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Forest damage and forest supply chains: a literature review and reflections

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ABSTRACT

Timber supply is affected by natural disruptions such as storms, wildfires, and insect infestations, which modify timber properties and disturb the supply to forest industries. Climate change threatens to increase the prevalence of forest damage and supply chain disturbances. This review analyzed the research between 2000 and 2022 on the effects of forest damage on wood supply chains and management measures to handle such disruptions. The review identified 23 studies from North America, Europe, and Australia and analyzed them regarding damage type and impact, research approach, and key findings. The literature on the topic covers the leading causes of damage: fire, wind damage, and insect infestation. In some cases, climate change was identified as the underlying cause of the supply disruptions. Research approaches involved calculations of consequences, scenario modeling, optimizations, and qualitative studies. This review identifies the essential considerations for successfully handling supply chains after forest damage. Robust supply warrants a range of adaptations, including choices for forest establishment, forest management methods, and collaborative planning. In addition, future research themes based on findings in the retrieved papers are suggested.

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Introduction

Forests are affected by extreme weather events and biological attacks by living organisms. Due to their impact on growing stock, such damage disrupts the wood flow from forests to industries, leading to wood quality reductions, changed management plans, long-term wood supply shortfall and risk, and increased costs. It is expected that forest damage will worsen, partially as a result of global warming; "projected climate change, combined with non-climatic drivers, will cause loss and degradation of much of the world's forests (high confidence)" (IPCC 2022, p. 12). More volatile and extreme weather is anticipated to occur in North America and other regions of the world (Washington Post 2021). This trend could increase storm damage, which leads to large forest volume losses (EFI 2010). Examples of windthrow events are the storm Gudrun in Sweden in 2005, Lothar in Germany and France in 1999, and Hurricane Ivan in 2004 in Alabama. Weather-related incidents such as wildfires and storms threaten to augment tree mortality and negatively impact forest harvests and other provisioning ecosystem services (IPCC 2022, p. 48).

An increase in wildfires has also been noted, for instance in North America, where the affected acreage figure has doubled since the 1990s (Congressional Research Service 2022), and also in Europe (European Environment Agency 2021). Recent extensive wildfires were recorded in Sweden in 2018, British Columbia in 2018, Greece in 2021, and several parts of Canada in 2023. A cause-effect chain may start where increased temperatures, long periods of drought, and unfavorable winds increase the frequency, severity, and duration of wildfires (IPCC 2022, p. 48).

Pests and insects also cause damage to forests. One such example is the extensive attacks by the mountain pine beetle (MPB) in western Canada and the United States, which destroyed millions of hectares of forests during the first decades of the 21st century. According to Sidder et al. (2016), insect infestations in the 1990s and the 2000s on 18 million hectares of forest land in British Columbia caused the loss of 700 million cubic meters of merchantable pine. European countries have also recorded severe insect damage, e.g. by bark beetles on spruce trees (Netherer et al. 2021). The unfortunate combination of windthrow followed by insect infestations by bark beetles damaged 110–140 million cubic meters of timber in central Europe in 2018–2019, predominantly in Austria, Czechia, France, Germany, Italy, Slovakia, and Switzerland. Northern Europe is experiencing increased bark beetle activity (UNECE/FAO 2019).

Although many factors drive forest damage, a continuous change in the climate can exacerbate the destruction of forests as temperatures increase and weather patterns vary with high energy levels in the atmosphere and oceans. Climate impacts on forests can create a sequence of stressful events that reduce tree health and cause disruptions and damage; for example, when dry periods are followed by wildfires (IPCC 2022, p. 18) or by insect attacks (Hanewinkel et al. 2011; IPCC, p. 2486). Consequently, these damages threaten forest operations and degrade wood resources and their value. Weather-related damage and events can change the regular flow of wood from forests to processing companies by disrupting supply chains and causing downstream effects. The severity of these impacts depends on the complexity of the damage, recovery

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opportunities, warning system, and if critical nodes are affected (Craighead et al. 2007).

Several analyses of supply chain risks in the forest sector have been devoted to market risk and demand variability (FPAMR 2021). However, disruptions at the source between the forest and the forest industry have received less attention. Incidentally, from a theoretical and empirical perspective, such disruptions may have an increasing significance for the forest sector for long-term and operational planning. Therefore, reviewing the existing knowledge on the subject is motivated from a precautionary viewpoint and can support the preparation for future timber supply disruptions. An overview of conducted studies can provide preliminary knowledge for researchers and managers and indicate areas that warrant further studies.

Thus, the objective of this study was to conduct a literature review of the impact of forest damage on forest supply chains and investigate how they have been managed to counter or minimize supply-side disturbances. This study is novel by focusing on the specific damage to timber supply and reviewing the existing studies on this topic. The review focused on industrial forest-based supply chains and disturbances with physical/biological causes. Economic, political, or institutional causes (such as logging bans or strikes) and supply chains within the informal sector or subsistence contexts such as fuelwood harvesting, were excluded. The motivation for the study was to support stakeholders to design resilient supply chain strategies that mitigate the impact of the increasing forest damage from biophysical processes.

Conceptual background

This analysis refers to and applies concepts from the supply chain management (SCM) framework, which refers to "The management of a network of relationships within a firm and between interdependent organizations and business units consisting of material suppliers, purchasing, production facilities, logistics, marketing, and related systems that facilitate the forward and reverse flow of materials, services, finances, and information from the original producer to the final customer with the benefits of adding value, maximizing profitability through efficiencies, and achieving customer satisfaction" (Stock and Boyer 2009). The definition highlights that the SCM concept encompasses different decision points and time perspectives (Tang 2006).

The analysis focused on forest damage and the associated disturbances and risks affecting the flow from the forest to the primary processing industry. SCM decisions can influence this flow by reducing a supply chain's exposure to disturbances or improving its resistance when affected (Tang 2006). Therefore, it is in both the supplier's and the buyer's interests to handle supply risks and improve its resilience (Shekarian and Parast 2021); this importance increases as climate change continues to disrupt the forest system and timber use.

Materials and methods

This study followed the method entitled "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA). The procedure leads to a systematic and transparent approach to assessing the trustworthiness and applicability of the findings (Page et al. 2021). The PRISMA method stipulates clear objectives for the literature review and documented criteria for inclusion and screening procedures.

The eligibility criteria for studies in this review required that they be published in peer-reviewed, recognized scientific journals. Only studies published in the English language were selected. The topic and scope were limited to studies on wood supply chains from forest sites to the initial primary processing industry. Further, management and supply chain aspects were selected since the study focused on input for improvements. The study period was 2000–2022, but no geographical delimitation was applied.

These criteria can be discussed as "gray" literature, e.g. from national research institutes, may provide interesting findings in some cases. However, because the scientific quality of these publications vary and can be difficult to assess, a selective approach was preferred. Furthermore, it can be argued that forest damage impacts not only the initial processing facility, but also secondary forest industries, and end-use stages. These later impacts are less clear and more challenging to study and were, for this reason, not in the scope of this review (Page et al. 2021).

The databases used for the search included Web of Knowledge, Scopus, and Google Scholar. Publications were also retrieved based on an inspection of the reference lists in the selected studies. Search terms are presented in Table 1, and the screening procedure followed a stepwise path, shown in Table 2.

The selection and screening procedure resulted in a final set of 23 papers included in the analysis. Although the general literature on biophysical aspects of forest damage is extensive (IPCC 2022, p. 12), identified studies focusing on how disturbances impact timber supply chains were scarce.

The studies were classified according to the following characteristics: year, country, damage caused, damage consequence, and forest type. Thereafter, the analysis focused on the selected research approach, conclusions, and implications for

Table 1. Search terms.

Selection criteria	Search terms				
	Wood material	Supply chain	Damages	Management focus	Supply impact
Search terms	timber, forest, wood, roundwood, logs	value chain, supply, flow, procurement, sourcing, distribution, supply	insect, pest, storm, weather, damage, fire, catastrophe, climate, warming, wildfire, wind, cyclone, hurricane	management, coordination, planning, synchronization, strategy, operations, flow	disturbance, risk, disruption, shortage

Table 2. Screening stages (PRISMA procedure).

Description of search and screening stage	Number of references obtained
First data search	4116
Removal of off-topic publications, e.g. the title of the article or journal reflects other focus/research fields (e.g. history, specifically ecology, chemistry, etc.)	295
Abstract check. Removal of off-topic papers after reading the abstract	54
Content check. Removal of papers after reading the content. Causes: Additional off-topic papers, unclear methods, or weak supply chain connection.	23

research and practitioners. The discussion section synthesizes the results and considers possible directions for further scientific inquiry.

Results

Overview of the studies

The 23 studies retrieved are commented on below and presented in Annex 1. Most analyses described forest damage and wood supply in North America, predominantly in Canada. However, research in the field has also been conducted in Europe, and one study described forest damage in Australia. The high number of Canadian studies reflects the importance of the forest sector in the country and the high incidence in the last decades of various types of forest damage. Furthermore, increased attention to the impact of forest damage on wood supply chains may be associated with the reliance of Canada's large-scale forest industries, in some cases with high capital costs, on a stable and predictable flow of input timber. Although the number of studies was low, Figure 1 indicates that the publication pace is increasing.

The studies were generally published in journals oriented toward forest science and management. The three top journals were the Canadian Journal of Forest Research (7 papers), Forest Policy and Economics (3 papers), and Forest Ecology and Management (2 papers). Other outlets with one paper each were Annals of Operations Research, Australian Forestry, Environmental Science & Policy, European Journal of Forest Research, Forest Science, Forestry Chronicle, Forests, International Journal of Disaster Risk Reduction, International Journal of Forest Engineering, International Journal of Wildland Fire, and Wiley Interdisciplinary Reviews – Energy and Environment.

Boreal coniferous or mixed-wood forests were most commonly studied, primarily focusing on forests in Canada (e.g. Armstrong 2004; Dymond et al. 2014) and Finland (e.g. Kärhä et al. 2018). Studies on continental Europe (Hanewinkel et al. 2011) and the United States (Russell et al. 2017) considered mixed forests. *Pinus pinaster* was considered in a Portuguese study (Garcia-Gonzalo et al. 2014), whereas Brack and McLarin (2017) analyzed fire damage in native Eucalyptus stands in Australia.

Damage type

Causes of forest damage included predominantly wildfires, windthrows, and insect attacks. Wildfires and insect infestations were frequently studied in Canada, whereas European studies mentioned and investigated windthrow damage more frequently (e.g. Hanewinkel et al. 2011), alongside analyses focusing on forest fires (e.g. Garcia-Gonzalo et al. 2014).

Forest fires were frequently examined damage causes in Northern America and Southern Europe. The preparedness to prevent or meet forest fires is not sufficient, according to Garcia-Gonzalo et al. (2014). Although fires are natural events in many forests, there is an upward trend where wildfires affect larger areas each year; there are cases in Canada where,individual wildfires have ravaged more than 500,000 hectares (Mansuy et al. 2018). It was even predicted by Gauthier et al. (2015) that forest fires could reduce the timber supply in northern Canada by the middle of the current century.

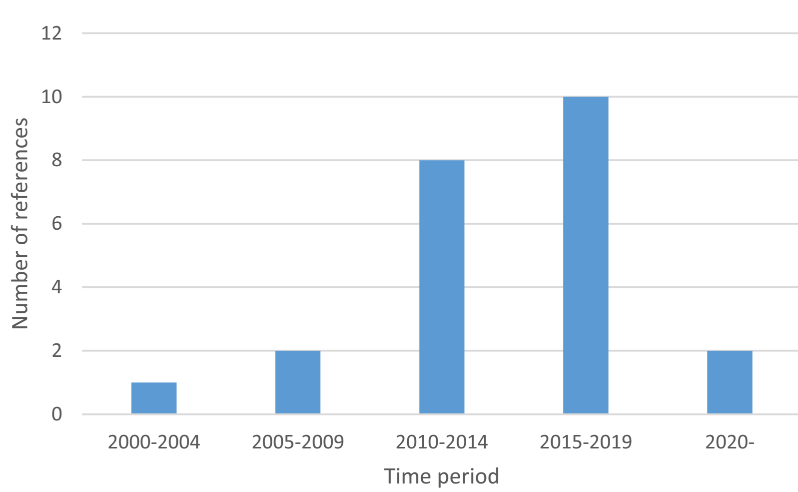

Figure 1. Number of studies per 5-year period.

Damage by insects are reported in eleven studies (e.g. by Mathey and Nelson 2010; Johnston and Hesseln 2012; Mushakhian et al. 2020). Pests and insects is one leading cause of forest damage in British Columbia, and western spruce budworms have severely affected 14 million hectares of Douglas-fir stands between 1960 and 2002 (Murdock et al. 2013). Mathey and Nelson (2010) describe impacts of the mountain pine beetle in Alberta and Kärhä et al. (2018) refer to bark beetles infesting spruce in Finland.

Wind damage has been described in North America (e.g. Russell et al. 2017), affecting timber supplies and dimensions, and in Europe, increasing unit logging costs (Kärhä et al. 2018). In some cases, windstorms are succeeded by salvage harvesting, as in 2011 for Minnesota and Wisconsin (Russell et al. 2017). Hanewinkel et al. (2011) noticed an increase in windstorms on the European continent.

Several studies in this review based their analyses on multiple causes of forest damage. They mentioned that climate effects could cause windthrow or prolonged drought that later prompted infestations or wildfires (e.g. Hanewinkel et al. 2011; Steenberg et al. 2011).

Impact on supply chains

The reported impacts on timber supply encompassed the flow rate, quantity, variability, quality, and predictability of timber supply (Daniel et al. 2017). These impacts, in turn, further disrupted operational (Brack and McLarin 2017) and business processes (Russell et al. 2017). Studies in this review explored both the industrial and ecological impacts of salvage logging (Saint-Germain and Greene 2009; Russell et al. 2017) and the management of supply disruptions, e.g. through buffer stocks (Raulier et al. 2014).

The review also identified studies that translated forest damage events to economic consequences, owing to costs for actions that prevent fires from escaping the initially affected area (Rijal et al. 2018a), the impact of disruptions on profits (Peter and Nelson 2005), logistics costs (Rijal et al. 2018a; Mushakhian et al. 2020; Ma et al. 2022) or downgrading quality (Peter and Nelson 2005).

Research type

The research approaches included quantitative optimization approaches (e.g. Zubizarreta-Gerendiain et al. 2017), overviews and risk assessments (e.g. Hanewinkel et al. 2011), and qualitative studies (Johnston and Hesseln 2012). Several analyses were based on simulations to explore the possible outcomes and risk levels impacting wood supply (e.g. Steenberg et al. 2011). The research type and findings are presented in Table 3.

.Mushakhian et al. (2020) analyzed the optimization of net profits for supply volumes, characterizing salvage harvesting approaches under different levels of insect outbreak intensity (low, medium, and high). Financial optimization calculations were instead used by Brack and McLarin (2017) to obtain the optimal harvest schedules for native eucalyptus forests in southeastern Australia. The forest types in their study ranged from mature eucalyptus to mixtures of mature stands and those in the regrowth stage. Similar attempts were made by Zubizarreta-Gerendiain et al. (2017) on wind damage; in this case, the authors used a deterministic, multistage stochastic programming model to compare the net present values under different scenarios and with even-flow harvesting constraints. Combined scenarios based on optimization were also used by Armstrong (2004), who applied Monte Carlo simulation with random proportions of land affected by wildfires. The yields in this model were recalculated to fit the shifting allowable cut levels, generating probability simulations of yields.

Simulations of management strategies to minimize supply disruptions were generated by Dymond et al. (2014), with alternatives evaluated through economic analyses based on a discounted cash flow assessment of harvesting and silvicultural interventions. Gauthier et al. (2015) applied simulations to evaluate timber supply vulnerability to risk scenarios based on historical forest growth, harvest rates, and current and projected forest burn rates. The authors compared the theoretical harvest rates without fire with the alternative scenarios. Peter and Nelson (2005) estimated “sustainable” harvest levels based on risk, tolerance to harvest shortages and fire suppression effects. Simulations were also applied by Mathey and Nelson (2010) in the assessment of stochastic pine beetle attacks. Steenberg et al. (2011) focused on the role of climate change in harvest operations using a landscape disturbance model in central Nova Scotia, Canada. The authors investigated the interaction between climate change, forest management, and the consequential impact on timber harvest. Other approaches combined scenario analyses of e.g. forest fire impacts, where policies for wood supply were balanced against social or ecological factors(Saint-Germain and Greene 2009; Rijal et al. 2018b).

Studies also included economic criteria in scenario analyses (e.g. Mathey and Nelson 2010; Murdock et al. 2013; Garcia-Gonzalo et al. 2014). Detailed economic analyses of increased harvesting costs for harvesting windfalls were calculated by Kärhä et al. (2018). In contrast, Russell et al. (2017) evaluated damage impacts on wood volume reductions, sale area, and the number of species.

Finally, studies used qualitative approaches to cover various contextual factors affecting wood supply. Mansuy et al. (2018) reviewed salvage logging operations after fire and insect outbreaks in Canada. Johnston and Hesseln (2012) conducted group discussions with over 50 forestry stakeholders across Canada, covering observations of climate change impacts, adaptive capacity, and perceptions of barriers to adaptation to increased damage risk. The ability of the Canadian forest sector to successfully adapt to climate change was then assessed. Hanewinkel et al. (2011) reviewed supply risk management in the European forest sector and described damage types and risk management, including the management steps taken to prevent and buffer damage effects.

Supply chain management implications

The findings of the studies have recommendations for managing disturbances in supply chains caused by forest damage. Generally, Johnston and Hesseln (2012) argued that institutional factors such as tenure agreements, regulatory systems, and communication and cooperation between regulators and

Table 3. Included studies: Research objective and type, and key findings and recommendations.

Authors	Publication Year	Research objective and type	Key findings and recommendations
Armstrong, GW	2004	Monte Carlo simulations on burned area. Calculation of harvesting volumes. Results are presented as probability distributions.	Fire regimes can lead to reduced harvests. Probability and time perspective are critical factors.
Brack, C. L.; McLarin, M.	2017	Risk calculations and optimizations for sawlogs and pulpwood	Optimal, long-term harvest schedules. Identification of robust operational decisions
Daniel et al.	2017	Stochastic forest management planning model. Monte Carlo simulations of future uncertainties, including uncertainties for wildfire.	The analysis demonstrates a modeling approach. There are increased risk of shortfalls in timber harvests. Risk-based framework for incorporating uncertainty into forest management, including the effects of climate change.
Dymond et al.	2014	Simulation methods calculating allowable harvests and silviculture strategies	Species diversity can create resilient forests with better net revenues over time
Garcia-Gonzalo et al.	2014	Simulation and optimization of maritime pine stands based on soil expectation value	Fuel treatments improve profitability. Shrub cleaning reduces fire severity. Management-oriented simulation models are helpful
Gauthier et al.	2015	Evaluation of the timber supply vulnerability. Scenario calculations	Increasing vulnerabilities are expected by mid-century High-risk areas can be identified.
Hanewinkel et al.	2011	Overview of natural hazards in Europe. Review of methods to assess forest hazards.	Application of bioclimatic envelope model. Interaction between hazards needs further study.
Johnston and Hesseln	2012	Stakeholder perspectives of forest hazards	Adaptive capacity is critical for risk reduction and sustainability. Institutional barriers can become constraints to adaptation
Kärhä et al.	2018	Time-study of productivity and costs for salvage harvests	Resource-efficient methods for salvage logging are needed. Logging costs of windthrown trees were 10–30 % higher than those of undamaged normal stems.
Leduc et al.	2015	Exploration of shortfalls under different burn rates Simulations are compared	A 100 % rate of salvage logging cannot fully compensate for timber losses to fire. Interannual burn rate variability reduces the efficiency of mitigation measures.
Ma et al.	2022	A probabilistic framework for quantitatively assessing wildfire risk	The framework can be used in what-if scenarios to assess the effect of pre-and post-wildfire risk mitigation measures
Mansuy et al.	2018	Review of salvaged bioenergy feedstock after natural disturbances	Salvaged wood has a bioenergy potential.The design of robust supply chains can be a challenge.
Mathey and Nelson	2010	Generation of a management plan and simulation of forest dynamics. Discounted net return is maximized.	The timing of insect attack affect the success of any strategy to reduce impact of forest damage.
Murdock et al.	2013	Calculation of insect outbreak scenarios. Development of a bio-economic evaluation model	Pest outbreak risk may increase during this century. Continuous economic modeling is needed.
Mushakhian et al.	2020	Development of a deterministic and multistage stochastic programming model of insect infestation. Results were compared with a deterministic model.	Salvage harvesting should focus on forest areas with the lowest level of infestation.
Peter and Nelson	2005	Estimations of sustainable harvest levels. Calculation of economic impacts.	Economic calculations can guide investment decisions and fire suppression policy.
Raulier et al.	2014	Timber supply simulations with or without fire protection actions.	Forest age structure in combination with fire has a large impact on supply. However, total protection is not effective or cost efficient.
Rijal et al.	2018a	Study of fire management options. Harvests for optimal net present value were obtained. Scenario comparisons.	Fire management increased the revenue from the sale of primary-processed wood products and reduced fire suppression expenditure.
Rijal et al.	2018b	Evaluation of alternative policies for three commercially-managed forests with different burn rates	Reducing the harvest volume also reduce job opportunities. A link between strategic planning is vital for revenues, despite natural disturbances.
Russell et al.	2017	Evaluation of a timber sale under different damage causes. Analysisof non-salvage and salvage sales for several tree species.	Public agencies should monitor and analyze forest damage to conclude policy and management.
Saint-Germain and Greene	2009	Analysis of industrial and ecological constraints to salvage logging with a focus on salvage timing.	Description of ecological impacts of salvage logging on regeneration, watersheds, and biodiversity
Steenberg et al.	2011	Study of climate change adaptation in forest management.	Climate adaptation of forests should be multi-faceted.
Zubizarreta-Gerendiain et al.	2017	Analysis of o optimal management of forests to minimize wind damage. Net present value was compared.	Minimizing height differences result in high, damage-adjusted net present value in forest management. Climate change slightly improves the total carbon balance of forestry.

the forest industry determine the possible ways to cope with forest disturbances. The authors refer to three categories of actors with essential roles: the forest industry, public authorities, and non-governmental actors such as certification bodies. Moreover, Armstrong (2004) highlighted that management opportunities and harvesting decisions depend on the damage event and general economic, social, and political factors. Similarly, Mansuy et al. (2018) concluded that the forest and energy sectors could create rules for promoting sustainable biomass harvest volumes. Their suggestion aligns with the view that close collaboration between managers and forest scientists is effective when "embedded" within forest management planning exercises (Johnston and Hesseln 2012).

Some studies in the review concluded that decision-makers and industries in alternative scenarios should compare the impacts of disruptions. Armstrong (2004) argue that any analysis must include probability distributions and time factors. Raulier et al. (2014) followed this principle when they studied the evolution of the forest age structure with harvest levels. According to several studies, the economic impacts of forest damage must be integrated into the analyses. Murdock et al. (2013) proposed bio-economic models that emphasize environmental conditions, policies, and mitigation/adaptation strategies. Such models may assist decision-makers in adapting to climate change without adverse economic impacts. However, multiple sourcing can help to reduce the disturbances in the wood supply (Hanewinkel et al. 2011).

Serious damage events, fires, or windstorms sometimes produce a large influx of salvage-harvested wood to markets, likely affecting local wood markets. Russell et al. (2017) suggest an impact assessment considering market reactions after forest damage events. Furthermore, supply vulnerability may be higher in areas with slow tree growth, a high frequency of wildfires, and a higher harvest rate than the theoretical harvest rate (Gauthier et al. 2015).

Several studies have focused on management actions to prevent or handle supply disruptions, including salvage logging (e.g. Leduc et al. 2015; Mansuy et al., 2018). However, Kärhä et al. (2018) found that salvage logging is 10–30 % more expensive than that of normal conditions and the volume losses could be even higher, and they called for more resource-efficient methods. Several recommendations were presented in the reviewed studies to prioritize stands to be salvaged; for example, Mushakhian et al. (2020) recommend that harvesting operations can focus on the lowest level of infestation in areas affected by pests and disease. However, the real challenge is to link the damage attack with its effects on the growing stock and how timber and revenue flows are impacted (Mathey and Nelson 2010). Furthermore, ecological considerations are also relevant, as logging can negatively affect the biodiversity of insects, birds, and fungi (Saint-Germain and Greene 2009; Zubizarreta-Gerendiain et al. 2017).

In addition, the findings presented potential preventive measures that counteract supply disturbances, e.g. to minimize the height differences between stands, hence, reducing the risk of wind damage (Zubizarreta-Gerendiain et al. 2017). Garcia-Gonzalo et al. (2014) focused on the method to remove flammable understory material (shrub cleaning) to reduce the risk of wildfires. Removing or avoiding high-risk species and establishing a diverse stand structure improve resilience in the long term (Dymond et al. 2014; Zubizarreta-Gerendiain et al. 2017). Pre-suppression efforts reduce the number of fires that escape initial stages by enhancing the early detection and rapid deployment of the initial attack force. These measures involve firefighters, infrastructure, early detection of fires, education, and investment in new facilities (Rijal et al. 2018a). An increase in pre-suppression expenditure can reduce the burned area and increase the net revenue, but the intervention must be cost-efficient (Raulier et al. 2014). Moreover, infrastructure investments such as road networks can be included in management plans to prevent forest damage (Brack and McLarin 2017).

The reviewed studies proposed analytical tools to evaluate management strategies. Stochastic programming models have been used to solve uncertainty problems (Mushakhian et al. 2020). Monte Carlo simulations provide models to support decision-making depending on attitudes toward risks, such as climate change (Hanewinkel et al. 2011). In this context, management models must be straightforward and easy to understand for managers (Hanewinkel et al. 2011; Murdock et al. 2013). Forest fire suppression modeling can determine resilient forest management strategies that project harvest volumes, profits, and landscape conditions (Peter and Nelson 2005). A similar perspective is presented by Ma et al. (2022) as they propose supply-network planning tools that simulate different "what-if" scenarios.

However, the measures suggested for achieving robust value chains are relevant only to a degree. As mentioned by Johnston and Hesseln (2012), beyond a certain level, adaptations become increasingly challenging, and uncertainties cannot be entirely removed because of the large distances between the feedstock and processing sites. Furthermore, long-term forest management plans that consider uncertainties cannot assume that pest outbreak risk will remain the same in the next as in the previous centuries (Murdock et al. 2013). Future vulnerability and resilience are influenced by the interaction of different hazards (Hanewinkel et al. 2011) and the age structure (Raulier et al. 2014). Long-term timber supply may dditionally at least regionally, be affected under warming climate conditions. Consequently, the vulnerability of timber supply could increase by the middle of the century in the boreal and montane forests of Canada (Gauthier et al. 2015) as long as abiotic and biotic disturbances occur more often. These uncertainties about the future motivate resource-efficient salvage logging methods (Kärhä et al. 2018) and a review of current tree species selection for forest establishment (Zubizarreta-Gerendiain et al. 2017).

Our reviewed analyses found that further research on forest damage and supply chain management approaches should address the sustainable conversion of salvaged feedstocks and portfolio thinking based on multiple supply sources (e.g. Mansuy et al. 2018). Moving to the administrative level, Russell et al. (2017) argued that regulators should document forest pre-disturbances conditions to improve the understanding of forest damage dynamics. These considerations imply that a multi-faceted and tool-rich approach to climate change adaptation is the best strategy to confront the risk and uncertainty of the future (Steenberg et al. 2011).

Discussion

This review focused on the impacts of forest damage on industrial supply chains, highlighting its growing significance worldwide. Most research on the topic analyzes regions with a highly developed forest industry sector where adverse events such as windthrow, wildfires, and insect pest attacks are the most severe and have a considerable impact on the forest industry. These regions include Northern America, Europe, and to some extent Australia. Wildfires are the leading cause of damage, although several studies address other causes, such as storm damage and infestations. The analyses include normative and descriptive research encompassing quantitative calculation, and qualitative studies of organizations and key stakeholders.

The described impacts may lead to severe difficulties for a sector of the economy that already depends on a bio-based raw resource of variable supply and properties (Dymond et al. 2014, Mansuy et al., 2018; Kärhä et al. 2018). Shortfalls or extreme oversupply of wood cause inventory problems along the supply chain connected to backlogs or oversupply and longer lead times (Armstrong 2004; Raulier et al. 2014). Moreover, inventory problems, or a less predictable quality reduce customer value and the opportunity for forest enterprises to obtain price premiums in the market (Saint-Germain and Greene 2009; Mushakhian et al. 2020).

Another downside is the economic and environmental impacts caused by reduced value creation, poor supply chain coordination, waste of unused wood volumes, and expensive salvage operations (Kärhä et al. 2018; Mansuy et al. 2018). Furthermore, when delivery precision, consistent quality, and availability are increasingly important throughout the economy, damage disturbances can erode the forest sector's business relations and, ultimately, its competitiveness.

Environmental problems caused by forest damage refer to greenhouse gas emissions (Johnston and Hesseln 2012, Mansuy et al. 2017; Murdock et al. 2013; Zubizarreta-Gerendiain et al. 2017). Moreover, biodiversity benefits that may be obtained from disturbances would be more cost-efficient if they could be controlled and targeted (Dymond et al. 2014) instead of being side-effects of damaging incidents (Johnston and Hesseln 2012). Moreover, forest damage may (in addition to hazards and damage to local communities) cause problems for non-wood ecosystem services (Dymond et al. 2014).

The impacts may differ according to the causes. Storms and fires generally create sudden impacts in the supply whereas insect infestations last longer, even over many years (Saint-Germain and Greene 2009; Gauthier et al. 2015). However, these impacts can be prevented in both cases through species selection and the creation of more diverse forest landscapes (Hanewinkel et al. 2011).

The suggested solutions in the reviewed studies encompass tenure agreements, regulatory systems, communication, cooperation between regulators and the forest industry (Johnston and Hesseln 2012), rules for promoting sustainable harvest volumes (Armstrong 2004; Raulier et al. 2014), risk-aware forest management planning (Mathey and Nelson 2010; Hanewinkel et al. 2011), scenario comparisons and economic consequence analyses (Peter and Nelson 2005; Zubizarreta-Gerendiain et al. 2017; Rijal et al. 2018b), stand properties and species diversification (Dymond et al. 2014), insights on market behavior (Russell et al. 2017), efficient salvage logging technologies (Kärhä et al. 2018; Garcia-Gonzalo et al. 2014; Mansuy et al. 2018), ecological considerations with shrub cleaning (Garcia-Gonzalo et al. 2014), fire suppression efforts through early detection, rapid deployment of an initial attack force (e.g. firefighters) (Peter and Nelson 2005; Rijal et al. 2018a), improved infrastructure, improved analytical tools, and resilient forest management that can meet alternative future developments (e.g. for species selection) (Hanewinkel et al. 2011; Murdock et al. 2013). Finally, these considerations need a coordinated multi-stakeholder collaboration to implement mitigation- and resilience-promoting actions optimally (Johnston and Hesseln 2012).

The study findings partially agree with the model described by Craighead et al. (2007), which states that supply chain vulnerability depends on multiple factors, particularly warning systems, adaptability, supply chain complexity, and node criticality. Hence, reasonable predictions of expected disturbances and possibilities to adapt operations quickly reduce the severity of forest damage (Peter and Nelson 2005; Johnston and Hesseln 2012; Gauthier et al. 2015; Brack and McLarin 2017).

This review does not represent all wood supply chain risks because it only focuses on supply-associated damages. Further studies may also need to consider the impact of other factors affecting supply chains from "both sides," such as the COVID-19 pandemic (Stanturf and Mansuy 2021) and possible future pandemics, trade restrictions, product policy regulations, and global trade flows.

Conclusion

Although much research has focused on the connection between global forests, climate, and damage caused by pests and insects, this review shows the specific impact of forest damage on timber flows. The risk of forest damage and disruptions restricts the adoption of efficient forest management practices that combine high wood utilization rates, ecosystem services, and limited carbon losses into the atmosphere. This literature review reflects an increasing awareness of the problem as climate change triggers various stress-related events that result in forest damage. Although forest damage occurs in all continents, studies that deal with forest supply chains are geographically limited, primarily to North America, Europe, and Australia. Future studies should expand this scope to all regions where the forest industry depends on a steady wood supply.

The review has yielded preliminary answers to its research questions:

The impacts on forest supply chains are multiple. A combination of disturbances is the worst-case scenario, with reduced opportunities to fine-tune supply chains that combine sustainable forest management with value creation and resource-efficient processing. Forest damage pushes timber supply back to a more unsophisticated and reactive enterprise with reduced possibilities for optimization.

Diverse management and collaboration opportunities can prevent and reduce the severity of forest damage. However, the potential of these tools depends on the ongoing climate change status and its impact on the forest's vulnerability.

The studies examined here included different damage types, impacts, geographical perspectives, and time horizons. They present diverse impacts on timber supply, lead times, capacities, and costs. In addition, the studies prescribe risk-minimizing measures. However, alternative risk management approaches concerning species diversity or sourcing strategies toward different supply sources must be further investigated. The studies have also recommended collaborations between academia, value chain actors, regulators, and industry. Welladapted strategies can enable firms to manage operational risks efficiently over time and they can facilitate a quick recovery after disruptions.

Further studies should involve multicriteria analyses, scenario modeling, market analysis, cost-benefit impacts of individual and concerted actions, and evaluation of strategies toward more resilient forest supply chains.

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Annex 1

Annex 1. Reviewed publications

Authors	Publication Year	Country	Forest type	Damage cause(s)	Supply chain impact of forest damage
Armstrong, GW	2004	Alberta, Canada	boreal mixedwood	Wildfire	Supply Chain disturbance
Brack and McLarin	2017	south-eastern Australia	Eucalypt forest	Various: storm, fire.	stochastic variation of yields
Daniel et al.	2017	Canada	Mixed forest types, mainly conifers	Wildfire	stochastic variation of yields
Dymond et al.	2014	British Columbia, Canada	Lodgepole pine, Douglas-fir, and Interior spruce	mountain pine beetle	Forest damage. Losses
Garcia-Gonzalo et al.	2014	Portugal	Maritime pine	Wildfire	Loss and damage
Gauthier et al.	2015	Canada	Boreal, taiga forests boreal and montane ecozones of Canada (taiga plains, boreal cordillera, boreal plains, boreal shield, and montane cordillera)	Climate, Wildfire	Reduced avaiability of timber. Harvest rate/intensity
Hanewinkel et al.	2011	Europe	Review paper	Climate, Storm, snow, wildfire, patogens	Losses and damages
Johnston and Hesseln	2012	Canada	Not specified	Climate change causing wildfires, insect damage	Not specified
Kärhä et al.	2018	Finland	Norway spruce-dominated stands	Wind damage, Barkbeetles	Damage, Salvage harvesting costs
Leduc et al.	2015	Canada	Black spruce	Wildfire	Volume reductions
Ma et al.	2022	Western United States		Wildfire	Supply chain costs
Mansuy et al.	2018	Canada	Conifers (Pine and spruce)	Wildfire, insect	Damage and costs due to salvage logging
Mathey and Nelson	2010	Alberta, Canada	Pine, spruce, aspen	Mountain pine beetle	Volume reductions and increased costs
Murdock et al.	2013	British Columbia, Canada	Pine, spruce	Spruce budworm, beetle	Reduced volumes and value
Mushakhian et al.	2020	Eastern Canada	**Spruce**	Spruce budworm	Harvesting and logistic costs. Reduced timber value.
Peter and Nelson	2005	British Columbia, Canada	Pine, Spruce, Aspen	Wildfire	Affected flow and variability of harvest volumes. Reduced profits
Raulier et al.	2014	Quebec, Canada	Pine, Spruce, Aspen	Fire	Timber supply disruptions and costs of buffer stocks
Rijal et al.	2018a	Quebec, Canada	Pine, Spruce	Wildfire	Costs and benefits from supressing fires.
Rijal et al.	2018b	Quebec, Canada	Conifers	Wildfire	Shortfall, quality loss
Russell et al.	2017	Minnesota and Wisconsin, USA	Analyses were conducted separately for species groups	Windstorms, insects, wildfires	Salvage logging and the wood supply chain.
Saint-Germain and Greene	2009	Canada	Various groups of species	fire, insects, fungi	Industrial and ecological constraints to salvage logging
Steenberg et al.	2011	Canada	Mixed species	Climate, insect, beetle	Impact on timber supply
Zubizarreta-Gerendiain et al.	2017	Finland	Scots pine, Norway spruce, Betula	Windstorms	Wind damage, ecological impacts