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The Management Response to Wind Disturbances in European Forests

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Abstract

Purpose of the Review The review synthesises the current knowledge of post-windstorm management in selected European countries in order to identify knowledge gaps and guide future research.

Recent Findings Despite the differences in forest ownership and national regulations, management experiences in Europe converge at (1) the need for mechanization of post-windthrow management to ensure operator safety, (2) the importance to promote operator training and optimise the coordination between all the actors involved in disturbance management and (3) the need to implement measures to consolidate the timber market while restoring forest ecosystem services and maintain biodiversity.

Summary Windstorms are natural disturbances that drive forest dynamics but also result in socio-economic losses. As the frequency and magnitude of wind disturbances will likely increase in the future, improved disturbance management is needed. We here highlight the best practices and remaining challenges regarding the strategic, operational, economic and environmental dimensions of post-windthrow management in Europe. Our literature review underlined that post-disturbance management needs to be tailored to each individual situation, taking into account the type of forest, site conditions, available resources and respective legislations. The perspectives on windthrown timber differ throughout Europe, ranging from leaving trees on site to storing them in sophisticated wet storage facilities. Salvage logging is considered important in forests susceptible to bark beetle outbreaks, while no salvage logging is recommended in forests protecting against natural hazards. Remaining research gaps include questions of balancing between the positive and negative effects of salvage logging and integrating climate change considerations more explicitly in post-windthrow management.

Keywords Storm · Salvage logging · Strategy · Storage · Safety · Biodiversity

Introduction

Windstorms are natural agents of forest disturbance. They shape forest ecosystem structure and composition and account for more than 50% of the timber disturbed in European forests [1]. Recent findings confirm that storms have already increased in Europe in the past decades [2], and an increase in wind disturbances is expected in the coming decades [3]. The storms that occurred in December 1999, for instance, had a critical impact on the forests of several European countries, e.g. Austria, Denmark, France, Germany, Sweden and Switzerland [4]. The estimated total damage of these storms was 180 million m^3, i.e. three quarters of the planned annual harvest in Europe [4], resulting in an economic loss of approximately ten billion euros [5]. In January 2005, storm Gudrun hit southern Sweden with average wind speeds of 33 m s^{-1} and gusts of up to 42 m s^{-1}

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[6]. Approximately 70 million m^3 of timber was disturbed which was almost as much as the average annual cut for the whole of Sweden [7]. In Poland, the severe weather event of 11 August 2017, when peak gust wind speeds exceeded 42 m s^{-1}, was one of the most severe storms in the history of the country [8]. It was initially estimated, that 79,700 ha of forest was disturbed, with damage of 9.8 million m^3 of timber [8]. In 2018, storm Vaia hit northeastern Italy with winds blowing at 55.6 m s^{-1}, affecting 42,000 ha in three regions and disturbing over 8 million m^3 of timber [9]. An overview of the regions affected, wind speed and volume of timber disturbed is presented in Table 1 [10, 11].

From the point of view of forest operations, wind disturbances lead to significant challenges mainly due to the organisation of salvage logging and work safety. They also affect forest management at strategic (e.g. logistics, labour and storage capacities, etc.) and economic levels (e.g. reduced timber prices, additional costs for re-planting, etc.). In addition, post-disturbance management also needs to consider the environmental impact such as decreased carbon sequestration, growing stock and variable biodiversity response. Trade-offs between the recovery of economic losses via salvage logging and the resulting impact on the environment due to harvesting operations potentially lead to conflicts between forest managers, people seeking recreation in forests, conservationists and policy-makers [12•]. At larger spatial scales, dealing with the potential collapse of the wood market after a large-scale storm event is of major concern to decision-makers [4]. There is a growing body of information regarding the impact of windstorms on European forests, and a number of best practice examples have been developed for responding to wind disturbances in management. However, this information is scattered and often published in languages other than English [1]. Previous efforts to synthesise experiences of managing wind disturbances across Europe date back several years [4]. An update on viable strategies for post-disturbance forest management [13••, 14••] is needed, in particular considering the context of climate change and the resulting change in the frequency and magnitude of extreme events.

To compile a state of the art in operational responses to wind disturbances in Europe, the literature from six European countries (France, Germany, Italy, Poland, Sweden and Switzerland) was reviewed. The current knowledge of post-management practices in four key management dimensions was synthesised, analysing the (i) strategic, (ii) operational (including safety), (iii) economic and (iv) environmental aspects of managing wind disturbances. This review is intended to help forest managers and policy-makers to establish benchmarks and respond efficiently to future windstorm events in European forests.

Methods: Systematic Literature Review

The aim of this literature review was to summarise existing experiences in the post-disturbance management of windstorms published in primary, secondary and tertiary sources. Primary sources provide first-hand evidence published in the scientific literature, while secondary sources describe, analyse and interpret information obtained from primary sources (e.g. review and synthesis papers). Tertiary sources

Table 1 The most significant storms affecting European forests over the last 30 years [9, 10]

Storm	Year	Regions affected	Maximum wind speed (m s^{-1})	Timber disturbed (Mill m^3)
Vivian (Wiebke)	1990	Germany, Great Britain, Ireland, France, The Netherlands, Belgium, Switzerland, (marginally northwestern Italy)	> 55.6	60–70
Lothar & Martin	1999	France, Belgium, Germany	71	240
Gudrun (Erwin)	2005	Ireland, Great Britain, Denmark, Norway, Sweden, Russia	> 50	75
Kyrill	2007	Ireland, France, Belgium, The Netherlands, Denmark, Sweden, Austria, Germany, Czech Republic, Slovakia, Switzerland and Poland	> 72	66
Klaus	2009	France, Germany, Italy, Switzerland, Spain, Andorra	> 55.6	NA
Xynthia	2010	Belgium, Denmark, France, Germany, Poland, Portugal, Spain, Sweden and United Kingdom	32.62	NA
Nicklas	2015	United Kingdome, The Netherlands, Belgium, Germany, Switzerland, Austria, Poland, Czech Republic, Slovakia	53	NA
Derecho	2017	Poland	> 42	8
David (Fiederike)	2018	France, Germany, Switzerland, Italy, Poland, Czech Republic	53	NA
Vaia	2018	Italy	> 55.6	6.0–8.0
Sabine (Ciara)	2020	United Kingdom, Ireland, Isle of Man, Spain, Germany, Austria, France, The Netherlands, Poland, Italy, Norway and Sweden	61	NA

represent the grey literature that is not included in the previous two categories (e.g. research reports, documents of governments and management bodies). The focus of the analysis was on European countries with strong forest economies which are frequently affected by wind disturbances, namely, France, Germany, Italy, Poland, Sweden and Switzerland. In general, systematic reviews are preferred since they use the full range of available evidence to analyse the state of the art in a specific field [15].

A literature search was carried out in English on the Web of Science (WoS) and Scopus in July 2020, and updated in January 2021. In each search string, a disturbance term (e.g. "windthrow") and an intervention term (e.g. "salvage logging") were included (Table S1). The logical (Boolean) search operators "AND" as well as "OR" were used to filter records based on more than one condition, while the "*" operator was used to include all derivatives of the key search terms. A search was made for terms in the title, abstract and keyword fields. To complete the bibliography, the reference list of relevant articles was screened, and grey literature sources in all five languages (French, German, Italian, Polish and Swedish) were included. Specific searches were also conducted using country-specific search engines (e.g. HAL for French publications) and forestry-related websites, namely, FCBA (https://www.fcba.fr/), the Austrian, German and Swiss platform "Waldwissen" (www.waldwissen.net), the Italian Academy of Forest Science and the Compagnia delle Foreste publishing database (https://italianforestscience.academy/), the State Forests in Poland (www.lasy.gov.pl), the Swedish Forest Agency (https://www.skogsstyrelsen.se/en/) and the Swiss Federal Office for the Environment FOEN (https://www.bafu.admin.ch/).

Relevant references were filtered in a stepwise selection procedure. First, the titles were screened and irrelevant references (e.g. fire disturbances) were discarded. Second, the abstracts were read and those referring to strategic, operational (including safety), economic or environmental aspects of post-windstorm management were retained. Furthermore, studies with global and European coverage were retained as long as they were related to the abovementioned countries. Any references not connected to the six focal countries were discarded. The relevant information was extracted and stored in an Excel spreadsheet (i.e. DOI, title, journal, author, year, source, country, language, keywords, search algorithm and search engine (Table S1)). The final list of relevant literature was sent to all the authors to assess its completeness. From the retained references, 68% were from primary sources, 13% from secondary and 19% from tertiary sources.

The references were categorised into four important dimensions of post-disturbance management: (1) strategy, (2) operations and safety, (3) economics and (4) environment. Strategic aspects refer to those addressing the long-term consequences, e.g. post-disturbance management decisions such as "clearing or keeping" as well as those discussing organisational aspects at the national level (e.g., central humidity-controlled storage capacities, organised by the state and open for all forest owner). "Operations and safety" summarises literature addressing issues related to field operations, machinery, work safety, transportation, timber storage and the conservation of timber quality. The "economic" category included studies on economic repercussions and the marketing of timber disturbed by wind. Finally, the category "environment" summarised papers dealing with the environmental impact of the disturbance and secondary damage such as that related to salvage logging and bark beetle outbreaks. Each reference could address one or several topics, as presented in the supplementary material (Table S2).

Excel (Microsoft Corporation, 2019) was used to store the key information from the reviewed papers (Table S1) and to facilitate descriptive analysis.

Results

Descriptive Analysis

The literature from the six countries covered the four dimensions of post-windthrow management well: strategy ($n=89$), operations and safety ($n=73$), economy ($n=36$) and environment ($n=74$) (Fig. 1). Regarding language, 49% of the selected articles were published in English while 17% were in French, 11% in German and 11% in Italian, 10% in Swedish and 3% in Polish. The key topics emerging from the review are presented as a conceptual diagram across spatial and temporal dimensions in Fig. 2. The figure provides an overview on which spatial and temporal scales individual topics are discussed. In other words, when and where do the different activities of windthrow disturbance occur. Topics such as adaptive silviculture, salvage logging and emergency plans, for instance, are usually addressed at the regional level while the marketing of windthrown timber and the response of market prices are topics of national and international concern. A synthesis of the experiences in post-disturbance management is presented in the following sub-sections.

Strategic Aspects of Post-windstorm Management

Across the six focal countries, several common objectives in post-windstorm management emerged, regardless of region or forest type:

1. The main priority is the safety of the general population and of forest users and workers engaged in clear-

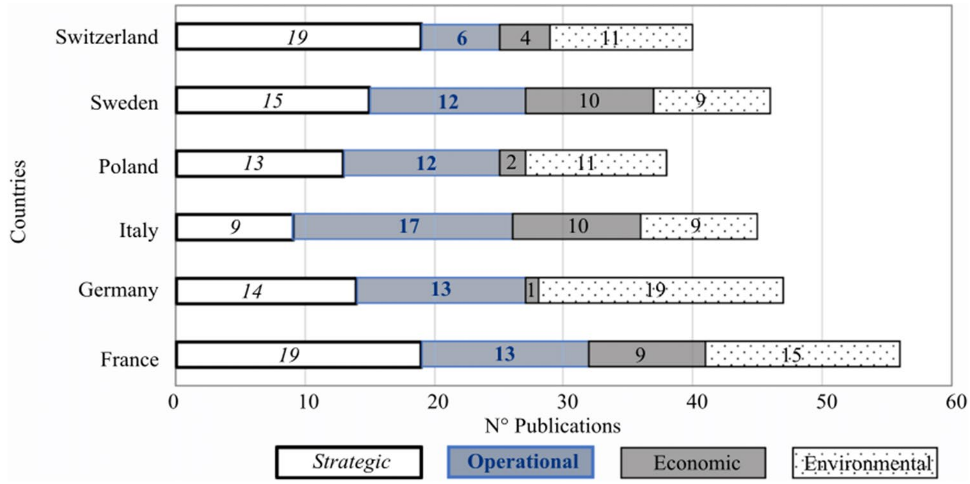

Fig. 1 Number of topic-related publications for each of the six countries (one reference can cover one or several topics)

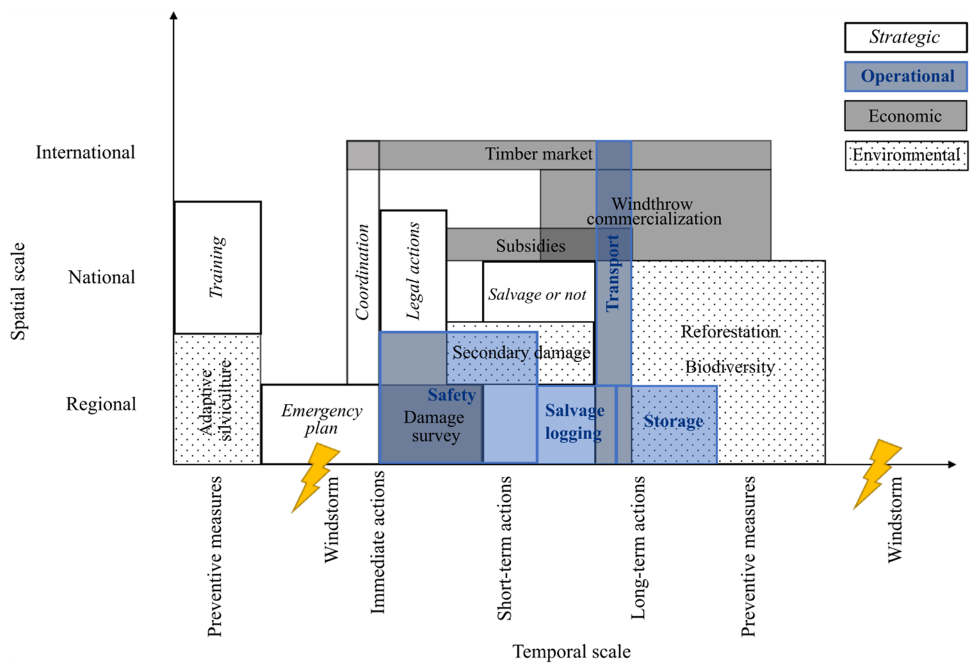

Fig. 2 Conceptual diagram illustrating the spatial (box height) and temporal (box width) coverage of the different activities related to windstorm disturbance at strategic, operational, economic and environmental levels

ing the windthrown trees [16–18]. Immediately after a storm event, power lines and roads should be cleared to facilitate the reestablishment of the power supply, to help prevent accidents and enable access for rescue and salvage teams. Injuries and accidents can be avoided by restricting access to disturbed areas. Direct risks that are associated with windthrows (e.g. leaning trees) should be identified, clearly marked (e.g. road closures) and, when necessary, communicated to the public (e.g. via news media).

2. The overall extent of the disturbance and the areas affected need to be identified swiftly in order to develop appropriate response strategies [19]. It is essential to estimate (as accurately as possible) the timber volume disturbed as well as to identify the areas affected by the disturbance in order to make decisions how to respond to the event (e.g. processing and marketing of timber). Forest owners should ideally contact the forest administration and inform them of the extent of the disturbance within the first three days after a storm, so that the overall extent of the event can be gauged and measures at the policy level can be considered.

3. Measures should be taken to mitigate a disruption of the timber market [17]. It is common for governments to temporarily restrict regular harvesting at the national level after a major windstorm in order to mitigate oversupply. For the same reason, it is recommended that timber disturbed by wind is retained in the forest for as long as possible (if forest health is not negatively affected) and is salvaged only when its utilization by the timber indus-

try is ensured. When windthrown timber must be harvested, high-quality timber should be put on the market first. Adequate storage facilities should be implemented to buffer the market from peaks in timber supply and conserve timber quality. Moreover, stakeholders should negotiate a fair market price after a storm event and set the term of the agreement.

Two more elements emerged from literature review but are only relevant under specific conditions (e.g. in the case of a protective forest or a conservation area):

4. The protective effect of a forest against gravitational natural hazards should be maintained or restored as quickly as possible to bridge the "protective gap" after a windstorm. Planting and temporary engineering measures are frequently recommended in areas where the protective function of forests is vital and regeneration is relatively slow, e.g. in mountain forests [20–22]. A recommendation for protective forests is to refrain from removing windthrown timber which is still rooted so as to protect against floods and avalanches during the regeneration stage [23, 24].
5. Biodiversity must be conserved and promoted [12•, 17, 25•]. Post-disturbance management decisions, such as whether to "salvage" or "not to salvage", can have long-term consequences on timber markets as well as on forest biodiversity. What constitutes a good approach in this regard remains an intensively discussed question [25•, 26], yet biodiversity often benefits if at least some disturbed trees are retained. Nevertheless, researchers and practitioners agree that this decision is strongly dependent on the main objectives of forest management (e.g. conservation or production) and on the risk of secondary disturbances (e.g. beetle infestation, wildfires, avalanches, etc.) that might affect post-disturbance forest development [14••].

In addition to the above-mentioned objectives, it is essential to prepare emergency plans in advance and define the different roles and responsibilities of each stakeholder to efficiently address future large-scale disturbance events [27]. To that end, amongst other things, a better coordination between the state and local authorities is needed [28].

Operational and Safety Aspects of Post-windstorm Management

Damage Assessment

The first premise of post-windthrow management is to ensure people's safety. The next important step in responding to a storm event is damage assessment, which should be completed shortly after the storm [17, 19, 29]. The aim of damage assessment is to give an overview of the situation and the extent of the event, providing essential information for strategic decisions regarding immediate action at national and regional levels [17]. It also includes assessing if the available resources such as machinery and workforce are sufficient or whether external help is needed. Foresters can carry out damage assessments through ground-based observations or aerial surveys based on satellite imagery and drone flights [9]. Aerial surveys can be used for strategic planning, whereas tactical planning generally requires direct visits to the affected sites [30, 31].

Salvage Logging and Safety

Salvage logging carries a high risk of accidents due to time pressure, stress, poor weather conditions, entangled trees and damp soils, as well as a limited workforce and resources. The main factors influencing the degree of risk during salvage operations are the level of experience and training of the workers; the operation status and maintenance of the machinery being used, the logging technique and degree of mechanisation; and the coordination between concurrent tasks [17, 32]. Good practice examples for carrying out salvage logging operations and reducing the risk of accidents have been presented recently [18]. One general recommendation is to conduct salvaging operations in a highly mechanised system, using cut-to-length (CTL) technology. Furthermore, it is important to ensure that the machinery used complies with all safety standards, such as laminated safety glass to protect the operator in the cabin, and a positioning system for GPS tracking. Occupational safety can also be supported by electronic devices and software, e.g. delineating accessible areas for machine traffic or providing information on the nearest rescue meeting points [33, 34]. After large-scale storms, formalised routines of decision-making [17, 35] can help to prioritise actions and thus reduce the risk of accidents.

When motor-manual work needs to be performed, at least one machine (commonly crawler excavators with flexible steel tracks and equipped with a grapple or heavy harvester machines) should be on site to support the operation [16]. Motor-manual work should be limited to separating stems from the root plate, while all further processing steps should be performed by a harvester or machinery situated outside the windstorm area, e.g. at a central landing. In steep terrain or on wet soils that are inaccessible to machines, cable yarding systems are recommended. They can support motor-manual work and reduce the risk of accidents. Where a general system of skid roads exists as part of regular forest management (e.g. skid roads every 20 to 40 m), the driving on site is limited also during salvage logging [16]. Moreover, temporary timber landings and roads can be built to ease the mobilisation of timber [19].

Transport and Storage

The effective clearing of windthrown Norway spruce (*Picea abies* (L.) Karst) stands is a delicate balance between a moderate supply of timber to the market to keep timber prices stable and the necessary salvage logging to avoid secondary disturbances (e.g. insect outbreaks). Immediately after tree processing, the logged timber should be transported to the industry for processing, or stored outside the forest to reduce breeding material for bark beetles [36]. However, transportation capacities are often a limiting factor in post-windthrow management. Improved communication between forest managers, machine operators, logistics providers and the timber industry is required to reduce delays. When immediate transportation and processing is not possible, several storage options exist [36], namely: (i) log yards outside the forest (> 500 m from the forest, if bark beetle infestations are of concern), (ii) humidity-controlled storage, (iii) debarking and (iv) the application of pesticides to protect against biotic risks. Humidity-controlled storage facilities (also known as wet storage) represent a promising alternative for the storage of high-quality spruce and pine timber for between 2 and 5 years [16, 37•]. However, they are cost-intensive, time-consuming to initiate and have to fulfil a number of legal regulations (e.g. regarding water quality). Studies show that the application of this storage method generally has low environmental impact, particularly when combined with a system to recover and recycle water [23, 38]. Timber quality does not significantly decrease for a storage duration of less than 3 years for spruce and up to 5 years for pine [16, 23, 37•]. Other species, such as European beech (*Fagus sylvatica* L.), do however decrease considerably in their quality [39].

Economic Impact of Post-windstorm Management

The management of storm-damaged stands in order to mitigate economic losses is complex and often not intuitive [40]. With pulses of timber entering the market, timber prices drop, while the cost of (salvage) logging greatly increases after a windstorm. Salvage logging after extreme disturbance events is thus often not economically viable [41]. Consequently, there is a low economic motivation for forest owners to salvage and sell timber. An alternative option is the storage of salvaged timber until market prices consolidate, yet storage incurs further costs. Large storm events can lead to the need for additional administrative staff and the purchasing of new machines (harvesters or forwarders). Therefore, financial support for post-disturbance management, e.g. supporting the wet storage of timber and the reforestation of disturbed areas, is crucial.

Environmental Concerns of Post-windstorm Management

There is an ongoing debate about the influence of salvage logging of disturbed sites on biodiversity, stand regeneration and subsequent stand development. Both negative and positive impacts on biodiversity have been reported. The removal of deadwood can reduce the biodiversity of saproxylic species dependent on this resource, and heavy machinery can lead to soil compaction. A recent review showed that harvester-forwarder systems cause less damage to soil, regeneration and residual stands during salvaging operations than a system using skidders or cable yarders for extraction [42••]. Pits and mounds from fallen trees as well as disturbances from salvage logging may have positive effects on seed germination after windthrow, particularly for pioneer species [43•, 44, 45]. But also retained windthrown logs can provide a good germination substrate as they decay [21]. Retaining tree tops and small-diameter trees helps to sustain heliophilous beetle species [46]. In addition, novel debarking approaches (e.g. bark scratching, where only strips of bark are removed to prevent bark beetles from completing a successful brood) can help to support deadwood-dependent populations [47]. Snags (i.e. standing dead trees) can serve as future habitat trees and foster biodiversity. Some authors recommend that forest managers should retain several habitat trees per hectare also after salvage logging—similar to regular harvesting operations—in order to conserve biodiversity [17, 24, 48, 49]. Moreover, scattered windthrows and less severe disturbances offer the opportunity to create conservation islands [50] and increase the structural diversity of ecosystems [51].

Country-Specific Experiences

France

In France, 31% of the land area is covered by forests and three-quarters of the French forests belong to private owners. Forests close to the Atlantic are particularly susceptible to windstorms. After storms Lothar (in the north of the country) and Martin (in the south-west) in 1999, France decided to delay the supply of the timber to the market and spread it out geographically [52]. A commercialisation network for windthrown timber was established to help coordinate harvest, storage and transport operations. As a consequence, the average timber prices did not decrease by more than 35–38%, instead of the 50% that were predicted without such measures [52]. Moreover, stakeholders agreed on the set timber prices to be maintained until supply exceeded demand [52] while a government relief programme offered financial support for clearing disturbed stands, improving road networks and purchasing new machinery [53]. In France, salvage logging after the storms of December 1999 was performed in a hurry and, according to the literature, often with little concern for the impacts on soil and biodiversity [54]. From this experience, a decision was taken that in the future only necessary action would be taken and heavy operations that may increase environmental impact and costs would not be rushed [54, 55]. Long-term wet storage was well established in France after the 1999 storms [23]. According to Hermeline [56], the role of transportation and storage was essential for the preservation of timber value after the windthrows in 1999 [52].

Germany

In Germany, 32% of the land area is covered by forests with an average growing stock of 336 m^3 ha^{-1}. Almost half of this forest area is privately owned with predominantly small and fragmented holdings with an average size of below 20 hectares. While no official national strategy exists to promote post-windstorm management, large wind disturbances in the past decades have resulted in a number of projects addressing disturbance management and leading to clear recommendations for practitioners [16, 36]. Specific recommendations have been developed following the emergency management cycle, including management measures for the dimensions preparedness, intervention, recovery and prevention [57]. With regard to salvage logging, one recommendation is to prioritise the tree species most vulnerable to bark beetle infestation, i.e. to first salvage Norway spruce and then other softwoods, leaving deciduous trees to be salvaged last [36]. Furthermore, salvage operations should be prioritised by disturbance size and the expected environmental impact: single trees and small clusters of windthrown trees should be given priority (to be cleared until mid of May after a winter storm), while larger disturbed areas should be managed after that (ideally until the beginning of June, but at least until the next spring) [36]. Practitioners often receive financial or administrative support from the federal forest administrations shortly after a windstorm event, for example, by increasing the admissible total weight for log transportation in the affected area from 40 to 44 t. Moreover, after storm “Kyrill” in 2007, one of the state forest administrations published a handout aiming to minimise the infestation of remaining stands by bark beetles. To store windthrown timber, the mechanical debarking of logs with modified harvester heads was also attempted in Germany: this approach succeeded in reducing the risk of bark beetle infestations and improving transportation efficiency, but also proved costly [58–60]. Therefore, instead of complete debarking, bark scratching was suggested as a cost-effective alternative, achieving the same goals at 28% lower cost [61].

Italy

In Italy, 31% of the country is covered by forest, of which 66% is privately owned [62]. The windstorm events experienced in Italy can be categorised according to their frequency and geographical characteristics. In particular, windstorm events can be (1) frequent (endemic) (e.g. typical for littoral stands where windstorms occur almost every winter, [63]), (2) infrequent and small-scale (e.g. in March 2015 in the area of Tuscany, [64]) or (3) infrequent and large scale (e.g. the 2018 storm “Vaia” that hit northeastern Italy [9, 63]). The different scales and characteristics of these three event types imply different post-disturbance management. Endemic disturbances are generally managed locally by small-scale contractors [65]. In contrast, local firms are usually not able to cope with large-scale disturbances and help must be sought from neighbouring regions and countries [66]. The challenges of massive and rapid salvage operations have favoured the application of mechanised harvesting technology among Italian logging companies [67]. However, limited investment capacity, uncertainty about future use and terrain constraints hamper the country’s mechanisation progress [68]. Before the latest windthrow event in 2018, the mechanization of salvage operations was introduced mainly to littoral stands in central Italy, where wind damage is frequent and favourable terrain conditions facilitate the use of machines [65, 69]. Because of the high costs of storage—and the limited availability of suitable storage sites—Italian experts estimate that only 5 to 10% of the total windthrown timber volume can be effectively stored [70].

Poland

Forests in Poland (30% of the land area) are mainly managed by the state forest administration, which is responsible for 77% of the total forest area [71], while the remaining areas are public (3.8%) and private (19.3%) forests. Therefore, when a large storm event occurs, the state forest administration takes most of the decisions. Cut-to-length (CTL) technology is a popular system and is used in the harvesting of ca. 40% of timber in Poland [71, 72]. It is recommended for post-windthrow salvage logging [73–75] because of considerations of work safety and efficiency. Motor-manual and chainsaw-based operations may also be used for clearing windthrown areas, as combined approaches where trees are separated from the stump with a chainsaw before being processed by a harvester [76]. When CTL-technology is used for clearing disturbed areas, lower productivity can be expected compared to conventional operations [74, 77] leading to higher harvesting costs [78–81]. Extra costs can occur when stumps have to be removed [82] after windthrow or when broadleaved species are processed due to difficulties in delimbing [83] and challenges of keeping accurate lengths [80]. Uncleared windthrow of Norway spruce can provide breeding material for insects and may therefore trigger outbreaks of bark beetles [84, 85]. Data concerning spruce stands in the Tatra Mountains (Tatra National Park) showed that, in the last century, bark beetle outbreaks followed all major wind or snow disturbances. However, infestations were avoided or contained when timber was salvaged [86] as, for example in the summer of 1963 in the Tatra Mountains, after the clearing of timber previously damaged by snow [84].

Sweden

Sweden is dominated by forests (69% of the land area), most of which are privately owned (72% of the forest area) [87]. Swedish forest policy is characterised by "freedom with responsibility" and the forest sector is based on free-market mechanisms. Windstorm events are frequent in the country, and despite the absence of an official post-windstorm strategy, guidelines are available on how to proceed after a windstorm [88]. After storm "Gudrun" in 2005, the Swedish Forest Agency's overall assessment was that the forest industry's performance in post-windthrow management had been excellent, despite the severity of the damage [89, 90]. The processing and handling of the timber disturbed by wind proceeded better than expected, thanks to the active participation of forest owners and the good communication between actors and authorities [91]. Moreover, a study showed that, after 10 years, the forest area affected by storm Gudrun had almost recovered its pre-storm conditions, suggesting that foresters had made good choices when aiming to restore the forest area [92•]. Generally, the state does not give subsidies to forest owners affected by windstorms [92•]. Yet, the government made an exception for Gudrun and, with the help of the EU, provided a financial support package of more than 3 billion Swedish crowns (corresponding to approx. 300 million euros). This included a tax reduction for storm-damaged timber, a diesel tax exemption, reforestation support, road support, storage support and abolished track and fairway fees [91]. Storm "Gudrun" also highlighted the importance of risk management awareness in forestry practices [93]. Indeed, many forest owners had no insurance against wind damage prior to the event in 2005 [7].

Switzerland

Swiss forests cover one-third of the country, are mainly owned by the public (ca. 70%) and extend across a wide range of topographies, from lowlands to mountainous regions, forcing managers to adapt their logging practices and post-windstorm management accordingly. Taking stock of the lessons learned from storms "Vivian" (1990, in the mountainous regions) and "Lothar" (1999, in the lowlands), the Swiss government published an official handbook in 2008 to advise foresters and other actors affected by storm disturbances [17]. Surveys showed a lower rate of accidents after "Lothar" compared to "Vivian", as salvage logging was mainly mechanised and was performed in the lowlands [94, 95]. The Swiss timber industry was only able to process a fraction of the large quantities of timber salvaged from these two wind disturbance events due to insufficient transportation capacities, which resulted in a loss of timber quality [17]. As a result, high volumes of deadwood were left in the forest, averaging 275 m^3 ha^{-1} for both storms [96], and thus considerably exceeding the minimum deadwood volumes proposed by Müller and Bütler [97] in a conservation context (20–50 m^3 ha^{-1}). A total of 49% of the Swiss forests are defined as protective forests against natural hazards, such as avalanches and rockfall, which highlights the importance of quickly recovering the functions of these forests after a storm event [17, 22]. Studies showed that at least 20 to 30 years are needed to restore the protective function after wind disturbance [20, 44, 98].

Outlook

Choosing between "clearing" and "keeping" windthrown timber after a storm event remains an intensively discussed question as this post-disturbance management decision has long-term consequences for timber markets, forest biodiversity and other ecosystem goods and services. The strategies applied in post-windthrow management need to be adapted to local conditions such as the severity of the disturbance, the growing stock and age of the disturbed stand and its accessibility. Yet, three commonly adopted strategies for post-windthrow management in Europe emerging from our review are (1) clearing, including windthrown trees and standing survivors, (2) salvaging a fraction of the windthrown timber but leaving standing trees and retaining some dead trees on site or (3) not salvaging at all [26]. Which post-disturbance management strategy is chosen strongly depends on the legal framework, but also on the type of forest, its topography and vulnerability to other disturbances, the resource availability to clear a site, as well as the prioritisation of management goals (e.g. production forest vs. high conservation value forest). The countries investigated here differed in their management response to windthrow, with differences being explained, in part, by various management objectives. Swiss forests, for instance, are managed for multiple uses and have a strong protective function against natural hazards, while roundwood production is the primary objective in a significant fraction of Swedish forests. These differences are reflected in national legislation for timber harvesting and biodiversity conservation, which inter alia guided decisions regarding salvage logging. Moreover, the further pathways of salvaged timber differed among countries. Long-term wet storage is well established in France, while in Germany also mechanical debarking of logs was adopted to address the storage needs in the context of pulses of disturbed timber. In Italy, the limited investment capacity in forestry also resulted in limited storage of windthrown timber (e.g. 5–10% of the total volume salvaged can be stored). Limited transport and storage capacities in Switzerland (e.g., compared to France) led to large amounts of timber being left on site. In Sweden, the forest legislation prohibits the storage of freshly felled roundwood in the forest and along forest roads during summer; thus, timber storage mostly takes place in mills. In Poland, large shares of windthrow timber are salvage logged while planned harvesting is put on standby to avoid a timber surplus on the market.

The ecological consequences of salvage logging remain unclear and are the subject of ongoing policy debates [14••, 99]. One consequence of salvage logging is the removal of disturbance legacies (i.e. the remaining structures of the original forest, which includes standing and downed dead wood, live trees and seed banks; [100]). There is increasing evidence of the role of biological legacies in forest resilience [21, 101], providing seed sources and substrate for the regeneration after disturbance and creating habitat for a wide range of species [97]. Moreover, not removing logs after a storm can temporarily protect against natural hazards (e.g. rockfall and avalanches) during a period in which the regenerating forest cannot fulfil its protective role [22]. However, it is not clear to which extent retaining disturbance legacies is in conflict with forest management for other ecosystem services such as provisioning (e.g. food and wood production), regulating (e.g. climate regulation) and cultural services (e.g. recreation) [102••]. Future research should thus focus on how to better include disturbance legacies in multifunctional forest management [102••]. Thorn et al. [25•] found that 75% of a disturbed area needs to be left unlogged to maintain 90% of its species richness. Consequently, more research is needed on how to manage deadwood (e.g. amount and spatial–temporal distribution) to promote forest recovery and biodiversity without compromising the economy of forest management or increasing the risk of secondary disturbances (e.g. wildfires or bark beetle outbreaks [12•],).

Storm events in Norway spruce forests often trigger bark beetle outbreaks [103] and can make forests more vulnerable to further wind damage [104] or other natural disturbances such as drought and wildfires [105]. Clearing windthrown areas is recognised as one of the most effective control measures for bark beetle (*Ips typographus* (L.)) outbreaks [85]. However, the efficiency of salvage logging for dampening bark beetle outbreaks is greatly reduced by climate change and salvage logging might not be able to prevent a climate-related intensification of bark beetle infestations (i.e. resulting from an increasing reproduction rate and decreasing winter mortality) [99]. Furthermore, not clearing windthrow in some parts of the landscape (e.g. because of conservation goals) does not seem to negatively impact the rest of the landscape [106]. Different post-disturbance management strategies thus can be applied at the landscape scale, yet need to consider successive interacting disturbances [102••]. This is particularly important in the context of climate change which will most likely amplify both the individual and combined impact of interactive natural disturbances [3]. In this regard, it is also important to note that disturbances such as major storms can be important drivers of changes in forest ecosystems and can facilitate their adaptation to climate change [107, 108]. To better quantify the potential of disturbances to facilitate adaptation, long-term data is required. Existing field experiments should thus be maintained to monitor the effects of different post-disturbance management strategies and how these affect forests resilience.

Stand regeneration is influenced significantly by post-windstorm management. Notable differences in succession have been observed for cleared and uncleared stands [109]. A current debate in European forest management is about whether to replant disturbed areas or not, with what species and where. Studies showed that advanced regeneration (i.e. saplings) can accelerate regeneration after a storm event, particularly at high elevations [20, 44, 98]. Natural regeneration should be promoted [17], but sometimes this process is slow. This is especially the case at high elevations, where forests often fulfil a protective function, e.g. against avalanches and rockfall. In these instances, planting is an important tool to quickly restore the protective function of the forest. Planted species should be adapted to local site conditions, and mixed species stands should be promoted to diminish the risk of future disturbances [17, 95, 110, 111]. A higher proportion of broadleaved tree species or wind-firm conifers (e.g. silver fir, *Abies alba Mill*) can reduce the vulnerability to wind of monospecific Norway spruce stands by a factor of three [110]. More broadly, the choice of species to be planted after a windstorm should consider (1) vulnerability to future storm events, (2) demanded products and services and (3) resistance and resilience to climate change.

A recent global meta-analysis concluded that the degree of salvage logging should be defined on a large scale (e.g. regional policy and management plants) while considering local variations such as climate, topography and species compositions [14••]. This meta-analysis also suggested targeting specific management goals rather than aiming to address all potential ecosystem services in post-disturbance management [14••]. A diversification of management strategies in space (i.e., zoning approaches) may be a potential solution for reducing trade-offs between management objectives. Changes in drought periods put more stress on regeneration but changes in soil frost, snow cover and tree species composition also make forest operations more difficult [112, 113]. These aspects underline the global change is posing considerable challenges for post-disturbance management.

We conclude that general recommendations regarding post-disturbance management need to be adjusted and tailored to each situation and context. Salvage logging might be essential in forests susceptible to bark beetle outbreaks while no salvage logging is recommended in protective forests and forests of high conservation value. Moreover, decisions on salvage logging will depend strongly on the amount of windthrown timber sawmills are able and willing to process, highlighting the importance of storage capacities (which vary by country) and timber prices (affected by the international market). We here suggest an integrative approach to post-disturbance management that considers strategic, operational, economic and ecological dimensions. A further important aspect is to align short-term operational considerations and long-term strategic goals. This can, however, only be achieved by an increased understanding of natural disturbances by the general public and support at the policy level. Remaining research gaps that should be tackled in future studies include (1) how to strike a balance between the positive and negative effects of salvage logging, (2) how to integrate climate change considerations more explicitly in post-windthrow management and (3) how to plan post-disturbance management in interactive disturbance regimes (e.g. with disturbances from bark beetles, windthrow and drought) rather than focusing on individual disturbance agents.

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Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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•• Of major importance

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