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Earth, wind and fire: A multi-hazard risk review for natural disturbances in forests

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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 observed that timber production is often the only ecosystem service considered. 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 propose to refine current economic models by improving the modelling of natural hazards in order to find better-adapted silvicultural strategies in the future.

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)

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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). 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.). Indeed, natural hazards are responsible for financial losses since the value of felled timber is lower due to loss of marketability, a reduction in future stand value, the supplementary cost of forest restoration and the loss of hunting or other income (Birot and Gollier, 2001). In addition, natural hazards pose a serious risk to the carbon stored in forests and, to a lesser extent, to the sequestration capacity of forests, representing potential economic losses (Thürig et al., 2005). Impacts on biodiversity and recreation are also common (Thom and Seidl, 2016). 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 to be $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 importance 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., 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 gathered 340 economics articles dealing with natural forest disturbances and how 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 and is quite broad. However, 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 hazards as an emergent and non-linear phenomenon, separate from the study of individual hazards (Buma, 2015; Agne et al., 2018).

In this context, Buma (2015) defines two types of hazard interactions based on their temporal effects: (1) 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 larger because of the stress caused by drought, reducing the defence capacities of the trees; (2) 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. 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 answer to 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 at stake in literature to assess multi-natural hazard risks? What are the relevant perspectives for future research?

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. Finally, we propose new paths for considering multi-hazard risk. 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). The existing literature mainly focuses on timber production and neglects the other ecosystem services. In addition, when several risks are considered, most of the economic studies consider them as being independent. We also identify relevant methodologies for considering interactions between natural hazards in future studies.

The rest of the paper is organised as follows. Section 2 describes the material and methods. Section 3 presents the main results. Section 4 is devoted to a discussion of the results, and a conclusion is provided in Section 5.

2 Material and methods

2.1 Concepts and definitions

A natural disturbance may be broken down into three main parts (IPCC, 2012):

- Hazard likelihood: the return rate of the hazard at a certain intensity level. For example, in the case of windstorm, it represents the annual probability of the wind load to exceed a certain threshold.
- Exposure: the value of the ecosystem subject to the hazard, considering all ecosystem services.
- Vulnerability: the predisposition of the ecosystem to be damaged by the hazard. For example, these predispositions encompass the height, species and age of the forest stand.

The direct impact, or severity, of a disturbance is the intersection between exposure and vulnerability at a given hazard intensity. It can, for example, be expressed as the volume of wood damaged and its economic consequences. In the case of the Lothar and Martin storms in December 1999, Peyron et al. (2009) showed that 175 Mm^3 of wood were destroyed, with estimated financial losses of €6 billion.

Hazard likelihood is then estimated. This is generally done by using statistical models based on past observations or models built on ecological processes or expected laws of probability. In the case of Lothar and Martin, the expected return time is 86 to 113 years for spruce and 357 to 408 years for beech (Schütz et al., 2006).

By knowing the probability of occurrence as well as the damage caused by a given hazard, it is therefore possible to measure the expected economic effect of a given natural hazard, corresponding, for example, to a storm hazard risk assessment.

Overall, our approach is inspired by the literature review of Hanewinkel et al. (2011), which addresses the question of the integration of risk assessment into forest management in the case of single hazard risk. The authors propose four steps:

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

This typology was initially created to consider single hazard risk, typical of the literature of the 1980s, as mentioned above. This literature should however be extended to multi-hazard risk. Indeed, 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.

2.2 Eligibility criteria

We conducted a systematic screening of the literature to identify peer-reviewed English-language publications up to 2020. The initial literature research scrolled four databases: ScienceDirect, JSTOR, Ingentaconnect and NRC Research Press. We looked for the occurrence of three keywords in the full paper (including title, keywords and text). The design of the automatic research was:

forest AND economics AND {catastroph OR damage OR mortality OR disturbance OR hazard OR risk OR stochastic OR uncertainty OR interaction OR cascad* OR multi-risk}*

Only papers whose titles and abstracts seemed relevant were retained for the study. A more exhaustive reading of these papers led to the discovery of relevant complementary references, which were added to the initial list.

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 variables listed in Table 1.

Variable	**Describing**
Characteristics of the article	
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
Characteristics of the study	
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: Variables included in the database.

The characteristics of the article 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 variables related to the core of this study, detailed below.

2.3.1 Disciplinary orientation

The screening of the literature focused on economic studies. However, during the article selection process, some ecology-oriented papers turned out to be interesting for our topic.[1] 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 interaction between natural hazards. Consequently, we propose to classify the articles according to their disciplinary orientation ("Orientation" variable in Table 1), as follows:

- Economics: papers that use economic tools. This includes maximising a criterion (land expected value, timber stock, sequestrated carbon, other ecosystem services, etc.), assessing costs and benefits, insuring against worst scenarios, etc.
- Ecology: papers that 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, playing on 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.

2.3.2 Multi-hazard group

During the article selection process, we observed that considering several risks in the same article is not the same as considering their interactions. As a consequence, the list of papers was divided into two exclusive groups: in the first group ("$\text{Group}_{\text{Ind}}$"), the papers consider several hazards but with no correlation between them. 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 tries to consider the dependency between the risk, either simultaneous or sequential (Buma, 2015).

2.3.3 Hazard types

Six main natural disturbances were explicitly retained in our review (Seidl et al., 2017; Montagné-Huck and Brunette, 2018): four abiotic hazards: *fire*, *wind*, *drought* and *ice/snow*; and two 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 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 $\text{N}_H \leq 10$. 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*.

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

2.3.4 Categories

We adopted two main categories to classify the articles:

- Hazard modelling: the assessment of the relevant hazard parameters defined in Section 2.1 (likelihood, vulnerability, exposure), corresponding to Step 2 of the risk assessment of Hanewinkel et al. (2011). We define 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.

- Impact assessment: the socio-economic impact assessment of the risk induced by several natural hazards, corresponding to Step 3 of the risk 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 to enter 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.

3 Results

3.1 Descriptive statistics

To present the descriptive statistics, we use our categorisation in Table 1. We first present some statistics about the characteristics of the article, and then some about the characteristics of the study.

3.1.1 Characteristics of the articles

Our review contains 101 articles published between 1916 and 2020 (see in Appendix A a full list of the references). Figure 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 is increasing 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.

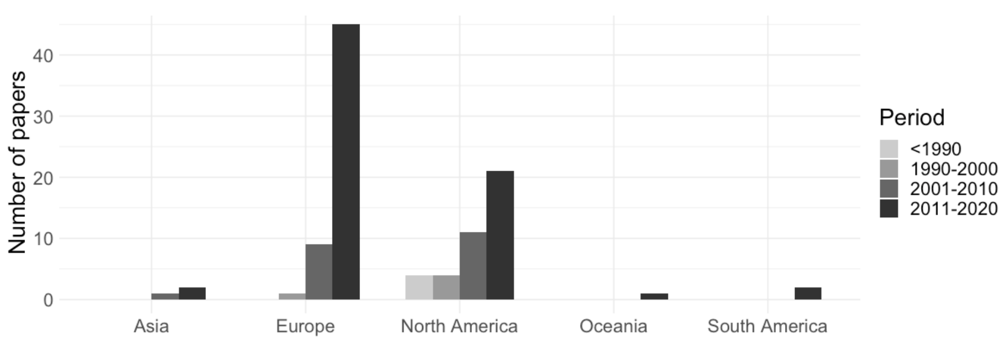

Figure 1: Evolution of the number of studies by decade for the five continents represented.

Looking at the "index keywords" indicated by the journals to sort articles, we obtain Figure 2. Note that among the 101 articles, only 96 were available.[2]

[2]We performed a similar analysis with the keywords declared by authors (see Appendix B).

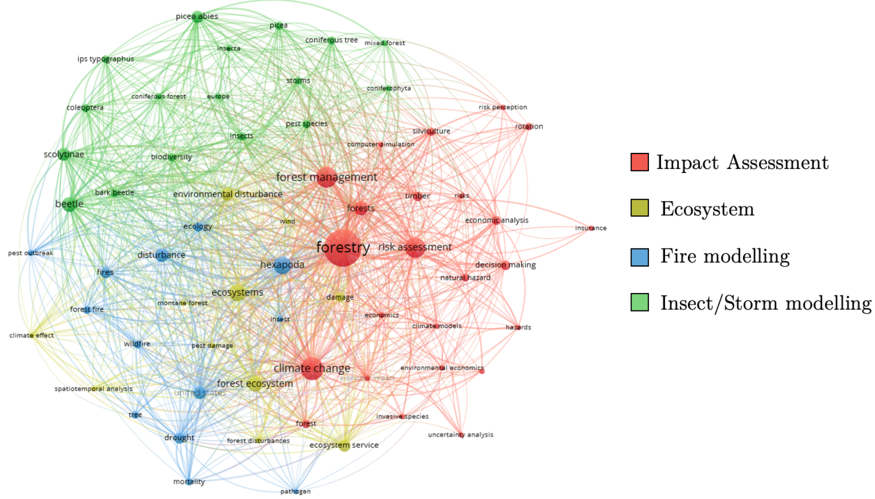

Figure 2: Index keyword co-occurrence network for 96 articles, created with VOSViewer software.

The size of the circle is proportional to the number of occurrences of the keyword. Only keywords that appear at least five times were conserved, restricting the network from 983 to 65 keywords. The keywords are linked together if they appear at least one time 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).

Figure 2 is divided into four clusters. The first cluster consists of impact assessment topics, like our category. The second and third clusters deal with fire hazard modelling with North American contributions and insect/storm modelling with European contributions, constituting our "Hazard modelling" category. Finally, a last cluster is devoted to ecosystem issues.

The total number of authors contributing to at least one paper in the review is 381. Among these, eight have more than three contributions, 27 have two contributions, and 346 only one. This shows that the literature is not really concentrated because many authors contribute, and generally only once. Moreover, 57 papers in the review were exclusively written by authors with only one contribution. 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.

To further extend this analysis, we represented the citation network of 265 authors in Figure 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*).

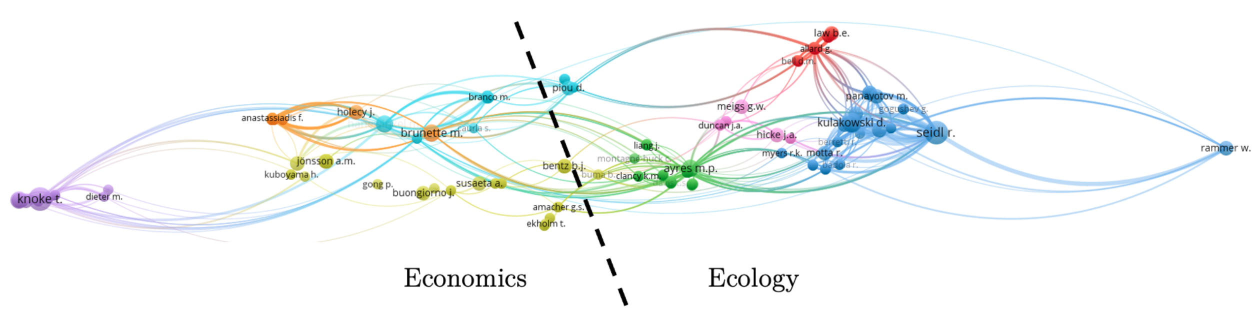

Figure 3: Citation network of contributing authors, created with VOSViewer software.

The network on Figure 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 cite each other. 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, however, exhibits a certain level of permeability between both disciplines.

3.1.2 Characteristics of the study

The following table presents the number of articles, among the 101 articles of our database, for each characteristic of the study presented in Table 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 2: Number of articles for each characteristics of the study.

The sample is almost equally split between economics-oriented articles and ecology-oriented ones. 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. The last column reveals that 38 articles belong to the category "Hazard modelling", with 28 in the sub-category "Statistical method" and 10 in "Vegetation process", and 54 in the category "Impact assessment" with a majority in the sub-category "Value assessment". It can be noted that the sum of the articles in these two categories is equal to 92, which is less than 101. Indeed, the 19 literature reviews included in our database are not considered in these two categories.

Table 3 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 3: Overview of the main scientific journals.

Figure 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 at a lower scale) 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 4 also allows us to conclude that most of the articles deal with temperate, Mediterranean and boreal forests from 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 other regions of the world like Asia, Africa and Oceania. This means that, at that time, economics had not yet grasped the problem of multiple natural hazards in tropical forests.

Moreover, if we look at the tree species studied, only 52 publications declare one or more species of interest. The distribution is the following: conifers represent 80% (majority of *Pinus* and *Picea*) of the studied species, and deciduous trees only 20% (majority of *Fagus*). This distribution can have at least three possible explanations: (1) conifers are more sensitive to natural disturbances; (2) conifers are found in more disturbed ecosystems; (3) conifers are economically more important than deciduous trees and, consequently, more studied.

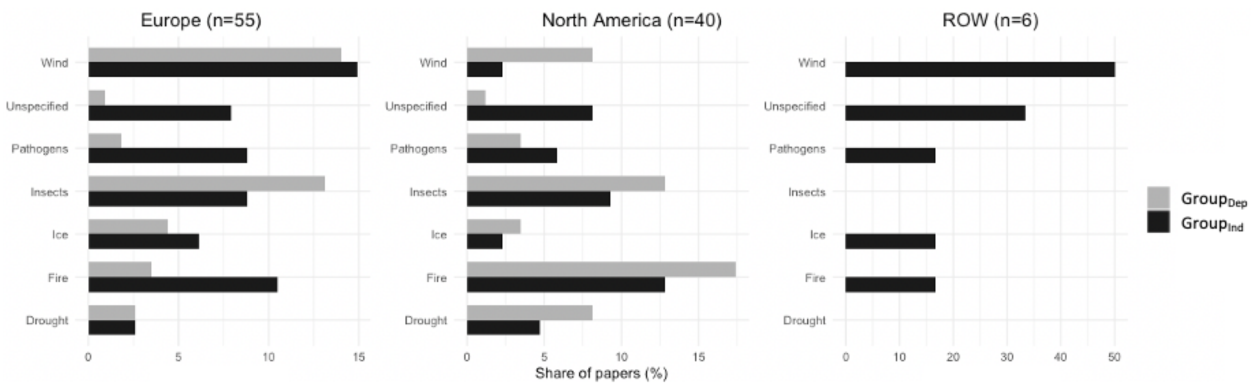

Figure 4: Prevalence (%) of each of the six + unspecified hazards by continent (ROW = Rest Of the World = Asia + Oceania + South America) for both groups.

3.2 Interactions between hazards

To analyse the relationship between the six hazards, we started from our classification in "Group$_{\mathrm{Ind}}$" and "Group$_{\mathrm{Dep}}$", and we looked to see if the hazards interacted and how (Section 3.2.1), and if there was an eventual correlation with disciplinary orientation (Section 3.2.2). 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 3.2.3).

3.2.1 Study of interactions

To study if and how the seven categories of hazard types considered interact with each other, a Venn diagram is proposed in Figure 5. This diagram includes two dimensions:

- The position of the label giving the hazards considered;
- Both numbers on the label "X;Y" with X (resp. Y) counting the number of Group$_{\mathrm{Ind}}$ (resp. Group$_{\mathrm{Dep}}$) 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 "Group$_{\mathrm{Dep}}$" as compared to three in "Group$_{\mathrm{Ind}}$". "Wind" and "Insects" are also the most highly represented hazard types in our database, as indicated in Table 2. This interaction is a typical "cascading" event, following the typology of Buma (2015). Indeed, they act sequentially: 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

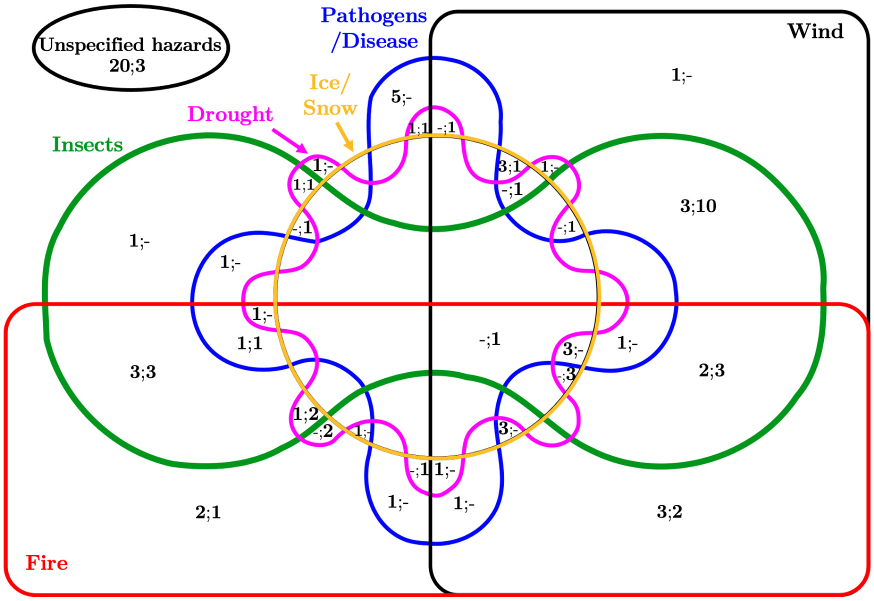

Figure 5: Venn diagram for distribution of the number of articles across six types of natural hazard. Key: “X;Y” with X (resp. Y), counting the number of $\text{Group}_{\text{Ind}}$ (resp. $\text{Group}_{\text{Dep}}$) studies. *Key: two (resp. three) papers of the $Group_{Ind}$ (resp. $Group_{Dep}$) are exclusively devoted to fire, wind and insect hazards.*

this interaction, and by economists because of the importance of the area of productive European forests concerned 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 2). 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”, the events are qualified as “cascading” by Buma (2015).

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 on 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) dealing with the drought-induced risk of forest decline from an economic perspective. However, 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).

Concerning the disciplinary orientation of the interactions, the authors observed that most of the articles classified as $\text{Group}_{\text{Dep}}$ are ecology-oriented, whereas the vast majority of the "unspecified hazards" are economics-oriented (for both groups). This shows that economists focus on general hazards, trying to extract universal results, whereas ecologists focus on specific disturbance regimes with particular hazards.

3.2.2 Disciplinary orientation as a key determinant

Table 4 presents the distribution of the articles as a function of their disciplinary orientation and of the group.

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

Table 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 4 thus reveals that 88% of the 52 economics-oriented papers belong to $\text{Group}_{\text{Ind}}$. 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).

3.2.3 Diversity of methods employed in the literature

Several methods exist and have been used to manage multiple natural hazards, as indicated in Figure 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 2.3.4 and the corresponding sub-categories. Finally, we allocated the different methods used in each publication to a sub-category.

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

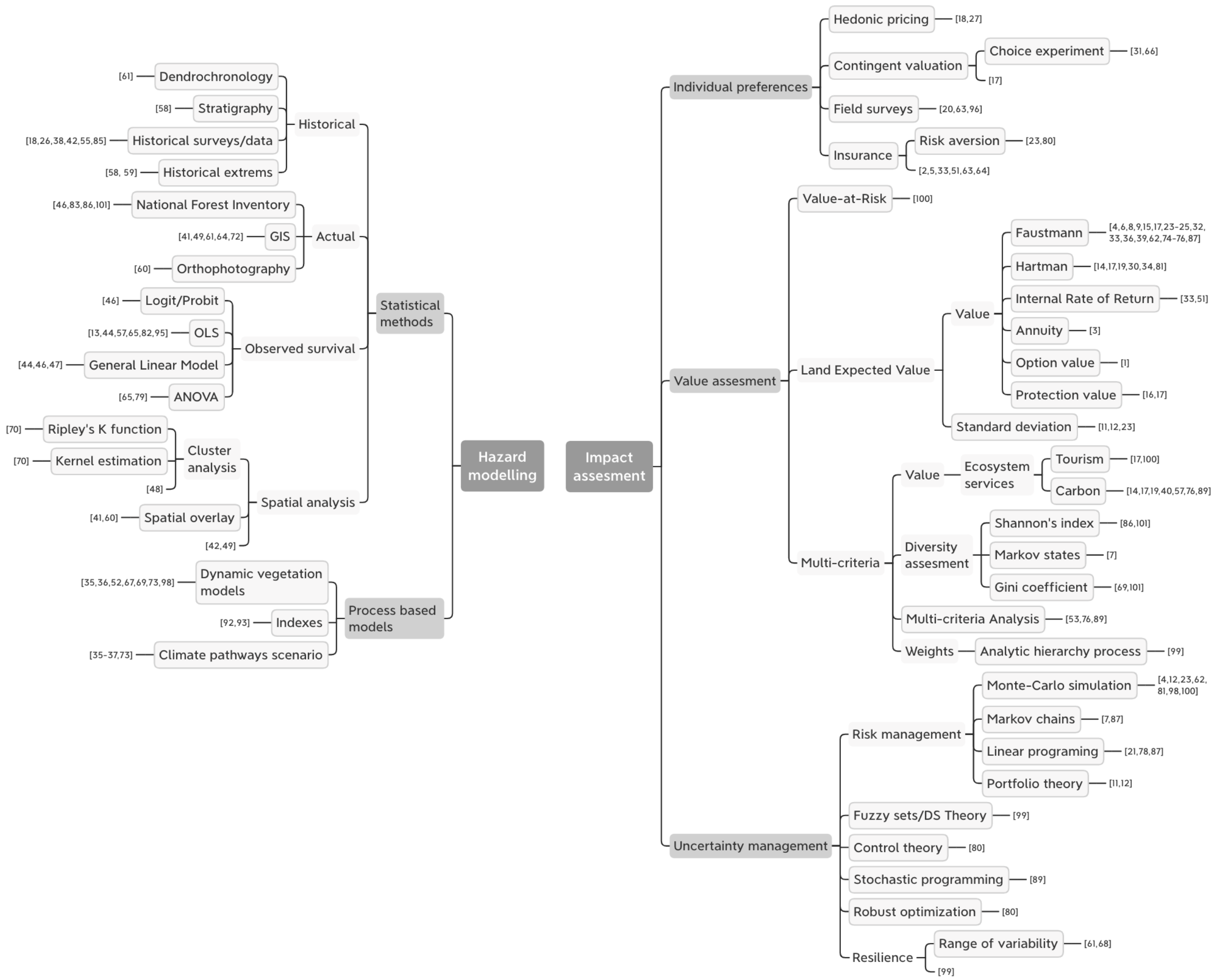

Figure 6: Mind map representing the panel of methods used to model hazards, determine parameters and assess hazard impacts. *Key: Dark grey = category; light grey = sub-category; framed = method; [...] = references of the papers using the method mentioned, listed in Appendix A.*

To go further in terms of methods, we propose another mind map in Figure 7 to summarise the different methods that are used to fix the hazard parameters in the risk assessment. This includes the main probability distributions and methodological tools commonly used in the literature. These methods can be divided into two different approaches:

- 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 keep 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 to know how well they fit with reality.

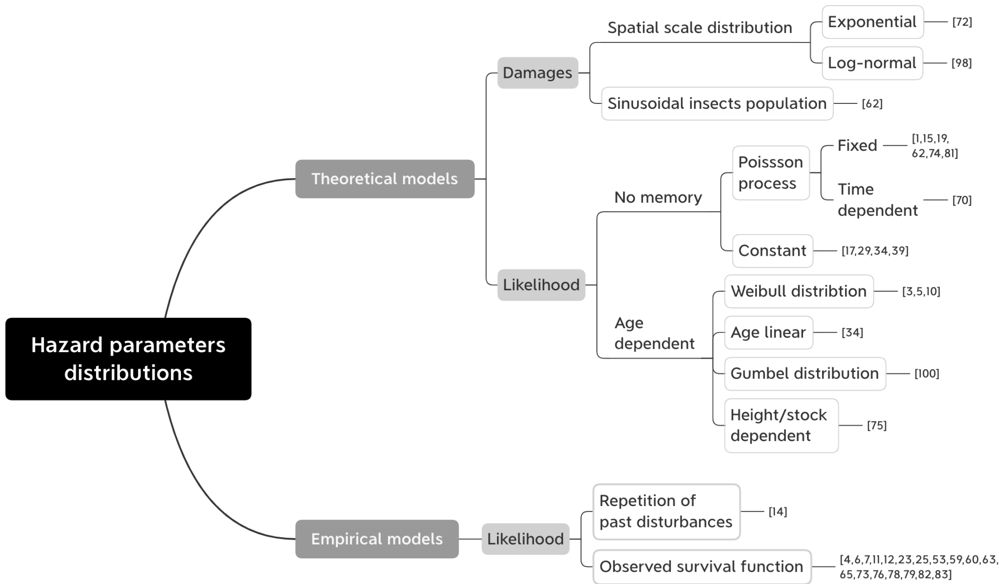

Figure 7: Mind map of the diversity of methods used to implement hazard likelihood in a model.

Figure 7 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).

4 Discussion

4.1 The interactions: diversity and modelling

Figure 5 shows that 33 of the 64 possible interactions have been studied in the literature, leading to some comments.

First, the diversity of the studied interactions is very broad. Nevertheless, the results may often not be generalised since the effect of disturbances and, *a fortiori*, the effect of their interaction, strongly depend on the local ecosystem and the current/projected climate conditions. For example, the interaction between fire and another hazard may be relevant only in fire-prone areas and, as a consequence, not studied in other regions. In addition, fire and another hazard like insects, for example, probably interact differently and have different consequences in North America compared to the Mediterranean region. Indeed, the tree species and the stands are different. Consequently, the vulnerability is different, rendering the generalisation of the results complicated.

Second, if 33 interactions were studied, this means that 31 were not. Among them, some will probably always remain irrelevant, regardless of where they are in the world, but it is likely that some will become relevant in the near future. For example, our literature review contains no publication concerning the "Insect"/"Storm"/"Drought" interaction. However, we can imagine the following hazard cascade: windstorm triggers an increase in opportunistic insect populations, which eventually thrive due to a concurrent severe drought. We can thus expect to see new interactions appear in the future and give rise to a new literature.

Third, among the 33 studied interactions, most hazards are analysed jointly as well as independently (i.e., $\mathrm{Group}_{\mathrm{Ind}}$). A way to introduce more hazard interactions in the economics literature is to continue to use statistical-based models. Indeed, the effect of single hazard on silviculture has been quite extensively studied, but interactions between risks have yet to be taken into consideration. This can be done by using statistical correlations in an economic framework to extend the results of single hazards. For example, on the theoretical economics side, Xu et al. (2016) proposed a generalisation of the result of Reed (1984) to several risks. The occurrences of these risks are independent and follow Poisson processes but with a possible correlation between damages. This enables the authors to find the best forest management among three possibilities, depending on hazard parameters. In another vein, Petucco and Andrés-Domenech (2018) investigated the effects of two simultaneous hazards (pine processionary moths and windstorm) on land expected value and optimal rotation age of maritime pine in France. The windstorm probability density function follows a Poisson process (severity depending on the height and thinning of the stand) and the insect population is sinusoidal, adjusted by a Brownian noise. "Subadditive effects" are found when risks are considered simultaneously as compared to separately. Moreover, the pure effect of windstorm (resp. pine processionary moth) is to reduce (resp. increase) the optimal rotation age. However, when considered together, optimal rotation age is increased compared to the "no-risk" alternative.

4.2 Other types of risk

We focused our study on the effect of natural disturbances on production, but other risks could have been investigated as well. Komarek et al. (2020) proposed a review of several risks in agriculture. The five following risks and the generated multi-risks are studied: production risk, personal risk, financial risk, institutional risk and market risk.

Even if we focused on production risk in our review, some papers deal with other risks; the effects of natural disturbances on human health (i.e., personal risk) is 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 more 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, 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 a proper 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).
- iid 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 the 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.

4.3 Other ecosystem services

Traditionally, the forest economics literature, based on Faustmann's model, considered only timber production loss in the event of natural disturbances (following the model proposed by Reed (1984)). However, Hartman (1976) proposed an extension of Faustmann's formula to include ecosystem services. Hartman's extension adds a value for standing timber, representing, for example, the value of the carbon sequestrated in the forest stand or the amenity from recreation in an old forest stand. Although the issue has evolved from single to multiple risks, our literature review reveals that taking ecosystem services other than timber production into account in forest economics analysis is still an exception. Other ecosystem services may be important. Indeed, the realisation of multiple natural disturbances in forests may have a large impact on biodiversity, for example, or on the provision of recreational services. It is easy to imagine that an insect invasion after a fire occurrence ("Fire-insects" interaction) increases the effects (as compared to fire alone) on the game population, on the forest ecosystem as a whole, and on humans living close to the stand as well.

Moreover, a crucial point may be the fact that natural disturbances may be detrimental in terms of timber production, but beneficial in terms of biodiversity. Indeed, natural disturbances generally have a positive impact on biodiversity and a negative one on other ecosystem services (Thom and Seidl, 2016). Timber production, water provisioning, protection against gravitational natural hazards and carbon storage were found to be predominately negatively affected by disturbances, whereas species richness, habitat quality and diversity indices were equally positively affected by disturbances (Thom and Seidl, 2016). This means that it may be necessary to prioritise forest management objectives when considering several ecosystem services when dealing with multiple natural hazards in forests.

4.4 An interdisciplinary perspective

4.4.1 Motivations

An important result of this literature review is that economics-oriented papers tend to consider hazards as being independent, while ecology-oriented ones take the interaction into consideration. This study reveals that economics papers more often consider hazards to be exogenous, or study them separately when they are endogenous, whereas, ecology-oriented papers focus on understanding the dynamics of the disturbances and, instead, study the interactions of the disturbances in order to assess their full possible impact. Few articles fit into the "Both" category (i.e., economics-oriented and ecology-oriented) using either multi-criteria analysis or an ecological process-based model with an economic framework.

Figure 8 shows that "Risk modelling", "Impact assessment" and "Optimal management" are strongly connected in a closed loop.

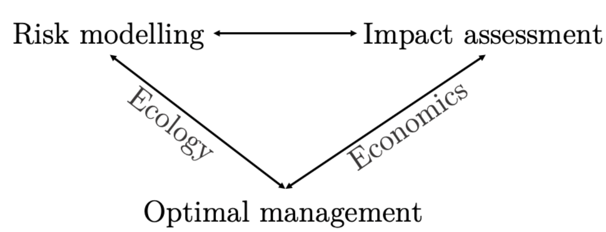

Figure 8: Loop of interactions between "Risk modelling", "Impact assessment" and "Optimal management".

The literature in ecology and economics raises different research questions.

- Ecology literature considers the existence of natural hazards and their effect on the forest ecosystem. The question 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 8. It often focuses on two scales: the tree or the region.

- 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, leaning economics to the right side of Figure 8. It often focuses on the scale of the forest stand, especially beneficial for assessing the impact of natural disturbances on a forest owner.

Finally, the connection between "Risk modelling" and "Impact assessment" could be improved in future research, especially to tackle future challenges such as climate change.

4.4.2 Dealing with climate change

More than one quarter of the articles in this review (28, Table 5) 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, such as Dale et al. (2001) who try to understand the implication of climate change on forest ecosystems for eight major production hazards.

	Number of papers
Economics	7
Ecology	18
Both	3
Total	**28**

Table 5: Overview of the orientation of the papers that study the impact of climate change.

Forest management research in a context of climate change is relevant for two main reasons. First, climate change modifies hazards and their interactions, directly impacting forest stands and requiring an adaptation of existing forest stands. However, there is also a retro-action of the forests on the world climate through carbon storage (Lewandrowski et al., 2014), which attenuates climate change. 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. Table 5 shows that only a few economics articles focus on climate change and its impact. 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.

4.4.3 Avenue for future research

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. For that purpose, two options exist: to either introduce ecology into economics studies or economics into ecological studies.

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 exogenous: there should indeed be a retro-action of economic results on silviculture, but this has, to our knowledge, not yet been developed.

Reciprocally, ecology-oriented papers can also benefit from the collaboration with economists since the future path of human-managed forests mainly depends on forest owners' decisions, which can be described using microeconomic tools. Forest management could thus become endogenous rather than exogenous as in most cases in ecology-oriented articles. For example, economic studies have shown that forest owners are risk-averse and that this attitude towards risk has consequence on forest management: reduction of the probability to harvest (Brunette et al., 2017), increasing demand for forest insurance (Brunette et al., 2013), reduction of adaptation (Brunette et al., 2020), etc. An economic approach also makes it possible to consider other types of forest owners' attitudes, like perception of climate change or perception of risks.

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. Second, we show that economics-oriented articles rarely consider the interactions between natural hazards. We thus indicate that relevant methods that can be used to consider this interaction may be to create theoretical inter-dependent hazard models or to assess statistical effects of the existing interactions. We also observe that timber production is often the only ecosystem service considered in the literature. Finally, 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, highlighting the need for interdisciplinary partnerships in the future.

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B Analysis of the keywords declared by the authors

Figure 9 was obtained by looking at the keywords indicated by the authors on the title page of their article to better represent their subject. Note that among the 101 articles, 11 did not include any keywords.

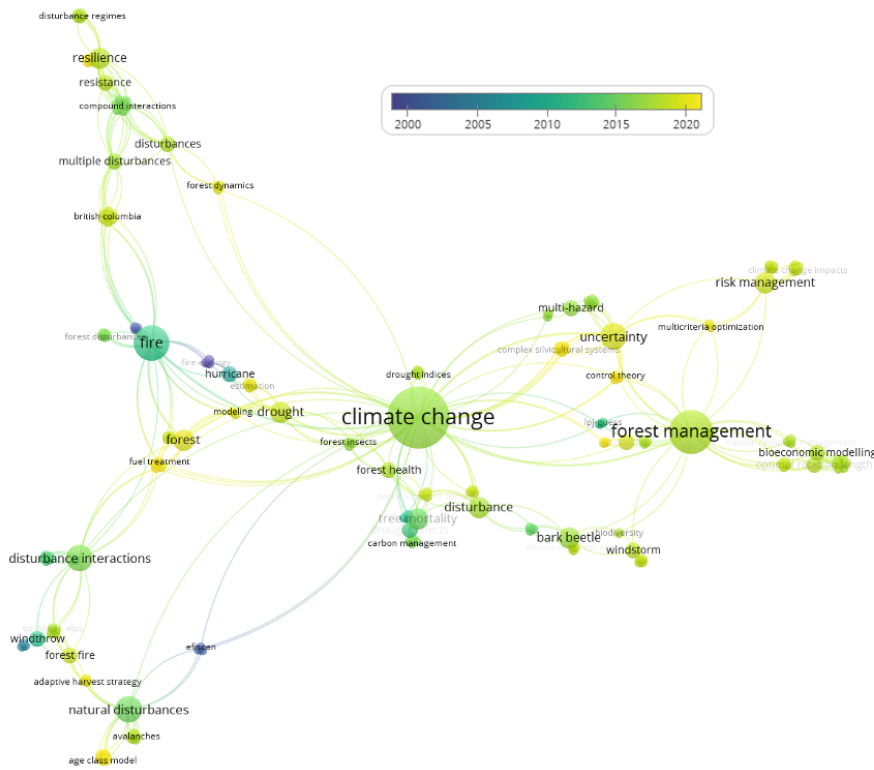

Figure 9: Keyword co-occurrence network for 84 articles (186 keywords), created with VOSViewer software.

The size of the circle is proportional to the occurrence of the keyword, and its colour corresponds to the mean date of appearance of the keyword. The keywords are linked together if they appear at least one time in the same publication, and the thickness of the link between keywords is proportional to their number of co-occurrences. Six papers (representing 31 of the 217 keywords) were not connected to the main network and are therefore not displayed.

The most frequently cited keyword is “Climate change” (13 times) represented in the centre of the word cloud. Words related to the natural disturbances that we considered, such as “drought”, “bark beetle”, “windthrow” and “fire” are also represented. Some main methodologies also appear with “age class model” and “multi criteria optimisation”.

Figure 9 can be divided into two parts: the direct impact of natural disturbances on the left, and their impact on forest management on the right. This is in agreement with our two categories, “Hazard modelling” and “Impact assessment”.