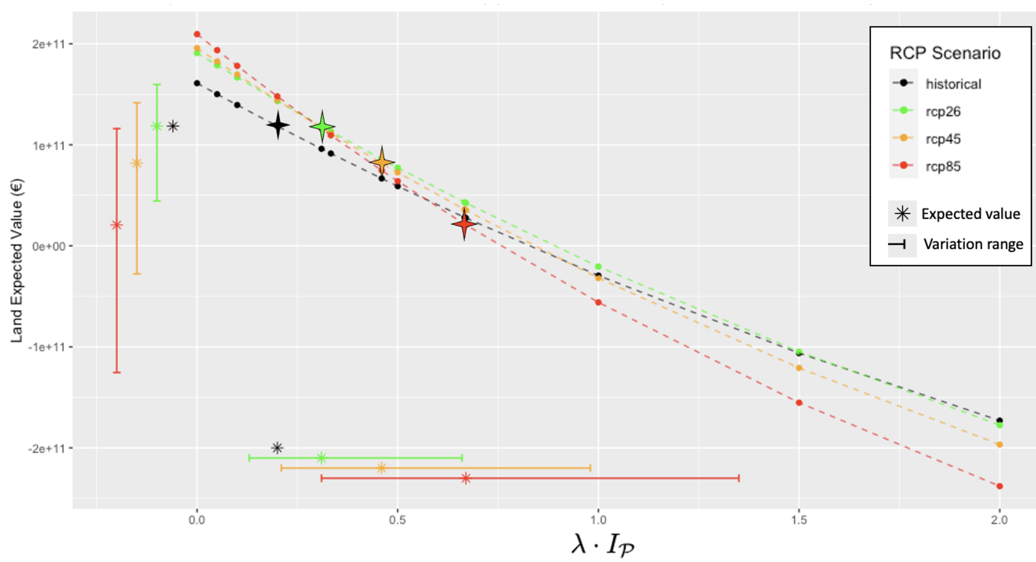

Figure 4.9: Land Expected Value (€) of European forests under different climate scenarios (mean of three climate models) for different values of $\lambda \cdot I_{\mathcal{P}}$.

To fully understand the change in Forest Value and its link with LEV, we suggest disentangling the Forest Value FV_{RCP} of a given climate scenario (including pulses and background risk) into several effects:

$$\begin{aligned}
\mathrm{FV}_{RCP} = &\ \mathrm{FV}_{RCP} - \mathrm{FV}_{RCP,\mathrm{NoPulse}} \\
&+ \mathrm{FV}_{RCP,\mathrm{NoPulse}} - \mathrm{FV}_{RCP,\mathrm{NoRisk}} \\
&+ \mathrm{FV}_{RCP,\mathrm{NoRisk}} - \mathrm{LEV}_{RCP,\mathrm{NoRisk}} \\
&+ \mathrm{LEV}_{RCP,\mathrm{NoRisk}} - \mathrm{LEV}_{Historical,\mathrm{NoRisk}} \\
&+ \mathrm{LEV}_{Historical,\mathrm{NoRisk}}
\end{aligned}$$

- Pulse effect: $\mathrm{FV}_{RCP} - \mathrm{FV}_{RCP,\mathrm{NoPulse}}$. This difference represents the value of the pulses and is thus the difference between the forest value with expected pulses and without.
- Background risk effect: $\mathrm{FV}_{RCP,\mathrm{NoPulse}} - \mathrm{FV}_{RCP,\mathrm{NoRisk}}$. This second difference estimates the effect of background risk on the Forest Value.

[18]Diameters are also larger, still increasing this effect.

- Initial volume effect: $\text{FV}_{RCP,\text{NoRisk}} - \text{LEV}_{RCP,\text{NoRisk}}$. This refers to the effect of the volume at the start of the simulation and is simply the difference between Forest Value and Land Expected Value.
- Productivity effect: $\text{LEV}_{RCP,\text{NoRisk}} - \text{LEV}_{Historical,\text{NoRisk}}$. This estimates the gain due to the difference of productivity (due to higher mean NPP) between a given climate scenario RCP and the historical reference.
- Baseline value: $\text{LEV}_{Historical,\text{NoRisk}}$, i.e. the value of the forest without any volume, in historical climate and without disturbances.

Figure 4.10 (see also Figure 4.19 in Appendix to see the differences) depicts these four effects. Pulse effects increase strongly with warmer climate, whereas background risk effect is less responsive to climate modifications.

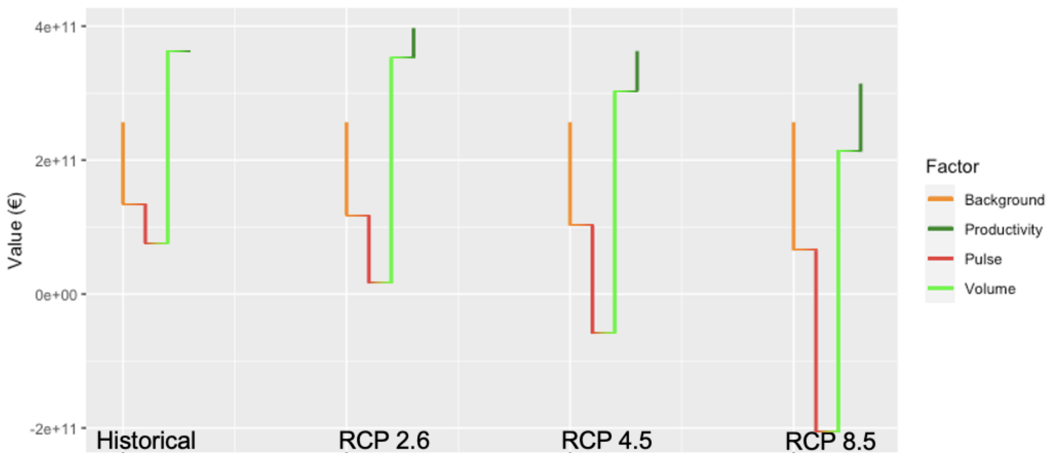

Figure 4.10: Separation of the four effects driving the Forest Value changes.

4.3.3 Potential redistributive effects of climate change

In the previous sections, we have explored the aggregated costs of forest loss at the continental scale. Here, we examine how these damages are distributed within Europe.

Per-pixel revenues vary substantially over the study area (see Figure 4.11). The largest gains in Forest Value from climate change are concentrated in mountainous regions like the Alps and (to a smaller extent) Pyrenees, as well as in Scandinavia and Northern Central Europe, where the level of background risk is relatively low, and climate change mainly drives increases in productivity rather than disturbance. However, Forest Value declines across the rest of Central Europe, as smaller NPP increases are not able to offset larger increases in background risk (see Figure 4.20 in Appendix for per hectare values).

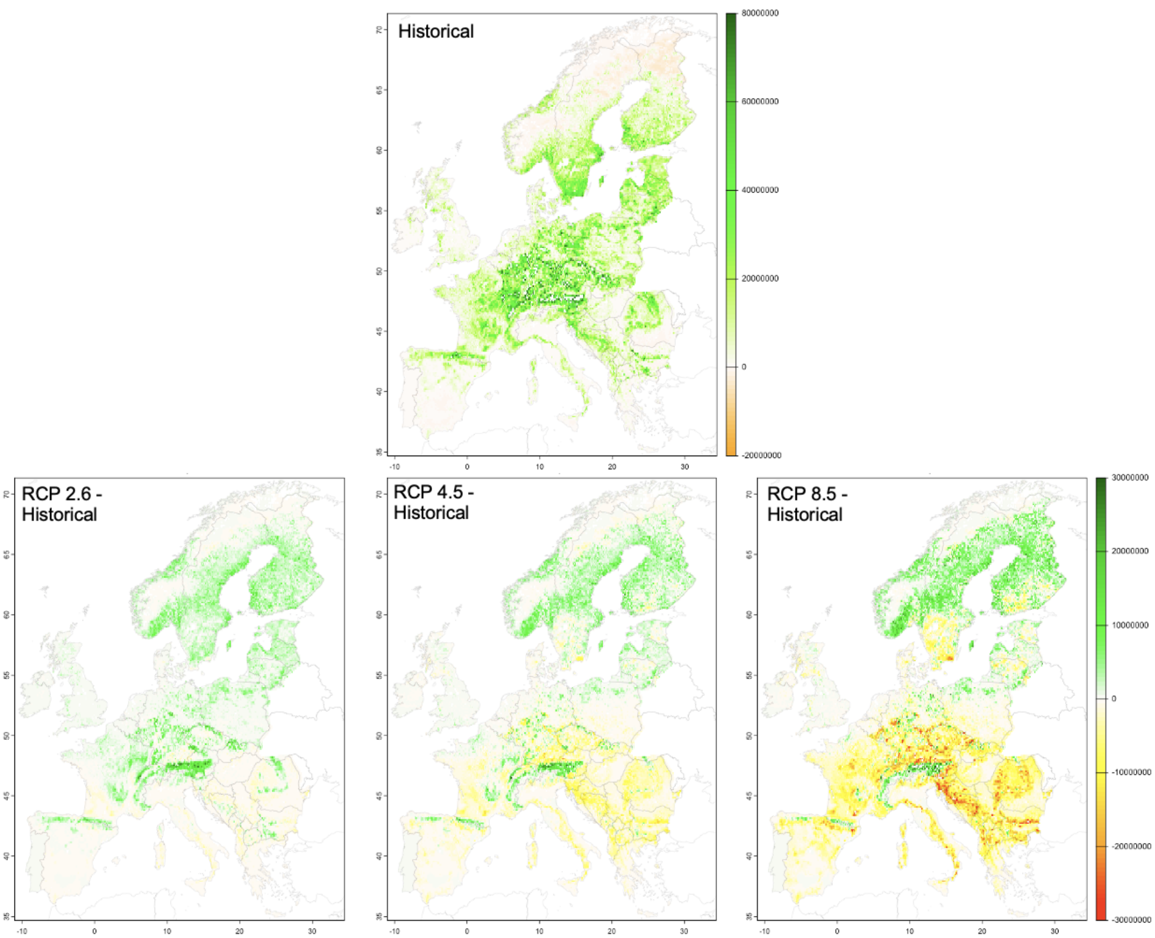

Figure 4.11: Geographical distribution of Forest Value (€/pixel) in Europe and difference with the historical scenario. The values are averaged over the three different climate models. Pulses paramters: $\lambda \cdot I_{\mathcal{P}} = 0.2$ (historical), 0.31 (RCP 2.6), 0.46 (RCP 4.5) and 0.67 (RCP 8.5).

A Gini coefficient is used to look at the distribution of the total European Forest Value among European forest regions and see the effect of climate change on the distribution of revenues across Europe. Generally, a Gini coefficient is a statistical measure of income or wealth inequality within a population Gini (1912). A higher Gini coefficient indicates greater income inequality[19] and a lower Gini coefficient indicates less income inequality. Instead of

[19] Generally, Gini coefficients are included in [0 ;1]. This is not necessarily the case here, because some pixels have a negative Forest Value so that the coefficient could be larger than one.

looking at income distribution, we use a Gini coefficient to see how the set of pixels contributes to the total European Forest Value (see Figure 4.21 in Appendix to see the shape of the inequality curves between the different climate scenarios).

Climate Scenario	Historical	RCP 2.6	RCP 4.5	RCP8.5
Gini coefficient	0.69	0.70	0.72	0.81

Table 4.10: Gini coefficient of European Forest Value for the 4 climate scenarios with median pulses (averaged over the 3 climate models). See Figure 4.21 in Appendix for the shape of the curves.

Generally, increasing catastrophic pulses generates higher Gini coefficients (see Table 4.10). Since the effect of catastrophic pulses is greater in regions where the background hazard level is already high (because the effect is multiplicative with respect to background mortality), these regions lose even more when the pulses increase. The pure effect of pulses exacerbates existing inequalities in the geographic distribution of forest value.

4.4 Discussion

4.4.1 How our study compares with previous ones

Hanewinkel et al. (2013) previously evaluated climate change's potential impact on the European Land Expected Value by focusing on the change in tree species distribution in Europe due to changes in potential ecological niches for each tree species. The loss of value is due to the decline of economically valuable species (those promising a high LEV) under a warming climate. We applied a complementary approach: namely, evaluating damages to currently existing forests, assuming a fixed species distribution and climate-dependent changes in productivity and disturbance risk.

Lindner et al. (2010) have also reviewed the potential effects of climate change on forests from different regions of Europe. In Northern and Western Europe, especially in the short term, they expect that increasing CO_2 concentration in the atmosphere and warmer temperatures will positively impact forest growth and wood production. On the other hand, adverse effects are very likely to outweigh positive trends in Southern and Eastern Europe, due to more intense droughts and disturbances. In the Mediterranean region, productivity is expected to decline due to increased drought and fire risk. Our results are therefore very much in line with theirs (see Figure 4.11).

At a finer scale, Schelhaas et al. (2002) conducted an analysis to determine the impact of windstorms, wildfires, and insect outbreaks in Switzerland with respect to climate variability. The authors evaluated the dynamics of the growing stock volume in various scenarios and determined that the effect of enhanced growth induced by climate change surpassed that of augmented natural disturbances. Switzerland being part of the Alpine region, we also expect this country to benefit from climate change from an economical point of view. This shows that even if we created a large-scale European model, it seems to fit well local scale expected results.

4.4.2 Climate change effect

The effect of climate change on European forests is rather small if we leave aside catastrophic pulses. For instance, if we keep the level of pulses fixed to a given threshold, the increase in background mortality due to higher temperature in Brandl et al. (2020) estimates is smaller than the effect of forest productivity increase (see Figures 4.8 and 4.10). There are several explanations for this.

First, the effect of the volume at the beginning of the simulation increasing with climate has already been discussed in the results. There are several ways to deal with this problem: only use the LEV (as suggested), to avoid using the first period ("burning" period) or even going further with a long simulation (several centuries) that would not be used but that enable to reach the long-term equilibrium in the forest composition.

Second, as discussed earlier, Brandl et al. (2020) took the mean climate into account (each climatic indicator corresponds to a 25 or 30-year period), but not the climatic extremes (which are represented by the variability from the mean). With climate change, climatic events will likely increase and lead to much more mortality. Moreover, past observations of the temperature and precipitations are not necessarily a good approximation for estimating the risk because a given temperature in the past does not lead to the same level of variability in the future.

Finally, the last and maybe most important effect is that Brandl et al. (2020) designed their study using past data, when the impact of climate was less severe. This could lead to two problems: first, a couple of precipitation/temperature in the past climate will not necessarily lead to the same hazard regime in the future climate. Furthermore, this data set was collected from European forests not too far from their historical climatic equilibrium. In our model, we always assume that the forest is at climatic equilibrium because the climate is fixed in each different climatic scenario to its value at the end of the 21$^{\text{st}}$ century. However, actual climate is changing fast, so each tree does not face the same climate when it grows and when it dies: the tree is 'out of climatic equilibrium'. Consideration should also be given to the possibility that trees may have been planted under certain precipitation/temperature conditions, and these conditions could change during the lifetime of the tree, causing the level of damage to also vary.

In terms of future research, it is still very interesting to note that focusing only on productivity increase and extrapolating past damages, i.e., not including catastrophic events linked to climate, could lead to a substantial underestimation of the potential effect of climate change on the forest and could lead to an underestimation of the need to mitigate climate change.

4.4.3 Policy implications

Our results show that the costs of natural disturbances are very high and will increase with warmer climates. The results are more nuanced regarding Forest Value, but it seems that the potential distribution of Forest Value embraces a larger range of variation.

Moreover, the European forest is an important lever in the fight against climate change because it is expected to behave as a carbon sink. However, Senf et al. (2021) have shown that an increased level of natural disturbance could modify the demographics of European forests and even make them younger.

Regarding policy implications, climate change could also have a rather different effect on the forest owner: the demand for timber products could increase drastically. Using timber products instead of carbon-intensive alternatives can help fight climate change (Cowie et al., 2021). Timber products sequester carbon, reducing CO_2 concentration levels in the atmosphere, and can be substitute for materials like concrete and steel that have high carbon footprints. Due to the increased demand, the price of wood products and forest owners' revenues could increase. Higher prices could also mean a larger timber supply, again decreasing the potential of the forest to store carbon. The case of using timber for wood energy to substitute fossil fuel has for example been extensively discussed in the literature. For example, (Churkina et al., 2020) suggested to use buildings as a global carbon sink.

Finally, two types of policies could be necessary in the context of climate change: policies supporting the forest owners who are always more impacted by catastrophic pulses and policies ensuring the forest owners follow a sustainable management of their forests, focusing on robustly adapting their forests to more intense disturbance regimes in the future.

4.4.4 Limits of this study

Lack of spatial correlation

Our model does not include any spatial interactions, meaning that what happens on a given pixel does not influence (and is not influenced by) its neighbors. This assumption facilitates the computation of each pixel's forest value separately (see Eq. 4.1) and the sum of the contribution of each pixel to obtain the European forest value without any complex interactions and associated non linearities. Considering such an absence of spatial correlation may be quite meaningful from a hazard perspective. For example, Venäläinen et al. (2020) assessed the effect of wind storms at the pixel level, with locally estimated time return of windstorms. Even if hazard occurrence is strongly spatially correlated, because the footprint of a windstorm is much larger than the size of a pixel, the level of damages between two pixels does not influence each other (the level of damages depends on windspeeds and local forest management).

This is not the case for economic effects of natural hazards, which can generate large-scale effects via changes in the timber market. Indeed, the timber price is not locally (i.e. scale of a pixel) defined, but at a much broader scale (regional, national and even global) (Prestemon and Holmes, 2000). When a large-scale disturbance occurs, such as a large windstorm, the timber price falls in the short term due to an excess of timber in the market and is expected to increase in the long term due to a lack of resources. This effect is roughly considered by the cash-flow-reduction coefficient in our study, but in reality, this should depend on the severity of the disturbance (Sun, 2020). Considering such effects in more detail, however, requires including the dynamics of the timber market, which is largely beyond the scope of this study.

Absence of forest management

One of the strongest simplifications of this study is to assume the absence of adaptative management by the forest manager to the hazard she is facing. This principle is particularly insightful to disentangle the potential impact of different hazard scenarios that show us how urgent adaptations to forest structures and management actually are.

For example, Reed (1984) demonstrated that the existence of a hazard should reduce the optimal rotation. Reducing the rotation period is a first adaptation strategy, but a large body of literature proposes other ways to manage natural hazards. These management strategies attempt to create forests that are more resistant and more resilient to natural disturbances. This can be done by creating more structured forests or forests with different species compositions (Thom, 2023). In this vein, Larsen et al. (2022) suggest, for example, using more adaptative forest management in the future to address uncertainties and encourage the use of Closer-to-Nature Forest Management.

4.5 Conclusion

The impact of disturbances on the economic outcomes of European forests has so far been underestimated. We have shown that the current cost of natural disturbances is around 180 billion euros. Without adaptive management, the enormous historical costs will significantly increase, mainly due to the impact of catastrophic events. It could reach half a trillion euros under the most pessimistic climate scenario. The effect of climate change on the value of forests is driven by two antagonistic forces: first, a potential gain in forest growth, especially in northern Central Europe and the Alps, and second, a higher level of damage, especially in Central Europe, due to higher background damage but also much larger catastrophic events.

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4.6 Appendix of chapter 4

4.6.1 Linking NPP and Yield Class estimates

For each climate model and each timber species, we take the distribution of NPP in historical climate. We suppose that the lower yield class is attributed to the first percentile of the NPP distribution and the higher yield class to the last percentile of the NPP distribution. The maps of NPP values over Europe for the different climate scenarios are exhibited on Figure 4.12.

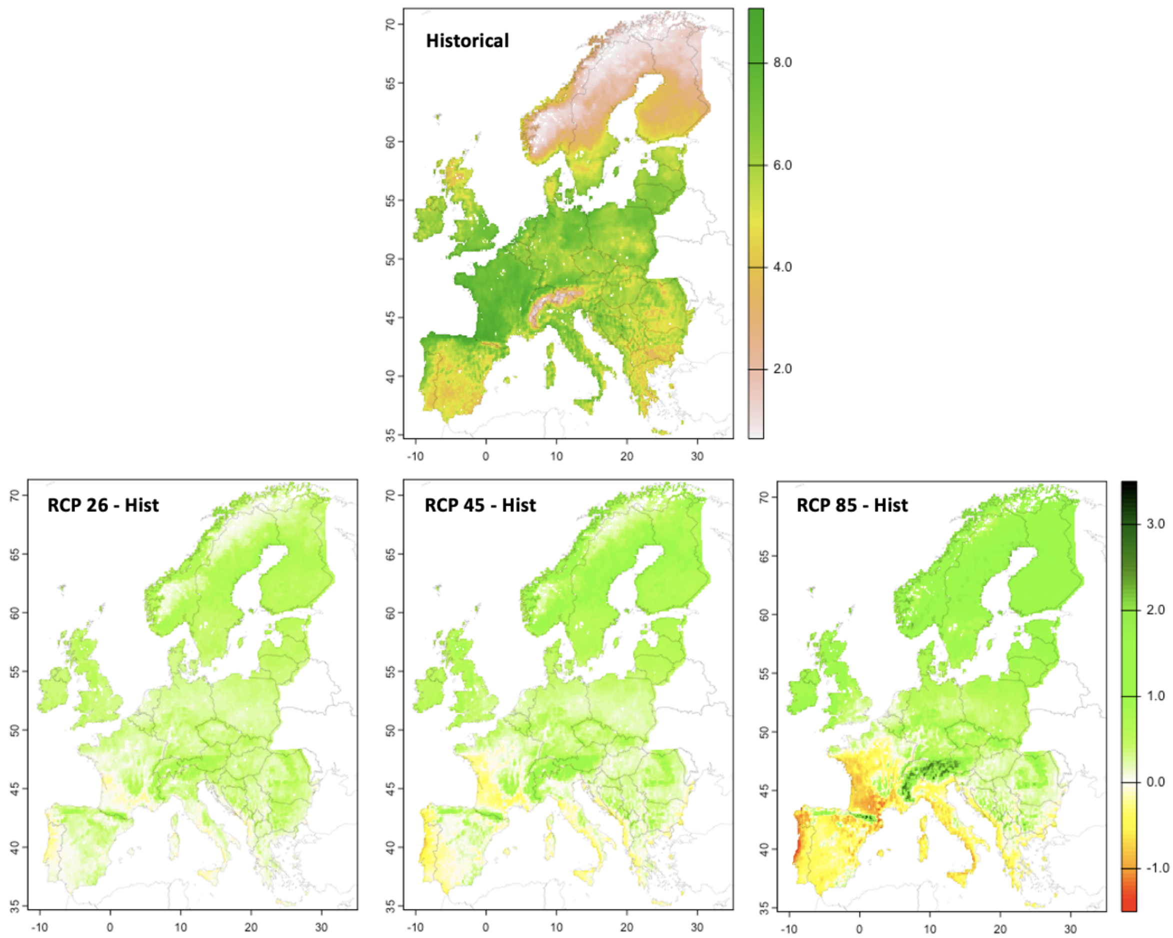

Figure 4.12: Estimates of NPP in historical scenario and difference with future scenarios (Grünig et al. (in preparation)).

Between both values, we extrapolate the link between NPP and Yield class from a quantile mapping method. The lower percentile of NPP distribution is associated to the lowest yield class and the higher percentile of NPP distribution is associated to the highest yield class. In between, we extrapolate yield classes from NPP estimates with a linear function. This assumes the fact that for a higher NPP, the growth is proportionally larger. For future climate, we extrapolate future yield class from future NPP maps but keeping the historical estimating function. Figure 4.13 exhibits the NPP estimates of spruce in historical climate and the Yield Class extrapolated with our method.

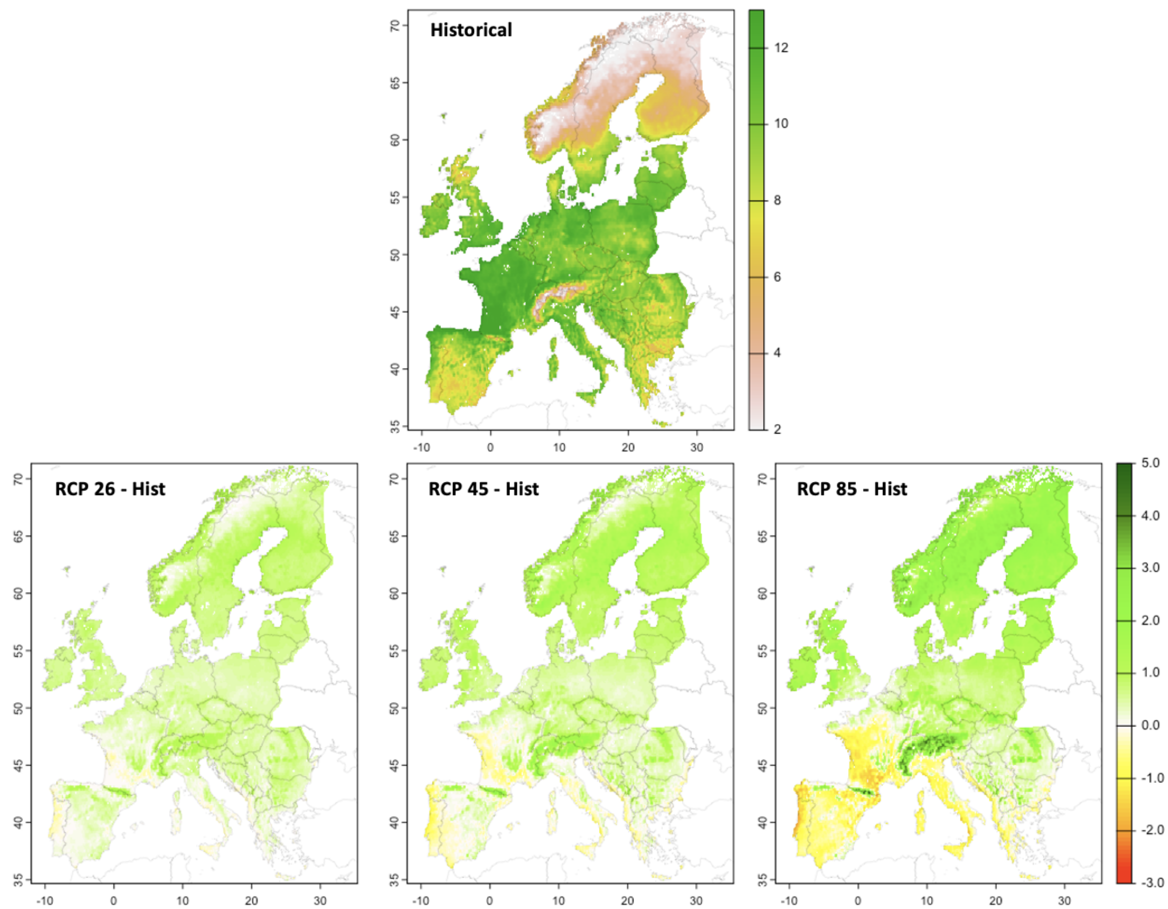

Figure 4.13: NPP estimates for spruce in historical climate and differences with the different climatic scenarios.

4.6.2 Yield Class functions

Volume Estimates

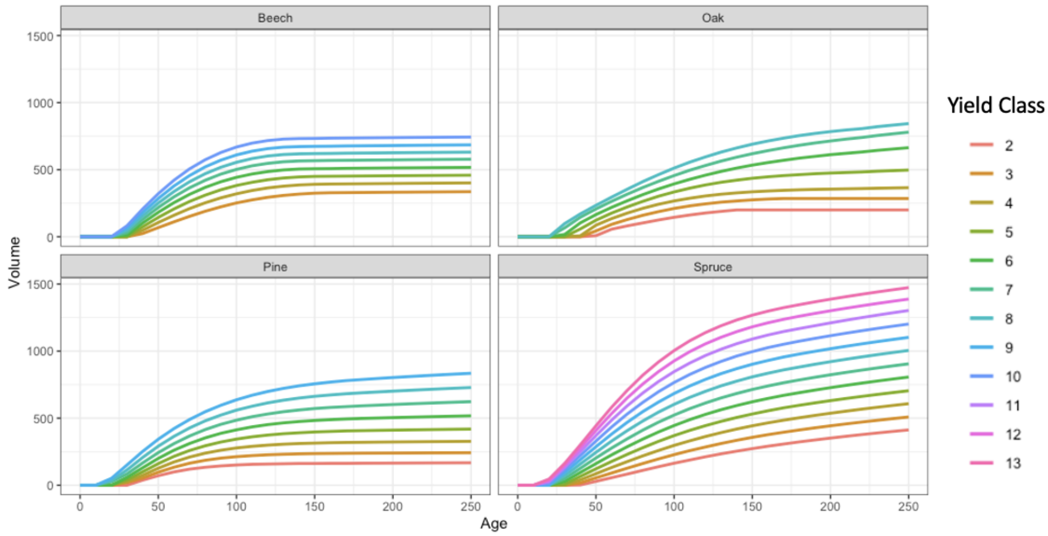

Figure 4.14: Volume $v_{a,s,y}$ (m^3/ha) function of age a for the different yield classes y for the four timber species s.

Diameter Estimates

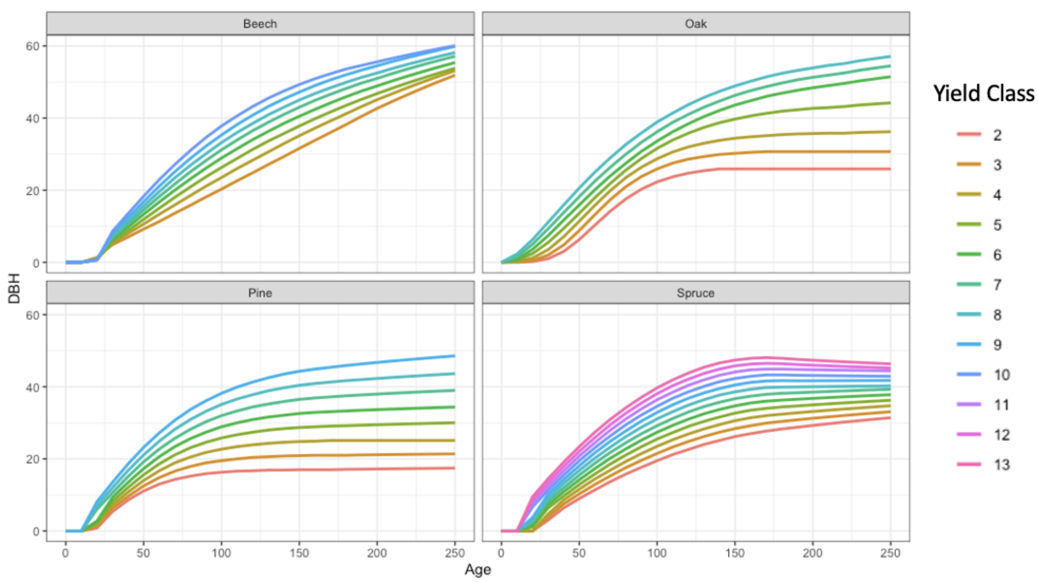

Figure 4.15: Diameter at Breast Height (DBH) (cm) function of age a for the different yield classes y for the four timber species s.

Price Estimates

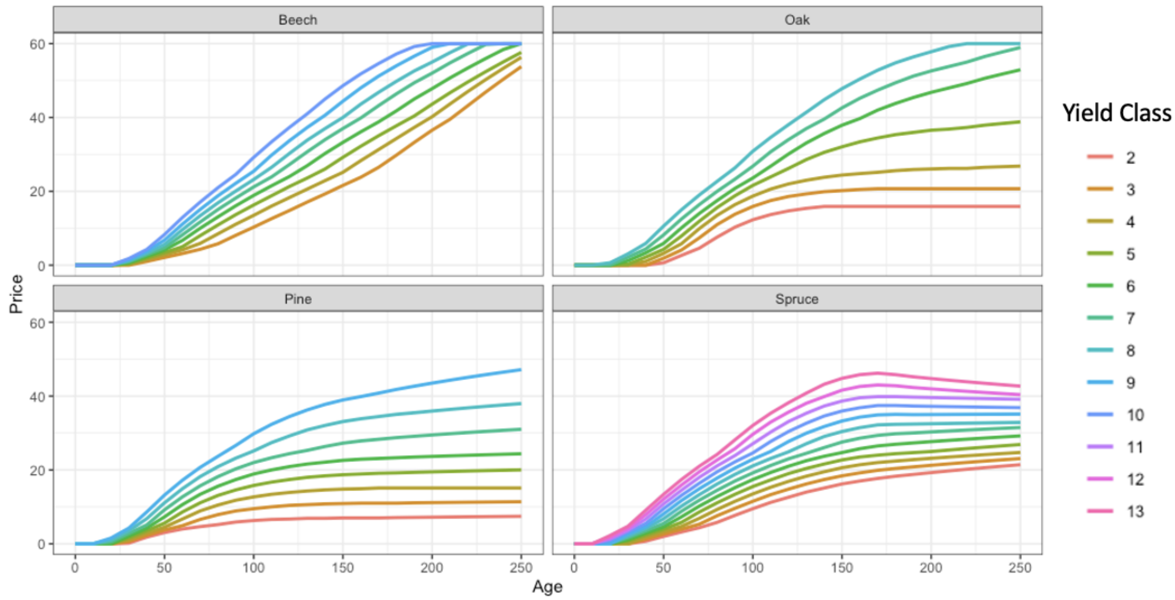

Figure 4.16: Price $p_{a,s,y}$ (€/m^3) function of age a for the different yield classes y for the four timber species s.

4.6.3 Discount rate

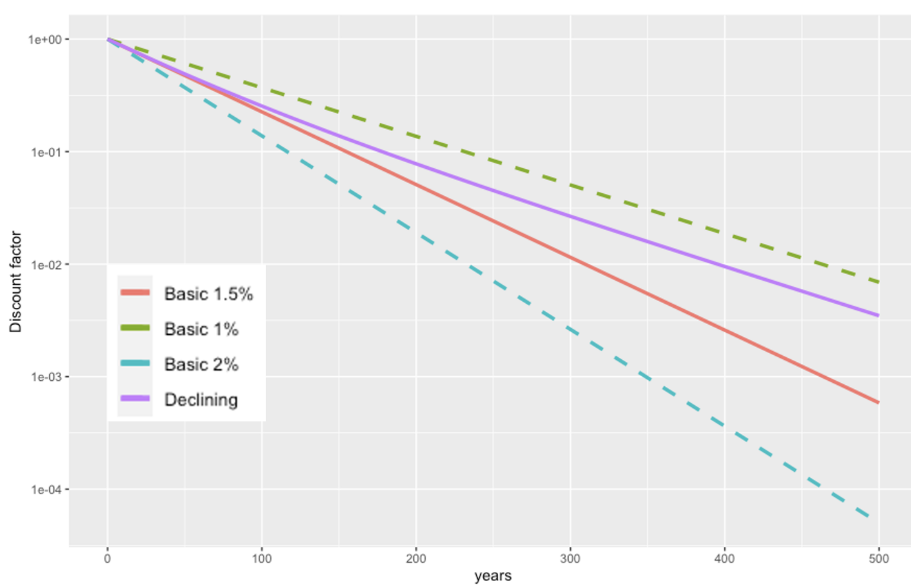

Figure 4.17: Discount factor for two different methods of discounting. Note that a log-scale is used.

4.6.4 Survival function and climate models

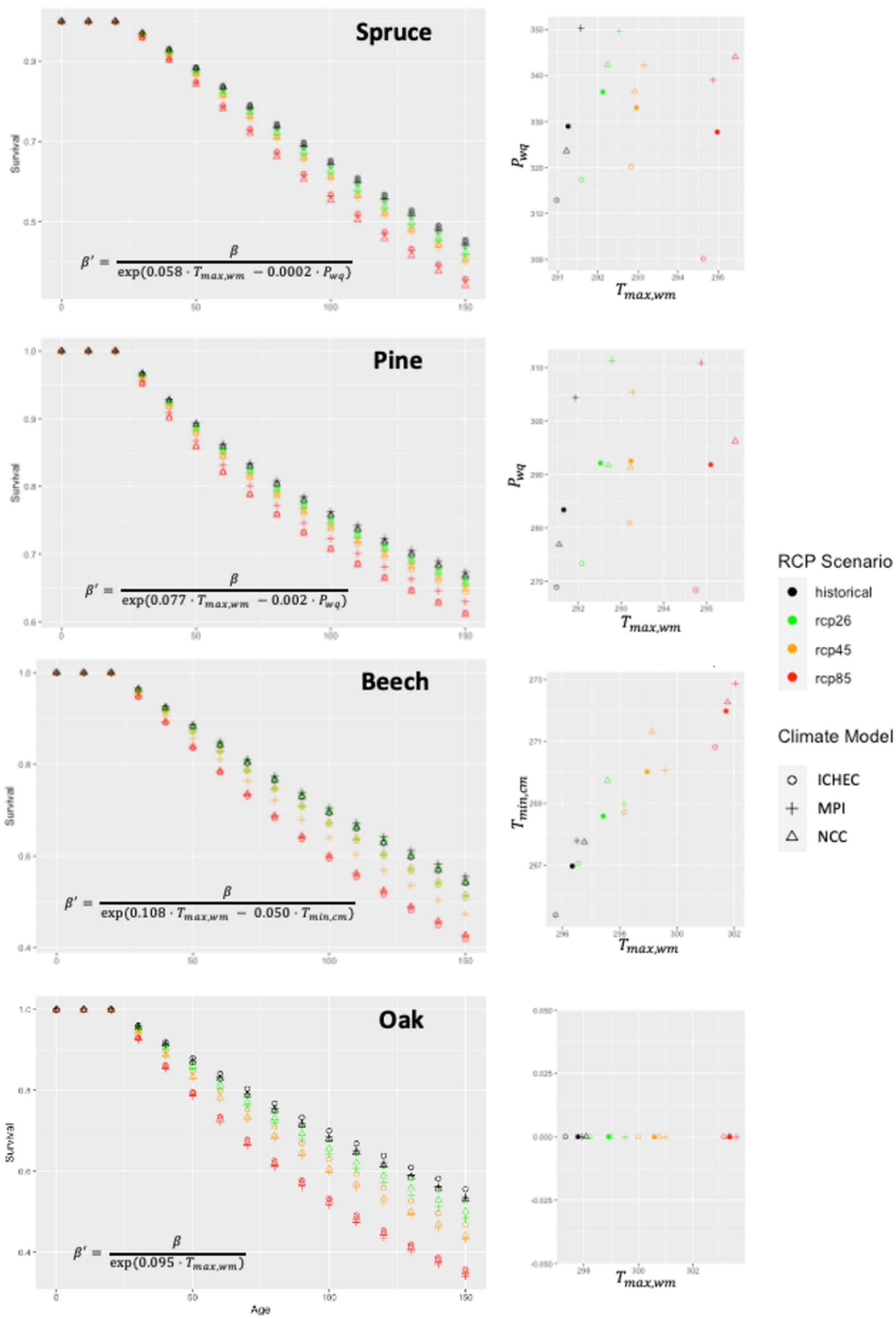

Figure 4.18: Left: Mean survival probability for ages from 0 to 150 years. Right: Mean climatic parameters playing a role in the survival function of each specie. Note that the means have been weighted with the area distribution of each species.

4.6.5 Cascade factors

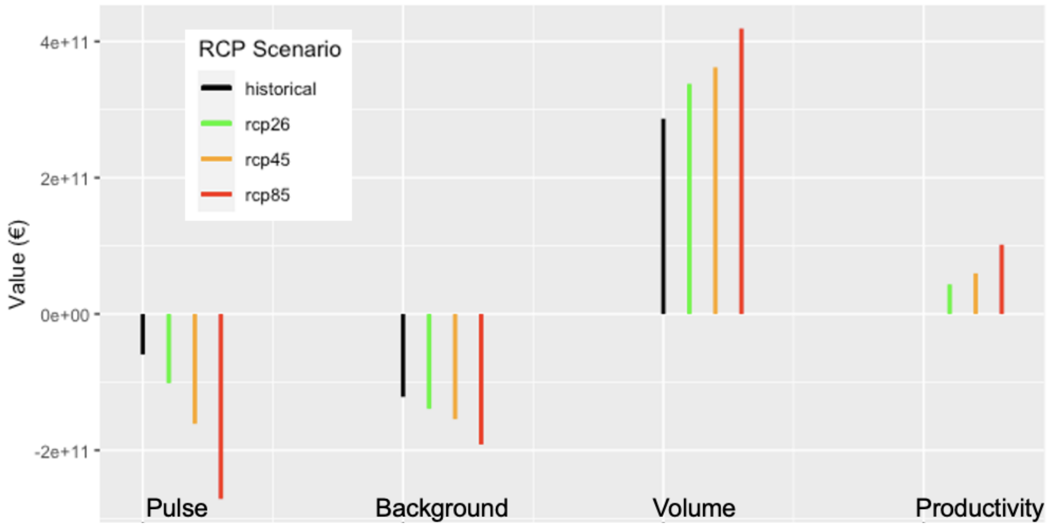

Figure 4.19: Separation of the four effects driving the Forest Value changes.

4.6.6 Distribution

Geographical distribution

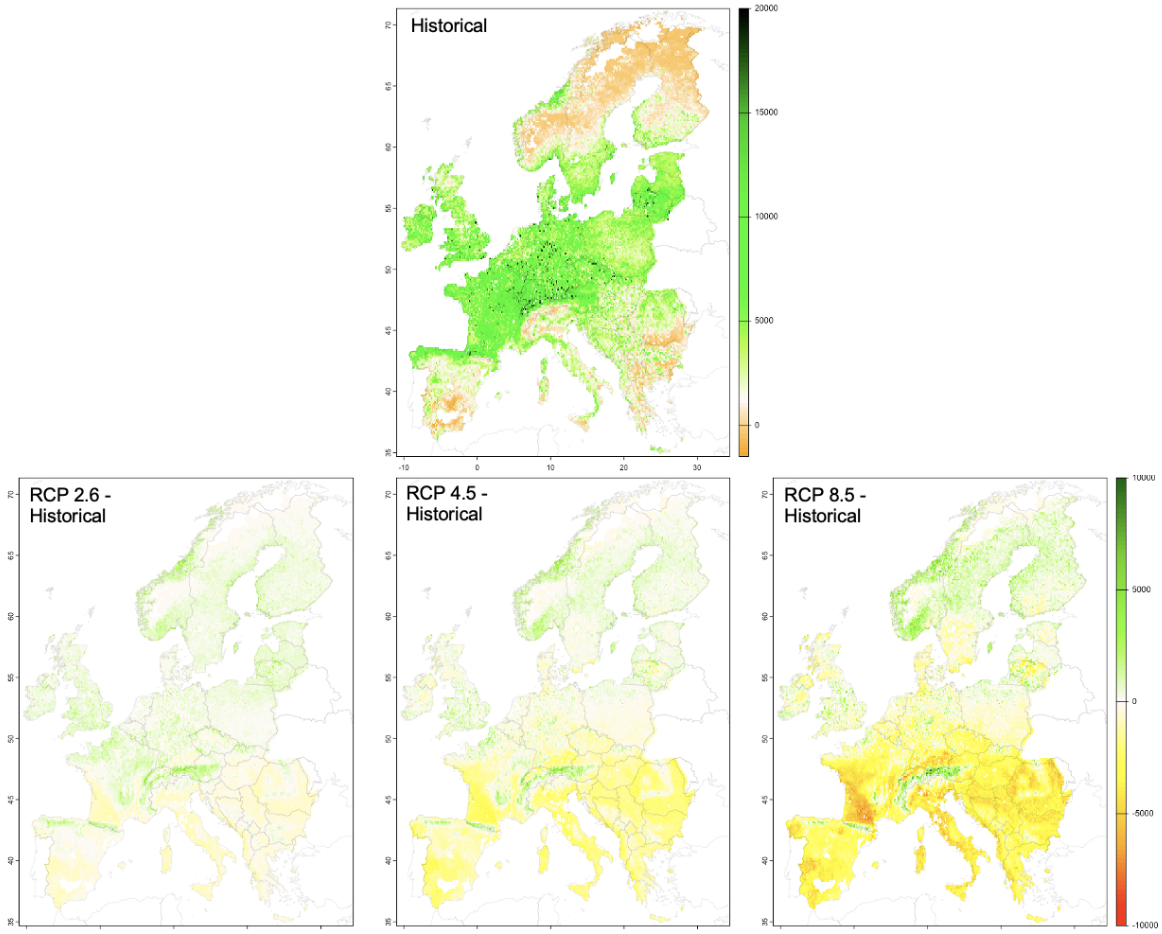

Figure 4.20: Geographical distribution of Forest Value (€/pixel) in Europe and difference with the historical scenario. Values are averaged over the three different climate models. ($\lambda \cdot I_{\mathcal{P}} = 0.2$ (historical), 0.31 (RCP 2.6), 0.46 (RCP 4.5) and 0.67 (RCP 8.5)).

Gini coefficient

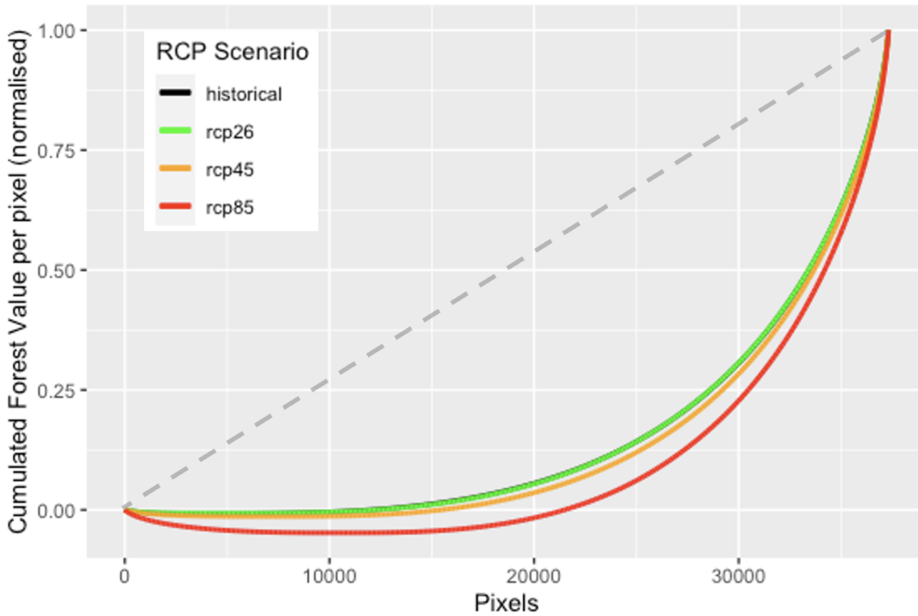

Figure 4.21: Cumulated distribution of the Forest Value among the 37,208 European pixels. This distribution is used to compute the Gini coefficient, that is twice the surface between the curve and the gray dashed line.

Conclusion

5.1 Main results, contributions and policy implications

European forests are vital ecosystems that provide numerous valuable services to the entire society, including timber production and carbon sequestration. However, forests face the growing challenge of natural hazards due to climate change, which pose significant threats to their resilience and the provision of their services. This thesis has aimed to examine the impacts of natural hazards on European forests, with a specific focus on the timber production as an essential ecosystem service. We have explored various natural hazards that affect European forests, their potential links and repercussions on the timber market.

This thesis has been organized into four consistent chapters along three complementary conceptual gradients (see figure 0.2 in Introduction): first, a literature review of multi-hazard risk in forest economics and management; second, a theoretical work investigating the resilience of a local timber market to large natural disturbances; third, the insertion of windstorms and pests outbreaks into the French Forest Sector Model; finally, the assessment of the market-based cost of natural hazards on the European forests under several climate scenarios. We present the main findings, contributions and policy implications of each chapter in the next section. Secondly, we attempt to look at the transversal perspectives of this thesis, especially in terms of climate change effects, trade and forest management.

5.1.1 Main results

An extensive review of the forest economics literature that includes multiple hazards was conducted. Our research endeavors involved the construction of a comprehensive database, which was based on the examination of a myriad of articles amounting to a total of 101 papers gathered. The variables that were scrutinized and taken into consideration, refer to both the article itself (including author(s), year, journal, keywords and country), as well as our own study's characteristics (such as disciplinary orientation, interaction consideration, type of hazard, and whether the article deals with hazard modeling or impact assessment). The results can be delineated as follows. Firstly, the most recurrent juxtapositions of hazards considered with each other were "Wind-Insects" in Europe and "Fire-Insects" in North America. Interestingly, insects and droughts were the only two hazards more often considered in the literature as dependent from other hazards than independent. Secondly, when we classified papers as either economics-oriented or ecology-oriented, we were able to underscore that the interactions that were rarely taken into consideration in the economics field, were frequently considered in the sphere of ecology, especially in the context of climate change. Lastly, we proposed a number of avenues for future research, particularly with respect to the plausible methods through which economics could potentially benefit from the incorporation of multiple interacting hazards and how these outcomes could also be advantageous for the progression of ecology and the comprehension of potential effects of forest management on the forests.

In the second chapter of our research, we assessed the stability of a timber bio-economic equilibrium. We tried to grasp the notion of resilience in the context of a local timber market facing natural hazards. To achieve this objective, we disturbed an equilibrium between the wood that is produced by a forest and the regional timber market with the occurrence of a natural hazard. Our key findings indicated that, on the basis of reasonable assumptions, there always existed a minimum forest inventory that must be reached to ensure the stability of the equilibrium of the forest inventory. It is important to note that above this minimum equilibrium inventory, the equilibrium was only locally stable and could lost if a sufficiently large disturbance occurred. However, the likelihood of such a severe disturbance seemed, in reality, relatively low. It is worth mentioning that this might change in the future as a result of climate change. Furthermore, many assumptions were made in this theoretical model, and were thus discussed. One of the main limit of this model was the absence of reliability with real data. This is why the next chapter, using the same methodology at the French scale, was a logical extension of this second chapter.

The third chapter integrated windstorms and bark beetles (interaction with windstorms) into a partial equilibrium timber model at the French scale in order to assess the resilience of the French forest sector to such natural disturbances. This led to several interesting results. First, we showed that it was possible to reproduce the classical effects of a windstorm at the level of the French forest sector. For example, we observed a price drop and a higher amount of timber sold right after the occurrence of a large storm. In the longer term, a higher price of timber was observed, especially in the most impacted regions. In total, this corresponded to a transfer of welfare from forest owners facing windstorm damage and from consumers to the forest owners that were preserved from the storm. Second, we have tried to establish the optimal level of harvest of dead timber biomass from the producer, sectoral and social perspectives. We found the various optimal supply elasticities to be quite different and thus not optimal for the global social surplus if the producers dictate their value. In this vein, we have also shown that the highest social cost linked to the occurrence of natural hazards is the social carbon cost, linked to lower sequestration in the forest in the long term. Third, we ran some Monte Carlo simulations to estimate the entire distribution of impacts of windstorms and insect outbreaks in the forest sector. Finally, we compared different scenarios of interactions between windstorms and insect outbreaks and we have shown that some French regions were susceptible to lose more from natural hazards than other. Moreover, we made a focus on the carbon balance of the French forest sector and showed that the French Low Carbon commitments to reach carbon neutrality in 2050 might be too ambitious.

The last contribution of this thesis aimed to estimate the European Forest Value and the associated potential cost of natural disturbances under various climate scenarios. Our findings revealed that the current cost of natural disturbances stands at approximately €180 billion. However, it is noteworthy that, under the most pessimistic climate scenario, this cost could potentially reach an alarming €500 billion. The effect of climate change on forest value was found to be predominantly driven by two antagonist forces. Firstly, there was a possibility of a gain in forest growth, particularly in Scandinavia and mountainous regions. Secondly, there was a higher level of damages in Europe due to more substantial background damages (largely driven by higher temperature) and more significant catastrophic events. Upon careful analysis, we anticipated the European Land Expected Value, primarily in Central Europe, to decrease significantly if no mitigation policies are implemented and the worst climatic path is followed.

5.1.2 Contributions

"Risk" is currently - and unfortunately - a thriving topic. Taking into account multiple hazards and multiple risks is nevertheless a rather recent approach. Only few work has been done on this topic before, but the scientific community is currently taking up the subject. For instance, we can cite the very fresh "X-Risks" meta-project of INRAE and the "Multi-Risk" working program in the even more recent PEPR (Priority Research Programs and Equipment) FORESTT. This thesis is a preliminary input to this research and has in fact led to several conceptual and methodological contributions to economic aspects.

Conceptual contributions

The first chapter has shown that there are some major holes in the existing literature. In fact, the segmentation between ecology and economics literature are major because ecology literature is focused on the description of the natural hazards whereas economics literature concentrates on the impact assessment. We have tried to show how both literature should in the future complement each other. It is indeed necessary to have more blended contributions, capitalizing on both disciplines to be able to tackle issues such as the future effects of climate change on the world forests. Only joined contributions can take an holistic point of view and arrive to optimal forest management in the long term.

The second chapter is a first attempt to link both market risk and production risk on a larger scale than the forest stand. Moreover, this model enables to grasp the notion of resilience that can only be hardly enclosed at a smaller scale by the essence of a stand dynamic (Knoke et al., 2022b). The advantage to work at a larger scale is to have the opportunity to get forest equilibria, that rarely exist at the stand scale.[20] Both aspects of the resilience are investigated: the time needed to reach back a previous equilibrium but also the robustness of a given equilibrium.

From a conceptual perspective, the third chapter of this thesis is a first try to incorporate a direct interaction between two hazards in a forest sector model, which had, to the best of our knowledge, never been done before. This link is for the moment relatively theoretical but still shows interesting effects, especially to properly estimate extreme effects. This chapter shows the importance of bringing together state-of-the-art ecological and economic concepts to be able to assess forest based public policies.

To our knowledge, most of the literature on climate change often focuses on growth estimates (Pretzsch et al., 2014) or on mortality estimates (Seidl et al., 2017). Moreover, the studies giving economic values to these appraisals are very scarce, especially at a scale as large as Europe. The interest of the fourth chapter is in fact to build a bridge between growth and mortality and to disentangle the net economic effect of climate change (productivity vs. mortality) at the European scale. This also enables us to evaluate the redistributive effects of climate change on the total value of European forests and establish who is expected to win and lose in the different scenarios.

Methodological contributions

The second chapter is a first shot to let aside the Faustmann model to assess the effect of natural disturbances in the literature. To do so, we have tried to take a larger spatial scale and to evaluate the resilience of a very simple timber market model to severe disturbances. From a methodological point of view, we believe that it could be interesting to continue on this path and use a larger scale than the stand scale to evaluate forest sector scale effects.

From a methodological point of view, the third chapter includes several steps forward. First, it is, to our knowledge, it is the first time that several windstorm scenarios, extracted from climate projected data, were included in a national forest sector model with Monte Carlo simulations. Windstorms have been the most important source of damages in the past, it is thus an interesting and necessary contribution. Second, we have created a simple way of including a direct link between two different natural hazards (windstorms and bark beetles). The linkage is for the moment rather elementary but should later be linked to other disturbances such as fires and drought. Last but not least, we needed to establish the elasticity of supply to the amount of dead wood, but the literature did not provide much econometrics analysis on the topic. Therefore, we have performed a sensitivity analysis of this parameter and evaluated the value that would maximize the producer, sectoral or social surpluses.

The fourth chapter has been the source of many new methodological contributions. To our knowledge, it is the first time that Net Primary Productivity (NPP) estimates are linked with classical yield tables to estimate forest growth dynamic. This link could be refined but enabled to make the forest growth dependent on climate scenarios and thus evaluate in

[20] Except in the case of irregular, continuous forest cover management.

economic terms the gains of forest productivity in the climate change context. It is also the first time that the value of the European forest is estimated, including the value of the current stock of timber. Moreover, we were the first to include simultaneously two different hazards, respectively corresponding to background level of hazard and catastrophic hazards at the European level. To do so, we have adapted the notion of catastrophic risk into large-scale "pulses" of mortality, where both intensity and frequency could be parametrised. Both variables are climate dependent, thanks to an interesting connection that we have made with IPCC (2021) data on the projected frequency and intensity of drought under future climate. Finally, we introduced the notion of Gini estimate in the context of total European Forest Value.

5.1.3 Public policy implications

The second and the third chapters show that timber market can be defective when a natural hazard occurs. Indeed, the estimation of the optimal elasticity of supply to dead timber quantity seems to be quite different if the producer or the global sector surplus is optimized. This shows that if a large scale event occurs, a social planner should incentivize the forest owners to sell more timber. The second market default is that in the long term, the level of timber can become too low due to natural hazard occurrence so that the forest management is not sustainable anymore. This effect does not seem to exist in the third chapter because the elasticities to increasing and diminishing inventories are not the same, but if it was not the case, such effects could also occur. This behavior could be problematic, because the forest owners have to follow some long term management plans, so that this kind of behaviors should be avoided. The problem is then that there could be a clear lack of primary products on the market for a relative long time and impact even more the final consumers.

The third and fourth chapters have also exhibited some interesting facts on the potential demand for insurance against natural hazard. Indeed, the third chapter has shown that there are large redistributive effects between the different forest owners in France after a windstorm on the territory. This suggests that a mutual fund could be created to cover the losses of the most impacted forest owners. The others also benefit in the long term of the windstorm occurrence because their timber will be sold at a higher price. Moreover, the fourth chapter has shown that the mean level of losses due to natural hazards should strongly increase in the future, even if the total value of their forest does not necessarily decrease a lot, especially if the climate scenario are not very optimistic. This could boost the demand for natural hazards insurance. However, it seems that the most important driver of the mortality will be catastrophic event that are not necessarily always easy to insure. In the end, the states should thus probably remain last-resort insurer for the forest owners, at least to ensure that the forest are replanted to keep a certain level of carbon stock in the European forests in the long term.

Our work has shown that there is a clear need to re-evaluate the different forest based policies to assess their robustness in front of natural disturbances occurrences. Even if the estimates are consistent with the median or mean level of damage, it is necessary to take a larger safe margin if really large events can happen and even more because such events seem to be more probable in the context of climate change with stronger interactions between natural hazards. For instance, our results show that leading no ambitious climate policies to mitigate the effect of climate change is risky at the European level. This means that even if the mean effect on the European Forest Value does not clearly decrease, the spread of the possibilities increases very fast when the climate becomes warmer. If policymakers are risk averse, they should lead policies to mitigate these risks. In the long term, the social planner should opt for more robust strategies and probably create a European target instead of simply a country scale analysis.

Finally, there is a clear need for "crisis-management guidelines" in both short and long terms. A French "sanitary crisis management guide" was published a few years ago (Brunier et al., 2020). This guide triec to build some common strategies to monitor and follow future sanitary crises from the feedback of several past crises. It could be especially interesting to extend this guide with forest economics notions and policies. Such toolkit should for example be based on the intensity of the observed damages, the spatial extent of the crisis, the possibility to store the timber, etc. Such elements could include insights from the different actors of the forest sector and lead to better strategies in the case of crisis occurring, when urgency and fast decisions are often the order of the day.

5.2 Discussion and perspectives for future research

5.2.1 Climate change effects

Though climate change is solely explicitly addressed in the last chapter, its presence can be felt throughout the entirety of this thesis like an underlying flow shaping the perspectives. In our opinion, climate change should be discussed with respect to three topics: first, understand how global warming could impact the interactions between the different natural disturbances. Second, dig more into the question of the various uncertainties related to climate change estimates. Finally, we suggest to leave for a moment the supply side to deepen the demand side in the context of climate change.

Multi-hazard and climate change

As expounded upon in the Introduction and underscored throughout this dissertation, multi-hazard risk has the potential to become particularly salient in the face of climate change. A substantial body of literature has demonstrated that the European hazard regime is projected to undergo a major shift due to climate change (Lindner et al., 2010; Seidl and Rammer, 2017; Senf et al., 2021). At the dawn of this millennium, Dale et al. (2001) had already suggested several possible interactions between different natural hazards in the context of climate change. For instance, windstorms, fire, insects, disease interact with each other.

The temperate oceanic European forests, out of which France are part, are expected to be more exposed to extreme events, especially storms, floods and droughts (Lindner et al., 2010). Interestingly, French forests face a large climate gradient between Northern and Southern regions, lowland and mountains. We could look at the precise effect of climate change in terms of growth and mortality with FFSM. FFSM has firstly mainly been built for policy evaluation. Including natural disturbances in FFSM facilitates the assessment of policy interventions aimed at mitigating or responding to disturbances. It enables policymakers to evaluate the effectiveness of different policies in reducing the impacts of disturbances, improving forest management practices, and promoting sustainable development of the forest sector. Incorporating natural disturbances into FFSM provides a more comprehensive and realistic representation of the dynamics in the forest sector, supporting informed decision-making and planning for sustainable and resilient forest management. To evaluate appropriately the effect of climate change on the French forest sector, it could be really interesting to use real climatic trajectories. We could create real scenarios for different risks:

- Windstorms: use PRIMAVERA dataset (Lockwood et al., 2022) with the exact same methodology as implemented in this thesis, once the extension to future climate for all the different climate models is available.
- Fire: use the same methodology as Riviere et al. (2022).

- Insects: damages should be linked to windstorms occurrence and yearly fire activity, as mentioned in the perspectives of the third chapter. Insects outbreaks would not directly depend on the climate but depend on variables that are related to climate (such as fire activity).

Deal with uncertainty

An important issue that should also be tackled in the context of climate change is uncertainty. This thesis has taken the prism of risk, defined by Knight (1921) as a well-defined distribution of damages, meaning that each possible state of the world is associated to a given probability. This is however not always the case, especially in the context of climate change, where the future climate scenario is very uncertain. This means that it does not seem reasonably possible to give a probability to the different climate scenarios, highly depending on future decisions that cannot be forecast (Loisel et al., 2022).

We have for example used three complementary climate scenarios in the third chapter and opted to present each time the results for the tree scenarios. In fact, climate models are a second layer of uncertainty on top of the first: even for a given RCP scenario, there is uncertainty on the climate model that is used. Concerning this layer of uncertainty, we have simply averaged the results over the different climate models. However, if management decisions must be taken, these strategies are generally not optimal. Different methods could be used. For example, Knoke et al. (2022a) opted for the same probability for the different scenarios. Another possibility is for example to lead policies that optimize the worst-case scenario. Whatever the method that is chosen, uncertainty in the context of climate change is especially important and should probably be investigated in the future.

This question of uncertainty modelling is fundamental to understand how the forest owners could adapt their management to climate change. It could thus be very beneficial to include this in FFSM. For the moment, the forest owners act as risk-averse decision makers to choose the type of forest they replant at each period. To do this, they go for the scenario with the highest expected value. To include uncertainty, it would be possible to change this optimal choice for a given scenario by the choice that brings the highest value in the worst scenario, thus ensuring a certain level of income, whatever the future scenario might be.

The demand side

The timber market could also be disturbed by climate change, because of its mitigation potential. In fact, the demand for timber products may increase with climate change due to several factors. First, climate change adaptation and mitigation strategies often involve carbon sequestration into long-leaving timber products, the goal being to compensate residual greenhouse gas (GHG) emissions. For example, investing in infrastructure projects such as sustainable housing is a commonly suggested policy, enabling to create a net carbon sink from the housing sector (Churkina et al., 2020). Second, it is possible to substitute some carbon intensive materials for renewable timber products, the goal here is to avoid GHG emissions (Geng et al., 2017; Leskinen et al., 2018). Timber is thus a versatile and renewable resource that can be used in construction, providing an alternative to carbon-intensive materials like concrete and steel. This is also the case when using timber based products instead of plastics. The demand for timber in packaging, infrastructure, energy production may rise as efforts to adapt to and mitigate the impacts of climate change increase. In the same vein, as societies transition to cleaner and more sustainable energy sources, there is an increasing demand for biomass energy. Timber can be used as a renewable source of biomass for heat and power generation, particularly in regions with abundant forest resources. Climate change may drive the expansion of renewable energy sectors, further increasing the demand for timber products (Cowie et al., 2021).

This thesis has not grasped the issue of the evolution of the demand side due to carbon commitments. The arguments mentioned above suggest to take this issue into account. In fact, as explained in the third chapter, forests play a crucial role in carbon sequestration, helping to mitigate climate change by absorbing carbon dioxide from the atmosphere. Forest carbon offsets have gained importance as a mechanism to compensate for GHG emissions in various sectors. The demand for carbon offsets in the forest increases but the demand for timber products and harvest is simultaneously increasing. There is currently a large scientific controversy on the intensity at which the forest should be exploited and for which purpose (Leskinen et al., 2018). Biomass energy use is for example very much discussed in the scientific community (Favero et al., 2020). Natural disturbances could play a major role in the assessment of the different strategies so that it seems fully relevant to include all the different effects (natural hazards and changing demand) into an economic framework to ensure the resilience of the different commitments.

It could be interesting to re-estimate the European costs of natural hazards from a more market oriented point of view, with increasing timber demand. Buongiorno (2015) developed a partial equilibrium model at the world level. Buongiorno (2021) for example used this model to estimate some long-terms effects of the demand shock induced by the COVID-19 pandemic. This model could thus be coupled with our damages estimations and be used to estimate simultaneously the effect of increased demand for timber products, the change of timber productivity at the European level and finally the market impact of natural disturbances, thanks to the partial equilibrium characterization.

5.2.2 Trade

Long-term coordination of timber production and consumption can be difficult to predict (Müller et al., 2004), especially in a context of climate change where both timber production and consumption are expected to be modified. The uncertainty linked to climatic events thus makes these prospective exercises even more difficult than they are. One the one side, regional forest productivity is expected to change due to climate change. As mentioned in the fourth chapter, there will be regions that will benefit from climate change, such as Northern Europe and mountainous areas. The demand should be relatively high in every countries in order to achieve their climate commitments. We could thus expect to observe much larger exports from these regions, which will produce more timber due to an increased forest productivity, to other regions, losing out from global warming, especially Southern Europe and at a smaller extent, Central Europe. These regions will have to deal with more complicated trade offs: stock more in their forests, face more natural hazards and produce more timber products. The opportunity to significantly increase trade routes between loosing and gaining areas in order to meet climate objectives in each country seems particularly relevant. International economics literature has shown that distance and transport costs are strong barriers to trade (Samuelson, 1952; Tinbergen, 1962) and important determinants of the location of production systems (Thünen, 1851). We could thus look at the evolution of timber trade roads maximizing the climate gains from timber trade in the future, taking into account the future productivity of European forests. Álvarez Miranda et al. (2019)for example developed mathematical programming tools to optimize the road network in Portugal from net present value, carbon sequestration and land erosion point of view. Such optimization framework could be extended to the continental scale to optimize the trade between the different regions under uncertain future climate.

Moreover, this thesis has also shown that there should be heterogeneous spatial effects of natural disturbances over Europe. Indeed, the occurrence of large disturbances, such as storms, at a relatively local (regional/country) scale, have direct and delayed impacts on timber supply and prices. In this case, we have shown that two effects will take place one after the other. Firstly, there will be a decrease in prices due to the outflow of wood from one region to the rest of France, and then in the long term, an exactly opposite trade will occur because of the scarcity of the resource in the most impacted regions. This means that the occurrence of a large disturbance can deeply impact the trade between different regions or the national timber market. This has for example been the case of Germany that has become a net exporter of timber due to the recent bark beetle outbreak even if it was importing a large share of its timber products in the past (WRI, 2020). We can expect that they will need to import even more timber in the future to meet their demand in primary products. In the case of the French bark beetles outbreak (2019-2021), the French state has for example subsidized the transport of dead spruce from the East to the Landes de Gascogne, where they were facing a lack of timber due to 2009 Klaus storm. This policy was beneficial to Eastern forest owners that could sell their timber but also to the Landes de Gascogne forest-based industry that could exploit the timber and ultimately to the rest of society by avoiding to loose too much carbon in dead, unexploited timber. It is certain that in both cases – i.e. climate induced trade and natural disturbance induced trade – public policies will need to be implemented in order to ensure a sustainable forest management in each region and to enable optimal resource exchanges at geographical large scale.

5.2.3 Manage the forest resource

This thesis has been written as a contribution to "knowledge models". This corresponds to models focusing on the description of the phenomenon and trying to understand better how they impact the different systems. This kind of models is necessary to have a clear comprehension of the different issues and get some scenarios consistent with observations. Most of the perspectives of this conclusion are devoted to improve these knowledge models. But the next step is to move to "decision models". These models aim to give insights on the policies that should be carried to achieve certain objectives. Concretely, this means expressing some constraints that the model should respect. Such constraints can be expressed as carbon storage constraints or as social surplus optimizations. Policies are simply the outputs of the decisions models. As discussed in the Introduction, decision models are important at different scales: at the stand scale (to guide the forest owner), at the regional scale (to coordinate the actions of the different forest owners), at the macro-regional scale (to carry socially optimal policies).

Forest management questions are often studied at the stand scale, because it is the scale at which the decisions should be taken. In the case of multi-hazard, Courbage et al. (2017) showed some interesting optimal strategies in the case of two interacting risks, whose level of prevention expenditures can be managed separately. In this case, they showed that correlations in the likelihoods of both risks modified the optimal strategy to adopt, independently from the sign of the correlation. This means that the prevention strategies of the forest owners very probably depend on the interactions between hazards, which are expected to increase in the future. For the moment, the literature has not tackled these questions but theoretical models should quickly take up this challenge. Once this is done, it should be possible to include these notions into large scale models such as FFSM and get the potential long-term and large scale effects of such forest owners' behaviors.

The methods used in this thesis got around the scale problem thanks to the creation of an artificial "pixel" scale, at which we supposed that the management was happening and that pixels where independent from each other. It could however be more complicated in some situations. For example, Busby and Albers (2010) have used game theory tools to study how the different forest owners have to behave with respect to fire prevention management: it is in the interest of everyone that the forest owner acts to diminish the probability and intensity of fire, but she is always better off not to do anything. It is a classical dilemma problem, which has been solved thanks to state regulation. We could however imagine the same kind of problems for the management of bark beetle outbreaks: if a forest owner extracts fast enough damaged trees, it is possible to stop the outbreak, this is however very costly because everyone has to monitor very precisely her own stand. These kinds of problems show that the different forest owners are not independent from each other so that there is a need for coordination. These coordination effects could also play an important role for biodiversity management, which is also strongly not linear.

To dig further into the forest management question at a wider scale, it would also be possible to include foresight to the forest owners in FFSM. Forest managers take into account the future damages in the management module, when they decide which forest to replant after the harvest. They can thus directly take natural hazards into account. Because forest management is a long time process, a long time period is necessary to observe the effects of a change in management. This is why instead of focusing on the 2011-2050 period, it would probably be necessary to go until 2100. In the same vein, it would be interesting to include a management module in the fourth chapter. It is indeed irrational to keep a timber specie that is less productive than another one. Moreover, as proven by Reed (1984), it is irrational to have the same rotation period in risk-free and risky contexts. Creating a management module at such a large scale could be complicated and very demanding in computational power but could be particularly useful to assess the potential directions that the European forests could take in the future. Moreover, this kind of modelisation, focusing on the supply side is very important for the downstream of the forest sector: they need to know what the forest will look like in several decades to be able to adapt their production process to the future supply. This is precisely the object of long-term coordination of timber production and consumption.

From a purely theoretical point of view, it is possible to opt for two different types of policies, if they respect hard or soft constraints. Soft constraints are often preferred by economists because they lead to smoother problems. In this last case, a social cost is computed to internalise negative externalities of the system and the goal is to optimize a welfare function. This kind of modelisation is for example partially used in FFSM to optimize each year the quantity of timber that is harvested. This is also the idea behind the social cost of carbon. To go in this direction we could test different public policies in FFSM and opt for the one optimizing the expected social welfare for a given distribution of natural hazards. On the other hand, hard constraints correspond to thresholds that should never be exceeded. It is the basis of viability or resilience theories. These theories acknowledge that there exists some states of the world that should not occur. This is the case in many climate policies where a temperature threshold is set as a hard constraint. Such policies should thus be robust to natural hazards occurrences. We have, for example, shown that without any change of forest management, the French Low carbon strategy could be too ambitious once natural hazards are taken into account. Once knowledge models are developed enough, digging further into the potential policies to ensure the resilience of large scale strategies seems a very promising avenue for future research.

5.2.4 Last words

Interdisciplinary PhD

This thesis is at the crossroads of many literatures. Rooted in economics, this thesis kept going back and forth between classical forest economics (notably using Faustmann model, production tables, etc.) and natural resource economics (notably in the second chapter). Indeed, I remember often asking myself the question: "What is a storm, anyway?". And there are a number of possible answers to this question: a micro-economist would probably reply that it is a probability of losing what is on a forest stand, and therefore of losing a long-period accumulated capital. A macro-economist would say that it is a distribution of damage leading to market volatility. A "meso-economist" will surely declare it is a complex spatial process that leads to heterogeneities among the different regions. Heterogeneities that an econometrician would certainly be happy to study in order to calibrate a model. An international economist would tell us that such crises can impact international trade and lead to a reversal of the usual trade routes.

So, there are many possible angles from which to approach the question "What is a storm, anyway?" in economics, and each of these answers is valid and provides a vision that complements the other answers. However, it soon becomes clear that these various perspectives are missing something. All these models need input data on the concrete effect of a storm on forest cover, i.e. they need to draw on notions of disturbance ecology. An ecologist would reply that windstorm is a recurrent ecological process to which forests adapt, for example by modifying their height/diameter ratio, and that it likely favors other hazards such as bark beetles.

To get a comprehensive answer, as we have shown in the third and fourth chapters of this thesis, it is therefore necessary to use simultaneously notions of ecology and economics, in order to deduce a wide range of possible effects. It is for this reason that this thesis was intended to be interdisciplinary. This explains, for example, why it was essential to involve publications in economics, ecology and forest management in order to study the question of multiple hazards in the literature review. This interdisciplinarity was the source of great richness and opens the door to numerous contributions through complementarities between the different approaches.

Afterwards?

This doctoral dissertation was funded by the French Ministry of Agriculture. This 3-year work is at the same time considered as a first position as civil servant and as a useful training for the rest of my career (called "complementary training through research"). This doctoral education has taught me several values. The most important is the prominence of the discussion in the academic world. This has several forms: discussion of the method and results in a paper, discussion with peers during conferences, etc. More generally, the spirit of the discussion is to plead an idea to the rest of the scientific community. Non-academic people often believe that discussion is simply some dithering and undecision from the scientists, but it is indeed the precise source of the academic trust: it is necessary to confront any result and method to the community to check their reliance. Each scientific production should be discussed and the limits always exhibited. I sincerely hope that I will not forget this notion and that I will be able to transfer it to the administration and more importantly to policymakers.

It also showed me that it can be interesting, for the common good, to get scientists to think before society takes decisions. Unfortunately, decisions are generally taken in a hurry, in a context of crisis that demands rapid responses, so there is generally no time for discussion. In this sense, it seems necessary for research to be a pioneer in the subjects that will need to be tackled urgently in the future. This certainly involves the orientation of research by the major research institutes – a subject that goes way beyond me – but it also involves the choice of questions in which researchers take interests. We should certainly be asking ourselves whether the question is a first building block for issues that could arise tomorrow. Climate change clearly falls into this category but this is also the case for biodiversity, which has largely been left aside for the moment.

Moreover, there has been a recent trend in the public interest for forest and natural hazards in France for a few years, especially since the important 2022 fire season. First of all, I am convinced that it is great that people take the forest for a crucial ecosystem in our society.

Since the end of the national forestry fund (Fonds Forestier National), which enabled forest replanting after the Second World War, few large-scale public forest policies have come to light. The most recent of these was the French government's economic recovery plan (France 2030), which included a specific allocation for forests. The role of forests in mitigating climate change and achieving France's carbon-neutral targets has been widely discussed in this thesis. However, these objectives can only be achieved through massive adaptation of French forests to climate change. My future position should enable me to continue to work with these notions of adaptation and mitigation in the forest sector, but also in the agricultural sector. There are huge challenges ahead of us, and while some avenues already exist, many others have yet to be explored.

Bibliography - Conclusion

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French summary

Contexte

La forêt européenne est une ressource majeure, représentant 227 millions d'hectares[21] (FOREST EUROPE, 2020), soit 35% de la superficie totale de l'Europe qui stocke 35 milliards de m^3 de bois (FOREST EUROPE, 2020) et accumule plus de 10 milliards de tonnes de carbone dans la biomasse vivante (Mauser, 2022). Les forêts européennes sont essentiellement des forêts tempérées en Europe occidentale et centrale (46% de la surface forestière totale), des forêts boréales en Scandinavie (40%), des forêts alpines dans les régions montagneuses (10%) et des forêts méditerranéennes (5%) dans les pays du sud, bordant la mer Méditerranée (European Environment Agency, 2017). Ces forêts diverses sont la source d'un grand nombre de services écosystémiques[22]: des services d'approvisionnement (nourriture, eau, bois, etc), de services de régulation (inondations, climat, qualité de l'eau), mais aussi de services culturels (loisirs, récréation, esthétique des paysages ou objectifs spirituels), et de services de soutien (formation des sols, cycle des nutriments) (Millennium Ecosystem Assessment, 2005). Tous ces services contribuent de manière significative au bien-être de l'humanité. En ce sens, nous pouvons considérer la forêt comme un système socio-écologique (Renaud et al., 2010) composé de deux sous-systèmes. Le premier sous-système écologique est la forêt en elle-même et sa dynamique écologique. Le second sous-système est socio-économique : la forêt est ici considérée comme une ressource, apportant des services écosystémiques à la société.

Les forêts constituent donc une ressource naturelle importante à l'échelle européenne, mais elles sont également confrontées à plusieurs perturbations naturelles telles que les tempêtes, les incendies de forêt, les invasions d'insectes, le gel et les tempêtes de neige, les agents pathogènes, l'abroutissement, etc. Ces perturbations naturelles font partie intégrante de la dynamique des écosystèmes[23] mais leurs effets restent importants. Patacca et al. (2023) ont tenté d'appréhender de manière exhaustive l'effet des perturbations naturelles qui ont frappé l'Europe entre 1950 et 2019. Leur travail est basé sur plus de 170 000 enregistrements provenant de 600 sources différentes. Les dommages moyens au cours de ces décennies sont estimés à 62,1 Mm^3/an. Au cours de la période 1950-2000, Schelhaas et al. (2003) ont estimé que les volumes endommagés représentaient plus de 8% de la récolte annuelle totale. Les tempêtes ont causé 46% des dommages totaux (24 Mm^3/an) sur l'ensemble de la période, mais deux décennies furent exceptionelles (Patacca et al., 2023) : les années 1990 avec 47,8 Mm^3/an (dues à Vivan et Wiebke en 1990 et à Lothar et Martin en 1999) et les années 2000 avec 38,8 Mm^3/an (dues à Gudrun en 2005, Kyrill en 2007 et Klaus en 2009). Les incendies de forêt sont également une perturbation importante dans les forêts européennes, représentant 24% des dommages totaux, contre 17% pour les scolytes (Patacca et al., 2023).

Le niveau des dommages dus aux perturbations naturelles a été élevé par le passé, mais il est actuellement en forte augmentation. L'impact des incendies a par exemple considérablement augmenté entre 1950 et 2019 dans toute l'Europe (Patacca et al., 2023), avec notamment une forte augmentation dans les années 1970. Le régime d'incendies est aussi caractérisé par des années spécifiques de fortes perturbations causées par des conditions météorologiques particulièrement propices. Enfin, les scolytes ne représentent que 1/6 des dommages totaux sur l'ensemble de la période, mais au cours des années 2010, les dommages causés par les scolytes sont devenus comparables aux dommages causés par les tempêtes de vent (23 Mm^3/an). Globalement, le niveau des perturbations est passé de 42,6 Mm^3/an pour la période 1970-2000 à

[21] Cela équivaut à 4 fois le territoire français métropolitain.

[22] Les services écosystémiques correspondent aux bénéfices, services et ressources que les êtres humains tirent des écosystèmes, par exemple des forêts.

[23] En fait, chaque écosystème forestier a évolué sous un régime de perturbations donné, de sorte que les perturbations ont façonné les forêts sur de longues périodes. Certaines espèces ont, par exemple, évolué pour devenir résistantes au feu, comme le chêne-liège (*Quercus suber*) dans la région méditerranéenne sujette aux incendies (Buma and Wessman, 2012).

78,5 Mm^3/an pour la période 2000-2019, soit quasiment un doublement (Patacca et al., 2023). Une partie de cette augmentation peut s'expliquer par l'accroissement du stock de bois européen total au cours de la période : s'il y a plus de bois dans la forêt, on peut s'attendre à ce que les dommages soient plus importants. Mais même en termes de part du stock total de bois sur pied (c'est-à-dire le volume endommagé divisé par le volume total de bois sur pied dans la forêt), les dommages ne représentaient que 0,23%/an dans la seconde moitié du XX$^{\text{ème}}$ siècle, alors qu'ils ont représenté 0,27%/an au début du XXI$^{\text{ème}}$ siècle (soit une augmentation de 17%). Les tendances de ces données suggèrent que le régime des perturbations est en train de changer (Seidl and Rammer, 2017). Senf et al. (2021) ont observé une dérive similaire à partir de données de télédétection, mentionnant une augmentation significative de la mortalité de la canopée en Europe. Il est avancé que si cette augmentation se maintient sur le long terme, les forêts européennes pourraient cesser de vieillir, ce qui modifierait profondément leur démographie et compromettrait même la possibilité de stocker davantage de carbone dans le puits forestier. Cette tendance a également été observée aux États-Unis par Cohen et al. (2016) au cours de la période 1985-2012. Ils ont mentionné que la récolte de bois[24] était la perturbation historique la plus importante de la couverture forestière, mais que c'est maintenant devenu le déclin de la forêt en raison de l'augmentation des perturbations naturelles, ce qui a d'ailleurs conduit à une diminution de l'intensité de la récolte. Seidl et al. (2011) ont déclaré qu'il y avait deux principaux moteurs de cette tendance à l'augmentation des risques naturels : le changement de la gestion forestière, qui explique notamment le changement des dommages causés par les tempêtes et le changement climatique, qui explique la majeure partie de l'augmentation des dommages causés par les incendies. Il est intéressant de noter que l'augmentation des dégâts causés par les scolytes semble être une association des deux effets. Seidl and Rammer (2017) s'attend d'ailleurs à ce que les dommages causés par les interactions entre aléas augmentent dix fois plus vite dans le contexte du changement climatique que les aléas historiques basiques.

Il y a quelques années, un commentaire paru dans Nature (AghaKouchak et al., 2018), intitulé "Comment les risques naturels se répercutent-ils en cascade pour provoquer des catastrophes ? Tracer des connexions entre ouragans, incendies de forêt, le changement climatique et d'autres risques", a soulevé la question de l'interaction entre les risques naturels. Leur analyse se concentre sur un glissement de terrain mortel causé par de fortes pluies survenant un mois après un important incendie de forêt en Californie. Ce dernier avait causé la perte de la couverture forestière qui protégeait auparavant cette pente contre l'érosion. En fait, ce type d'interaction entre les risques a déjà été théorisé en écologie forestière. Buma (2015) montre qu'en dépit du fait que nous en savons désormais suffisamment sur chaque risque naturel, la prise en compte de plusieurs risques en interaction peut entraîner au moins quatre changements par rapport à la prise en compte d'un seul risque : une plus grande étendue (augmentation de l'intensité ou de la gravité du risque) ; un changement dans la probabilité des risques ; une diminution de la résilience de l'écosystème ; un changement global de l'ensemble du régime de risque pour l'écosystème. Ces effets émergents induits par la prise en compte d'aléas multiples plutôt que par le traitement d'aléas uniques et indépendants, résonnent avec la définition du risque composé par l'IPCC (2022) : "découle de l'interaction des dangers, qui peuvent être caractérisés par des événements extrêmes uniques ou de multiples événements coïncidents ou séquentiels qui interagissent avec les systèmes ou les secteurs exposés". En termes plus concrets, Dale et al. (2001) ont donné un premier aperçu des différents aléas qui affectent les forêts tempérées, expliquant comment ils peuvent interagir dans le contexte du changement climatique. Les épidémies de scolytes sont un exemple typique de risques composés et méritent

[24]La littérature sur l'écologie considère souvent la récolte comme une perturbation de l'écosystème induite par l'homme. Du point de vue de notre économie forestière centrée sur l'homme, la récolte est considérée comme une gestion normale et seuls les risques naturels sont considérés comme des perturbations de la gestion forestière.

donc d'être explicitées.

Le scolyte est un type de petit coléoptère qui infeste et se nourrit de l'écorce interne des arbres. Il appartient à la famille des *Scolytidae*. Nous nous intéresserons ici à *Ips Typographus*, inféodé à l'épicéa commun (*Picea Abies*). Les scolytes ont évolué avec leur arbre hôte et ciblent généralement les arbres affaiblis ou stressés, creusant des galeries à travers l'écorce et perturbant le système de transport des nutriments et de l'eau de l'arbre. La destruction prématurée des arbres stressés peut même être bénéfique pour le reste du peuplement forestier, car elle élimine les arbres qui gaspillent la ressource hydrique. Ceci est le rôle des scolytes au niveau endémique. Dans certaines conditions, les grandes épidémies de scolytes peuvent entraîner la mortalité des arbres sains et avoir un impact écologique et économique important sur les forêts. Par exemple, si le niveau de défense d'un peuplement entier d'épicéas est réduit, les scolytes peuvent se développer de manière exponentielle.[25] Les ravageurs ont tendance à se multiplier jusqu'à atteindre un niveau épidémique de population et sont alors capables de tuer même les arbres sains dont les défenses sont d'autant plus affaiblies que le nombre d'attaques augmente (Berryman et al., 1984). La transition entre les deux niveaux de population est un cas typique d'interaction multirisque. La plupart du temps, les épidémies de scolytes sont causées par une tempête qui produit une grande quantité de chablis (Wermelinger et al., 1999), dont les défenses sont réduites à néant. Si ce bois mort n'est pas récolté rapidement, les scolytes ont l'occasion de faire une première génération sur ce bois sans défense. En cas de sécheresse sévère, la vitalité des arbres est également diminuée, et il est donc plus facile pour les scolytes de submerger la défense de ces arbres (Wermelinger, 2004). Les tempêtes de vent et les sécheresses ont donc un effet direct sur les dégâts causés par les scolytes. Enfin, les épidémies de scolytes peuvent également avoir un effet sur un autre risque naturel : les incendies de forêt. Dupuy et al. (2015) ont montré que l'effet des scolytes sur le régime des incendies dépend du stade d'infestation du peuplement. Par exemple, il y a une augmentation de l'aléa incendie après une épidémie de scolytes au stade "rouge" (c'est-à-dire lorsque l'arbre est sec mais a encore ses aiguilles) et un faible effet antagoniste au stade "gris" (lorsque l'arbre a perdu ses aiguilles), en raison d'une quantité de combustible réduite dans la couronne. Les épidémies de scolytes constituent donc un cas intéressant de risque dont l'occurrence est liée à plusieurs autres aléas naturels.

Enfin, pour clore le contexte de cette thèse, il faut observer que la production de bois est un service écosystémique important qui dépend fortement du prix du bois. Prestemon and Holmes (2000) ont démontré que les perturbations naturelles ont deux effets sur le marché. À court terme, elles peuvent entraîner un excès de bois mort sur le marché, tandis qu'à long terme, elles réduisent la quantité de bois disponible dans la forêt. Dans le cas d'une tempête, Gardiner et al. (2010) ont noté que les dommages peuvent entraîner une augmentation inattendue et soudaine de l'offre de bois, ce qui affecte les prix du bois et, par conséquent, le gain financier des producteurs et des consommateurs. Les conséquences de la tempête Gudrun en 2005, qui a entraîné une réduction de 63% et 86% des prix habituels des grumes d'épicéa et de pin, dans le sud et le centre de la Suède, par rapport à l'année précédente, en sont une illustration notable. Le lien entre les aléas naturels et le risque du marché est donc très fort.

Dans cette thèse, le terme "aléas multiples" fait référence à plusieurs aléas naturels ayant un impact simultané sur le même élément exposé (Gallina et al., 2016), c'est-à-dire que plusieurs aléas naturels ont en même temps un impact sur les forêts. C'est par exemple le cas si une forêt est soumise à des tempêtes, des incendies, des invasions d'insectes ou si une forêt est confrontée à plusieurs régimes possibles d'aléas, tels que des aléas normaux et des aléas extrêmes. D'autre part, le terme "risques multiples" signifie que plusieurs types de risques sont pris en compte en même temps, à savoir le risque de production et le risque de marché

[25] Les écologistes appellent ce comportement une stratégie r, ce qui signifie que le développement de la population est basé sur un taux de croissance élevé et qu'une petite partie des descendants atteint l'âge adulte.

(Gallina et al., 2016). Enfin, mentionnons qu'il est possible de considérer simultanément les multi-risques et les multi-aléas, c'est d'ailleurs ce qui sera fait dans le troisième chapitre de cette thèse.

Présentation des chapitres de thèse

Trois gradients conceptuels complémentaires sont mis en exergue dans cette thèse. Les trois derniers chapitres peuvent être placés sur ces gradients conceptuels (voir la figure 6.1).[26]

Premièrement, un gradient de type de risques : les premier et dernier chapitres de cette thèse ne considèrent qu'un risque de production, alors que les deuxième et troisième chapitres se concentrent à la fois sur les risques de production et de marché. Cela a de fortes implications en termes d'indicateurs possibles à étudier. Si nous nous concentrons sur la seule production, le paramètre clé est la valeur de la forêt, alors que si l'ensemble du marché est pris en compte, nous pouvons nous concentrer sur d'autres paramètres tels que le bien-être social, la dynamique des prix, etc.

Deuxièmement, un gradient de types d'aléas inclus dans les modèles est crucial. Des dommages très génériques aux modèles multirisques spatialement explicites, un large gradient de types de risques peut être traité. Le premier chapitre vise d'ailleurs à examiner l'étendue de ce gradient conceptuel dans la littérature existante. Le deuxième chapitre traite d'un aléa générique. Le quatrième chapitre tente de distinguer l'effet des aléas naturels de base de celui des aléas naturels catastrophiques, tandis que le troisième chapitre se concentre sur la modélisation de deux aléas spatialement explicites interagissant entre eux.

Enfin, un gradient d'échelles spatiales est également une dimension clé. Un large éventail d'échelles est pertinent pour étudier l'effet des perturbations naturelles sur la forêt : de l'échelle du peuplement, où les gestionnaires prennent des décisions forestières, à l'échelle mondiale, où les flux commerciaux ont lieu. Le deuxième chapitre s'appuie sur une étude régionale pour estimer les effets du marché. Le troisième chapitre comprend trois couches spatiales : la couche de gestion forestière (pixels de 8 km), une couche régionale (avec 12 couches sur la France) et une couche pays.[27] Le quatrième chapitre comprend deux couches spatiales différentes : l'échelle du pixel (pixels de 15 km) pour la gestion forestière et l'effet des aléas, et l'échelle européenne, à laquelle les résultats sont agrégés pour obtenir certains résultats.

Chapitre 1

Le contexte a montré l'importance de prendre en compte des aléas naturels multiples pour évaluer correctement l'impact potentiel des aléas naturels sur le secteur forestier. Une première piste de recherche consiste donc à savoir comment les différents aléas naturels sont pris en compte dans la littérature d'économie forestière : les aléas multiples sont-ils déjà pris en compte dans la littérature ? Si oui, avec quelles méthodes ?

À notre connaissance, Yousefpour et al. (2012) est le premier article de revue axé sur la question des risques et des incertitudes dans l'économie forestière. En effet, leur travail, sous le prisme du changement climatique, a étudié la littérature sur les adaptations des décisions des propriétaires forestiers. Quelques années plus tard, Montagné-Huck and Brunette (2018)

[26] Veuillez noter que chaque chapitre se concentre sur un niveau différent de chaque gradient. Il serait présomptueux de croire qu'un modèle unique pourrait répondre à toutes les questions, de sorte que chaque chapitre a nécessité certains compromis (qui doivent être mentionnés et motivés) pour pouvoir répondre à des questions très différentes.

[27] En réalité, il y a même une quatrième couche spatiale car le modèle inclut le reste du monde pour échanger certains produits. Cependant, il s'agit d'une couche totalement exogène.

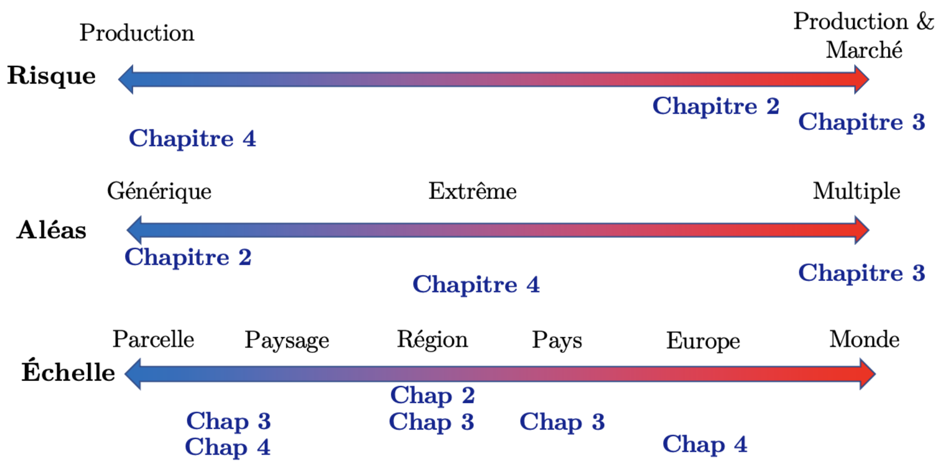

Figure 6.1: Graphique illustrant les 3 gradients conceptuels permettant de contextualiser chaque chapitre.

ont passé en revue plus de trois cent articles portant sur des risques naturels uniques (incendie de forêt ou ravageur ou pathogène ou tempête ou broutage ou neige/glace).

À notre connaissance, il n'existe pas de contribution passant en revue la littérature sur l'économie forestière traitant de risques naturels multiples. C'est pourquoi, pour répondre aux questions de recherche précédentes, nous avons procédé à une analyse systématique de la littérature sur l'économie forestière en tenant compte de plusieurs risques. De plus, nous avons élargi la littérature aux articles traitant plus généralement de la gestion optimale des forêts dans l'hypothèse de plusieurs aléas.

Nos efforts de recherche ont impliqué la construction d'une base de données complète et bien organisée, basée sur l'examen d'un grand nombre d'articles, dont nous en avons retenu 101. Les variables examinées et prises en considération, relatives à l'article lui-même (auteur(s), année, revue, mots-clés et pays), ainsi qu'aux caractéristiques de l'étude (orientation disciplinaire, considération de l'interaction, type de danger, et si l'article traite de la modélisation des dangers ou de l'évaluation de l'impact) ont été documentées. Les résultats peuvent être décrits comme suit. Tout d'abord, les juxtapositions les plus récurrentes d'aléas naturels examinés sont "Insectes-Tempête" en Europe et des "Insectes-Feu" en Amérique du Nord. Il est intéressant de noter que les insectes et les sécheresses sont les deux seuls aléas qui, dans la littérature, sont plus souvent considérés comme dépendants d'autres aléas qu'indépendants. Deuxièmement, lorsque nous avons classé les articles selon qu'ils étaient orientés vers l'économie ou vers l'écologie, nous avons pu souligner que les interactions qui sont rarement prises en considération dans le domaine de l'économie le sont fréquemment dans la sphère de l'écologie, en particulier dans le contexte du changement climatique. Enfin, nous avons proposé un certain nombre de pistes de recherche pour l'avenir, notamment en ce qui concerne les méthodes plausibles par lesquelles l'économie pourrait potentiellement bénéficier de l'incorporation d'aléas multiples en interaction et comment ces résultats pourraient également être avantageux pour la progression de l'écologie.

Chapitre 2

Les objectifs de ce chapitre sont doubles : tout d'abord, il s'agit d'une tentative de réconciliation du risque de marché avec le risque de production. Rakotoarison and Loisel (2017) ont fait un premier pas intéressant dans cette direction en incluant des effets de marché d'une tempête sur la valeur de Faustmann. Cependant, ce choix d'échelle ne semble pas très pertinent pour prendre des effets de marché en compte, qui opèrent à une échelle bien plus large. C'est pourquoi l'échelle régionale semble plus cohérente pour estimer correctement ces effets. Par ailleurs, nous tentons d'évaluer la résilience de ce marché vis-à-vis de perturbations extrêmes. En effet, bien que la théorie de la résilience soit plus exploitée en écologie, nous souhaitons étendre cette notion au système socio-écologique forestier constitué de la forêt et du marché du bois qui lui est associé. Knoke et al. (2022) ont récemment étudié la résilience de la valeur d'un peuplement forestier, exprimée grâce au temps nécessaire pour revenir à la valeur économique que le peuplement avait avant l'occurrence de l'aléa naturel (Perrings, 1998). Nous aimerions étendre ce travail à une échelle géographique plus large, afin d'inclure l'effet des perturbations naturelles sur le marché, mais aussi d'envisager une autre définition possible de la résilience, à savoir le passage potentiel du marché du bois forestier à un état indésirable (défini comme non durable).

Pour ce faire, nous avons développé un modèle macro-stylisé qui établit un équilibre entre l'inventaire et la croissance des forêts, ainsi qu'un marché du bois, face aux risques naturels. Notre approche consiste à relier un modèle simple de croissance de la forêt et un modèle de marché, qui rend compte de la gestion de la forêt par les propriétaires, pour cela nous avons fait recours à un modèle de déplacement d'équilibre. Cela nous permet d'étudier la manière dont le marché réagit aux perturbations naturelles. Ces modèles de déplacement d'équilibre sont couramment utilisés pour expliquer les fluctuations à court terme des marchés du bois causées par des aléas naturels, comme la baisse des prix du bois à la suite de l'ouragan Hugo en Floride en 1989 (Prestemon and Holmes, 2000).

Nous avons pu déterminer l'inventaire critique nécessaire pour assurer la durabilité à long terme de l'inventaire forestier et maintenir sa stabilité en présence de perturbations naturelles stochastiques. Nous avons également montré que, quel que soit le volume de bois dans la forêt, il peut exister une perturbation suffisamment importante pour entraîner l'épuisement du stock de bois. De plus, nous essayons d'estimer le temps de retour admissible pour les perturbations afin d'assurer la résilience de la dynamique forestière. En outre, nous montrons que l'augmentation de la moyenne ou de l'écart-type des perturbations a un effet négatif sur la résilience de la forêt, malgré le fait que le changement climatique devrait augmenter ces deux facteurs : il y aura plus d'événements et des événements plus intenses.

Le cadre du deuxième chapitre de cette thèse est assez simple et ne s'applique qu'à des situations particulières (voir les limites du modèle dans la discussion du document). Cependant, il correspond assez bien au modèle régional de FFSM. En effet, les équations permettant de dériver la demande et l'offre à partir des prix et des stocks sont relativement similaires. Une limite importante de ce modèle est néanmoins qu'il est abstrait et théorique. En revanche, FFSM est très concret car il représente la dynamique du secteur forestier français. C'est donc un moyen d'étendre logiquement ce travail à un cas particulier, appliqué et plus sophistiqué.

Chapitre 3

Les forêts métropolitaines françaises s'étendent sur plus de 17 millions d'hectares, avec un volume de stock atteignant 2,8 milliards de mètres cubes, selon le rapport IGN (2022). Ces forêts constituent actuellement un puits de carbone net, stockant environ 1,3 milliard de tonnes de carbone. En outre, la croissance de cette ressource précieuse a été significative, la surface forestière française ayant augmenté de plus de 20% depuis 1985, et le stock sur pied ayant augmenté d'environ 50%. C'est pourquoi la forêt française est au cœur de la stratégie nationale à faible intensité de carbone (Ministère de la transition écologique et solidaire, 2020), qui vise des émissions nettes nulles en 2050. Pour atteindre cet objectif, les forêts françaises devraient stocker 35 $MtCO_2$/an et les produits du bois 20 $MtCO_2$/an, ce qui représente plus des deux tiers des différents puits de carbone évoqués dans la stratégie bas carbone française. Les forêts françaises sont cependant confrontées à de nombreuses perturbations de grande ampleur : les tempêtes Martin et Lothar en décembre 1999, la tempête Klaus en 2009 et, plus récemment, une épidémie de scolytes de l'épicéa dans l'est de la France. Ces graves perturbations ont un impact global sur le secteur forestier français et pourraient nous empêcher de respecter nos engagements en matière de climat. Un modèle bio-économique tel que FFSM est nécessaire pour évaluer les impacts des aléas naturels sur le secteur forestier français car il capture simultanément la dynamique écologique de la forêt mais aussi la dynamique du marché et de la gestion forestière, qui impacte profondément la dynamique de la ressource.

Ce chapitre vise donc plusieurs objectifs. Tout d'abord, d'un point de vue méthodologique, il s'agit d'une première tentative d'inclure le régime de l'aléa tempête dans un modèle du secteur forestier, la tempête étant l'aléa naturel le plus important au niveau français. Deuxièmement, nous essayons de créer un cadre conceptuel pour relier les épidémies d'insectes aux tempêtes de vent dans un modèle d'équilibre partiel. Troisièmement, nous discutons la résilience de la stratégie française bas carbone en évaluant l'effet potentiel du stockage du carbone dans l'inventaire forestier en cas d'aléas naturels de grande ampleur.

Capitalisant sur l'existence d'un modèle de feux de forêt dans FFSM (Riviere et al., 2022), nous avons inclus deux autres aléas naturels spatialement explicites dans le modèle : les tempêtes de vent et les scolytes. La dynamique temporelle des tempêtes de vent est modélisée à partir d'un ensemble récent de tempêtes estimé à partir d'un vaste ensemble de modèles climatiques dans le cadre d'un climat historique (Lockwood et al., 2022). Les dommages spatiaux causés par les tempêtes sont basés sur le modèle mécaniste ForestGALES (Hale et al., 2015; Chen et al., 2018), déduisant la part des dommages sur chaque pixel FFSM à partir de la vitesse du vent local, du diamètre et du type de forêt. En ce qui concerne la dynamique du scolyte, nous avons utilisé un processus de Markov simple avec deux états : la population endémique, sans aucun dommage, et la population épidémique, où des dommages se produisent. La probabilité de passer d'une population endémique à une population épidémique est déterminée par les dommages causés par les tempêtes de vent locales (Schelhaas et al., 2002; Roux et al., 2020).

Nos résultats sont triples : premièrement, nous décrivons les différents effets d'une tempête sur le secteur français à l'échelle nationale. Notre modèle confirme qu'il existe un transfert de bien-être économique entre les producteurs et les consommateurs, toujours confrontés à une perte de bien-être due à une augmentation des prix. De plus, il existe un transfert de bien-être depuis les producteurs des régions touchées par la tempête vers ceux des régions qui en sont préservées. Ceci pourrait motiver la création d'un fonds mutualisé entre les différentes régions françaises pour redistribuer ces effets. Deuxièmement, en ce qui concerne la redistribution entre les secteurs en amont et en aval, il semble que les décisions des propriétaires forestiers pourraient être prises au détriment du reste de la société, car il est dans leur intérêt de vendre moins de bois que ce qui est socialement optimal pendant la crise. Deuxièmement, nous avons montré que le principal effet économique des tempêtes correspond à une perte de bien-être social due à une perte nette de stockage de carbone dans la forêt massive. Enfin, les simulations de Monte Carlo montrent que la distribution des dommages causés par les tempêtes est très volatile entre les différents scénarios et que les aléas en interaction pourraient compromettre le potentiel de stockage du carbone dans les forêts françaises.

Les chapitres précédents se sont concentrés sur deux notions : la résilience et le secteur forestier. Mais ces deux chapitres étaient orientés vers les effets du marché. Dans ce dernier chapitre, nous allons changer de point de vue et nous concentrer sur la partie amont du secteur : la valeur économique de la forêt, vue du point de vue du propriétaire forestier. Cela signifie que nous nous concentrerons essentiellement sur la valeur que le propriétaire forestier peut extraire de la forêt. Nous avons choisi de nous limiter au risque de production car nous souhaitons étendre l'échelle spatiale de l'étude au continent européen. Le coût pour cet élargissement est donc d'abandonner la notion de risque de marché et de modéliser les risques naturels de manière très concise, mais cohérente au niveau européen. L'originalité de ce chapitre est de n'utiliser qu'un aléa générique mais d'inclure deux types d'aléas : un aléa de fond et un aléa catastrophique. De plus, ce chapitre inclut les effets du changement climatique simultanément sur la productivité et l'intensité des aléas, pour la première fois à une telle échelle.

Chapitre 4

Les forêts européennes sont très diverses et peuvent être divisées en au moins trois biomes différents : les forêts tempérées, boréales et méditerranéennes, avec différents régimes de risques naturels, l'échelle européenne est néanmoins assez pertinente du point de vue de l'économie forestière. Tout d'abord, le nombre d'espèces principales de bois d'œuvre est relativement faible : quatre espèces (épicéa, pin, chêne et hêtre) représentent 61% de la forêt totale. Mais l'échelle européenne est aussi une échelle géographique appropriée pour appréhender le marché commun européen et les politiques environnementales.

À notre connaissance, Schelhaas et al. (2003) ont produit la première étude sur les perturbations passées en Europe, essayant de saisir le niveau des perturbations naturelles à partir de sources publiées au cours de la seconde moitié du XX$^{\text{ème}}$ siècle. Une mise à jour de cette étude (Patacca et al., 2023) s'est également concentrée sur l'évolution des aléas naturels au cours de la période 1950-2019. De telles analyses des dommages causés par les perturbations naturelles sont essentielles pour la recherche, mais aussi pour éclairer la prise de décision publique, en particulier dans le contexte du changement climatique. Cependant, Hanewinkel et al. (2011) ont expliqué qu'il y a quatre étapes pour inclure l'effet du changement climatique dans la gestion forestière. Les études sur les risques naturels s'arrêtent à la deuxième étape : elles analysent le cadre et évaluent la probabilité du risque. Cependant, elles ne vont pas plus loin en estimant le coût des dégâts et les gains attendus de différentes actions.

Une question intéressante est donc d'évaluer le coût des risques naturels à l'échelle européenne et d'évaluer l'effet potentiel du changement climatique sur ce coût. D'une part, cette évaluation pourrait inciter les décideurs à adapter les forêts européennes au changement climatique, mais d'un point de vue méthodologique, elle permettrait également d'évaluer différentes stratégies pour atténuer les émissions de gaz à effet de serre.

Hanewinkel et al. (2013) ont évalué le coût du changement climatique en estimant le changement de la productivité économique des forêts dans le cas où la niche écologique de chaque espèce change en raison de l'évolution des paramètres climatiques. Cette estimation a le mérite de répondre aux critiques formulées dans les deux études susmentionnées. Il est intéressant de noter que cette estimation repose sur un modèle qui se situe à la frontière entre l'analyse des processus et l'analyse statistique. Toujours en ce qui concerne l'évaluation des coûts du changement climatique, Callahan and Mankin (2023) ont récemment estimé, grâce à des simulations de Monte Carlo, les pertes économiques mondiales en lien avec l'accroissement de la probabilité des événements El Niño.

Dans le chapitre précédent de cette thèse, nous avons essayé de modéliser spatialement et explicitement deux aléas naturels. Dans ce dernier chapitre, nous modifions notre perspective sur les aléas multiples. Au lieu de simuler explicitement la dynamique des risques naturels et d'essayer d'obtenir des effets émergents à partir des interactions entre les aléas, nous nous appuyons sur une analyse purement statistique des risques naturels. Ceci est rendu possible par la récente contribution de Brandl et al. (2020), qui ont estimé des fonctions de survie pour six espèces de bois différentes à l'échelle européenne. Ces fonctions de survie permettent de calculer la valeur des forêts européennes dans un cadre "avec et sans": un scénario incluant des aléas naturels est comparé à un scénario (hypothétique) où aucun aléa ne se produit (Zhai and Ning, 2022). En outre, de récentes vagues de mortalité extrême ont été observées en

Europe, comme dans les années 1990, au cours desquelles plusieurs tempêtes dramatiques s'y sont produites (Patacca et al., 2023), et à la fin des années 2010, où une grave crise des scolytes de l'épicéa s'est déclarée en raison d'un niveau élevé de sécheresse. Nous avons donc tâché d'inclure aussi ce type de crises catastrophiques dans notre modèle.

Pour estimer les coûts de ces deux régimes d'aléas, la forêt européenne est divisée en un grand nombre de pixels. Sur chaque pixel, nous simulons la dynamique de quatre espèces de bois économiquement productives (épicéa commun, pin sylvestre, chêne et hêtre commun). Notre modèle est un modèle matriciel qui répartit la surface forestière sur chaque pixel pour une espèce donnée en différentes classes d'âge. Pour estimer la dynamique du volume des différents pixels, nous utilisons des tables de production standardisées et nous attribuons à chaque pixel une productivité donnée grâce à des estimations de la productivité primaire nette (PPN), qui dépendent des scénarios climatiques. Nous comparons la valeur de la forêt européenne avec trois modèles climatiques différents et quatre scénarios climatiques (historique, RCP 2.6, RCP 4.5 et RCP 8.5) afin d'obtenir un gradient de résultats.

Plusieurs conclusions peuvent être tirées de ce travail. Premièrement, nous montrons que le coût des aléas naturels s'élèvent actuellement à environ 180 G€. Deuxièmement, nous confirmons que le coût total des perturbations naturelles à l'échelle européenne devrait augmenter dans le contexte du changement climatique. Troisièmement, nous montrons que ce résultat cache plusieurs effets qui jouent dans des directions opposées et qui ont tendance à stabiliser la valeur totale de la forêt. L'effet net doit être séparé en un gain de productivité et des pertes plus importantes dues à un niveau plus élevé de risque de fond et à des impulsions de mortalité catastrophiques plus intenses et plus fréquentes. Quatrièmement, il convient de mentionner une forte hétérogénéité spatiale au niveau européen. On s'attend à une augmentation importante de la valeur de la forêt dans certaines régions (notamment en Scandinavie et dans les Alpes), où de grandes forêts font face à un niveau de mortalité relativement faible et à un gain de productivité élevé, tandis que d'autres régions (méditerranéenne et Europe centrale) perdront beaucoup de valeur en raison d'une forte réduction du taux de survie des forêts et une augmentation de leur croissance plus modérée.

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Le vent se lève !... Il faut tenter de vivre!
L'air immense ouvre et referme mon livre,
La vague en poudre ose jaillir des rocs !
Envolez-vous, pages tout éblouies !

Paul Valéry, Le Cimetière marin

An economic approach of multiple risks in temperate forests

Forests are exposed to a multitude of hazards such as wildfire, windstorm, drought, etc. The likelihood, magnitude, and interplay of these hazards are augmented by climate change. This dissertation endeavors to quantify the repercussions of these hazards in accordance with three theoretical gradients: their spatial expanse, the encompassed risks (production vs. market), and the type of natural disturbances considered.

This thesis is divided in four chapters. Firstly, a review of the forest economics literature exposed research avenues in the field. The second segment involved examining the resilience of an autarkic timber market in the face of catastrophic hazards from various perspectives. This model was subsequently applied to the context of the French forest sector by incorporating storms and beetle outbreaks in an explicit spatial manner. Lastly, the potential cost of climate change based on timber production on a European scale was estimated for diverse hazard scenarios.

Une approche économique des risques multiples en forêt tempérée

La forêt subit de nombreux aléas : feu, tempête, sécheresse, etc. Le changement climatique augmente leur probabilité, leur intensité et leurs interactions. Cette thèse cherche à mesurer l'impact de ces aléas selon trois gradients conceptuels : l'échelle spatiale, les risques inclus (production vs. marché) et les aléas naturels considérés.

Ce travail s'articule autour de quatre parties. Tout d'abord, une revue de la littérature d'économie forestière a montré quelles étaient les pistes de recherche au sein de la discipline. Dans un second temps, la résilience d'un marché autarcique de bois face à des aléas d'ampleur catastrophique a été étudiée selon plusieurs aspects. Puis, ce modèle a été étendu au contexte du secteur forestier français en incluant des tempêtes et des pullulations de scolytes de façon spatialement explicite. Enfin, le coût potentiel du changement climatique basé sur la production de bois à l'échelle européenne a été estimé pour divers scénarios d'aléas.