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Windstorm impacts on European forest-related systems: An interdisciplinary perspective

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ABSTRACT

Windstorms are considered the main disturbing abiotic agent in European forests. They affect a multiplicity of forest-related dimensions, such as forest ecology, forest operations, geomorphology, economy, and socio-cultural aspects. Due to the complex dynamics set off by windstorms, the design of post-windstorm forest management should be characterized by an interdisciplinary approach able to address multiple environmental and social needs. However, scientific literature investigating the impacts of windstorms on forests appears mainly focused on specific aspects. An interdisciplinary and more comprehensive approach is needed to cope with such multi-facet phenomena and to address future forest research.

We reviewed current literature analyzing consequences of windstorms on European forests focusing on interconnections and cascade effects among forest-related dimensions in post-windstorm dynamics. We performed an in-depth review of 111 articles to detect most recurrent direct and indirect impacts as well as cascade effects among ecological, geomorphological, operational, economic, socio-cultural, and institutional forest-related dimensions. Our analysis aimed at providing a detailed analysis of the state of the art of windstorm impacts on European forests reported in literature, and suggesting an innovative approach to analyze windstorm consequences at a systemic level to acquire a comprehensive overview of post-windstorm dynamics.

Our results showed that most of the studies dealt with interactions among ecological components of forests, but links between ecology, geomorphology, and society have been poorly studied. These knowledge gaps reduce the comprehension of windstorm impacts in the short and long terms and overlook the influence of societal-related aspects in post-windstorm forest management. Moreover, our analysis suggested the need of a post-windstorm management acting at systemic and comprehensive level, supported by forest policies that promotes multifunctionality to overcome challenges derived by natural disturbances intensification.

1. Introduction

Covering 33% of the European territory, forests provide a large variety of ecosystem services (ES), which are fundamental to fulfill environmental and societal needs, as well as for tackling challenges posed by the current climate change crisis (Blanco et al., 2017; Forest Europe, 2020; Härtl et al., 2016; Nordström et al., 2019). Nonetheless, forests are among the most vulnerable ecosystems to changes in climate and are exposed to a growing number of stressors (Forzieri et al., 2021; Johnstone et al., 2016; Wunder et al., 2021). Climate change is increasing the

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frequency and severity of natural disturbances, and poses important questions about the adaptability of current forest management approaches to future challenges as well as about the future provisioning of forest ES (Lundholm et al., 2020; Messier et al., 2019).

Wind has been identified as the main abiotic disturbance agent in Europe (Forzieri et al., 2020; Roberts et al., 2014; Spinoni et al., 2020). Between 1950 and 2000, windstorms accounted for 53% of the total damage caused by abiotic agents to European forests, totaling more than 900 million m^3 of windthrown timber with an average yearly damage of 18.7 million m^3 (Gardiner et al., 2013; Schelhaas et al., 2003). Though often unevaluated and poorly studied, wind damage also affects many relevant non-wood forest-related ES, such as water purification and nature-based recreation (EEA, 2017). Due to current changes in climate and disturbance regimes the vulnerability of forests and forest-related systems is increasing (Seidl et al., 2016), and current climate projections suggest a potential increase in windstorms' vulnerability and exposure (Moatti and Thiébault, 2016; Patacca et al., 2022; Spinoni et al., 2020). Under these conditions acquiring a broader vision of windstorm impacts that encompasses both environmental and human forest-related dimensions is necessary.

However, most of the scientific literature investigates windstorm impacts on forests adopting a discipline-specific approach, with a predominant focus on environment-related and management-related aspects (Härtl et al., 2016; Leverkus et al., 2018a; Müller et al., 2019). This approach is in line with the majority of studies investigating natural disturbance impacts on forests, that mainly adopts a unidimensional and discipline-specific approach (Messier and Puettmann, 2011; Nikinmaa et al., 2020; Rist and Moen, 2013), focusing on disturbance consequences on single forest-related dimensions (e.g. silviculture, forest operations, forest value chain, etc.) or in few specific aspects of forests or forest-related systems (e.g. forest regeneration, species composition, timber prices fluctuations, forest operations techniques etc.) (Filotas et al., 2014; Härtl et al., 2016; Huber et al., 2013; Messier et al., 2019).

Due to this lack of interdisciplinary and systemic analyses, research on forest-windstorms relations might lead to a partial understanding of the multi-facet consequences of windstorms (Filotas et al., 2014; Wunder et al., 2021). In particular, post-windstorm dynamics driven by cascade effects and causal relations among forest-related dimensions remained often unexplored. Similarly, the interactions between societal and environmental aspects that characterize windstorm response (e.g. bottom-up community recovery strategies and forest management) are often neglected and overlooked (Aquilué et al., 2020; Heinimann, 2010), thus not properly guiding policymakers and political actions.

This paper is a first attempt to overcome fragmentation and sectorization of the knowledge concerning windstorm consequences and post-windstorm management in European forests. We performed an interdisciplinary review and analysis of the scientific literature to gain a better understanding of post-windstorm dynamics on European forests and forest-related systems. We approached the analysis of literature using a systems thinking approach. Systems thinking is an approach and analytical framework that aims at understanding the dynamics underpinning a system through the analysis of the interactions and causality nexus among its components (Kim, 1999; Meadows, 2008; Sterman, 2001). Applying this approach, we focused on the interactions, cascade effects and cause-effect relationships among the different forest-related dimensions (Bi et al., 2021; Hossain et al., 2020; Rehman et al., 2019).

Our goal is to complement current scientific research on windstorms-forest relationship, providing an improved understanding of windstorm impacts on European forests and stressing interconnections and cause-effects relationships among forest-related dimensions. Moreover, this interdisciplinary approach might help to highlight drivers reducing vulnerability and boosting adaptability at both ecological and social level (Filotas et al., 2014; Klein et al., 2019; Messier et al., 2016). To achieve this, we reviewed the existing scientific literature to identify (i) the forest-related dimensions that have been most frequently analyzed, (ii) the direct and indirect windstorm impacts on forest systems, and (iii) whether and to what extent current research addresses the role of cascade effects in post-windstorm recovery of forest and related systems. To better highlight the role played by cascade effects and cause-effects relationships in post-windstorm dynamics, we graphically represented the most relevant interconnections among forest-related dimensions in a causal map.

To help the reader in understanding the terminology and the concepts that underpin our analysis and the framework used we developed a **glossary of terms**:

Windstorm direct impacts: windstorm impacts that directly affect a variable/component of the forest-related system (e.g. windthrowing; uprooting).

Windstorm indirect impacts: impacts or consequences that may follow from direct windstorm impacts (e.g. change of forest structure due to windthrows; change in wood biomass presence)

Cascade effects: Cascade effects are chains of consequences triggered by windstorm that, starting from a direct windstorm impacts cause sequential indirect impacts on one or more dimensions (e.g. decrease of prices due high timber availability) (Bi et al., 2021; Rehman et al., 2019).

Cause-effect relationships: cause-effect relationships are the causal relations connecting direct and indirect windstorm impacts. For instance, cause-effect relationships might be connections among the components of the cascade effects (Kim, 1999; Powell et al., 2018).

Forest-related dimensions (hereafter dimensions): forest-related dimensions are sub-systems composing forests and forest-related systems. In this study we considered for the analysis the following forest-related dimensions: Forest Ecology and Management, Forest Operations, Geomorphology, Socio-economic and Forest Governance. In section 2.1 are outlined the main characteristics of each dimension.

Forest-related categories (hereafter categories): forest-related categories are conceptual subsets of forest-related dimensions grouping variables related to specific aspects (e.g. forest ecosystem dynamics is a category of forest ecology and management dimension).

2. Materials and methods

To identify and chart the variety of direct and indirect windstorm impacts detected in the literature we adopted a systematic mapping review approach (Grant and Booth, 2009; James et al., 2016). Systematic mapping reviews are as rigorous and objective as a systematic review (i.e. they follow a defined and reproducible procedure), but they aim at fully analyzing and categorizing existing literature and mapping state of knowledge related to complex and multi-faceted questions (James et al., 2016). Moreover, the outcomes can highlight the need for more comprehensive and detailed analysis of certain topics (Grant and Booth, 2009) or underpin policy formulation (James et al., 2016). We synthesized the results collected in a causal map, which provides a systemic overview of the windstorm impacts and their interconnections, highlighting the relations among dimensions.(Arksey and Malley, 2005; Pawson, 2002).

To ensure reliability and transparency of our study, the whole literature review process and causal representation of the results took inspiration from the framework for systematic mapping in environmental science proposed by James et al. (2016). Our review followed four main steps, each of them composed by several sub-actions: i) Design of the review approach; ii) Papers searching and screening; iii) Data collection and categorization iv) Results discussion and graphical visualization. Each step and the associated sub-actions are presented in the next sections.

2.1. Design of the review approach

An interdisciplinary team composed by researchers from different forest-related fields and with different academic backgrounds was established to ensure the coverage of all environmental and socio-economic fields relevant in the analysis of forests-windstorms relations. The review approach and the coding structure partially followed the methodology adopted by Romagnoli et al. (2022). The core objective of the paper published by Romagnoli and colleagues (2022) was to explore how windstorm impacts on socio-economic and institutional sectors affect resilience and adaptability of forest socio-ecological systems. Although this latter work focused exclusively on societal-related aspects, the approach implemented resulted suitable for the aim of our work, thus understanding post-windstorm dynamics characterizing forests and forests-related systems with a broader perspective, identifying the role of cascade-effects triggered by dimensions interconnections. In doing so, we built on existing literature but expanded it in terms of scope and purposes.

First, we identified via existing scientific literature the forest-related dimensions mostly affected by windstorms in Europe (Fleischer et al., 2017; Forzieri et al., 2021; Gardiner et al., 2013; Härtl et al., 2016; Hlásny et al., 2021a; Leverkus et al., 2018b; Wunder et al., 2021): Forest Ecology and Management, Forest operations, Geomorphology, Forest socio-economic related aspects, and Forest governance. In supplementary material (A) are outlined most relevant characteristics of the dimensions underpinning the analysis and are mentioned main and most recurrent windstorm impacts.

For each dimension we identified several forest-related categories, grouping specific variables that could be affected by windstorm (Table 1).

After having identified the forest-related dimensions, we proceeded to keywords identification for the papers selection, a crucial step to ensure consistency within the review and across the dimensions identified. Formulation of search strings followed a two-step procedure: i) firstly, we identified a base query including relevant keywords for all of the five dimensions: "forest* OR woodland AND wind* AND disturb* OR damage"; ii) secondly, for each dimension we added a few specific keywords in order to better tailor the analysis to each forest-related dimension. Ultimately, eight queries were defined (Table2).

Literature search was performed using title, abstract and keywords search for papers published until the 31st December 2020 in the Scopus® database, copyright Elsevier. To guarantee consistency and reliability in articles selection and screening stages, the main features of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach have been adapted to the scope of the review and combined with the methodology adopted (Page et al., 2021). Inclusion and exclusion criteria were set to ensure that scientific articles retrieved were in line with the review scope. Only articles matching the following criteria were included in the analysis: i) published in peer review journals; ii) analyzing windstorm impacts on European forests; iii) written in English. No limitations regarding the time span were set. Despite we recognize the importance of models and simulations-based papers in studying windstorm-forest system relationships, we excluded them because we aimed at examining windstorm impacts effectively measured, while models provide predictive analysis and estimations. Similarly, review articles were excluded to avoid double counting of papers.

2.2. Paper searching and screening

The screening procedure steps are described below:

Table 1
Forest-related dimensions and related categories.

Forest- related dimensions	Forest-related categories
Forest Ecology and Management	Forest ecosystem dynamics Forest planning Pest and pathogen risk
Forest operations	Forest operations and logistics Forest infrastructures Environmental impacts
Geomorphology	Channel dynamics Slope dynamics
Socio-economic	Economic Socio-cultural
Forest Governance	Institutional governance Stakeholders and actors' relations

Forest-related dimensions and related categories used in the analysis.

Table 2
List of strings used for literature search.

Forest-related dimensions	Strings of keywords used for literature search
Forest ecology and managment	(forest* OR woodland) AND wind* AND (disturb* OR damage*) AND ecolog* OR management* OR "climat* chang*" (forest* OR woodland) AND wind* AND (disturb* OR damage*) AND ecosystem* AND service* (forest* OR woodland) AND wind* AND (disturb* OR damage*) AND (beetle* OR pest* OR "bark beetles" OR "wood boring insects" OR "wood-boring insects" OR pathogen* OR outbreak*)
Forest operations	(forest* OR woodland) AND wind* AND (disturb* OR damage*) AND harvest* OR "salvage logging"
Forest governance	(forest* OR woodland) AND wind* AND (disturb* OR damage*) AND institution* AND govern*
Forest socio-economics aspects	(forest* OR woodland) AND wind* AND (disturb* OR damage*) AND soc* AND economic* OR financial*
Geomorphology	(forest* OR woodland) AND wind* AND (disturb* OR damage*) AND sediment* OR "large wood" (forest* OR woodland) AND wind* AND (disturb* OR damage*) AND flood

Note the base query is the same across all five forest-related dimensions ("forest* OR woodland AND wind* AND disturb* OR damage"). Dimensions-specific keywords were then added to perform a literature search specific for each dimension.

i) A search of title, abstract and keywords was performed for the searching strings defined. Successively, articles retrieved from different search strings were merged into a single database. To avoid double counting of articles we performed a duplicate cleaning.
ii) Preliminary screening of title and abstract to ensure consistency with the review's purpose and inclusion/exclusion criteria.
iii) In depth- reading of articles with title and abstract matching with review criteria to assess pertinence and compliance with the aim of the study.

In steps ii) and iii) articles retrieved were analyzed according to the authors' expertise.

At the end of this process and consistently with PRISMA approach guidelines, we added a few papers particularly relevant to the issues under investigation, identified via citation searching and scholars' consultation.

This final list of papers was scrutinized, and data were extracted, following detailed coding and categorization procedures, as described in the following section.

2.3. Analysis and categorization of the results

The pool of papers selected with the review process was analyzed in depth, implementing narrative and content analysis approaches (Pawson, 2002; Snyder, 2019). The information extracted was categorized based on a combination of generic and topic-specific fields (James et al., 2016) in three different databases:

1) Generic bibliographic information and methodologies adopted for data collection.
2) Data related to the windstorm analyzed (i.e. year of the storm, geographical area affected and case study area).
3) Data related to windstorm impacts. This database represented the core of the data collection and included:

- Direct and indirect windstorm impacts analyzed in each article (indirect impacts were recorded only when specifically mentioned in the article).
- Time needed to record a direct or indirect impact (e.g. a bark-beetle outbreak was recorded three years after the windstorm).

The data collection of direct and indirect windstorm impacts was based on a specific hierarchical coding. The core idea of the coding system was to identify the cascading effect of windstorms along and among the forest-related dimensions. Each direct or indirect windstorm impact was classified within a specific category related to one of the dimensions that underpinned the analysis. Categories are sub-sets of dimensions, grouping specific variables that are directly or indirectly affected by windstorm (e.g. dimension: Forest ecology and management; category: forest ecosystem dynamics). In Table 1 are outlined all the dimensions and related categories used for impact categorization, the complete lists of variables composing direct and indirect impacts connected to the different categories is available in Supplementary Material (B). A direct impact can be linked to an indirect one, which in turn is classified under a specific category and dimension (Fig. 1). This linkages between direct and indirect impacts forms the so-called cascade effect (see Glossary box). Following this coding structure, direct and indirect windstorm impacts were detected in the selected literature, paying particular attention to cascade effects within and among forest-related dimensions.

For what concerns changes in ES after windstorm, in order to avoid double counting of impacts and redundancy in data collection, we have associated windstorm impacts to a related ES following CICES V5.1 categorization (Haines-Young and Potschin, 2018). The full list of ES associated with direct and indirect windstorm impact is reported in Supplementary Material (B).

2.4. Discussion and graphical visualization of the data collected

Once windstorm impacts were categorized, they have been graphically represented in a causal map drawing inspiration from Causal Loop diagram approach (Hossain et al., 2020; Powell et al., 2016; Rehman et al., 2019). Bearing in mind the nature of the relations and that windstorm impacts simultaneously affect several forest-related dimensions, we allowed multiple interconnections between the map elements. The aim of the map was highlighting factors that escalate or mitigate windstorm impacts at environmental and/or social level and boost/ reduce forest-system ability to recover from wind hazards.

3. Results

3.1. Results of articles searching and screening process

The keyword searching process led to the identification of 2.979 articles in the Scopus database discarding the articles incompatible with or irrelevant for the review scope. A first screening of title and abstracts reduced the number of eligible articles from 2.979 to 505. After the full-text screening process, the final pool of scientific publications matching the review criteria amounted to 98 articles. To these, 13 articles identified from citation searching were added because they were considered pivotal for the scope of the study, for a total number of 111 papers. The Fig. 1 in Supplementary material C outlines the papers screening procedures and shows the number of papers analyzed in each step, while in Supplementary material (D) is reported the full list of papers analyzed in the review.

3.2. Publication period and geographical area

The pool of articles identified as eligible for the analysis were published between years 2000 and 2020. In the time span analyzed, there has been a constant increase in publications related to windstorms impacts on forests, with a peak in 2016 (Fig. 2).

Most of the studies were performed in Central/Northern Europe countries (83.7%), while a much lower proportion of studies reported data on windstorms affecting Eastern Europe countries (7.3%) and only a limited amount analyzed windstorm consequences on Southern Europe countries (3.6%), Italy being the only country investigated. The remaining articles did not specify the geographical scope (3.6%) or targeted the whole of Europe (1.8%) (Fig. 3). Wind damage can be traced to major storms of the last century in Europe in just 30 cases, in the majority of cases the windstorm under study has not been mentioned or was unnamed.

3.3. Characterization of direct windstorm impacts

The final database consists of a total of 476 windstorm impacts, 272 related to direct impacts and 204 to indirect impacts. The lower number of indirect impacts is explained by the fact that for some direct impacts, no subsequent impact was reported (25.1% of direct impacts did not have further consequences).

Most of the impacts categorized, for both direct and indirect impacts, belonged to environmental related aspects. Forest ecology and management is the dimension that totalized the highest number of impacts (60.7% of the total impacts), more than half related to changes in forest and ecosystem dynamics (59.7% of the direct impacts within the dimension). However, to clearly understand this result, it has to be taken into consideration that impacts in this dimension include consequences related to bark beetles' proliferation (34.1% of the direct impacts within the dimension). Windstorms directly impact forest provisioning and regulating services. Consequences in the provisioning service have been recorded in 5.5% of direct windstorm impacts on forest ecology and only

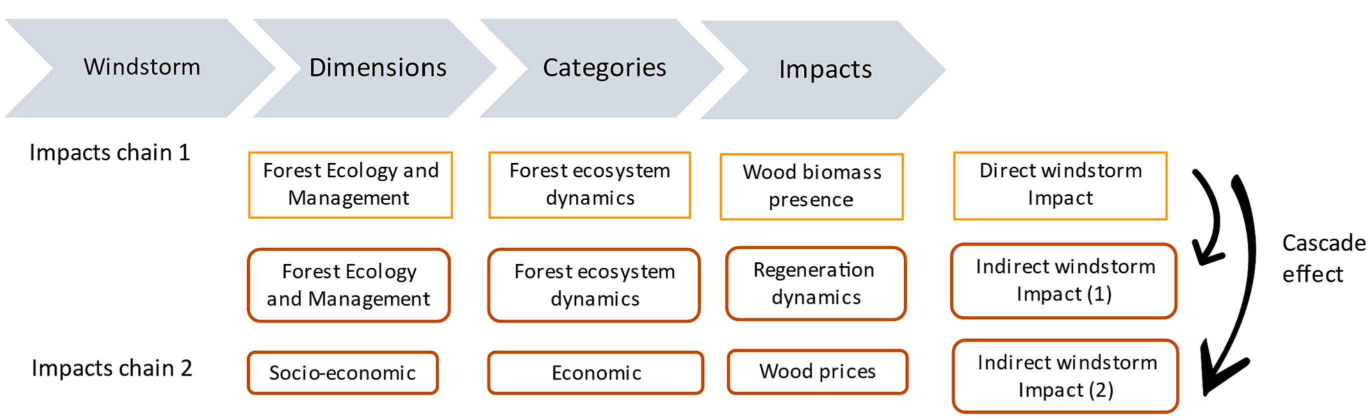

Fig. 1. Practical application of the coding system used to categorize impacts. The grey arrows indicate the overflow of the coding system. In the orange rectangles are reported the dimensions, specific categories and impacts directly caused by windstorm (direct impact). In the red rounded rectangles are reported the dimensions, specific categories and impacts are triggered indirectly, as consequence of direct impact (indirect impacts). The black arrow that connects direct and indirect impacts indicates the cascade-effect relationship. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

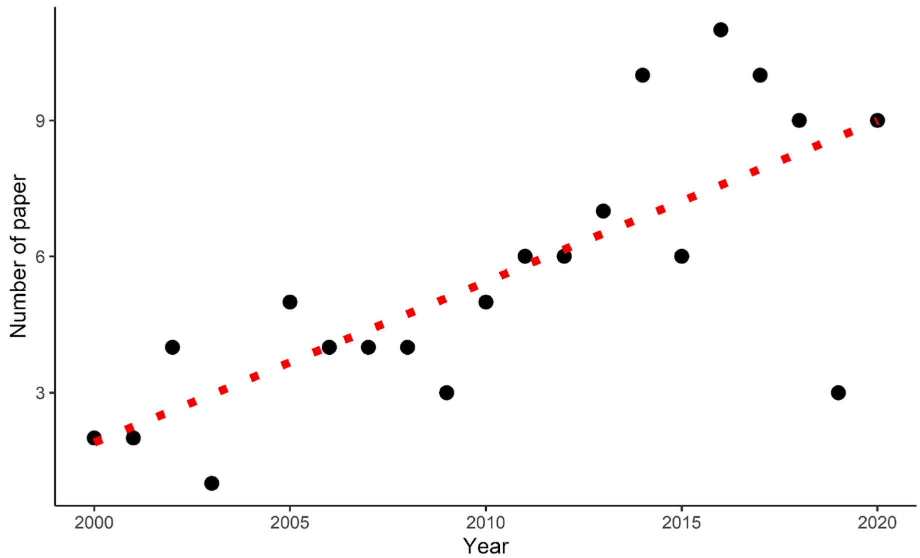

Fig. 2. Numbers of articles published per year. The red dotted line indicates the trend during the time span considered in the review. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

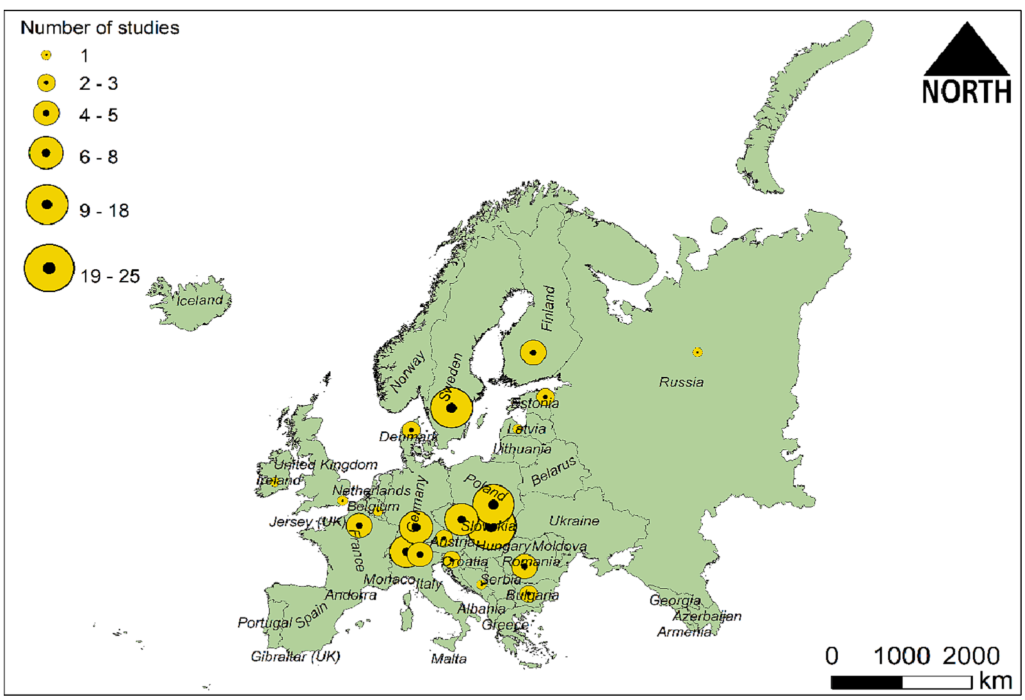

Fig. 3. Distribution of retrieved studies Distribution of reviewed studies across European countries. The size of the circles indicates the numbers of studies found for each country.

regards changes in biomass quantity. For what concerns the regulation and maintenance function, several services can be modified due to a change in forest structure, in particular the variables mostly affected were forest ecosystem biodiversity, regeneration dynamics, changes in soil chemistry / quality and absorption of CO_2. Changes in these aspects were recorded in relation to 20.3% of direct windstorm impacts on *forest ecology dimension*.

Direct impacts recorded in forest operations amounted to 18.9% of total direct impacts. They record direct consequences on ecosystem components (52.9% of impact in forest operation dimension) and changes in business-as-usual of forests and logging operations (45.1%, within forest operation dimension). Geomorphology is the environment-related dimension that totalized the lowest number of direct impacts (6.6%) and the case study areas were located solely in the mountainous environment. In terms of direct impacts analyzed in this dimension, 94.4% investigated negative windstorms effects on mountain slope dynamics, increasing slope instability and sediment production. A minor part (5.5%) analyzed how windstorm affect channel dynamics, particularly riparian vegetation.

Considered together, impacts on societal-related aspects (i.e., socio-economic and institutional) accounted for about a quarter of direct (13.6%) impacts. The majority of them belong to the socio-economic dimension (10.7% of the total direct impacts) and mainly relate to individual and societal aspects and specifically to non-industrial private forest owners' livelihood and management capacities (36.8% of the impacts on socio-economic dimension). Direct impacts in governance dimension have been seldom analyzed (2.9% of direct impacts) and the totality of them refers to changes in institutional compensation measures.

3.4. Characterization of indirect windstorm impacts

Windstorm impacts tend to be transboundary, as indirect impacts spread through multiple dimensions, causing several cascade effects (Fig. 4).

Over the dimensions investigated, forest ecology and management had a lower degree of cross-dimensionality, quantifying more than half of the indirect impacts (56%) in the same dimension (Fig. 4). In accordance with the results of direct impacts, indirect impacts were recorded primarily in forest ecosystem dynamics (65.3%), especially interesting changes in forest biodiversity, species composition and regeneration dynamics, and secondly in pest outbreak dynamics (29.2%). Changes in forest planning (e.g. forest management plans, protection from natural hazards) have been poorly analyzed as direct and indirect windstorm consequences (6.1% and 4.6% respectively). Direct impacts in forest ecology triggered indirect effects in socio-economic aspects (8%) related predominantly to negative consequences on wood-markets dynamics (e.g. decrease in wood prices, deterioration of raw material, etc.) and, in minor extent to changes in the cultural functions of forest (i.e. recreational activities). Moreover for 34% of direct impacts on forest ecology no indirect effect was recorded.

Changes in forest operations after windthrows highly affected forest ecology and management dimension, and most of the indirect effects (53%) concerned regeneration dynamics and forest biodiversity. Harvesting operations after a windstorm implies important changes throughout the main steps of the forest operations value chain and in the storage and transportation logistics. These changes represented the 29% of indirect impacts derived by modification of forest operations business-as-usual. Changes in forest operations caused cascade effects in socio-economic aspects (12.2%), concerning changes in wood quality and prices. How post-windstorm forest operations affect the provision of ecosystem services as well as changes on landscape value and perception were not addressed in the analyzed literature. There were no indirect impacts in 6% of the cases.

Windstorm direct impacts in the geomorphology dimension concerned only slope dynamics. These impacts trigger indirect impacts primarily in channel dynamics (44%), and also in forest ecosystem dynamics (39%) in particular influencing protection from natural hazards and soil composition. Few indirect impacts (17%) were also recorded in the socio-economic dimension, related to changes in the perceived quality of forest landscape.

Indirect impacts triggered by direct windstorm consequences in socio-economic dimension remain clustered in this dimension. The majority of indirect impacts (41%) regarded forest owners' abilities in managing disturbed forests, while 17% of the indirect impacts were recorded in governance dimensions and concerned changes in policy and legislation as consequence of changes in timber market. A few percentages of indirect impacts were recorded in forest ecology dimensions (7%) and relate to changes on forest management plans. Finally, 34% of direct impacts did not show an indirect impact on other dimensions. Indirect impacts triggered by changes in forest governance dimension mainly had consequences on private forest management choices and private forest owners' wellbeing (75%) and in minor extent in adaptation of forest management plans (25%).

4. Discussion

The review showed a higher focus of scientific research on Northern and Central Europe countries, rather than Southern Europe. This finding was not surprising due to (i) the higher frequency of high intensity windstorms and the consequent large amount of damage caused to forests, (ii) the large extent of forests at higher latitudes, and (iii) the large occurrence of wind damage-prone species (especially Norway spruce) in Northern countries (Forzieri et al., 2020; Roberts et al., 2014). However, the almost total absence of studies regarding windstorm impacts on Southern European forests shows an important knowledge gap, especially when considering that future wind hazards are forecasted to change their spatial patterns and becoming more frequent in Southern Europe (Patacca et al., 2022; Spinoni et al., 2020).

4.1. Forest ecosystem dynamics, structure and regeneration

The most recurrent direct windstorm impacts reported in the literature concern the Forest Ecology and Management dimension. Among the direct impacts, great focus has been dedicated to post-windstorm changes in forest ecosystem dynamics (e.g. in species composition, ecosystem biodiversity, gross primary product) and forest structure, while modifications in management strategies were mainly focused on post-disturbance management, as it will be discussed in the next paragraph. The causal loop composed by (i) forest ecosystem dynamics, (ii) forest structure and composition, and (iii) regeneration dynamics plays a central role in forest-system post-windstorm dynamics and gives rise to several direct and indirect impacts (Fig. 5) (Fischer et al., 2002; Fischer and Fischer, 2012; Simon et al., 2011; Vodde et al., 2015). For instance, windstorm impacts on forest have strong consequences, especially on structure (e.g. in species composition) (Schütz et al., 2006; Seidl and Blennow, 2012; Marangon et al., 2022) that consequently influence post-disturbance regeneration dynamics (e.g. time of regeneration)

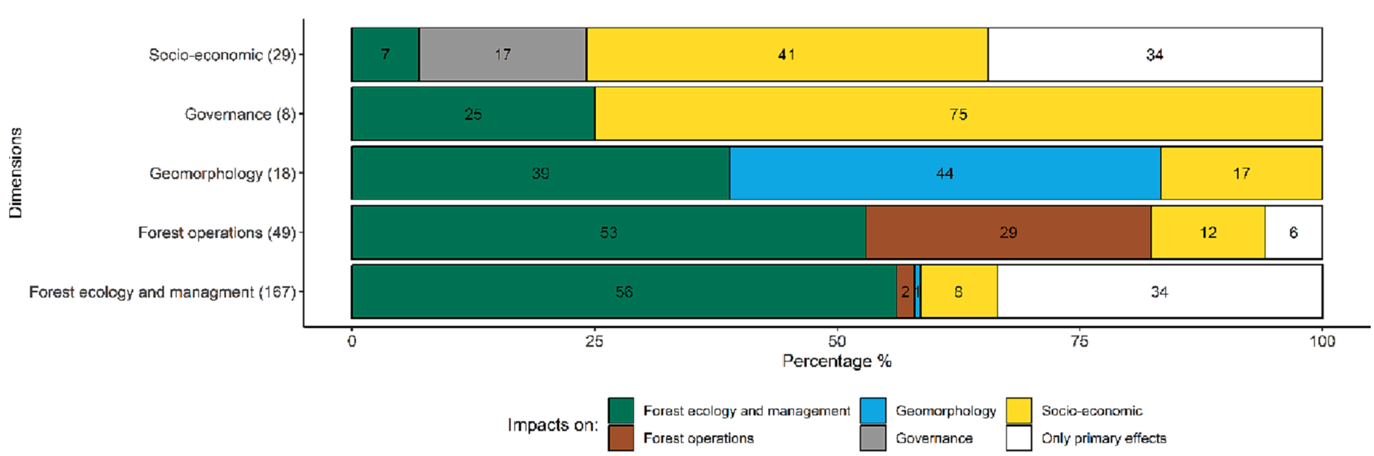

Fig. 4. Quantification of indirect impacts via direct impacts. The Y axis lists the dimensions of direct windstorm impacts and in brackets are reported the total number of direct impacts recorded in that specific dimension. The X axis records the share of indirect impacts, defining the related dimension.

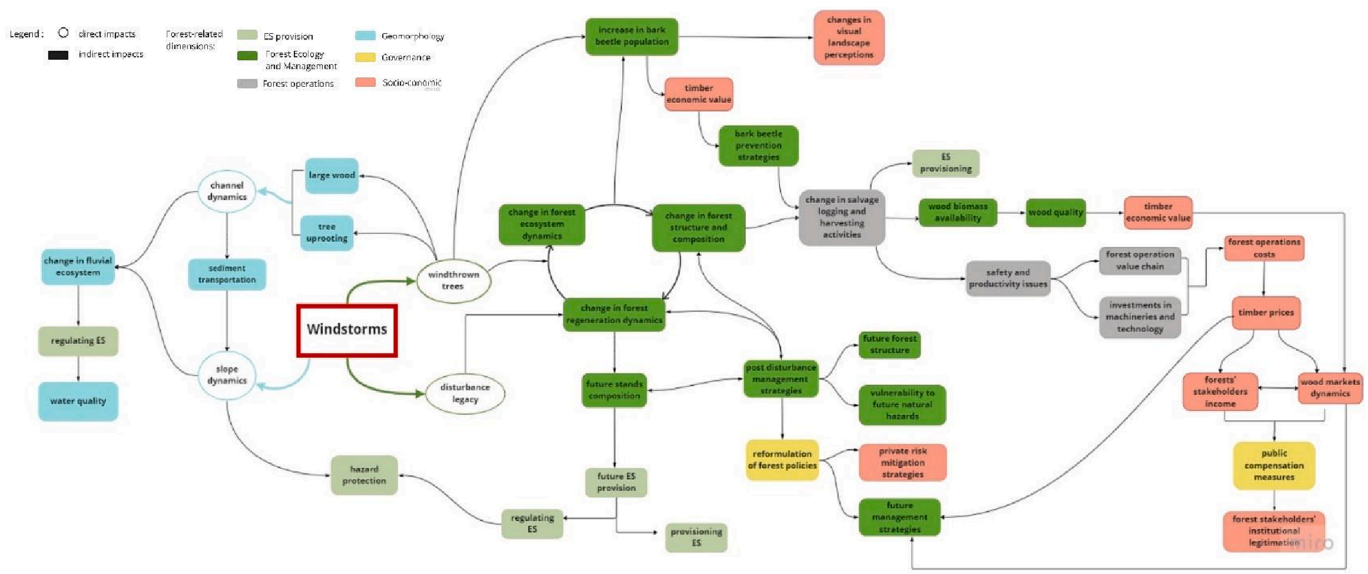

Fig. 5. Causal map of direct and indirect impacts. Map of the most relevant windstorm cause-effect linkages among forest-related dimensions considered resulted from the literature analyzed. Causal relations among windstorm impacts and forest dimensions have been visualized using arrows, where the arrows define the direction of the impact. The color of the rectangle identifies the corresponding dimension.

(Fischer et al., 2002; Simon et al., 2011; Vodde et al., 2015). This cluster of knowledge indicates close-related and well-studied aspects, which play a critical role in post-windstorm recovery strategies, thus influencing the future forests composition (Vodde et al., 2009).

Besides this strong causal loop, regeneration patterns might also depend on the disturbance legacies left by a storm and on the post disturbance management strategy chosen (see chapter 4.3). These two factors drive species composition influencing the future forest stands and the provision of ES (Fleischer et al., 2017; Seidl and Blennow, 2012) (Fig. 5). Changes in forest structure will affect regulating ES, such as forest biodiversity, microclimate and CO_2 absorption (Gömöryová et al., 2014; Nagel et al., 2017; Šoltés et al., 2010). Furthermore, a decrease in stand wood biomass implies a temporary reduction of provisioning ES, triggering negative cascade effects in wood-forest value chain (Meyer et al., 2008). However, provision of ES is also strongly sensitive to time since disturbance, that determines how the supply of the service could change after the event (Thom and Seidl, 2016).

4.2. Post-windstorm management: A debated question

The large amount of damaged wood lying on ground in wide damaged areas can heavily affect future forest management and so, management plans (Fleischer et al., 2017; Seidl and Blennow, 2012, Valinger et al 2014). To reduce economic losses, a key point is the decision of the most appropriate post-disturbance management strategy, that may vary from total salvage logging to no intervention at all (Taeroe et al., 2019). Salvage logging, i.e. removing of uprooted and wind-broken trees, can negatively impact many aspects, such as regeneration dynamics (Fidej et al., 2018; Lindenmayer et al., 2019; Thorn et al., 2016), slope stability (Frey and Thee, 2002; Schönenberger et al., 2005), and biodiversity (Bouget, 2005). The management of laying logs and other disturbance legacies (i.e., stumps or snags), appears to be a critical aspect in post-windstorm management (Costa et al., 2021; Ringenbach et al., 2022), playing a crucial role in the ecological response of forest ecosystems to wind damage. On the one hand, disturbance legacies can benefit forest recovery and regeneration processes (Szwagrzyk et al., 2018; Valinger et al., 2014), on the other hand, they can heavily interfere with established management objectives (Fidej et al., 2018) and create favorable condition for other natural disturbances, such as bark beetles.

In wind-affected forests, pest outbreaks, especially bark beetles, are a well-known and well-documented windstorm consequence (Eriksson et al., 2005; Grodzki and Fronek, 2019; Louis et al., 2014), as windthrows provide available resources for these insects (Fig. 5) (Bouget, 2005). Large scale outbreaks might have tremendous impacts on forest ecosystems, increasing forest vulnerability and exacerbating economic damage caused by wind (Mezei et al., 2017). For that reason, foresters usually implement prevention strategies, such as sanitation felling, deadwood manipulation or debarking (Hlásny et al., 2021a; Schroeder and Lindelöw, 2002; Taeroe et al., 2019) and the larger demand of such operations might also affect the modification of business-as-usual forest operations (Stadelmann et al., 2013) (Fig. 5). Sanitation logging is the most common strategy aimed at mitigating bark beetle outbreaks. However, for being effective, a large number of fallen trees need to be removed (Dobor et al., 2020), thus strongly modifying the environment.

Indeed, for their direct and indirect consequences, post-windstorm forest operations are one of the most debated issues in forest management. Further than affecting several forest ecosystem dynamics, they also have important effects on various forest-related sectors and stakeholders (Angst and Volz, 2002; Kärhä et al., 2018). Harvesting plans and log volumes harvested have direct impacts on wood-sector, not only for what concerns the economy and profitability of these operations, but also in the organization and management of the entire value chain (Björheden, 2007; Broman et al., 2009; Riguelle et al., 2015). The wood harvesting, storage, transportation and processing sectors have to respond to important changes on (i) the quantity of raw material to be logged and the logging conditions, and (ii) the type of harvesting systems to implement, logistics and storage dynamics, labor competences and forest-related infrastructures (Broman et al., 2006; Caurla et al., 2015; Kärhä et al., 2018; Magagnotti et al., 2013; Nieuwenhuis and O'Connor, 2001). From the harvesting side, in the case of large amounts of windthrown and of difficult terrain, mechanized or semi-mechanized harvesting systems are generally used to minimize the hazardousness of logging operations (CTBA, 2004; Kärhä et al., 2018). These systems, despite improving the safety and stability of the damaged areas and optimizing the productivity of the operations, increase the overall costs and the initial investments potentially reducing the profitability of the entire operation (Björheden, 2007; Broman et al., 2006; Nieuwenhuis and O'Connor, 2001) (Fig. 5).

In the end, the decision of the most appropriate post-disturbance management is crucial not only to avoid chains of natural disturbances compound or linked disturbances (Buma, 2015; Taeroe et al., 2019), 2019), but also to define adequate forest management for the long-term guaranteeing the integrity and health of the forest stands and reduce the risk of instability-prone areas (Hlásny et al., 2021b; Wohlgemuth et al., 2017).

4.3. Windthrows and Geomorphology: A poorly integrated and documented subject

The activation or reactivation of instability-prone areas is one of the major windstorm's impacts that directly influence the channel and slope dynamics, thus increasing the sediment and large wood fluxes from slopes to channel networks (Fig. 5) (Pilotto et al., 2016). In fact, large-scale windstorm events create and reactivate new sediment sources (Rainato et al., 2021) that, depending on their connection with the channel network, can become an important source of risk for villages located downstream of windstorm affected areas (Mikuś and Wyżga, 2020; Strzyżowski et al., 2018).

Further than affecting territorial morphology, windstorm have relevant cascade effects on regulating ES. Tree uprooting, in fact, exposes new areas of bare soil and removes the water absorption capacity of roots. Both these consequences promote (i) faster soil saturation, (ii) a subsequent increase in the surficial landslide susceptibility (Gerber et al., 2002) and (iii) different chemical composition of groundwater solutes (Hellsten et al., 2015). In addition, large wood recruitment and sediment transport have relevant cascade effects on river and stream biodiversity. If, on the one hand, the extreme floods often associated with windstorms overturn channels morphologies and dynamics, on the other hand they naturally restore the entire fluvial ecosystem favoring the creation of new habitats for microorganisms and fish fauna thanks to the influx of new material composing the fluvial environment (Fig. 5) (Coe et al., 2009; Pilotto et al., 2016).

4.4. Stakes and stakeholders affected

Windstorms direct impacts and cascade effects on wood sector economy could potentially be very large and affect the profitability of the entire sector (Brunette and Couture, 2008; Caurla et al., 2015; Fleischer et al., 2017). However, these negative trends can be partly compensated by the introduction of technological advancements, improvements in forest-related infrastructures and by the value added to wood products due to contingency situation (e.g. value of wood pellets, considering the actual energy crisis) (Caurla et al., 2015; Hartebrodt, 2004; Sullman and Kirk, 2001). The maximization of forest operations could partially offset the decrease in prices, and increase efficiency of single enterprises as well as of the overall sector (Björheden, 2007; Broman et al., 2009; Hartebrodt, 2004; Kärhä et al., 2018). Thus, the severity of windstorm consequences on wood markets and forest related industries is deeply connected with the adaptive and technological ability/possibility of wood industry (Riguelle et al., 2015; Romagnoli et al., 2022; Sullman and Kirk, 2001).

Further than affecting wood industry, fluctuations in timber market and price influence also post-windstorm management strategies of non-industrial private forest owners. Forest management choices implemented at private level, especially those concerning planting and forest regeneration decisions, are strongly driven by projection of timber prices and by predicted trends in wood and timber markets (Blennow, 2008; Lidskog and Sjödin, 2014). To ensure long-term forest resistance, planting choices should primarily consider species' vulnerability to disturbances and should aim at species diversification (Zubizarreta-Gerendiain et al., 2017). However, due to their strong risk-adverse behavior (Brunette and Couture, 2008; Couture et al., 2016), private forest owners often prioritize and consider mainly expected economic risks and tree species' profitability (Brunette and Couture, 2008; Lidskog and Sjödin, 2014) (Fig. 5). Financial subsidies and public compensation policies could be as relevant as future economic projections in shaping private forest owners' management practices (Brunette and Couture, 2008), thus direct influencing future forest composition and consequently forest vulnerability to future hazards (Fig. 5) (Brunette and Couture, 2008; Sousa-Silva et al., 2018).

Considering what drives private forest owners post-windthrows forest management strategies, it is not ensured that their choices would be the most appropriate to increase forest resistance to future hazards nor ensure long-term financial recovery (Andersson et al., 2018; Lidskog and Sjödin, 2014).

In relation to windstorm impacts on forest governance and public forest owners, two important positive cascade effects deserve to be mentioned. Management of wind hazards has been recognized as an opportunity to improve the capacity of forest government agencies to deal with extreme events. This, in turn, leads to higher private forest owners' confidence in institutional action and legitimation of governmental measures implemented (Lidskog and Sjödin, 2015; Romagnoli et al., 2022). On the other hand, an unwanted consequence that might follow from government aid is the polarization of power relations among forest stakeholders and in networks and alliances, giving rise to potential conflicts (Caurla et al., 2015).

4.5. Socio-cultural impacts: The overlooked consequences

The consequences of windstorm at cultural and social levels did not appear in the literature analyzed. Few authors reported that bark beetle outbreaks, forest operations and changes in slope and channel dynamics are likely to affect the quality and perceived value of the landscape, thus affecting its attractiveness and eventually decreasing the provisioning of cultural and recreational activities (Angelstam et al., 2013; Constantine et al., 2012; Leverkus et al., 2021; Mezei et al., 2017). Nevertheless, no consideration has been made on how to integrate visual quality of the landscape with its ecological functions during post-windstorm forest management to fulfill both ecological and societal needs (Angelstam et al., 2013; García-Abril et al., 2019). We highlighted a knowledge gap regarding the influence of socio-cultural aspects in post-windstorm forest management choices (e.g role of expectations and experience in forest management choices), as well as in the comprehension of interactions between forest and non-forest sectors' stakeholders (e.g. public forests managers and local community). The importance of covering these knowledge gaps as well as of considering needs and expectations of all involved stakeholders in post-windstorm forest management, and more broadly in forest resource management has been extensively analyzed and discussed in literature (Filotas et al., 2014; Rocha et al., 2022; Romagnoli et al., 2022). Windstorms affect a variety of sectors and stakeholders beyond the traditional forest sectors (i.e. wood-forest value chains), considering the needs of concerned actors would promote the implementation of post-windstorm policies that address expectations of different social groups, achieve forest multifunctionality and long-term recovery of forest-related systems (Sotirov and Arts, 2018).

4.6. Study limitations

The complexity of the topic addressed prompted us to develop a systematic mapping review, thus preferring a broad-spectrum analysis overlooking windstorm impacts on specific aspects. This limitation is reflected in the structure and keywords chosen for papers search. We decided to insert only the general concept, namely mentioning only the dimension of reference (i.e. ecology or geomorphology) or a broad concept connected to it (i.e. management or flood) and not the specific sub-concepts. This choice enabled us to simplify the analysis, however we are aware that there are two major drawbacks: i) a risk of an oversimplification of the analysis of certain forest-windstorm relationships; ii) limitations in the number of articles and type of information retrieved.

Also the representation of the results in the causal map suffers some limitations. Deserve to be mentioned the impossibility of quantifying the nature and type of impacts in positive or negative. As outline in several articles (Fleischer et al., 2017; Thom and Seidl, 2016) disturbances could have an ambiguous impacts on forest ecosystem, and the same impact could be both positive and negative depending on the time since disturbance considered (e.g 5/10/20 years after disturbance). Considering that in our analysis we have not taken into consideration the time variable, quantifying the impacts would have conveyed misleading and imprecise information. However, we acknowledge that this aspect is of major importance and we believe it should be explored in further research.

Restricting the analysis to English-written articles has certainly excluded relevant articles and prevented us from acquiring information that would have enriched our discussion. Furthermore, the papers collected were mainly reporting studies investigating consequences of windstorms that affected mainly Northern and Central Europe forests. This highlights a knowledge gap in the study of small-scale windstorm consequences and in the comprehension of post-windstorm responses of Southern Europe forests and forest-related systems. The existence of these knowledge gaps highlights several aspects that would need further investigation and open room for future research improvements.

5. Conclusions

This paper presented a first attempt at an overall and interdisciplinary understanding of the windstorm impacts in Europe. We believe that the use of an interdisciplinary approach increases awareness and comprehension of the complex dynamics triggered by windstorm disturbances in European forests and forests-related systems, thus guiding future system thinking oriented research and more systemic policy actions. Four major research outcomes, which might drive future research, were highlighted.

1. First, our results revealed that the current scientific knowledge is characterized by a strong focus on those effects concerning the environmental dimensions, with a particular emphasis on windstorm impacts on ecological dynamics and post-windstorm managerial aspects. We found many studies focusing on forest dynamics, regeneration, management strategies and related changes in forest structure and composition, suggesting a strong cluster of well-studied topics.
2. Post-windthrow forest management turned out to be a particularly debated and multifaceted topic. The management of windthrow affects ecological, managerial and societal dimensions across different temporal and spatial scales.
3. Many trade-offs exist and depend on both local and landscape factors, such as forest ecosystem impacts, forest operations strategies and related costs, and consequent response of wood-forest value chains. These dynamics affect windthrows management strategies, having repercussions on soil cover restoration and future forest planning.
4. Despite windstorms proved to be transboundary events, whose impacts affect a multiplicity of dimensions and stakeholders an interdisciplinary approach analysing windstorm impacts is missing. For instance, relations between geomorphology dimension and the other dimensions have been poorly studied, likewise impacts and interactions between natural dimensions, social and governance dimensions. Besides emphasis has been placed on tangible aspects, such as financial trends and allocated subsidies, non-tangible aspects, such as changes in cultural services or social wellbeing, were very rarely mentioned. There is a need to reinforce the attention on these aspects, both in scientific research as well as in decision and policy making.

Our research highlighted the importance and the advantages of adopting an interdisciplinary approach in windstorm impacts assessment, to acquire a better understanding of forest-related systems response to windstorms and of existing trade-offs or potential conflicts connected with resource management. This approach could be replicated in other research investigating impacts of climate changes and natural disturbances (e.g. droughts, fires and pest outbreaks) on forest-related systems. Furthermore it supports the design of effective and long-term strategies acting at systemic and comprehensive level, and tackle multiple challenges affecting environmental and societal aspects linked with natural disturbances intensification.

CRediT authorship contribution statement

Federica Romagnoli: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Alberto Cadei:** Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Maximiliano Costa:** Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Davide Marangon:** Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Giacomo Pellegrini:** Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Davide Nardi:** Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Mauro Masiero:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision. **Laura Secco:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision. **Stefano Grigolato:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision. **Emanuele Lingua:** Conceptualization, Writing – original draft, Supervision. **Lorenzo Picco:** Writing – original draft, Writing – review & editing, Supervision. **Francesco Pirotti:** Writing – original draft, Writing – review & editing. **Andrea Battisti:** Writing – review & editing, Supervision, Funding acquisition. **Tommaso Locatelli:** Conceptualization, Writing – original draft. **Kristina Blennow:** Conceptualization, Writing – original draft, Writing – review & editing. **Barry Gardiner:** Conceptualization, Writing – original draft. **Raffaele Cavalli:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The co-author Andrea Battisti is member of the editorial board of the journal to which we are submitting (Forest Ecology and Managment).

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2023.121048.

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