

Review

Windstorm Impacts on Forest-Related Socio-Ecological Systems: An Analysis from a Socio-Economic and Institutional Perspective

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Abstract: Windstorms are considered among the most impacting natural events for European forests and related Socio-Ecological Systems (SES). Given that their intensity and frequency are increasing, an in-depth understanding of their impacts is crucial to mitigate risks and potential negative effects. However, so far, scientific research on windstorm impacts has mainly focused on environmental dimensions, while socio-economic and institutional ones are rarely taken into consideration. Our analysis aims at enriching the current scientific knowledge on windstorm impacts on forest SES by providing an overview of the state-of-the-art academic investigations on windstorm impacts on socio-economic and institutional dimensions. Overall, 46 papers were reviewed to identify the most recurrent post-windstorm dynamics and drivers that influence resilience and adaptation of socio-economic, institutional and related governance dimensions of European forest SES. Results show that the current scientific knowledge on socio-economic impacts of windstorms mainly concentrates on forest-related stakeholders and sectors, paying little attention to the broader social, cultural and institutional drivers that contribute to forest SES resilience. Further, cascade effects linking environmental, social and institutional dimensions are poorly analyzed. This restricted focus could lead to an incomplete understanding of the dynamics shaping socio-economic adaptability to windstorms, affecting long-term and sustainable recovery from extreme natural events. To correctly frame effective, intersectoral and coordinated recovery strategies gaining a deeper understanding of human–environment interactions is needed, as well as acknowledging the positive influence of causal relationships in improving forest-related SES resilience.

Keywords: windstorms; climate change; socio-ecological systems; cascade effects; socio-economic and institutional impacts; forest health; interdisciplinary approach

Citation: Romagnoli, F.; Masiero, M.; Secco, L. Windstorm Impacts on Forest-Related Socio-Ecological Systems: An Analysis from a Socio-Economic and Institutional Perspective. *Forests* **2022**, *13*, 939. <https://doi.org/10.3390/f13060939>

Received: 21 April 2022

Accepted: 13 June 2022

Published: 15 June 2022

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1. Introduction

Forests are complex socio-ecological systems (SES), where environmental and ecological functions interrelate and are shaped by human needs, e.g., [1–5]. However, in the last few decades, these systems and the multiple services they provide are increasingly triggered by—among others—the growth in frequency and intensity of disturbances, including extreme climatic events [6–8]. These threats are becoming particularly relevant for the European forests whose vulnerability has been increasing in the last years, mainly due to the expansion of the growing stock and increased exposure to climate change effects [9,10].

Within Europe, wind and wind-related disturbances were identified as being among the most damaging agents of forest ecosystems [11,12]. In addition to greatly endangering the ecological condition [13], windstorms strongly threaten forest-dependent communities causing several repercussions at the socio-economic level [14]. The forecasted intensification of extreme events [15,16] stresses the urgency of identifying effective policies and

strategies to mitigate risk and increase the resilience of forest-related SES [17–19]. In recent decades, despite a growing scientific interest in analyzing windstorm impacts on forest SES [14,20] data remained extremely scattered in terms of scope and issues analyzed [11,21]. Several knowledge gaps hinder a complete understanding of windstorm consequences on forest SES and how associated changes in forest structure and ecosystem services provisioning ultimately affect societal well-being [22,23].

At the European level, empirical evidence of windstorms' consequences on socio-economic and cultural aspects is lacking [17,24,25]. Windstorm impacts on these dimensions are poorly investigated in scientific terms and their understanding remains quite limited [10,26,27]. This is confirmed by recent reviews on windstorms or natural disturbance impacts on forests [19,28–30]. These studies show that the analysis of windstorm impacts mainly entails environmental and ecological aspects [31], paying less attention to indirect and spillover effects affecting other SES dimensions [32–34] or the provision of ecosystem services. From a socio-economic perspective, the prevalent focus of the scientific investigation is on windstorm impacts on forest-related industries and timber markets, with limited analysis of the repercussions on communities and stakeholders at the psychological and behavioral level [35]. Similarly, effects on governance dynamics and changes at the institutional level are poorly studied [36–38].

The paucity of scientific analysis on windstorm impacts on social-related aspects (namely socio-economic, cultural, institutional, governance and management aspects) strongly contrast with the coupled nature of forest SES [39,40]. Further, considering that forest management is aimed to satisfy different human needs [41,42] and is strongly influenced by socio-economic drivers [43,44], the lack of a clear understanding of how windstorms impact society-related dimensions could lead to several drawbacks. Among others, two are particularly outstanding. On one hand, it could hinder the identification of adequate policies and risk management strategies to enhance forest-related SES resilience [30,45]. Indeed, if we define resilience in social-ecological systems as the outcome of the adaptive capacity of different attributes and components of the system [4,40,46], exploring windstorm impacts and consequences mainly on environment-related dimensions will prevent having complete comprehension of dynamics and features that influence the resilience of forest SES [1,39]. On the other hand, it could limit the achievement of long-term sustainability at ecological, economic and social levels [3,47].

Through a detailed review of scientific literature and content analysis of scientific articles, this paper aims at complementing and advancing the current state of academic knowledge on primary and secondary windstorm impacts, specifically focusing on socio-economic, institutional and governance dimensions of forest-related SES in Europe. In particular, we aim to: (i) identify the most recurrent post-windstorm dynamics observed and reported in the dimensions of reference, with a focus on the identification of cause–effect cascade linkages, and (ii) provide suggestions for effective post-windstorm policies and management strategies, helping to boost the resilience of forest-dependent communities and related SES. To achieve these goals, we visualized through a causal map the cause–effect interconnections among multiple dimensions. The map points out spillovers directly or indirectly impacting socio-economic, cultural and institutional-governance dimensions [48]. Furthermore, it highlights how windstorm consequences propagate their impacts along the cascade from environmental damage to the forest ecosystem to the provisioning of ecosystem services and functions, affecting human well-being [47,49].

The paper is organized into five sections. After the introductory section—i.e., this one—in the second section, the methodological steps that underpinned the scientific literature review are highlighted; a third section presents the results, while in the fourth section, results are discussed, paying particular attention to the cause–effect linkages among SES dimensions. The fourth section also includes a visualization of causal links among dimensions and some recommendations for developing appropriate post-windstorm strategies. Finally, conclusions are drawn in the fifth section, summarizing the main

research findings and reporting the main limitations as well as future research needs and possible developments.

2. Materials and Methods

A combination of mapping [50] and scoping review [51] approaches were applied. These methodologies are commonly used to map the existing literature on a certain topic, clarifying concepts and eventually highlighting research gaps [45]. The implementation of mapping and scoping approaches allowed windstorm consequences to be examined using an innovative perspective, answering the need to analyze natural events consequences with an interdisciplinary and multisectoral focus [52] rather than adopting mono-sectoral and highly specific analysis. Further, scoping reviews provide a better structure to map out existing literature summarizing issues that have received high scientific attention on the one hand [53] and, on the other, identifying current knowledge gaps and the need for more in-depth research [54].

Following Doyle [55], the review process involved five main steps, with various sub-actions that are briefly described in the following sub-sections. For screening and selection of relevant papers, main features of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approaches were adopted [56].

2.1. Step 1: Framing the Review Approach

The paper focuses on currently available European scientific literature that has described windstorm impacts on socio-economic, cultural, governance and institutional dimensions linked with forest-related SES in Europe. Key aspects and main topics of interest were identified based on the currently available academic literature including review studies [10,43,57–60] and previous studies that have assessed impacts of climate change or extreme natural events on social-ecological systems [19,28,40,61,62]. From these, research questions and key search terminology were identified. Considering the wide array of windstorm-impacts-related issues, a continuous process of adjustment and improvement of search terms and resulting queries were performed. This process led to the implementation of two rounds of papers search, both conducted in SCOPUS database. The first was performed in April 2020 and then updated in October 2020.

In the first round, the search terms used to detect relevant literature were composed of the following subgroups: (windstorm or hurricane or wind* or disturb*); (Europe or European); (forest* or woodland); (soc* and econom*); (impact* or effect* or damage* or cost*); risk*; community. The second round included specific search terms to detect papers with consequences on governance and institutional dimensions (institution* and govern*), post-windstorm policy implemented (poli*) and ecosystem services provisioning (ecosystem* and service*). “Europe or European” keywords were removed because the first round stressed that very few of the papers gathered included “Europe or European” in the title, abstract or keywords. Thus, introducing these keywords would have biased identification of the relevant papers.

Regarding the second round, it is worth specifying that the queries used were part of a larger, multidisciplinary review implemented within the Vaia Front project (further details regarding the project are accessible in the following link https://www.tesaf.unipd.it/sites/tesaf.unipd.it/files/VAIA%20FRONT_2019_12_4_finale_1.pdf (accessed on 10 May 2022) aiming at identifying the cascade of effects among multiple forest dimensions hit by a windstorm, including the ecological and environmental ones which are excluded from this analysis. A few articles excluded from the multidisciplinary review due to specific exclusion criteria (namely this review excluded review articles and models from the pool of papers scrutinized) were considered for the aims of this paper as they provide valuable in-depth information about windstorm impacts focused on socio-economic and institutional dimensions.

The complete list of queries used in the two rounds is reported in Appendix A.

After having defined research questions and keywords, eligibility criteria for article selection were set. The criteria set ensured pertinence and relevance of every single study to the review goals and are summarized in the following inclusion criteria:

- (i) Articles published in English and only in peer-reviewed journals, thus excluding technical reports and grey literature;
- (ii) Pertinence to the scope of the review: analysis of windstorm impacts on forest-related dimensions relevant for this study (socio-economic, institutional, cultural and governance dimensions);
- (iii) Geographical restriction: focus on windstorms that hit European forests only.

No limitations related to research methodologies or time span were set.

2.2. Step 2: Papers Search and Screening

Relevance and pertinence of articles retrieved to the review goals were assessed through a skimming procedure developed adapting PRISMA methodology to the current scope of the review. The skimming procedure was identical for both review rounds and followed the steps described below:

- (1) A first and preliminary screening of titles and abstracts to ensure articles comply with the inclusion criteria mentioned above;
- (2) Papers with relevant titles and abstracts were further screened via an in-depth reading to assess articles' compliance and pertinence to research questions, review scope and main objectives;
- (3) A duplicate-cleaning procedure between first and second review rounds to avoid eventual double accounting of papers;
- (4) Finally, the pool of papers collected via search terms was complemented by papers suggested by advisory scholars' consultations after having assessed their relevance and pertinence to this study.

The final pool of articles was scrutinized, and information categorized following the coding criteria defined below.

2.3. Step 3: Data Categorization and Analysis

The selected articles were thoroughly scrutinized through content analysis. For each article, during the in-depth reading process, parts of the text considered relevant were categorized and coded using MAXQDA analytical tool (VERBI Software 2019, MAXQDA 2020, Berlin, Germany).

In particular, information related to three main thematic categories was identified and organized into three different Excel databases (Microsoft Corporation, Seattle, WA, USA):

- (i) A first database was created to report bibliographic and specific case-study information such as: methodological approach implemented, data concerning the study area and (eventually) estimated economic damages related to the study area.
- (ii) A second database summarized information on storm characteristics, including: name and year, spatial scale and size of the affected area, total loss of forest cover and overall insured losses.
- (iii) A third database included primary and secondary windstorm impacts and cause-effect linkages identified in the papers reviewed. In addition to windstorm impacts, the database included information regarding methodology used to assess the impact, time span and nature of the impact (i.e., if the impact had positive or negative consequences in the dimension considered). It is worth remembering that the main goal of the paper is analyzing windstorm impacts on socio-economic, cultural, governance and institutional dimensions. Thus, impacts related to non-socio-economic dimensions (e.g., forest ecology, mechanization, etc.) were

included in the database only if articles reviewed assessed direct consequences or cascade effects on key reference dimensions.

To compile the third database a hierarchical coding system was designed.

Firstly, forest-related SES dimensions crucial for our analysis, i.e., institutional, cultural, social, economic, insurance, were identified. Secondly, dimensions likely to have relevant consequences on socio-economic and institutional aspects, i.e., forest management and operations, forest ecology and forest ecosystem services provisioning, were identified.

The dimensions identified, other than those used for studying windstorm impacts among the articles reviewed, are in line with those used in most recent scientific literature studying climate change impacts on ecosystem services [62–64].

Lastly, considering that windstorms can have multiple impacts in one dimension and can affect multiple stakeholders, each dimension was further divided into two specific categories: (i) macro-categories that refer to specific thematic subsets connected with a certain forest SES dimension (Figure 1), and (ii) sub-categories that identify a cluster of windstorm effects related to a specific sector or stakeholder group. Impacts found in the scientific literature analyzed were grouped into specific categories according to the dimension of reference and actors/sectors affected. This categorization enabled the identification of windstorm cause–effect linkages affecting multiple sectors and stakeholders of the European forest context.



Figure 1. Dimensions and macro-categories considered in the analysis. Dimensions are reported in full-colored circles, while sub-dimensions are reported in smaller and plain circles (Source: own elaboration).

We structured this coding system taking inspiration from main frameworks used in scientific literature for analyzing impacts of extreme weather events in social-ecological systems [61,65].

The coding system was applied to detect both primary and secondary windstorm impacts. For the aims of this paper, primary impacts are defined as direct windstorm consequences in socio-economic, as well as, ecological forest-related SES dimensions (e.g., changes in forestry operations costs; changes in risk perceptions; increase in deadwood and wood biomass; post-windstorm salvage logging, etc.); secondary impacts refer to cascade and spillover effects derived by cause–effect interrelations among forest-related SES dimensions (e.g., changes in timber prices; changes in landscape aesthetic value; changes in private owners forest management practices, etc.). No classification regarding the severity/importance of the impacts was made during the categorization process. Every impact analyzed in the articles, primary as well as secondary, was coded as observation. For each impact-related dimension, macro-category, sub-category, and method of assessment were reported. When mentioned, it was recorded if the windstorm impact analyzed had a positive/negative consequence in the dimension/categories considered and this information was used in the discussion session. Appendix C reports an example of the process followed to categorize impacts.

Figure 1 shows forest SES dimensions and macro-categories considered in the analysis, while the complete list of macro- and sub-categories for each SES dimension is available in Appendix B.

2.4. Step 4: Cause–Effect Map Representation and Guidelines Formulation

Direct impacts and cascade effects resulting from the analyzed scientific articles were represented visually with the aid of a causal map. The visualization of cause-effect linkages and causal relationships among dimensions allows the system functioning to be appreciated, and its reactions to external or internal events (disturbances). Causal mapping is generally identified as a specific type of cognitive mapping used to represent individuals' mental model of interconnections among system dimensions [66,67]. By identifying the complexity of feedback upon which systems are built [2], causal mapping was identified as a useful tool to grasp causal relationships among key dimensions and variables of forest-related SES and illustrate how these relationships are observed to change after a windstorm. We applied the methodology behind visual mapping to identify and provide a complete representation of interconnections among forest-related SES dimensions, feedback and variables reported in the reviewed literature. We adopted the classical structure of causal maps, where dimensions constitute causal concepts and are connected among one another by arrows that indicate the presence of cause–effect relationships [66,68]. However, differently from classical causal mapping, in our study, we assumed that relationships can be bidirectional, and dimensions can be connected among one another by multiple relations, depending on the number and nature of windstorms impacts and their related consequences.

The analysis of the results and cause–effect linkages delineated in the map will be the starting point for a broader discussion on effective post-windstorm strategies to increase socio-economic resilience and adaptive capacity to windstorm risk.

2.5. Step 5: Analysis of the Results

A summary of key findings from the academic articles reviewed was developed, providing an overview of existing scientific knowledge on windstorm impacts on socio-economic, institutional and governance dimensions in Europe. Using a combination of narrative and visual approaches, the most frequent primary and secondary windstorm impacts recorded in papers analyzed were reported, discussing the interconnections and spillover consequences on forest-related SES dimensions, and identifying core variables influencing socio-economic, institutional and governance resilience capacity.

3. Results

This section reports the information coded from the analysis of the scientific literature investigated and is structured as follows: (i) results of the study selection are reported, accounting for the number of records identified, records discarded and final pool of papers considered for the analysis; (ii) main features of the articles analyzed are presented, reporting information on study areas and windstorms studied and main methodologies applied; (iii) most common primary and secondary windstorm impacts and main dimensions hit are described.

3.1. Scientific Literature Search

From the two review rounds, 18,115 potentially relevant papers were retrieved. For the sake of clarity, it is necessary to clarify that such a high number of papers comes from the removal of “Europe or European” keywords in the second round. Thus, the second round included a relevant amount of Non-European studies that were excluded during the skimming procedure.

The title and abstract screening procedure papers not complying with the review inclusion criteria were eliminated. This step shortlisted the number of eligible papers to 142. These papers underwent an in-depth reading to ensure full pertinence and relevance to the scope of the review. After the full-text assessment, the number of papers further diminished to 38. Advisory scholars’ consultation highlighted seven additional relevant studies. The final pool of articles considered for the analysis amounted to 45 papers in total.

Figure 2 summarizes the steps composing the skimming procedure, reporting the number of potentially eligible papers retrieved at each step, as well as those excluded. The full list of papers retrieved by the review process is available in the reference session.

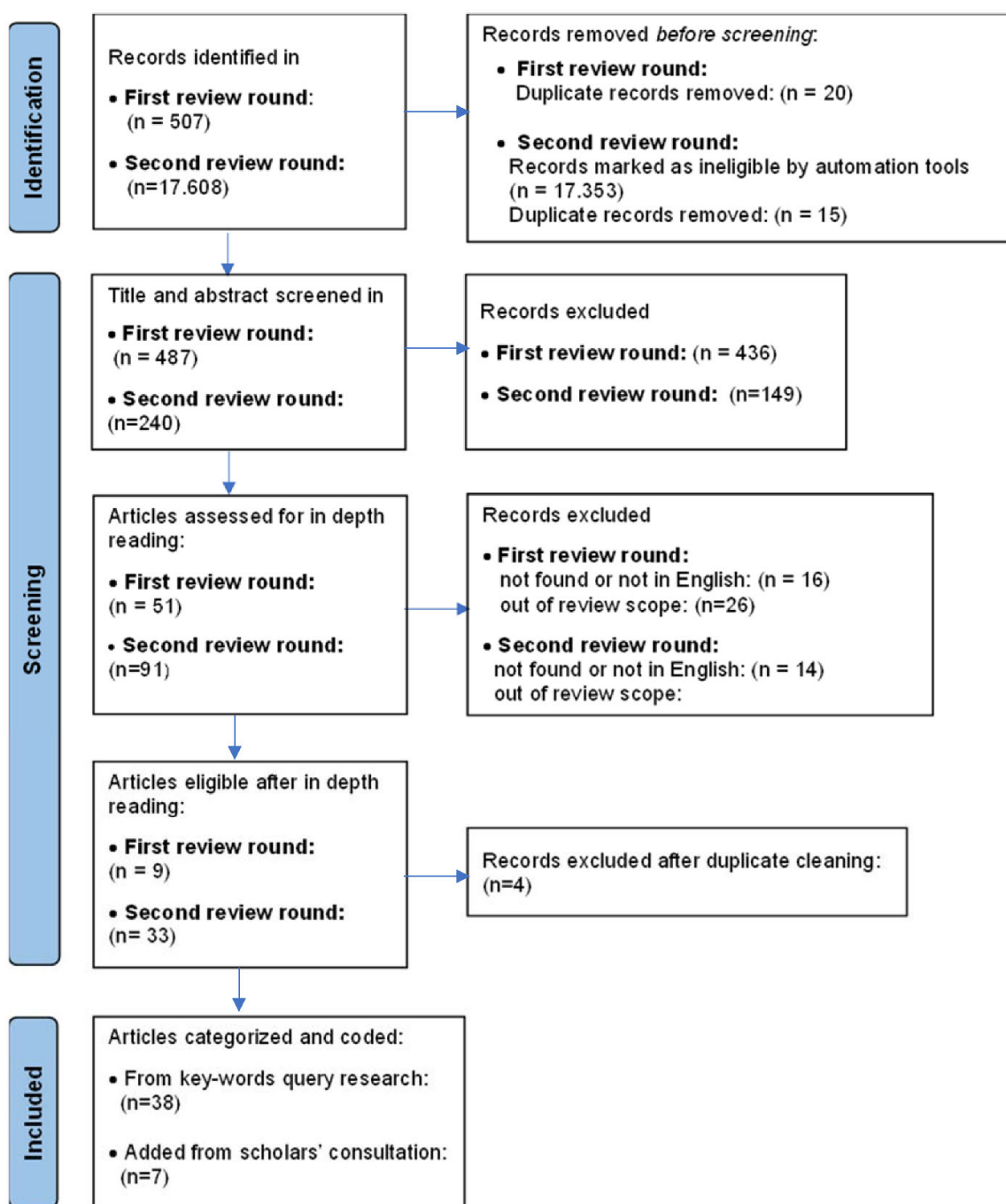


Figure 2. Flow diagram of skimming papers procedure based on PRISMA procedure. Diagram adapted from Page, 2021(source: own elaboration).

3.2. Time Span and Geographical Scope

The trends in publications reflect the general increase in academic interest in the analysis of natural disturbances experienced at the beginning of the 21st century [20,69]. Whilst academic literature reports an increase in storminess starting from the beginning of the 1990s [59,70], papers retrieved within this review focused only on windstorms happening from the end of the 1990s onwards. All the articles were published between 2000 and 2020, with an important increase in publications between 2010 and 2020: 76% of the

overall papers categorized were published from 2011 onwards, with an average of four publications per year (Figure 3).

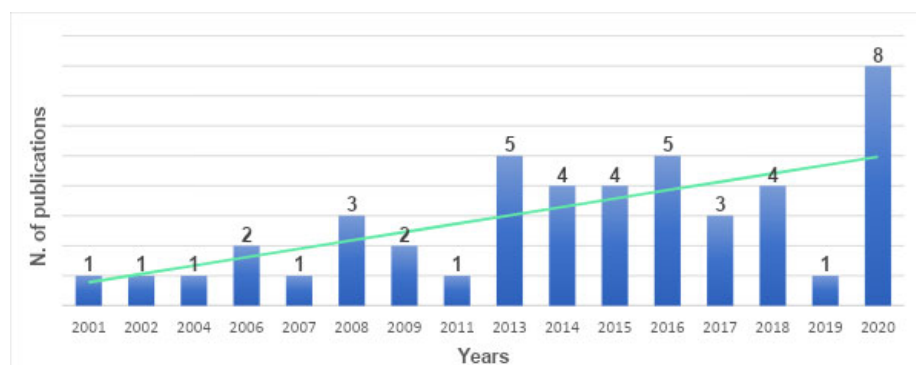


Figure 3. Numbers of articles published per year (source: own elaboration).

Concerning the windstorms analyzed, most of the articles reviewed (63%) focused on large-scale windstorms that have affected European forests in the last few decades, namely Lothar and Martin (1999) in France, Switzerland and Germany, Elisabeth (2004) in Slovakia, Gudrun (2005) in Sweden and Klaus in France (2009) (Detailed data and information as well as comparative assessments of windstorms mentioned are available within the existing literature, including (but not limited to (see: Gardiner et al. 2010; Gardiner et al. 2013; Roberts et al. 2014; Hewson and Neu 2015; Feser et al. 2015; Forzieri et al. 2020)). The remaining articles did not base their analysis on empirical data connected to a specific windstorm. Rather, they estimated windstorm impacts by simulating changes in selected variables through modeling. The study areas analyzed were concentrated in Northern/Central European countries, even for articles using simulations to predict wind hazard impacts. The majority of studies were conducted in Sweden ($n = 9$), followed by France and Germany ($n = 8$ each) and Latvia, Switzerland and Slovakia ($n = 3$ each) (Figure 4). The geographical concentration of studies was an expected result because Northern/Central European countries experienced the majority of extreme windstorms that have affected Europe in the last three decades [15,21]. Moreover, within most of these countries, the forestry sector and forest-based industry have, traditionally, major economic importance in terms of contribution to the gross domestic product, thus attracting attention from researchers and policy makers.

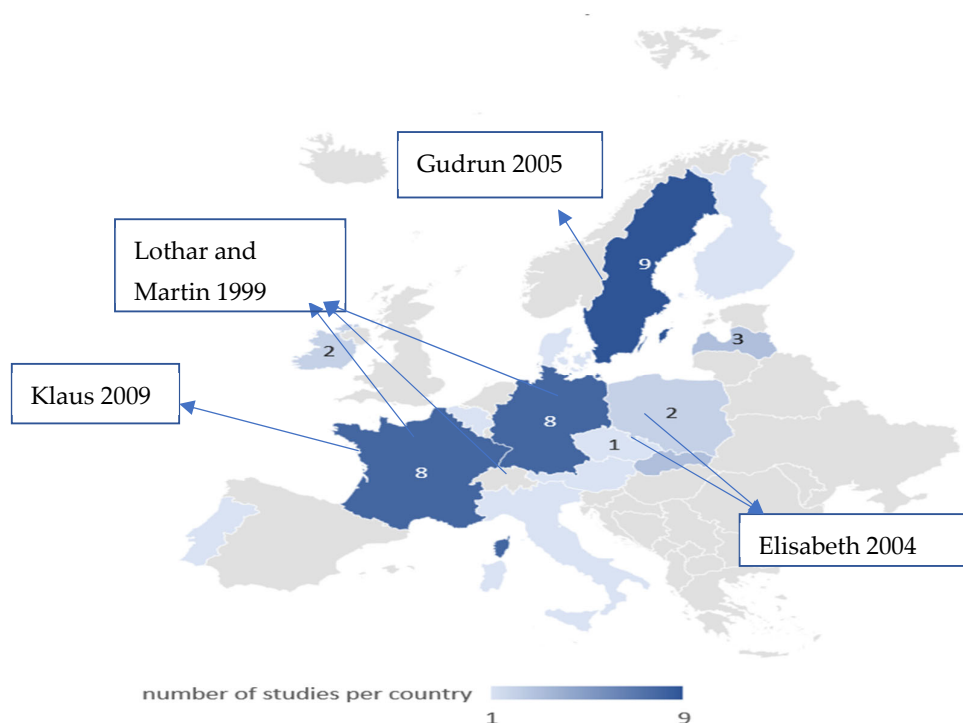


Figure 4. Distribution of studies reviewed across European countries. The most relevant storms mentioned in the articles analyzed and the impact year are reported in the squares (source: own elaboration).

A relatively small number of studies ($n = 10$) adopted a comparative approach to investigating and comparing the results of studies developed in different European countries hit by wind hazards.

3.3. Data Collection Methodologies

Primary data analysis (80%) is more often used than secondary data investigation (Figure 5). Secondary data analysis, mostly literature review, is mainly used for comparing forest management or risk mitigation strategies implemented by different kinds of forest stakeholders under different legal frameworks and in different geographical areas.

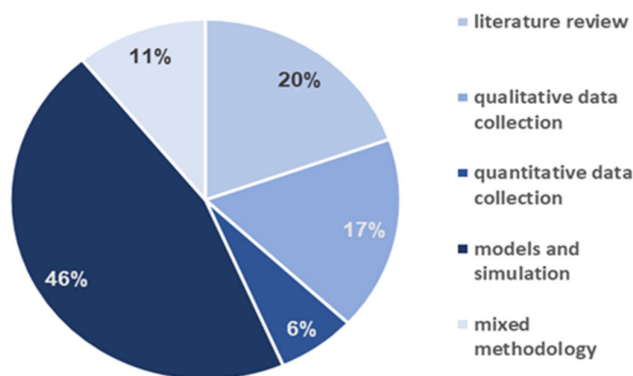


Figure 5. Frequency of different data collection and analysis approaches (source: own elaboration).

Concerning primary data analysis, a mix of quantitative and qualitative methods is used. Qualitative data collection is applied by 17% of papers, mainly adopting semi-structured interviews and questionnaires, e.g., [38,71,72]. These approaches dominate when

researchers aim at detecting factors influencing: (i) decision-making processes related to forest management and silvicultural strategies, and (ii) risk perceptions and mitigation measures implemented by forest-related actors. Direct stakeholders' involvement (with workshops and participatory actions) was applied in two papers (20% of papers that adopted qualitative data collection) to assess private forest owners' satisfaction with post-windstorm measures implemented in one case and to develop a decision support tool for managing windthrow in the other [73,74].

Modeling and simulations stand out as the most frequent methodology adopted to identify windstorm impacts. Empirically based models are widely used to predict windstorm consequences and possible adaptation strategies in economic, decision making, wood market and management of ecological/ecosystem dynamics, i.e., [27,75–78]. Model design is often used to predict multidimensional responses and expected cascade effects among multiple forest SES dimensions. A combination of different modeling frameworks is employed to test actions aiming at attaining simultaneous impacts on multiple dimensions, such as, for example, minimizing forest vulnerability while maximizing productivity.

Similarly, theoretical models are adopted to explore direct and indirect influences of post-windstorm institutional subsidies, insurance programs, and price fluctuations on forest stakeholders' decisions and practices, e.g., [27,79].

However, several studies have emphasized strong limitations to the validation of the model forecasts, mainly due to a lack of data collection and empirical validation of model results [80,81]. This issue is mostly pointed out in relation to analytical models because of the typical oversimplification of the reality implicit in these tools, often based on the use of a few variables not able to comprehensively grasp complexity [82]. Despite their potential in exploring, e.g., large sets of data and covering large spatial areas [14,21,59,83], analytical models tend to not take into consideration, e.g., the role of subjectivity (personal belief and attitudes) or the influence of the external context (peers' or cultural norms influence) in stakeholders' decision making and strategies implementation, even if these elements have a determinant role in policy formulation and measures implementation taking decisions and actions [36,84,85].

3.4. Primary Windstorm Effects

As mentioned, the third database collects primary and secondary windstorm impacts found in the scientific articles analyzed, focusing mainly on consequences on socio-economic, cultural, institutional, and forest governance dimensions. Impacts on silviculture, ecology, mechanization, pest outbreaks, or other non-socio-economic and institutional aspects affected by wind events were identified during the review and included in the analysis only if they were reported as having consequences on or being affected by socio-economic, cultural, institutional and forest governance aspects.

The total number of primary impacts mentioned amounted to 267 observations in total, with an average of six windstorm effects recorded per paper. The scientific articles reviewed pay particular attention to windstorm direct impacts on forest management operations and associated costs, i.e., changes in forest management plans; adaptation of harvesting and forest operations; technological and economic investments, etc. (31% of reviewed papers) [79,86–88]. In particular, the focus was driven by changes in harvesting and salvage logging operations and in forest management plans. Additionally, several in-depth analyses and simulations have considered the spillover effects that these changes had on the economic domain, i.e., timber markets and forest-based value chains.

Conversely, the analysis of direct windstorm impacts on the timber market and wood supply chain corresponds to only 9% of primary windstorm impacts.

The second most studied aspects are forest sector recovery practices and their impacts on forest stakeholders and forest stakeholders' networks (23%)—i.e., changes in forest practices; relations between industrial and non-industrial forest owners; power relations among stakeholders, etc. However, not all forest sectors' stakeholders received the

same level of attention: most of the articles (80.3%) focused on private forest owners' reactions and mitigation strategies, while post-windstorm strategies implemented by public owners, such as municipalities, or in public-managed forests have not been explored. Similarly, post-windstorm recovery measures and changes in practices of other forest sector stakeholders, such as forestry technicians or forest-related industries, were barely assessed.

Windstorm direct consequences at the community level or reactions and mitigation strategies implemented by actors out of the forest sector have received very little attention, representing just 3.8% of total direct impacts categorized within the reviewed papers. A limited number of studies deal with windstorm impacts on cultural dimensions and the tourism sector. Only 4.1% of direct windstorm impacts refer to the cultural dimension, and most of them are related to changes in the landscape and territorial features, while consequences on local tourism and recreational activities are barely considered.

Windstorm impacts on legislative and institutional frameworks constituted 13.5%—i.e., changes in decision-making procedures; changes in forest policy and legislation; changes in governmental aid and technical assistance to private forest owners, etc.—of the total direct windstorm impacts categorized. However, as for the social dimension, impacts on the institutional domain mainly concern the analysis of subsidies and recovery programs implemented in favor of the forest sector and specifically of non-industrial private forest (NIPF) owners. The articles reviewed did not mention institutional measures addressed to other economic sectors, such as linear infrastructure reconstruction.

However, damages to buildings and infrastructures and related economic impacts cover 3% of direct windstorm impacts addressed by the scientific literature reviewed. Similarly, despite the fact that insurance is one of the key measures to cover economic losses deriving from natural hazards [26] and that several authors have depicted ambiguous behavior in relation to their purchase policies [75,89], direct windstorm impacts on insurance markets and policies are also very poorly investigated (3%)—i.e., changes in insurance policies and changes in insurance markets. Finally, impacts on ecological dimensions and ecosystem services—i.e., changes in forest structures and species composition; forest ecosystem biodiversity; changes in forest functions, etc.—together made up 10.0% of total direct windstorm impacts.

3.5. Secondary Windstorm Effects

The direct windstorm impacts had indirect spillover effects on several forest-related domains. In fact, the number of secondary impacts collected almost doubled the number of direct ones, recording a total of 507 spillover/indirect effects.

The economic dimension was most affected by multiple factors, among which a predominant role is played by post-event management strategies and spillover effects arising from harvesting and salvage logging operations (16%), as well as windfall timber management (12%). Additionally, policies implemented at the institutional level, especially subsidies and compensation measures to cover damages and costs, as well as changes in forest management plans have some remarkable consequences at the economic level.

Concerning the social/human-related dimension, the reviewed articles have mainly considered the collateral effects of perceptions, attitudes, and actions implemented by private forest owners (36%) and the influence of post-windstorm institutional strategies on forest stakeholder networks, decision-making process, and power relations (21%).

Indirect impacts on the ecological dimension amount to 17% of the total indirect impacts recorded. Ecological and silvicultural dimensions are mainly altered by changes in forest structure and species composition introduced by private and public forest owners after windstorm occurrence. These changes generally point to introducing more wind-resistant species to mitigate the negative effects of possible future windstorms on the timber market and the forestry sector in general. Indirect windstorm consequences in forestry operations and forest management practices correspond to 13% of the total indirect impacts recorded. This dimension is mainly influenced by changes in post-windstorm

management practices and in forest management plans implemented at a private level. Finally, spillover effects on governance and institutional dimensions correspond to 10% of the total mentioned indirect impacts and are mostly connected to modifications of pre-existing legislation frameworks or to the introduction of ad hoc recovery measures [75,90,91]. Introduction of post-windstorm policies and/or review of the current normative frameworks have cascade effects on forest stakeholders' perceptions and legitimization of institutions that are also considered within the existing scientific literature [38,72].

Figure 6 displays windstorm impacts composition and distribution in the different forest SES dimensions considered, showing how overall windstorm consequences are the result of multiple-interconnected impacts coming from different forest-related SES domains and sectors. Among the most outstanding and relevant aspects, modifications in forest management strategies and forest stakeholders' practices show the highest share and frequency. Focusing on socio-economic and cultural dimensions, the greatest influence is played by windstorm impacts on institutional dimensions, meaning that changes in the institutional role and legal frameworks have repercussions also on socio-economic and cultural domains and, to a lesser extent, on forest operations and ecological dimensions. Windstorm changes at the silvicultural level (dotted squares) have major impacts on environmental dimensions, mainly concerning ecological aspects and ecosystem services provisioning.

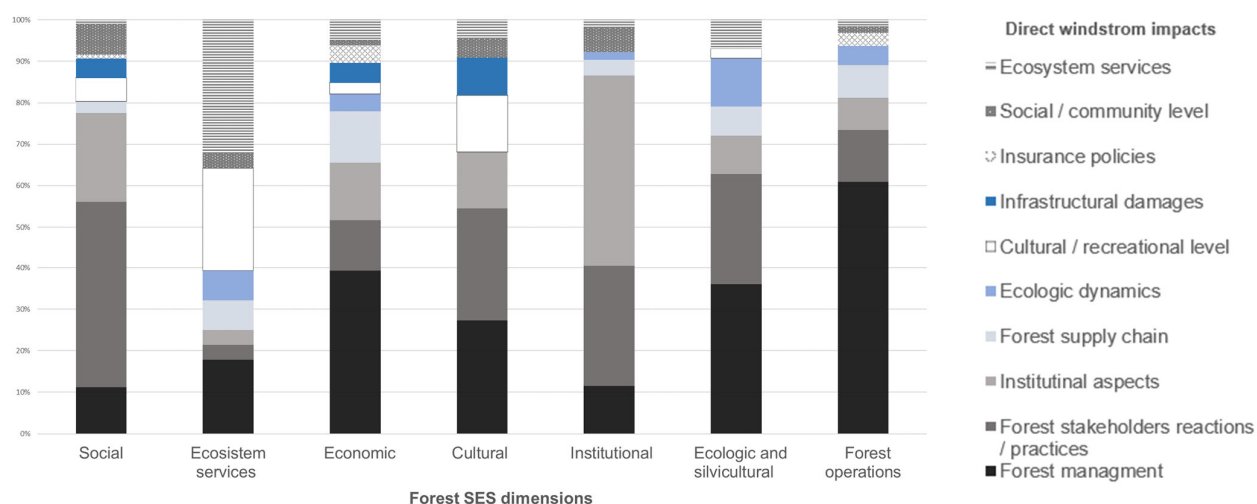


Figure 6. Share of direct windstorm impacts across forest SES dimensions considered (source: own elaboration).

A detailed explanation of cascade effects and interdimensional cause–effect linkages triggered by windstorm impacts on forest-related SES is presented in the discussion session.

4. Discussion: Windstorm Cause–Effect Linkages among Forest-Related SES Dimensions

The review performed for this study confirms that current research assesses windstorm impacts on forest-related SES mainly adopting sector-specific and unidimensional approaches. The scientific literature mainly concentrates on traditional aspects and components of the forestry sector (e.g., forest operations and wood markets) rather than adopting a broader view and more holistic approach, including other relevant societal-related dimensions. This is confirmed by the fact that papers examining windstorm repercussions at the community level or on forest-related goods and services without a direct market value (e.g., cultural ecosystem services) account for only 13% of both the total

primary and secondary windstorm impacts. Similarly, cascade or spillover effects starting from environmental forest SES dimensions and having consequences on the overall society or other, non-forest-related cultural sectors have not emerged. This result points out an important knowledge gap in current scientific research studying windstorm impacts on forest socio-ecological systems. Further, it stresses how, despite forests being widely recognized as socio-ecological systems, the SES framework is not frequently applied in analyzing system response to external shocks.

However, and as expected, the review stresses the existence of strong interconnections among socio-economic and institutional dimensions as well as ecological, environmental, and technical aspects. In the following section, the most relevant windstorm impacts retrieved during the review and the analysis are discussed in detail, stressing transboundary linkages among various dimensions. The issues are aggregated into three thematic groups: (i) forest management strategies; (ii) forest stakeholders' reactions and practices; (iii) institutional support and the role of institutions. A final summarizing sub-section reports the main messages.

4.1. Forest Management Interventions and Strategies

Adaptational changes in post-windstorm forest management strategies are the factors causing major repercussions on all the other forest SES dimensions considered, in particular on economic, forest technology and silvicultural aspects. Windstorms profoundly alter forest management decisions both in the short and long term, involving changes in strategies and policies at the private and public levels [82,91].

The available scientific literature has stressed that in the short term, i.e., within three to four years after a storm, the main problems faced by private and public forest owners regard windthrown harvesting and removing salvaged wood from affected areas [18,90,92]. The urgency of these operations is justified by the need to limit wood quality decline and the consequential decrease in its economic value [93] and timber prices [77,94]. Indeed, assuming that forest stand conditions (e.g., tree age, stability and species composition) are among the main determinants for changes in wood quality and value [73,76], many studies have emphasized the strong impact of immediate forest management response in contrasting wood quality decline [87,95]. In addition, the prompt removal of windthrown and damaged timber would reduce the incidence of pest outbreaks and other biotic agents [28] that often negatively affect the forest health, stability and productivity in the following years. Although there is rich literature on bark beetle proliferation and other pest attacks after windstorm events, this seems to fall outside the scope of the review performed for this study as none of the reviewed papers mentioned these issues. This shows the existence of a significant inter-disciplinary gap in the comprehension of cause-effect linkages between institutional- and environmental-related dimensions. This knowledge gap could consequentially affect the capacity of policymakers and practitioners to react in due time to reduce the medium- and long-term economic and social consequences of natural disturbances (e.g., further reduction of forest production value, degradation of the aesthetic value of forest landscapes, increased ecosystem instability and vulnerability) [28,48]. While intervention measures should be implemented in a timely manner to minimize risks of further damages they also imply additional costs that may challenge especially NIPF owners [96]. Unscheduled harvesting and salvage logging operations generally imply unforeseen costs, derived from investments in machinery and employment of highly specialized workers to minimize the hazardousness and riskiness of post-windstorm forestry operations [74,96]. However, increases in labor and equipment costs are rather necessary to avert work accidents and casualties during the clean-up. Indeed, although the articles analyzed have poorly addressed these aspects, an increase in work-related accidents is one of the major issues connected with post-windstorm forestry operations [97]. As stressed in most of the reviewed papers, the above-mentioned increase in harvesting costs is likely to negatively affect the overall profitability of forest management [18,27,85,98]. The trade-offs between necessary forestry operations and

overall economic outcomes could ultimately discourage private forest owners from implementing unplanned operations [78], especially if the expected stumpage value is negative due to the additional costs borne [88,89]. Besides the increment in costs and expected reduction in profits, the limited availability of adequate human resources and technologies and difficult work-site conditions could disincentive post-windstorm salvage logging operations, again, especially for private forest owners [38,99]. As for the latter, however, empirical studies investigating private forest owners' attitudes towards post-windstorm forest management have highlighted how institutional subsidies, if specifically addressed to harvesting operations or technological improvements, could encourage investments in adequate forest technology [72,100]. The adoption of more efficient harvesting technologies leads to positive effects on timber value, limiting the decrease in quality and consequently in prices [95,101].

What remains out of the lens of the scientific analysis so far are management and recovery strategies implemented in a public forest, and how public forest owners design and organize in a coordinated (or uncoordinated) way post-event interventions at the landscape level. According to the latest survey, the share of European Forests under public ownership exceeds the share of those privately owned [9] (53.5% public owned and 46.5% privately owned). Thus, during post-windstorm forest management formulation, public owners should be a reference for the implementation of strategies that simultaneously satisfy a variety of ES services. Public owners, in fact, in addition to having the responsibility of guaranteeing a fast restoration of the damaged area, should also ensure the provision of a broad range of ecosystem services of public and community interest [102,103], combining timber production with services that meet societal and environmental demands. However, in the papers explored, there is no mention of public forest managers designing restoration strategies. This is another clear knowledge gap that should be addressed in future research.

Concerning the forest industry beyond the forest gate, windstorms, other than determining a shrink in forest productivity and strong fluctuations in wood prices [76], may have several direct and indirect repercussions along the whole wood supply chain. Saturation of the market in the short term could lead to operational difficulties in wood logistics, in particular storage and transportation [27] affecting also the import-export trade balance and domestic wood market [93,104]. While on the one hand storage can be a potential strategy to reduce wood prices drop associated with market saturation [77], storage capability and windfall absorption are strongly dependent on the preparedness of the primary processing industry (e.g., sawmills and pulpmills) to absorb large amounts of raw materials and by infrastructure availability and suitability (e.g., forest road network, wood storage yards and sites, etc.) [34,85]. Besides wood productivity and profitability, also the forest labor market can be indirectly affected at the local level. Indeed, depending on the quantity of windthrown timber and the specificities of forestry operations, the local workforce can be complemented or even replaced by non-local (including foreign) highly specialized companies and workers, especially for salvage harvesting and transportation [85,92].

While in the short term, the forest management choices and forestry operations adopted can influence the economic performances of companies and, more in general, timber prices, in the long term wood market preferences and needs strongly influence forest management strategies and choices, including forest management plans [18,86,90]. Empirical studies developed in Northern European countries have shown how post-windstorm reforestation strategies, in particular with reference to forest regeneration options (e.g., through planting or natural regeneration), forest structure and species selection, are strongly shaped by wood market demand [27,42,105]. The influence of the wood business sector has several implications on forest management: on the one hand, it could affect the implementation of effective risk mitigation and forest resilience strategies [85] and on the other, it could potentially cause conflicts among different forest management approaches and/or the provisioning of different forest ecosystem services and functions

[17,37,72]. For instance, wood market needs for high productivity and profitability often push forest planning toward monospecific stands and wind-vulnerable species [76,106] even though this choice could decrease forest resistance to future windstorms.

Although changes in forest management practices and forest structure are known to affect landscape composition and the associated aesthetic value [97,107,108], a few studies among those reviewed ($n = 8$) focused on how forest aesthetic value is directly or indirectly affected by windstorms. Apart from broad and very general conclusions that report a decrease in forest recreational value after windstorms [2,36,109], specifications or further insights to clarify causes for loss of landscape value are extremely limited. For example, Andersson [81] stressed how recreational attractiveness decreases in young as well as highly managed forests. Fleischer [28] reported a decline in visitors to forests damaged by windstorms due to higher injury risk. Although several articles paid attention to windstorms' repercussions on the overall supply of forest-based ecosystem services [101,110,111], our review has not identified specific studies on the consequences of ecosystem service shortage. This mirrors the still dominant approach of considering forests relevant mainly (or solely) for their provisioning service of timber production, while cultural services (e.g., heritage and territorial identity of the local communities) remain unexplored and undervalued. This is another relevant gap that should be better addressed to recognize and unlock the full potential of forests for improved human well-being.

Lastly, among articles that explored windstorm impacts on forest management strategies, special attention was paid to limitations and barriers that prevent optimal forest management from being implemented that will minimize forest vulnerability to future hazards and maximize the provisioning of different ecosystem services. Many studies modeled various forest management options that, customized on forest structure, tree species and territorial features, simultaneously maximize forest productivity, minimize wind risk damage and balance the supply of different provisioning and regulating ecosystem services. However, their implementation is often tied to several external variables linked with forest owners' attitudes, knowledge availability and economic conditions [112–114] that may limit their effectiveness.

4.2. Forest Stakeholder Reactions and Practices

Economic outcomes of forest-related sectors and wood value chains are strongly tied to forest management practices. Similarly, perceptions, behaviors and information held by stakeholders—i.e., including forest owners, forest consultants, and forest agencies—are key variables in framing forest decision-making and determining response to windstorms.

According to most of the reviewed studies, risk perception, knowledge availability and technical skills are core variables in determining forest owners' response strategies and future management plans for windstorms [38,82,115]. Several articles identified the fact that private forest owners perceive wind risk as one of the most frequent and impacting risks that are likely to affect their forests [36,91]. Experiencing a windstorm increases forest owners' risk perceptions as well as their awareness of the importance of implementing measures to minimize wind risks [38,85]. Nonetheless, all the reviewed studies investigating forest owners' management practices stressed how the implementation of new and more efficient management practices after a windstorm is almost absent [85,116]. When implemented, they mainly consist of minor and reversible changes linked to technological aspects [36,72]. Thus, although the importance of implementing wind-risk adaptation measures is broadly recognized, their implementation in practice remains extremely limited and hindered by several constraints.

One of the main determinants limiting forest owners' adaptation capacity is the strong risk-aversion characterizing their behavior and managerial approach [79,89]. This was confirmed by Lidskog and Sjödin [90] who stressed how, especially after having experienced windstorm damage, forest owners' managerial preferences are oriented towards long-term and experience-based practices rather than the application of expert-

based recommendations. The economic losses, combined with the feeling of sadness and powerlessness caused by the destruction of the forests [90,91] lead to the implementation of reforestation practices that tend to re-establish the pre-windstorm forest structure and species composition, despite their inadequacy in decreasing forest sensitiveness to wind hazard [72]. In addition to a risk-averse attitude, implementation of innovative forest management practices are hampered by NIPF owners' lack of knowledge and technical abilities [85,91]. The investigated articles stressed a limited knowledge regarding the management of tree species different from those already planted or innovative forest management practices and technologies [36,72]. Additionally, a great percentage of private forest owners showed a general lack of information about practices to minimize risks caused by biotic and abiotic damaging agents [62]. This gap on the one hand limits the adaptation of forest practices and improvements in forest management, and on the other, it influences relations among forest sector stakeholders. Andersson [60] and Keskitalo [113] pointed out how limited access to financial resources and technical information restricted the bargaining and market power of NIPF owners with respect to industrial ones. Different needs and expectations regarding the final use of forest products and services in some cases cause disagreements and conflicts relative to management practices, reforestation plans, formulation of public policies and the overall post-windstorm management [72,117]. Surprisingly, no specific information is available on public forest owners and their reactions and organizational capacity.

Quite surprisingly, the review has also highlighted an ambiguous forest owners' attitude towards forest consultants and technicians. If on the one hand, NIPF owners recognize the usefulness of their assistance in managing extraordinary situations in the short term, on the other, the uncertainty around future windstorm impacts, the economic profitability of different tree species, and future return of technological investments threaten the credibility of consultants' advice and implementation of the suggested measures [38,91]. Conversely, windstorm occurrence increases information exchange and the role of the group of peers in decision-making and implementation of forest management practices [90]. Indeed, windstorms have a positive influence on private forest owners' ties, increasing collaborations and mutual support [25], thus leading to the feeling that overcoming the storm was a social and common achievement [100].

The analysis of scientific literature has revealed a consistent research gap regarding windstorm direct and indirect effects on the forest-related community and non-forest sector stakeholders. Despite there being greater recognition of the role that community or private corporate partnerships have in restoring damaged forest areas, none of the articles analyzed response actions from a societal point of view in depth. The few articles that addressed the impacts of windstorms from a societal point of view mainly focused on personal attitudes and perceptions in relation to climate change. Blennow [37,97] reported higher sensitivity towards climate change issues and higher individual engagement in natural resource management after having experienced wind hazards. This was also confirmed by Angst and Volz [74] and Sousa-Silva [114] who reported similar reactions during their empirical investigations in Switzerland and Slovakia. However, a more comprehensive and elaborated analysis of improvements in natural resource management or empirical examples of formal and informal resilience actions proving higher community participation in forest and other natural resource management has not been reported. Undoubtedly, the highly fragmented and localized nature of the post-windstorm community and corporate actions hinders the exploration of these measures. However, considering their relevance, further research is needed to fully explore this phenomenon. Finally, our analysis also highlighted a research gap in understanding windstorm impacts on society's wellbeing, sense of place and risk perception. Windstorm repercussion on communities was explored only in terms of infrastructural damages and shortages in services, e.g., [97,110,118,119] without deepening possible impacts at the psychological level or changes concerning the sense of place and community identity.

4.3. Institutional Support and Role of Institutions in Post-Windstorm Management

Institutions and governmental agencies dedicated to the management of forest and forest-related resources are identified as leading actors in post-windstorm management [34,90]. Besides designing and applying direct interventions for mitigating immediate losses deriving from forest damage and wood price fluctuations [77,100], they play a key bridging role among actors [120]. On the one hand, they have to mediate among needs and expectations of different forest sector stakeholders [34], ensuring the widest acceptability of the solutions proposed [104], while on the other, they should balance economic profitability with the fulfillment of broader societal expectations linked, for instance, to environment and natural resources protection and different forest ecosystem services [17,42]. Fragmentation of roles and responsibilities, and lack of communication among agencies are among the most frequent potential risks for ineffective post-windstorm management [34]. The wide range of actors and their demands/needs for different and sometimes diverging forest resources and services makes the identification of adequate and broadly supported solutions and programs difficult. This was empirically confirmed by Cauria in [104], which highlighted how the acceptance of proposed solutions and programs strongly depends on the equity among the different activities and specific sectors subsidized. Apart from affecting power relations among forest stakeholders [36] and governance dynamics within the forest sector [21], the allocation of compensation measures has a decisive impact on stakeholders' legitimization of governmental measures [38]. However, if private owners' acceptance of economic strategies proved to be ambiguous, the involvement of consultants' and forest technicians' support increased confidence in governmental institutions [90,100]. The availability of public forestry extension services and their technical support in forest management were valued extremely positively by non-industrial forest owners [117]. The articles retrieved only mention public consultants, while private consultancy services are not taken into consideration. This may be due to a scarcity of private forest consultants and larger availability of public forest assistance, however, currently available research does not confirm this hypothesis. An in-depth study comparing the availability of private and public forest consultancy services in European countries could represent a useful future development.

From an economic perspective, several authors, e.g., [71,119] stressed that the financial compensation mechanisms are not always able to support the long-term financial recovery of the forest sector's stakeholders, especially with reference to private forest owners. While governmental subsidies can limit negative consequences in the immediate post-event phases and boost technological investments [100] the lack of a long-term view limits non-industrial forest owners' economic self-sufficiency [75]. This was discussed in several articles, especially in relation to forest owners' wind risk adaptation strategies, stressing how the expectations of governmental aid compensating windstorm damages decreases the implementation of preventive wind risk-reducing measures [75,89,104]. Post-windstorm governmental compensation measures are likely to have a negative impact on private forest owners' risk behavior, inhibiting the introduction of efficient risk-reducing measures, as well as the efficiency of the insurance market [71].

The correct management of public compensation measures after windstorms can be approached as a free-riding problem [121,122]. Indeed, the presence of public subsidies restrains the formulation of adequate insurance policies that meet forest owners' needs and willingness to pay [71,79]. Thus, despite insurance coverage being identified as a good option for compensating wind damages [27,98], the limited number of stipulated insurance policies hampers the identification of optimal insurance features that respond to forest owners' preferences and utility function [71,89].

Our analysis showed that institutional policies not only have several short- and long-term repercussions on: (i) economic performances of the forest sector, (ii) insurance market efficiency, and (iii) forest stakeholders' behaviors but they also strongly influence ecological and environmental dimensions [117]. Windstorms could be seen as external drivers that question the efficacy of current forest management [102]. Thus they could be an

opportunity for introducing new normative and/or managerial frameworks that will ameliorate existing forest management and planning approaches [84,86,87]. This aspect was explored in several articles [73,74,103], especially those examining post-windstorm policies and models aiming at conciliating timber economic profitability with the provision of other ecosystem services. However, none of the articles retrieved reported post-windstorm policies that successfully improved the existing forest management moving towards a multifunctional and multi-purpose one [102,115]. Evidence about how windstorms could improve forest management is still lacking [19,23], while informal discourses emerging among practitioners, scholars, politics and public authorities show that windstorms might have also positive implications. For example, they may determine an increase in research funds, more political attention on forests, and landscape changes that are more appreciated by tourists in certain mountain contexts (e.g., from forests to pastures, or other types of open scenarios). Further research would help in better understanding these secondary effects, that seem currently neglected.

A relevant gap that emerged from the analysis of the scientific literature is the paucity of studies that investigate management and post-windstorm strategies implemented in publicly managed forests. Indeed, in the articles reviewed, the role of forest-related institutions is analyzed in relation to measures and policies addressed to the management of private forests and private forest stakeholders. Nonetheless, public forest owners represent a relevant percentage of total forest ownership and would have a special role in restoration strategies for the benefit of the entire community, as mentioned in the previous section.

4.4. Main Traits of Socio-Economic and Institutional Windstorm Impact Analysis and Cause–Effect Visualization

The scientific literature considered for the aims of this paper has revealed that current knowledge on windstorm impacts at socio-economic and institutional levels is quite clustered on specific, highly-focused variables and dimensions, mainly related to forest management, forest stakeholders and forest industry sectors. Nonetheless, the influence of social and cultural variables was stressed not only as concerns relations among stakeholders but also on forest management strategies definition and implementation [115] (Figure 7). Within the reviewed articles, a strong emphasis was given to private forest owners' management and behavioral/attitudinal changes and timber market fluctuations, while no attention was paid to windstorm cascade impacts along the entire forest-based sector value chain.

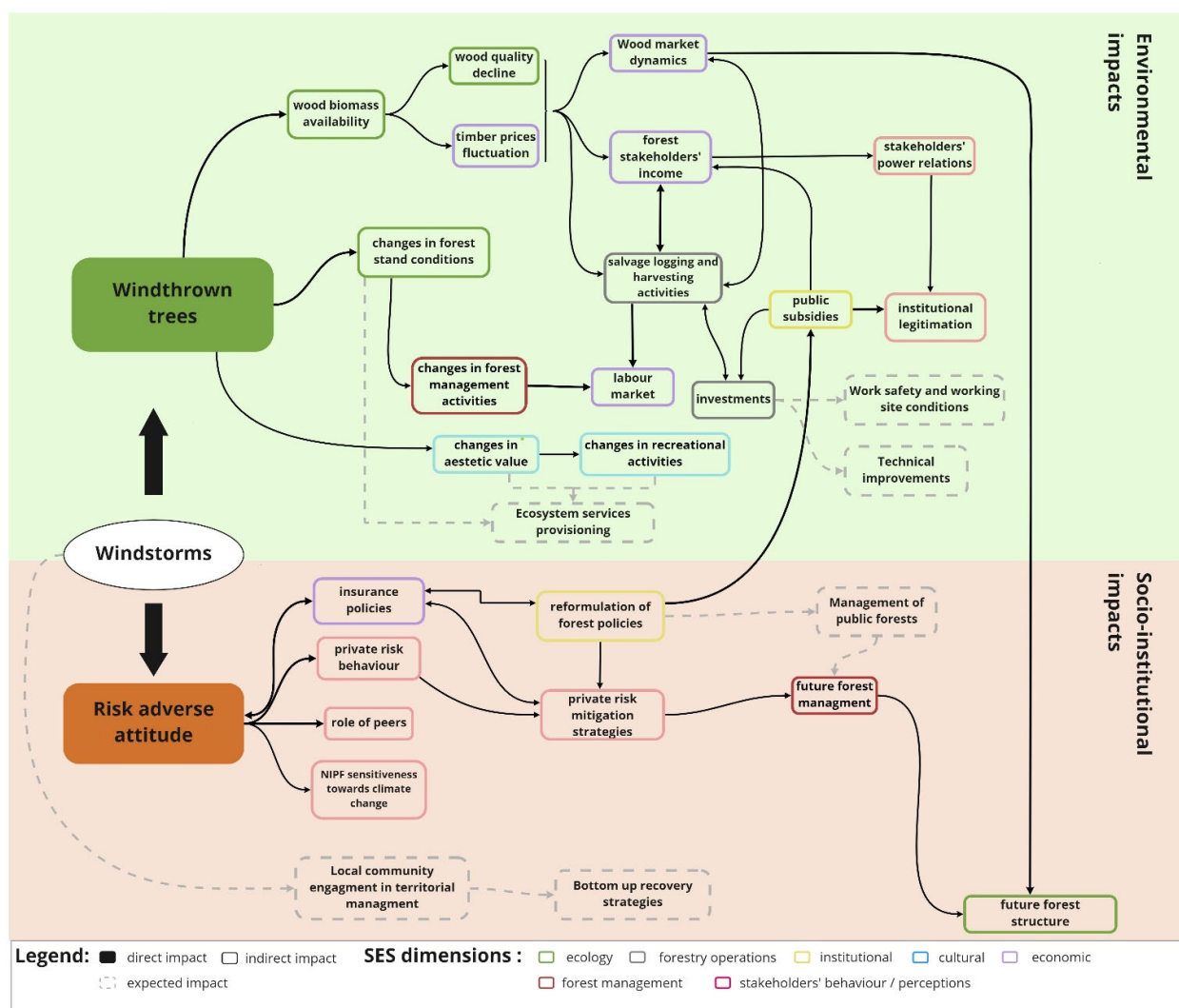


Figure 7. Causal map of the most relevant windstorm cause–effect linkages among forest SES dimensions and related knowledge gap as emerging from the articles analyzed. (Source: own elaboration).

Despite existing studies having been mostly undertaken with a unidimensional focus, the systemic approach implemented in the review has allowed the framing of a wider picture of windstorm impacts on forest-related SES. Several spillover and cascade effects influencing resilience while building on socio-economic and institutional dimensions were identified, thus contributing to a more comprehensive understanding of current knowledge gaps and future research needs. Figure 7 displays the most recurrent cause–effect linkages and windstorm spillover effects discussed in the papers we analyzed, mainly focusing on drivers influencing socio-economic and institutional resilience. The figure is a simplified version of the broad net of multiple cascade effects and feedback loops provoked by windstorms in forest-related SES. Thus, not all the impacts retrieved are included, as the focus is on the most relevant and recurrent ones. Direct windstorm impacts are reported in squared colored shapes and indirect impacts in rectangle plain shapes. Dotted arrows and shapes in light grey refer to impacts not discussed in the papers reviewed, but that—in our opinion—are likely to strongly influence one or more of the dimensions considered. They were included in the causal map to highlight knowledge gaps in the current scientific literature, identifying aspects not yet explored by scientists.

The final aim of the map, and of the overall approach implemented, is to increase the visibility of interconnections between human and environment-related dimensions and better acknowledge their role in shaping socio-economic and institutional adaptability towards extreme natural events. Moreover, it helps to identify socio-economic and institutional impacts of forest windstorms that have not been explored yet.

The most significant direct windstorm impacts (square shapes) identified from the reviewed papers could be grouped into two main categories: (i) ecological ones (upper part of the map) that starting from windthrown trees have primary consequences at the environmental and ecological level and secondary spillover effects on socio-economic and institutional dimensions; and (ii) social-institutional ones (lower part of the map) that mostly deal with changes in individual risk perceptions triggering cascade effects at institutional and managerial level and influencing forest ecosystem dynamics in the long run. These two blocks have spillovers and cascade effects in several forest-related SES dimensions that interact with each other and influence private forest management choices, institutional policies, timber, and insurance markets.

Post-windstorm institutional frameworks and private forest owners' risk perceptions can be identified among the most relevant factors influencing post-windstorm recovery strategies. These aspects mutually influence each other and have further consequences on forest management plans and actions implemented at the public and private levels, determining future forest structure and composition [71,87,90]. On the one hand, institutional support, both in technical and financial terms, boosts the forest sector's responsiveness, limiting losses [75,95] and smoothing economic disparities among multiple actors in timber and forest-related markets. On the other, post-windstorm policies and strategies strongly influence the legitimization of public institutions by the stakeholders, as well as the acceptance of existing forest management rules and legal frameworks [18,81,108]. Besides influencing socio-economic dimensions in the short term, post-windstorm institutional arrangements have long-term consequences in shaping forest stakeholders' risk perceptions and the implementation of mitigation strategies [71]. Private risk behaviors and forest management decisions shape features and characteristics of future forest ecosystems and influence forest resilience and resistance to future climatic events [33,123]. This cause–effect interaction can serve as an example to demonstrate how the bi-directional link between the social and the ecological components of forest-related SES works in practice [3,65].

Building on visual mapping of cause–effect linkages, it is possible to highlight aspects that are already covered by existing research, such as post-windstorm dynamics relevant for the recovery of forest SES and windstorm economic consequences, as well as research gaps, i.e., issues that are still poorly studied in the existing scientific literature. The map also includes effects that have not explicitly emerged from the papers reviewed, but that are nevertheless considered relevant based on our empirical experience of windstorm effects in Italy: they are reported in the form of dotted rectangles (light grey color) and discussed below. This represents our original contribution to the identification of the most relevant existing knowledge gaps and to potential future research directions to enhance the comprehension of complex interactions amongst social and institutional aspects of forest SES.

While various economic and institutional aspects were explored, even if not in a systematic way, windstorm consequences on social aspects seem to be far less investigated. In particular, post-windstorm recovery strategies informally implemented by citizens, civil society, third sector associations and private enterprises have not been taken into consideration. Nonetheless, they have emerged as increasingly relevant for climate mitigation actions and the promotion of resilience strategies, especially at the local level [124,125]. The role of local communities (beyond forest owners and local agencies and institutions) as a key player in enhancing resilience capacity is not sufficiently considered. Similarly, windstorm consequences at the individual level were analyzed only for NIPF owners. Among articles analyzed subjective reactions of community members are not

considered. Undoubtedly several methodological challenges exist in assessing individual post-windstorm responses and attitudes, however, such an analysis could provide important feedback on individual risk and resilience perceptions [126]. Thus, it is crucial that future research acknowledges and investigates the role of bottom-up post-event action organized by the civil society, as well as examining windstorm responses at the individual level (including psychological consequences in the long term, that might not be temporary).

Likewise, social and economic costs derived by changes in forest ecosystem services without an explicit market value, in particular cultural services such as recreational ones, have received very poor attention. Little emphasis was given to strategies implemented to cover losses in the tourism sector, rural development and agriculture or to mitigate the decrease in the provision of forest socio-cultural and recreational services. Although non-wood forest product gathering is one of the most performed forest-related activities and the associated market value is extremely relevant [9], no attention was paid to windstorm impacts on this domain.

An additional research gap, already stressed in the previous sections, is the lack of analysis of management and restoration strategies implemented by public forest owners. Even if the existing scientific literature seems to neglect the role of public forest owners in post-windstorm forest management and planning, their management choices are extremely important. Being responsible for public and common goods, public forest owners' strategies should have broader restoration goals than private forest owners' ones, aiming to reconcile different services and functions of forest SES and harmonize trade-offs and conflicts [47,103].

Lastly, the articles considered by the review have mostly analyzed technological innovation and investments concerning forest mechanization and forest operations in relation to their positive impacts on production, timber quality and value. Nonetheless, investments and improvements in technology also have positive spillovers and impacts on workers' safety, ultimately limiting the hazardousness of operations. Considering that work-related accidents are one of the major issues connected to forest damage, windstorm impacts on mechanization and the forest operation dimension should be disentangled also from a societal perspective, mentioning positive or negative repercussions on the labor market and work-site conditions.

Since our study focused on analyzing primary and secondary windstorm consequences on socio-economic, institutional, governmental and cultural aspects, interactions among biotic and abiotic disturbances that may arise after windstorms have not been deepened. However, interactions among natural disturbances with effects on socio-economic and institutional dimensions deserve to be further investigated in future research.

4.5. Suggestions for Post-Windstorm Policy Design

Besides disentangling several cause–effect linkages and cascade effects among multiple forest SES dimensions, the above-reported map allows some blueprints useful for effective post-windstorm strategy formulation to be identified. A systemic and comprehensive approach is crucial to having a full understanding of the short-, medium- and long-term repercussions of designed strategies [23,45]. Such an understanding, in addition to entangling the full range of consequences deriving from strategies, is likely to positively impact the coordination among forest and non-forest stakeholders, address multiple needs and expectations concerning forest-related goods and services, and reduce potential conflicts [27,127]. A multidisciplinary perspective in policy formulation would also benefit the formulation of robust indicators to monitor the effectiveness and appropriateness of post-windstorm strategies implemented in the long run [27,45]. To grant interdisciplinarity, improving research funders/donors' awareness regarding the importance of supporting multidisciplinary research through diversification of project mandates and financing would also be important.

Moreover, forest policy analysis should include extreme climatic events under their lenses and research attention: the current scientific knowledge gap on institutional and policy impacts of windstorms might be due to the fact that the forest policy (and governance) studies are often conducted in global, European or national levels; while the windstorms impacts at institutional level occur mainly at the local level in those administrative units that were directly affected by the event.

Review outcomes have also underlined some strengths and weaknesses that should be considered during policy design and the decision-making process. The support of multifunctional forestry by including multiple forest-related services in the formulation of forest management plans will positively impact the effectiveness of resilience strategies while ensuring a balanced and sustainable use of forest resources in the long term [102]. Looking at community resilience, the role of private actors and civil society in post-windstorm recovery and, more in general, in climate change mitigation, should be emphasized and supported by public policies [128]. Bottom-up recovery and mitigation strategies are extremely important for ensuring widespread and comprehensive resilience. Institutional support for these actions can, on the one hand, empower local communities, and on the other, stimulate interest in the environment and climate-change-related issues [129]. Likewise, private companies and enterprises are emerging as key partners that should be included in the development of climate-change mitigation actions, by means of, e.g., new public–private forms of partnership for forest management. In order to boost resilience to future climate-change risks and natural events, encouraging bonded and collaborative communities is as important as developing sustainable and integrated forest management strategies [130].

5. Conclusions

This paper represents a first attempt to improve the current state of scientific knowledge related to windstorm consequences on forest-related SES in Europe. We provided an integrated analysis of major windstorms' cascade effects and cause–effect linkages on socio-economic, institutional and governance aspects analyzed in scientific research, which are not comprehensively explored.

Although scholars and policymakers tend to emphasize the plurality of stakeholders and actors connected to forest-related SES and the wide range of ecosystem services provided by forests, our review highlighted that existing knowledge is still quite limited and specialized in a few aspects: windstorm impacts are prevalently investigated with a narrow and mono-sectoral focus (wood sector industry and related stakeholders), ultimately failing to consider the full range of sectors, actors and SES dimensions that are directly or indirectly affected by windstorms. A system thinking and system dynamics approach is missing.

Very little attention is paid to consequences on community wellbeing, social risk perceptions/attitudes, and factors that boost the resilience of forest ecosystem services different from timber with no direct market value, but with high identity values such as traditional landscape, non-timber forest products and cultural heritage. Similarly, the understanding of socio-economic drivers in play behind the implementation of forest management strategies, and the cascade effects that such strategies have on social dimensions and ecosystem services provisioning is still very limited. So far, scientific investigations have approached issues related to forest management and forest operations dimensions mainly from a technical and economic point of view. Nonetheless, entangling forest operations repercussions on social dimensions, such as consequences on the local labor market, workforce working conditions and safety, would be extremely important to support the local workforce, promote specialized training courses (e.g., on how to manage the special dangerous conditions of forest operations after windstorms), reduce the risk of illegal/informal employment and support safer working conditions.

Finally, the retrieved articles focus predominantly on: (i) short-term windstorm consequences (i.e., within five years of the event); and (ii) large windstorms affecting

Northern and Central European countries. These results highlight the need to draw scientific attention to long-term impacts at different economic, spatial and social scales and exploring also small windstorm consequences, which are likely to have strong socio-economic repercussions on affected local communities. Additionally, reporting the consequences of windstorms that hit Southern European forests would allow us to identify eventual differences in impacts and consequent resilient strategies implemented across European countries.

The limited knowledge of windstorm consequences on socio-economic, institutional and governance dimensions leads to an incomplete and short-term focused understanding of variables and dynamics shaping adaptability to windstorms. These knowledge gaps potentially hinder the development of effective measures to increase the resilience of forest SES thus inhibiting a sustainable and effective long-term recovery of communities hit by storms. Likewise, the operationalization of resilience strategies is reduced by a poor understanding of specific contextual factors and drivers that guide decision-making and policy implementation, causing a mismatch between theoretical models for the improvement of forest management and the management choices and operations that are actually implemented on the field.

Due to the specific aim of the review, the analysis of socio-economic and institutional dimensions was prioritized. On the one hand, this has prevented gaining a complete overview of windstorm impacts on forest SES, but on the other, it has highlighted topics and scientific areas where further research is needed. Further, some biases are caused by the inclusion–exclusion criteria set for the papers search, e.g., restricting the research to English-written articles might have excluded relevant studies written in other languages in countries directly affected in the past by important events (e.g., France, Czech Republic). Moreover, we choose to focus only on peer-reviewed literature, excluding from the analysis grey literature and technical reports. While we acknowledge the existence of a rich grey literature in relation to windstorm impacts management, a systematic review of this literature would have been extremely challenging and would have very likely resulted in being incomplete and difficult to replicate. Combining the analysis of academic and non-academic knowledge related to windstorm repercussions on forest SES would be an important aspect to address in future research.

Despite the above-mentioned limitation, our research has identified several aspects that would deserve further research to provide scientific knowledge able to contribute to reducing the vulnerability to windstorms of European forests. On the one hand, a more in-depth understanding of socio-economic and institutional windstorms' response dynamics would help to support the formulation of more effective policies and strategies to boost community and forest-related SES resilience; on the other, it might help to identify appropriate indicators to address the evaluation of post-windstorm policies and strategies implemented on the ground.

In line with the most recent international studies on complex SES, our research highlighted the need to implement an analytical approach consistent with the holistic nature of forest SES. Further than improving the understanding of windstorm consequences, the approach used in this paper could also be applied to assess the impacts of extreme events and hazards in general (e.g., wildfires, floods, pest outbreaks). This methodology would allow a broader and more complete picture to be obtained of extreme weather event impacts on multiple stakeholders and sectors involved in forest resource management. In turn, this would enable the development of more comprehensive considerations about the resilience of forest-related communities.

Author Contributions: Ideation and conceptualization, L.S., M.M. and F.R.; database searches, application of inclusion criteria, data collection and analyses and paper draft preparation, F.R.; study design and methodology definition, F.R., M.M. and L.S.; review and editing, M.M. and L.S.; supervision: M.M. and L.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research has been by the University of Padova in the framework of the project “Vaia FRONT” (grant CAVA_SID19_02).

Acknowledgments: We thank TESAF Department of University of Padova for supporting this research through the provision of a Ph.D. scholarship in the LERH Doctoral School. We thank the “Young Scientist For Vaia” initiative. We would like to acknowledge Kristina Blennow for the insightful feedback she gave to the manuscript and also thank several colleagues that have provided feedback and hints throughout the development of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Search Strings

Table A1. List of search strings used in Scopus database for paper selection.

Round of Review	Search string in Article, Abstract, Keywords	No. of Papers
First round	Windstorm OR hurricane AND Soc* AND econom* AND European	33
	Wind* OR hurricane* AND damage* AND cost* AND community	132
	Forest* AND wind* AND soc* AND econom* AND impact* AND Europe	12
	Forest* AND wind* AND soc* economic* AND damage*	51
	Forest* AND wind* AND soc* economic* AND damage* or cost*	85
	Forest* AND wind* AND soc* AND econom* AND effect*	135
	Forest* AND wind* AND soc* AND econom* AND risk*	59
Second round	Forest* OR woodland AND wind* AND disturb* OR damage* AND soc* AND economic* OR financial*	84
	Forest* OR woodland AND wind* AND disturb* OR damage* AND ecosystem* AND service*	99
	Forest* OR woodland AND wind* AND disturb* OR damage* AND institution* AND govern*:	5
	Forest* OR woodland AND wind* AND disturb* OR damage* AND poli*	17.420
Total of both rounds		18.115

The asterics * is used to replace multiple characters, thus allowing to search for several related words (e.g., disturb* could stand for disturb, disturbs, disturbance or disturbances).

Appendix B. Dimensions and Categories Used in Data Categorization

Table A2. List of dimensions, macro-categories and sub-categories used in data categorization.

Dimensions	Effects	
	Macro-Categories	Sub-Categories
Cultural	Recreational activities	(1) Leisure activities
	Knowledge production	(2) Hunting activities
	Tourism sector	(1) Academic knowledge
	Traditional forest use	(2) Technical information
	Landscape value	
Economic	Timber market and prices	(1) Wood quality
		(2) Timber prices fluctuations
		(3) Raw material availability
	Forest stakeholders' income	(1) Non-industrial private forest owners
		(2) Forest sector supply chain
		(3) Forest related industries

		(4) Primary processing industries
	National and international trade	(1) Import/export balance trade (2) National timber market features
Ecosystem services provisioning	Provisioning services Regulating services	
	Forest management	(1) Plans (2) Strategies (3) Operations
	Forest operations	(1) Costs (2) Investments (3) Labor specialization (4) Technological improvements (5) Windthrown management and logging
Forest management and operations	Wood logistics	(1) Transportation (2) Storage (3) Infrastructure
	Risk mitigation strategies	
	Pest Outbreaks	
	Forest structure	(1) Species composition (2) Fragmentation and tree dieback (3) Natural subsequent disturbance
Forest ecology	Forest regeneration dynamics	
	Role of institution	(1) Policy formulation (2) Leadership and coordination
	Institutional support	(1) Financial compensation/subsidies (2) Technical assistance
Institutional	Local population engagement	
	Stakeholders' engagement	(1) Management of different interests
	National and international legal framework	(1) Risk mitigation strategies
Insurance sector	Insurance market Insurance policy	
	Private forest owners' reactions	(1) Post-windstorm behaviors (2) Beliefs and attitudes (3) Technical skills (4) Management Plans (5) Psychological wellbeing
Social	Forest stakeholders' interactions	(1) Private/public sector interactions (2) Stakeholders' networks/peers relations (3) Power dynamics (4) Decision making process
	Community related aspects	(1) Health and wellbeing (2) Engagement in Environmental protection
	Forest consultants	(1) Attitudes and perceptions (2) Technical skills
	Infrastructural damages	

Appendix C. Methodological Approach for the Categorization of Observations: An Example

The text below is extrapolated from the article “In the eye of the storm: adaptation logics of forest owners in management and planning in Swedish areas” [36]. In this paragraph direct and indirect windstorm consequences are detected and coded following the “Dimension” — “Macro-category” and “Sub-category” coding system explained in Section 2.3 of this review.

“The economic implications of storms are thus a great concern and challenge to the interviewees in their forest ownership, mainly because of their level of economic dependence on their forest. A number of them talked about their own and neighbors’ losses due to the storm, and emphasized the great values that disappeared overnight and the dreams and plans connected to these”...“This situation of uncertainty introduced instability into the discourse on forest management and the authorities within the field. In relation to their own capacities and resources, some of the forest owners expressed this uncertainty about whom to trust, both in terms of advice on forest management and in the event of a future storm”...“How the storm altered their perception of forests and forestry was thus a recurring theme among many of the forest owners. It forced them to change not only their understanding, but also their actions in relation to their forest.”

Table A3. Exemplification of coding and categorization process.

ID	Direct Windstorm Effect			Related Text	Secondary Windstorm Effect			Related Text
	Dimension	Macro Cat.	Sub. Cat		Dimension	Macro Cat.	Sub. Cat	
1	Forest Ecology	Forest Structure		<i>their own and neighbors' losses due to the storm</i>	Economic	Forest stakeholders' income	NIPF owners	<i>The economic implications of storms are thus a great concern</i>
					Social	Private Forest owners' reactions	Belief and attitudes	<i>great values that disappeared overnight and the dreams and plans connected to these</i>
2	Social	Private Forest owners' reactions	Belief and attitudes	<i>This situation of uncertainty</i>	Forest management and operations	Forest management	Plans	<i>instability into the discourse on forest management and the authorities</i>
					Social	Private Forest owners' reactions	Technical skills	<i>In relation to their own capacities and resources</i>
					Social	Private Forest owners' reactions	Belief and attitudes	<i>some of the forest owners expressed this uncertainty about whom to trust, both in terms of advice on forest management and in the event of a future storm</i>
3	Social	Private Forest owners' reactions	Belief and attitudes	<i>the storm altered their perception of forests and forestry</i>	Forest management and operations	Forest management	Strategies	<i>It forced them to change their actions in relation to their forest</i>

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