Resilience of Selected European Forest Value Chains: social-ecological challenges and implications for forest bioeconomy

by

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Certificate of Authorship

I hereby declare that this dissertation, titled " ***Resilience of selected European forest value chains: social-ecological challenges and implications for forest bioeconomy***", was created independently and ethically. All sources used have been appropriately acknowledged and cited. I confirm this dissertation has not been previously submitted for any degree or qualification in any university or other institution. The thesis was written under the guidance of doc. Ing. Martin Jankovský, PhD.

I agree with the publication of the dissertation according to Act No. 111/1998 Coll. on universities as amended, regardless of the outcome of its defence.

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***All manuscripts can be found in the appendix at the end of this document**

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Summary

This doctoral research investigated the resilience of European forest value chains (FVCs) within the framework of the forest-based bioeconomy, integrating social-ecological, economic, and institutional dimensions. Grounded in the concept of social-ecological resilience as the capacity to absorb, adapt, and transform under stress while maintaining essential functions, the study seeked to operationalize resilience assessment and inform adaptive governance of sustainable forest systems.

A mixed-methods design was employed, combining qualitative and quantitative analyses. Three main objectives guided the study: (1) a bibliometric and qualitative literature analysis to map the forest bioeconomy research landscape, complemented by a comparison of policy alignment between the Czech Republic and Sweden; (2) quantitative Operational Resilience Framework (ORF) based studies of FVC performance under climate-induced disturbances across five European case studies (Czech Republic, Croatia, Germany, Finland, and Spain); and (3) a local-level economic analysis examining predictors of resilience, market dynamics, complemented by stakeholder perspectives on adaptation.

Results revealed a rapidly expanding research landscape in forest bioeconomy innovation, led by Europe, with growing cross-sectoral collaboration but a predominant focus on technical over social and governance-oriented innovation. Regional analyses showed that resilience varies across contexts: proactive management, diversified processing capacity, and strong stakeholder networks fostered higher stability, while overharvesting and reactive responses increased vulnerability. Economic analyses highlighted that while salvage logging and short-term price adjustments offered temporary relief. However, long-term resilience depended on market diversification, adaptive management, and ecosystem-based strategies.

In conclusion, achieving resilient FVCs required broadening innovation beyond technology to include institutional diversity, participatory governance, and ecological stewardship. Forest and bioeconomy policies must be aligned with resilience principles and local strengthened capacities. These steps are essential to ensure that Europe’s forest-based sector can withstand systemic shocks while contributing to a sustainable bioeconomy transition.

Keywords: Salvage logging, timber assortments, innovation

Summary (in Czech)

Tato disertační práce zkoumá odolnost evropských lesních hodnotových řetězců (FVC) v rámci lesnické bioekonomiky, a to integrací sociálně-ekologických, ekonomických a institucionálních dimenzí. Vychází z konceptu odolnosti chápané jako schopnost absorbovat, adaptovat se a transformovat pod tlakem při zachování klíčových funkcí. Studie usiluje o operacionalizaci hodnocení odolnosti a o poskytnutí podkladů pro adaptivní řízení udržitelných lesních systémů.

Byl použit výzkumný design kombinující různé metody, integrující koncepční, regionální a lokální analýzy. Studie měla zadané tři hlavní cíle: (1) bibliometrická a kvalitativní analýza literatury za účelem zmapování výzkumného prostředí lesnické bioekonomiky (BE), doplněná o srovnání souladu politik mezi Českou republikou a Švédskem; (2) aplikace kvantitativního Rámce operační odolnosti (Operational Resilience Framework, ORF) k hodnocení výkonnosti FVC vůči klimaticky indukovaným disturbancím v pěti evropských případových studiích (Česká republika, Chorvatsko, Německo, Finsko a Španělsko); a (3) lokální ekonomická analýza zkoumající prediktory odolnosti a dynamiku trhu, doplněná o názory zainteresovaných stran na adaptační opatření. Výsledky ukazují rychle se rozvíjející výzkumné prostředí inovací v oblasti lesnické bioekonomiky, vedené Evropou, a rostoucí meziodvětvovou spolupráci. Přetrvává však převaha technologických inovací oproti sociálním a institucionálně-správním inovacím. Regionální analýzy potvrzují, že odolnost se napříč kontexty liší: proaktivní řízení, diverzifikovaná zpracovatelská kapacita a silné sítě zainteresovaných stran podporují vyšší stabilitu, zatímco nadměrná těžba a reaktivní přístupy zvyšují zranitelnost. Ekonomické analýzy dále ukazují, že kalamitní těžba a krátkodobé cenové úpravy sice mohou nabídnout dočasnou úlevu, avšak dlouhodobá odolnost závisí na diverzifikaci trhů, adaptivním managementu a ekosystémově založených strategiích.

Závěrem lze říci, že dosažení odolných FVC vyžaduje rozšíření inovací nad rámec technologií směrem k institucionální rozmanitosti, participativnímu řízení a ekologicky zodpovědnému hospodaření. Lesnické a bioekonomické politiky musí být uvedeny do souladu s principy odolnosti a je nezbytné posílit lokální adaptační kapacity. Tyto kroky jsou klíčové pro to, aby odvětví založená na evropských lesích dokázala čelit systémovým šokům a zároveň přispívala k přechodu na udržitelnou bioekonomiku.

Klíčová slova: kalamitní těžba, sortimenty dříví, inovace

Summary (in Spanish)

Esta investigación doctoral analiza la resiliencia de las cadenas de valor forestales (FVCs) europeas dentro del marco de la bioeconomía basada en los bosques, integrando dimensiones socioecológicas, económicas e institucionales. Basada en el concepto de resiliencia entendido como la capacidad de absorber, adaptarse y transformarse bajo condiciones de estrés mientras se mantienen las funciones esenciales, el estudio busca operacionalizar la evaluación de la resiliencia y orientar la gobernanza adaptativa para sistemas forestales sostenibles.

Se empleó un diseño de métodos mixtos que combina análisis conceptuales, regionales y a nivel local. El estudio se guió por tres objectivos principales: (1) un análisis bibliométrico y cualitativo de la literatura para mapear el panorama de investigación en bioeconomía forestal (BE), complementado con una comparación del alineamiento de políticas entre la República Checa y Suecia; (2) un marco cuantitativo de Resiliencia Operacional (Operational Resilience Framework, ORF) para evaluar el desempeño de las FVCs frente a perturbaciones inducidas por el clima en cinco estudios de caso europeos (República Checa, Croacia, Alemania, Finlandia y España); y (3) un análisis económico local que examina predictores de resiliencia, dinámica de mercado, complementado con perspectivas de los actores clave sobre la adaptación.

Los resultados revelan un panorama de investigación en rápida expansión en materia de innovación en bioeconomía forestal, liderado por Europa, con una creciente colaboración intersectorial, aunque con un enfoque predominante en innovaciones tecnológicas por encima de las sociales y de gobernanza. Los análisis regionales muestran que la resiliencia varía según el contexto : la gestión proactiva, la capacidad de procesamiento diversificada y las redes sólidas de actores favorecen una mayor estabilidad, mientras que la sobreexplotación y las respuestas reactivas aumentan la vulnerabilidad. Los análisis económicos destacan que, si bien el aprovechamiento sanitario forestal y los ajustes de precios a corto plazo pueden ofrecer alivio temporal, la resiliencia a largo plazo depende de la diversificación de mercados, la gestión adaptativa y las estrategias basadas en ecosistemas.

En conclusión, lograr FVCs resilientes requiere ampliar la innovación más allá de la tecnología para incluir diversidad institucional, gobernanza participativa y gestión ecológica responsable. Las políticas forestales y de bioeconomía deben alinearse con los principios de resiliencia y fortalecerse las capacidades adaptativas locales. Estos pasos son esenciales para garantizar que los sectores forestales europeos puedan resistir choques sistémicos mientras contribuyen a una transición hacia una bioeconomía sostenible.

Palabras clave: aprovechamiento sanitario forestal, clasificacion de madera, innovación

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"The Cosmos is all that is or ever was or ever will be... remind us that humans have evolved to wonder, that understanding is a joy, that knowledge is prerequisite to survival...The cosmos is within us. We are made of star-stuff. We are a way for the universe to know itself."

Carl Sagan

"…We are not just a part of Nature. We are Nature"

CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Forestry and Wood Sciences

Ph.D. THESIS ASSIGNMENT

Sandra Paola García Jácome

Global Change Forestry

Thesis title

Resilience of Selected European Forest Value Chains: Social-Ecological Challenges and Implications for Forest Bioeconomy

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Objectives of thesis

The thesis shall focus on the effects of climate change-induced forest disturbances and the shifts in the societal demands for forest ecosystem services on the associated forest value chains. The student shall focus on identifying the main predictors and co-drivers of forest value chain resilience from a local perspective while adhering to the operational resilience framework approach as designed within the RESONATE project by Lloret et al. 2023.
Specifically, the aims are:
1. To select appropriate case studies from the pool of case study regions available within the RESONATE project;
2. To create a methodical approach in line with Lloret et al. 2023, which enables the identification of resilience predictors and co-drivers in local forest value chains
3. To gather data of sufficient quality and quantity to enable the analysis of local forest value chain resilience in the selected case studies
4. To evaluate the differences between value chain setups and assess their resilience.

Methodology

The methodical approach should reflect the operational resilience framework, as described by Lloret et al. (2023). Based on this, the student will:

1. Design a robust case study protocol, intended to govern the data-gathering process in the particular case studies of the RESONATE project

1.a Identify the data to be gathered by the case study representatives, the appropriate range of historical data, and negotiate the shortest feasible observation span (e.g., a month, quarter or a year)

1.b Create a common data shell and case study report template for the case study representatives to ensure a data comparability

2. Create a robust forest value chain resilience assessment method, in line with Lloret et al. (2023)

3. Use appropriate statistical analytical methods to evaluate the data

4- Synthsize the results of the analyses into a coherent assessment of the forest value chains from a local perspective.

5. Provide sound recommendations for the forestry practice and research, and identify gaps for future research.

The proposed extent of the thesis

110 pages including bibliography

Keywords

resilience; forest value chains; innovations; technologies; logistics; timber

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Recommended information sources

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Contents

1 Introduction

1.1 Research background

Forests are essential ecosystems that provide a wide range of ecological, economic, and social benefits: from biodiversity conservation and climate regulation to timber production and rural employment (Brockerhoff et al., 2017; Mace et al., 2012; Orsi et al., 2020). However, forest ecosystems and the industries they support are increasingly exposed to complex and compounding disturbances such as pest outbreaks, droughts, windstorms, and market fluctuations (Seidl et al., 2017; Thom & Seidl, 2016). These events compromise forest health but also disrupt forest value chain (FVCs), threatening their ability to deliver goods, services, and livelihoods. In this context, the concept of resilience has emerged as a critical lens for understanding and strengthening the capacity of forest systems to cope with, adapt to, and transform in response to stressors (Seidl & Rammer, 2014; Nikinmaa et al., 2023).

Resilience is commonly understood as a system's ability to absorb shocks, recover from them, and reorganize while maintaining essential functions (Gunderson & Holling, 2002; Cinner & Barnes, 2019). Within the forest sector, resilience is particularly relevant when viewed through a social-ecological systems (SES) perspective, which recognizes the tight coupling between natural ecosystems and human society (Scheffer et al., 2001). This perspective enables a holistic understanding of how forest management, policy frameworks, and economic behaviour interact across multiple scales; from local governance to global trade, shaping forest system outcomes. In such coupled systems, adaptive and transformative capacities are both necessary: adaptation allows incremental adjustments in the face of change, while transformation enables more fundamental shifts toward sustainability when existing systems prove inadequate (Termeer et al., 2017).

The European Union has advanced the bioeconomy as a pathway toward sustainability, aiming to replace fossil-based resources with renewable biological alternatives (Hetemäki et al., 2024; Rinn et al., 2022). The EU Bioeconomy Strategy (2025) emphasize sustainable resource use, circularity, and the development of innovative biobased value chains. Within this broader strategy, the forest bioeconomy plays a central role by leveraging forest resources not only for traditional products but also for innovative biobased materials, energy, and ecosystem services (Bugge et al., 2016; D' Amanto et al., 2020). However, realizing this transition requires that forest value chains (FVC, spanning from forest management to final product delivery) become both economically viable and resilient to growing uncertainties (Knoke et al., 2023). The ability to maintain timber supply and revenue, especially under stress, is central to ensuring the long-term viability of forest enterprises and rural economies.

While aggregated market analyses offer macro-level insights, there is a growing recognition that resilience must also be addressed at the local level, where the actual responses to ecological and economic disturbances are enacted. Local actors such as forest owners, processors, and cooperatives are the first to adapt, and their capacity to innovate, collaborate, and manage risk defines the overall system's resilience (Bezama et al., 2018). This study builds on these insights to investigate the resilience of forest value chains in selected European regions, focusing on how ecological, economic, and institutional dimensions interact within a sustainable forest bioeconomy. Through this analysis, this thesis aims to provide operational tools and policy-relevant knowledge for strengthening the adaptive and transformative capacity of forest systems facing an uncertain future.

1.2 Research objectives

The overarching goal of this thesis is to assess and enhance the resilience of FVCs in selected European contexts by integrating the social-ecological, economic, and institutional dimensions within the framework of a forest bioeconomy. The study seeks to bridge conceptual thinking with operational tools and local evidence through the specific objectives listed below. Each objective relates to a published paper provided in the appendices, which contains the full article.

1. To map the current innovation landscape in forest bioeconomy in Europe by identifying key clusters of researchers, institutions, and publication trends through a combined bibliometric and comparative policy review (Papers I and II).

   Research question 1: Where is the core/focal point of bioeconomy innovation in forest of world regions?

   Research question 2: Is the innovation driven by the policy frameworks?

2. To apply an integrated, quantitative operational resilience assessment framework that can guide case study-level forest value chain management in response to climate-induced disturbances across Europe (Paper III).

   Research question 1: How can we quantify the resilience of timber supply at a local level?

   Research question 2: Are there identifiable drivers of resilience present?

3. To examine the economic impacts of natural disturbances on forest value chains at the case study level, and to identify the key factors that drive market resilience in these European contexts (Paper IV and V).

   Research questions 1: Are European institutions driving innovations in bioeconomy?

   Research question 2: How resilient to natural disturbances are local stakeholders from economic perspectives?

1.3 Scope of the thesis

This thesis builds upon existing literature and recent advances to explore the resilience of FVCs within the European forest-based bioeconomy. It examines how forest management practices, market dynamics, and innovation processes interact to shape the adaptive capacity of forest-based systems under environmental and economic stressors. A particular focus is placed on local and regional perspectives, recognizing their fundamental role in revealing context-specific dynamics that underpin broader systemic understanding. By comparing patterns across diverse European settings, the research highlights how governance structures, management traditions, and market responses jointly influence resilience outcomes. Collectively, the studies presented in this thesis aim to provide an integrated perspective on how local insights contribute to a more comprehensive and sustainable vision of Europe's forest bioeconomy.

To ensure a coherent and a clear basis of this work, the thesis is organized as follows:

- **Section 2** offers a review of relevant literature, outlining the current knowledge and theoretical perspectives on resilience, forest bioeconomy and forest value chains, including the economic dimension, the role of adaptation and innovation in this topic. Furthermore, this chapter also identifies key knowledge gaps, establishing the conceptual foundation for the objectives developed in the following chapters.

- **Section 3** explains the methodological framework applied throughout the research. This includes descriptions of the study design, data sources, analytical tools, and statistical techniques used to examine the interconnections between of social and ecological aspects and how ecological and ecological factors influence on the resilience across European forest systems.
- **Section 4** presents the results, structured into five subchapters, each one a connected to the objectives and reflected them in the published papers.
- **Section 5** provides a discussion of the main findings in the context of existing research, highlights their broader social-ecological significance, and outlines the principal limitations and recommendations for practice and policy.
- **Section 6** concludes the thesis by summarizing key outcomes, assessing how they meet the stated objectives, and suggesting potential avenues for future investigations.

2 Literature review

2.1 Resilience as a foundation for adaptation

Forest ecosystems and their associated industries are increasingly exposed to climate-induced disturbances. These events threaten not only the health of forests but also the stability of forest-based value chains that provide timber, bioenergy, and other products (Boiger et al., 2025). In response, resilience has gained prominence as a framework for adapting to and coping with such stressors. Resilience generally refers to a system's capacity to absorb disturbances, to recover, and to reorganise while essentially retaining its core functions (Gunderson and Holling, 2002; Walker et al., 2004). However, the term carries multiple interpretations across disciplines.

In broad terms, engineering resilience emphasises a quick return to a prior equilibrium state (i.e. "bouncing back"; Holling, 1996; Pimm, 1984), whereas ecological resilience emphasises a system's ability to resist disturbance and persist within a given stability domain (Holling, 1996; Scheffer et al., 2015). Meanwhile, social-ecological resilience captures the capacity of interconnected human–natural systems to reorganise, learn, and adapt, (potentially into a novel stable state) while continuing to provide essential services (Biggs et al., 2015). In this study, the social-ecological perspective on resilience is the primary focus.

One useful analytical tool for examining resilience is the social-ecological system (SES) approach, originally developed by Ostrom (2009) and later refined by McGinnis and Ostrom (2014). The SES approach provides a structured approach to analysing forest systems by recognising that ecological processes and human institutions are intrinsically linked (Nikinmaa et al., 2024). Forest systems operate across multiple spatial and temporal scales, from local landscapes to global markets (Burton et al., 2014). Cross-scale interactions can create both opportunities and vulnerabilities within a given SES (Young, 2022). In the context of forest ecosystems, local management decisions interact with regional policies and global market forces to shape outcomes. Cash et al. (2006) emphasise the importance of "scale matching" must aligning institutional arrangements with the spatial, meaning that the temporal and functional scales of management align with those of the ecological and social processes. Indeed, mismatches between scales can undermine governance effectiveness and, in turn, reduce system resilience.

Resilience thinking in social-ecological systems often distinguishes between adaptive and transformative approaches managing change (Gotham & Campanella, 2010; Wang & Yamashita, 2015). An adaptive approach emphasises adjusting practices to better cope with change, whereas a transformative approach involves fundamentally reconfiguring systems in response to new realities (Folke et al., 2010). In the context of the forest sector, the emerging concept of the bioeconomy has been linked to resilience not in the sense of "business as usual," but rather a concept that foster transformability (the capacity to change structures and practices) guided by sustainability principles. In other words, a resilient bioeconomy is not about resisting change; it is about transforming a system with a sustainable direction when necessary. This perspective suggests that a system (such as a regional economy or a value chain) can remain functional during crises by: (1) considering cross-scale and cross-sector dynamics (embracing a second-order resilience thinking; Williams et al., 2021; Proestou et al., 2025), (2) clearly defining its resilience goals (for example, whether the aim is to resist change or to transform in response to it), and (3) embedding explicit sustainability criteria as boundaries for its operation (Rockström et al., 2009). This view lays a conceptual foundation in which resilience and sustainability go hand in hand, steering the bioeconomy toward long-term robustness in the face of social-ecological disruptions (de Schutter et al., 2019).

2.2 Resilience from the perspective of forest bioeconomy and forest value chains

The bioeconomy concept has become a cornerstone of European Union policy in the past decade. Since the EU's first Bioeconomy Strategy in 2012 and its 2025 update emphasising sustainability and circularity (European Commission, 2025). Forests are central to the EU bioeconomy, providing the majority of woody biomass and a large share of biomass used for energy production, supplying timber for traditional uses, as well as bioenergy, biochemicals, and novel biomaterials. The notion of a forest bioeconomy refers specifically to the segment of the bioeconomy based on forestry and wood resources (including non-timber forest products and ecosystem services, Winkel et al., 2017; Wolfslehner et al., 2016).

The implementation of forest bioeconomy principles varies across Europe and depends on national policy frameworks, which determine how forest resources are managed, which value chains are prioritize, and how sustainable and innovation objectives are integrated into forest governance

(Hetemäki et al., 2024). For instance, Sweden places the bioeconomy at the centre of its National Forest Programme, aligning forest policy with a vision of a fossil-fuel-free economy supported by high value-added wood industries. Its strategy aims both to promote sustainable forest products and to contribute to climate goals by substituting fossil-based materials with bio-based alternatives (Purwestri et al., 2021). In contrast, the Czech Republic acknowledges the EU Bioeconomy Strategy but has not yet fully translated its principles into practice, maintaining a focus on traditional forest management and regional development without explicit links to bioenergy or fossil-fuel substitution. These differences reflect how national context shapes bioeconomy trajectories: Sweden's mature forest sector and climate orientation support a holistic bioeconomy agenda, whereas the Czech Republic's recent forest crisis (e.g., bark beetle outbreaks; Hlásny et al., 2021) has shifted policy toward restoring forest health and stabilising timber supply, with bioeconomy concepts only gradually emerging. A related policy goal is shifting toward higher value-added forest products. Forest-rich countries aim to move from raw material exports to domestic production of refined goods (Mersmann, 2004). In the Czech Republic, this involves securing sustainable wood supply while expanding processing capacity for furniture, engineered wood, and specialty bioproducts (Babuka et al., 2020). Sweden similarly promotes advanced biofuels and modern timber construction materials to offset declining paper demand and capture global markets for sustainable products.

In the context of forest social-ecological systems, the forest value chain (FVC) encompasses the full sequence of activities that transform forest-based resources into goods and services for end consumers, ultimately leading to their disposal or recycling. Primary activities include harvesting, logistics, and packaging, while supporting activities involve planning, marketing, and management (Kaplinsky and Morris, 2000; D'Amours et al., 2017). The FVC thus links forest resource management to the processing and delivery of products and services, forming the backbone of the forest bioeconomy, which builds on this structure through bio-based innovation (Hetemäki et al., 2017). By linking forest management to product markets, the FVC provides the backbone of the forest bioeconomy (Hetemäki et al., 2017) and highlights where economic, social, and environmental value is created or lost across the sector.

Forest value chains must be resilient to withstand and recover from environmental and market shocks while remaining sustainable (Asada et al., 2023). Climate-driven disturbances can cause both oversupply and undersupply of timber. For example, a large windstorm or pest outbreak may create an excess of salvage timber, while prolonged drought or wildfire may lead to resource scarcity. Both situations tend to induce volatility in wood markets and can force shifts to lower-value uses (e.g., an excess of low-quality salvage timber being used for energy instead of higher-grade lumber; Fuchs et al., 2022). Therefore, resilience must be addressed not just of the level of a forest ecosystem, but across the entire value chain, from forest operations and logistics, through processing industries, to the markets that consume forest products (Hoeben et al., 2023). This broader perspective underscores the need to integrate social-ecological resilience into forest policy and economic planning.

Economic resilience is the capacity of the forest sector to withstand shocks, adjust to change, and transform operations when necessary to remain functional and competitive (Pinto et al., 2022; Ferreira et al., 2025). Economic resilience depends on how value is distributed among actors and on their capacity to adapt (Baldwin & Schulman, 2003; Kaplinsky & Morris, 2000; Lindner et al., 2020). Small forest owners and local enterprises often capture only a limited share of total value because processing is dominated by larger companies (FAO, 2007; Hrib et al., 2024), reducing their ability to invest in innovation or survive downturns. Timber availability can also be constrained by ecological conditions and landowner objectives (Tian et al., 2017; Hurmekoski et al., 2018), limiting flexibility in supply. Meanwhile, market fluctuations, such as oversupply following disturbances or demand declines in construction, can depress prices and threaten enterprises operating on narrow margins (Hanewinkel et al., 2011). Such dynamics highlight how volatility can undermine forest economies and reinforce the need for adaptive strategies.

A promising resilience strategy is to increase value per unit of wood rather than focusing on higher harvest levels. Research shows that reallocating wood to higher-value uses, such as converting by-products or lower-quality logs into materials rather than energy, can generate greater economic benefit without raising extraction (Brunet-Navarro et al., 2021; Hurmekoski et al., 2020). This shift requires innovation in products and markets, including engineered wood, bio-based chemicals, or advanced biofuels. Heavy dependence on a narrow set of commodity exports (e.g., roundwood, pellets) increases vulnerability to external price swings (Hurmekoski et al., 2023), whereas diversification improves stability.

Structural measures can further strengthen resilience. Vertical integration, where firms combine forest ownership with processing, enables better value capture and reduces reliance on external processors. Horizontal cooperation through cooperatives or clusters allows smaller actors to pool resources and achieve economies of scale, distributing risk more evenly and stabilising local incomes (Rametsteiner et al., 2005; Niskanen, 2007).

The economic side of innovation plays a dual role in resilience: it enables transformation toward new business models and technologies, while requiring sufficient economic capacity (capital, labour, knowledge) to be adopted effectively (Chesborough, 2003; Van Lancker et al., 2015). The ability to invest in processing technology, logistics, and workforce skills determines whether forestry actors can participate in a high-value, sustainable bioeconomy or remain dependent on low-profit raw material production. Ultimately, without economic viability, even ecologically resilient systems may lack the means to sustain operations under stress or participate in long-term transitions.

2.3 Operationalising resilience: framework and metrics

Resilience of FVCs is highly context specific. Factors that bolster resilience in one region or community may differ in another due to variations in ecology, management practices, industry structures, and socio-economic conditions (Ludvig et al., 2024). Resilience is context-dependent, demanding insight into the local drivers influencing each value chain. Case studies help identify the specific predictors and co-drivers that matter at the local level; be it a particular silvicultural technique, a supply-chain coordination mechanism, or a policy incentive that influences outcomes when disturbances strike (Lloret et al., 2024). Major disturbance agents affecting European forests include insect outbreaks (such as bark beetle infestation during droughts), windstorms, wildfires, and extreme weather events like heatwaves or ice storms (Seidl et al., 2017; 2021; De Rigo et al., 2017). For example, the severe bark beetle outbreaks in Central Europe during the late 2010s led to extensive salvage logging of Norway spruce (Sommerfeld et al., 2021; Das et al., 2025). This response created a short-term glut of wood on the market but also depressed timber prices and compromised wood quality, undermining revenues for forest owners (Asada et al., 2023). Likewise, a big windstorm (Storm Vaia in northern Italy, 2018) threw down millions of cubic meters of timber, flooding the market with salvage timber and disrupting supply chains (Udali et al., 2021). These examples illustrate how ecological disturbances can destabilize timber supply and markets.

Conversely, market-side shocks, such as a sudden downturn in construction activity that reduced timber demand, or international trade restrictions that impede exports, can also disrupt FVCs and test their resilience, as seen during the economic crisis of 2008 in the U.S., when timber prices fell sharply and FVCs faced widespread economic stress

Aside from characteristic at a global level, FVC are also distinctive on at a regional and local level. To enable systematic and comparable assessments of resilience at an operational level, Lloret et al. (2024) developed an Operational Resilience Framework (ORF). This framework involves defining clear system boundaries (e.g., a particular region or an enterprise), identifying key system variables (such as timber supply or revenue), and selecting resilience predictors (variables that can be intentionally influenced) and co-drivers (variables that cannot be meaningfully altered but provide important contextual information) can be identified, enabling an operational assessment of the system's resilience. By doing so, the ORF provides a holistic and consistent foundation for establishing a common protocol in resilience studies, facilitating comparability and supporting the use of more specific tools for a resilience assessment.

The ORF offers a quantitative yet flexible approach for analysing such scenarios by translating the abstract concept of resilience into operational metrics and decision-support tools (Lloret et al., 2024). For instance, when applied at a local scale, forest managers and policymakers can pinpoint weak links in a value chain and target interventions accordingly, for example, by strengthening a predictor like road infrastructure for timber extraction, or by fostering a co-driver such as landowner cooperation to improve collective response capacity.

In evaluating resilience, two fundamental system variables, reflecting both ecological and economic dimensions of forest system within FVCs: timber supply and economic return (revenue) from forest operations. These system variables capture different dimensions of FVC resilience.

Timber supply reflects the ecological dimension of resilience. As the link between forest growth (ecological process) and harvested volumes (industrial inputs), timber supply indicates the system's capacity to maintain a steady flow of raw material despite disturbances. Fluctuations in the timber supply (caused by storms, pests, droughts, or management constraints), signal potential instability both for forest ecosystem sustainability and for downstream industries such as sawmills, pulp mills, and energy producers. If timber supply becomes highly variable or declines, it threatens the structural continuity of the entire value chain (Fuchs et al., 2022; Greenwood et al., 2023).

In contrast, revenue captures the economic–financial dimension of resilience. For forest owners, logging companies, and processors, stable revenue streams are crucial for maintaining operations, reinvesting in management, upgrading technologies, and retaining skilled labour. A severe drop in revenue (due to falling prices, market shocks, or rising costs) can lead to reduced harvesting, mill closures, or bankruptcies, thereby eroding the adaptive capacity of the sector (Hanewinkel et al., 2011). Even when ecological supply remains stable, financial instability can weaken the value chain's resilience by undermining its capacity to respond, reorganize, or innovate. Taken together, timber supply and revenue illustrate that FVC resilience depends on the interaction between biophysical continuity (availability of wood) and economic viability (ability of actors to profitably operate). Disruption in either dimension can propagate throughout the chain, but each reveals a different mechanism of vulnerability and recovery.

2.4 Innovation as a driver of adaptive capacity in forest value chains

Adaptive capacity is the ability of a system to adjust in response to disturbances or changing conditions, is greatly enhanced by innovation (Hoeben et al., 2023). New technologies, products, and business models can provide alternatives or backups when traditional practices come under stress. Indeed, recent studies suggest that deploying an efficient and sustainable forest bioeconomy will require a broad spectrum of innovations (Aguilar et al., 2019). These innovations range from technical (in products and processes) to organisational and social innovations that change the ways value chains are structured or how consumers use forest products. For example, product innovations (such as novel wood-based materials or biochemicals) can diversify the portfolio of forest products, reducing reliance on any single fossil-based commodity Process innovations can improve efficiency by either extracting more value from the same amount of resource or reducing waste (Alemede, 2025). Organisational and social innovations, reviewed as new ways to coordinate, collaborate, and share knowledge, can introduce greater flexibility and learning capacity into the value chain.

It is critical to understand how specific innovations contribute to resilience, and to combine them in ways that are complementary across the whole value chain. Innovations aimed at product diversification, efficiency gains, and flexibility should reinforce rather than undermine the effect of one another (Folke et al., 2010). Changes in business models can also enhance resilience. For example, vertical integration can stabilise supply and demand internally by insulating operations from external market swings (Wu et al., 2025; Bakshi et al., 2025). Conversely, horizontal collaboration can achieve economies of scale and improve bargaining power, making participants less vulnerable to price fluctuations (Mrabti et al., 2022; Ramjaun et al., 2022). Innovations in stakeholder interaction are equally important: new platforms or networks for collaboration and knowledge-sharing (e.g., co-design processes involving forest managers, wood processing industries, and end-users) help ensure that different parts of the value chain innovate in sync rather than in isolation (Hoeben et al., 2023; Suominen et al., 2017; Guerrero and Hansen, 2021).

A recurring theme in the literature is the need to complement top-down innovation strategies with bottom-up, local innovation (Scordato et al., 2021). By focusing on specific regional value chains or forest enterprises that are pioneering novel approaches, researchers and practitioners can observe real-world evidence of both successes and challenges in building a sustainable forest bioeconomy. The case studies can demonstrate how local context and active stakeholder engagement play a crucial role in translating broad bioeconomy and resilience concepts into practice on the ground (Overbeek et al., 2016).

Bringing these themes together, a coherent narrative emerges. The increasing frequency of climate-induced forest disturbances highlights the urgent need to approach forest management and FVC through the lens of resilience. The bioeconomy concept offers a useful framework for this shift because it links economic development with ecological sustainability and aligns directly with the Sustainable Development Goals (within this paradigm, FVCs become more than production; they represent processes where resilience must be actively built into everyday operations. Innovation (whether technological, organisational, or social) plays a critical role in enhancing the adaptive capacity of these value chains, ensuring that they can continue to function despite shocks and contribute to broader sustainability objectives (Hoeben et al. 2023).

At the same time, it is evident that innovation must be applied strategically, with careful attention to potential trade-offs (Ruml et al., 2025). A clear example is the practice of salvage logging in disturbance-hit forests. Salvage logging, rapidly harvesting timber from trees thrown down by storms or killed by pests, can provide immediate economic relief and make use of resources that would otherwise be lost (Leverkus et al., 2021). Yet this adaptive strategy exemplifies the tension between short-term benefits and long-term sustainability. Excessive salvage logging can remove seed sources and other biological legacies essential for natural regeneration, or push harvesting beyond ecological limits, ultimately compromising future forest productivity and resilience (Donato et al., 2006; Lindenmayer et al., 2006). In other words, a measure that boosts short-term recovery can undermine longer-term transformability if it perpetuates the system's vulnerabilities (for instance, by re-establishing a monoculture that remains susceptible to the same disturbances; Huuskonen et al., 2021). The challenge is to balance such trade-offs. In this case, the challenge involves moderating the extent of salvage operations and pairing them with restorative measures, replanting with diverse of species and promoting structural diversity, so that the forest regenerates in a more resilient state instead of simply reverting to its previous, vulnerable state.

Overall, the literature indicates that building resilient forest value chains requires an integrated approach that links ecological and social considerations, aligns bioeconomy development with sustainability goals, leverages innovation wisely, and remains sensitive to local context. This research builds on those insights and aims to assess and enhance the resilience of FVCs in selected European regions, with a focus on how local-level ecological, economic, and institutional factors influence adaptive capacity. The study addresses challenges posed by climate-induced disturbances (e.g., pest outbreaks and storms), shifting species suitability due to climate change, biodiversity decline, and changing societal demands for forest products and ecosystem services. It seeks to develop regionally grounded adaptation pathways that help stabilise timber supply and maintain economic returns to downstream industries, while ensuring the long-term sustainability and resilience of the forest-based bioeconomy.

3 Materials and Methods

The methodological framework of this thesis was shaped by the need to understand the resilience of European FVCs under climate-induced disturbances and within the evolving forest bioeconomy. Rather than relying on a single analytical approach, the research integrates conceptual, regional, and local perspectives. The detailed procedures for each stage are provided in the published articles that compose this dissertation; what follows is a synthesis intended to connect these individual studies into a coherent methodological narrative.

At its core, the research combined three complementary components. First, the bibliometric and qualitative mapping of forest bioeconomy research provided the conceptual and policy background (Papers I & II). Second, a regional resilience assessment was implemented using the ORF and resilience thresholds that translate theoretical resilience concepts into measurable indicators of FVC performance and stability (Papers II & IV). Third, local-scale economic analyses expanded the understanding of resilience drivers at the enterprise level, including sensitivity and panel regression models (Papers III & IV). Finally, an online survey (Paper V) broadened the empirical base by gathering stakeholder perspectives on adaptation measures across European FVCs.

3.1 Mapping the forest bioeconomy research landscape

To situate the research within the broader scientific and policy landscape, the first step was to map the evolution of forest-based bioeconomy research and its relation to European bioeconomy strategies. A dual-method approach, bibliometric mapping and qualitative content analysis, offered both a structural and interpretative perspective on the field.

The bibliometric analysis, based primarily on the Web of Science, traced patterns of collaboration among authors, institutions, and countries, identifying clusters of activity and the journals through which forest BE innovations have been most actively disseminated. The temporal lens revealed how attention within the field has shifted over time, delineating core thematic areas and emerging intersections between research and policy.

Complementing this quantitative layer, a qualitative content analysis explored the underlying narratives and policy orientations of the selected literature. It identified recurring innovation themes and conceptual gaps that informed the design of the subsequent resilience framework. To anchor this understanding in concrete policy contexts, a comparative analysis was undertaken between Sweden and the Czech Republic. Forest sector indicators were drawn from FAO Global Forest Resources Assessments, Eurostat, and national reports, while the 2018 Swedish National Forest Programme and the 2020 Czech Forest Policy were systematically reviewed. The Rapid Automatic Keyword Extraction (RAKE) algorithm was employed to derive single- and two-word keyword frequencies, which were then scored and organized into thematic matrices. Thematic analysis (Braun & Clarke, 2006) enabled the identification of convergences and divergences between the two national strategies.

A modified scoring scheme (++, +, 0, –, —) was applied to determine whether specific measures reinforced, enabled, constrained, or contradicted the objectives of the 2012 European Bioeconomy Strategy. Taken together, these procedures provided the conceptual and policy foundation for the thesis, situating its later resilience assessment within both academic and institutional discourses.

3.2 Local resilience assessment

Once the conceptual ground had been established, the next step was to employ the ORF framework (Lloret et al., 2024). This tool translates the abstract idea of social-ecological resilience into quantifiable dimensions, focusing on two key system variables (timber supply and revenue) as indicators of both ecological and economic resilience in FVCs.

The framework defines resilience as the capacity of these variables to maintaining defined reference state through disturbance events. Eleven potential predictors and co-drivers were identified based on literature review and gather data availability, reflecting operational, environmental, and market dimensions that influence system behaviour. The dataset covered 2001–2021 and included harvesting volumes, disturbance impacts (such as pest outbreaks, windthrow, wildfires), market price fluctuations, and salvage logging records.

Five European case studies were selected: Kostelec, Czech Republic (CZ); Upper Rhine Valley, Germany (DE); Istria, Croatia (HR); Kainuu, Finland (FIN), and Galicia (ESP; Figure 1); representing distinct forest types, management regimes, and disturbance patterns (Table 1). These case studies were chosen to represent major European biogeographic regions and diverse forest management and FVC systems. CZ, DE, and HR featured mid-scale wood industries whose limited export capacity kept most timber use regional. In contrast, FIN and ESP had more varied processing sectors with strong international links, dominated by large companies in FIN and by numerous small, community-based firms in ESP.

In each country, a forest enterprise was chosen as an exemplar. To keep the case studies comparable, enterprises managing 500–5,000 ha of forest were preferred. This range allowed inclusion of both medium operations with limited processing capacity and larger ones with stronger economic roles. When no enterprise within this range was available, a cooperative exemplar was selected, and its managed area was scaled up or down to fit the target range, CZ and DE required no adjustment, while HR, FIN, and ESP data were downscaled.

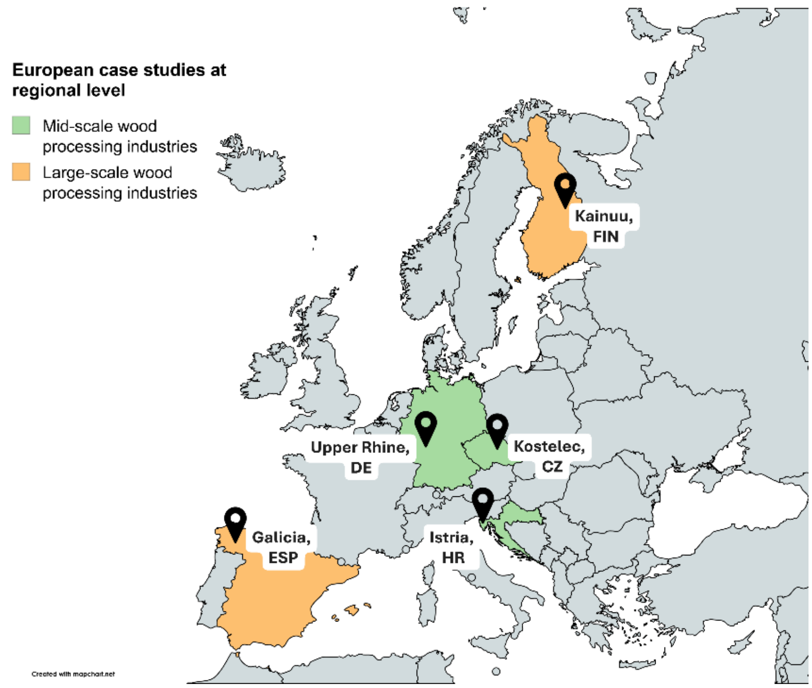

Figure 1. Five European case studies by wood processing industry scale: Mid-scale: Kostelec, Czechia (CZ), Upper Rhine Valley, Germany (DE), Istria, Croatia (HR). Large-scale: Kainuu, Finland (FIN), and Galicia, Spain (ESP). (MapChart. 2025).

Table 1. General description of the case studies

Case Study	Wood processing industries	Species composition	Regulatory framework	Most common disturbance
Kostelec, CZ	Mid-scale, regional level	Predominantly composed of Norway spruce.	All historic management systems are allowed, with clear cut up to 1 ha in a single area or up to 2 ha in certain conditions	Windthrows followed by bark beetle
Istria, HR		High diversity, with broadleaved species dominating.	Shelterwood and selection management systems are allowed	Ice storms and windstorms
Upper Rhine Valley, DE		Primarily beech, along with fir and Norway spruce.	All historic management systems are allowed, with clear cut up to 1 ha in a single area	Windthrows followed by bark beetle outbreaks
Kainuu, FIN	Diverse processing industries with broad access to international markets	Predominantly coniferous, mainly pines and softwood species.	Well-known management systems are allowed (clear-cut, shelterwood, selection or high-grade systems)	Windstorms and snow-induced damage.
Galicia, ESP		Broadleaved species dominated, particularly eucalyptus, followed by pine.	All mentioned management systems are allowed	Wildfires

To assess timber supply and revenue resilience across case studies, 11 key predictors were identified (sensu Lloret et al., 2024; Table 2) that capture mechanisms supporting a system's capacity to absorb disturbances and adapt (Standish et al., 2014). This approach supports locally tailored insights while contributing to broader European strategies for sustainable forest-based economies.

Table 2. List of resilience predictors and co-drivers.

Variable cluster	Variables	P/C	Units
Harvesting system	Annual volume of total timber supply	P	m^3 $year^{-1}$
	Annual volume of salvage logging	P	
	Percentage of salvage logging relative to total timber supply	P	
	Usage of Cut-to-length harvesting systems	P	
	Usage of horses for timber extraction	P	
Management and silviculture	Harvestable timber stock[a]	C	m^3 ha^{-1}
	Total resource availability[b]	C	
Timber Production	Volume of sawlogs	P	m^3
	Volume of pulpwood	P	
	Volume of wood for energy production	P	
Market price	Price per m^3 at which sawlogs are sold	P	USD/m^3
	Price per m^3 at which pulpwood is sold	P	
	Price per m^3 at which wood for energy is sold	P	

*C: resilience Co-driver; P: resilience Predictor. [a] Indicate the amount of timber in the exemplar's forests eligible for harvesting. [b] Indicate the total amount of timber in the exemplar's forests. The harvesting system and timber production variables were used in both the timber supply and revenue resilience assessments, whereas management and silviculture variables were used only within timber supply. Market price, in turn, was used only for the revenue resilience assessment.

Resilience was evaluated through a threshold-based approach (Figure 2), in which a forest enterprise was considered sustainable and resilient when it could operate continuously without degrading the forest it manages while also maintaining financial viability. This assessment relied on two boundaries that together define the system's safe operating space.

The Upper Resilience Threshold (UTH) reflected the ecological or economic capacity of a system. For timber supply, UTH corresponded to the average annual logging prescribed (so etát) in the forest management plans available for the observed period (e.g. 2001-2021). Revenue UTH was obtained by converting this volume into product assortments provided by the case studies representatives and applying mean market prices. Mean market prices were used because companies refused to share company-specific price data. Although the economic UTH provides an indication of sustainable revenue levels, it is not an absolute limit; temporary market price increases, for example, can raise revenues without implying ecological overuse.

The Lower Resilience Threshold (LTH) denoted the minimum level needed to maintain operations & forest health while ensuring financial viability. The values for LTH, were estimated using country-specific profit margins from existing literature, allowing the calculation of the lowest sustainable performance level for each enterprise. System performance was tracked against these thresholds to record the magnitude and duration of deviations. This allowed a nuanced reading of how long systems remained outside the "safe operating space" and how quickly they recovered, a dynamic portrayal of resilience that integrates both exposure and recovery capacity. In this integrated framework, a forest enterprise is resilient when it stays within both ecological limits (UTH) and economic viability constraints (LTH), ensuring long-term sustainability of forest resources and enterprise operations.

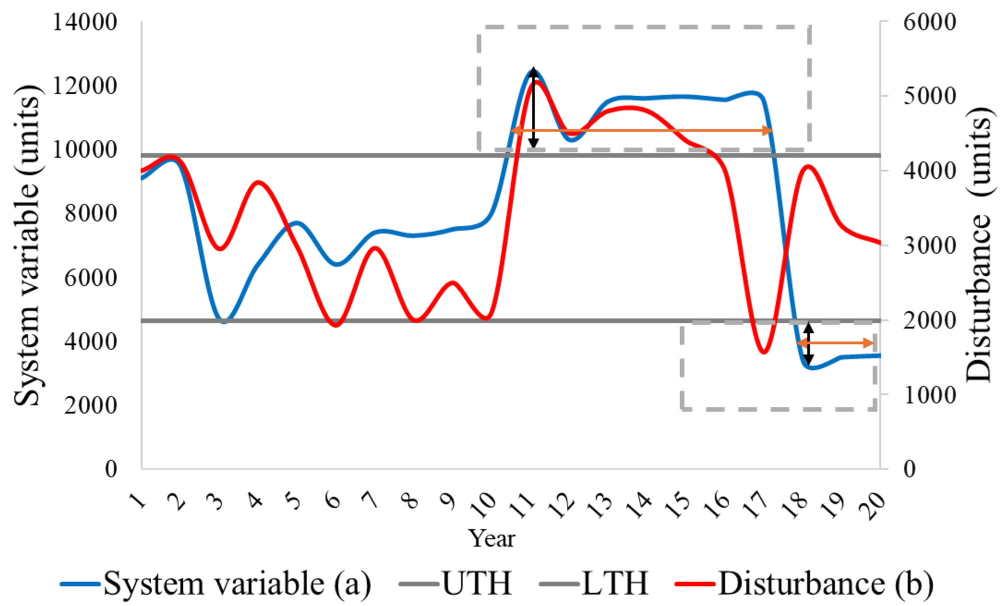

Figure 2. Representation of resilience metrics and measurement for resilience assessment. The blue line represents the System variable (a), which in this case is timber supply, the red line represents the Disturbance (b), summarized as salvage logging in this study, and the grey straight lines are upper (UTH) and lower thresholds (LTH). The time series from 1 to *n*, corresponds to a selected number of time intervals (e.g., years). In this example, the dotted grey rectangles highlight periods where the system exhibits a lack of resilience, i.e., when timber supply exceeds both UTH and LTH. A vertical double arrow (black) is used to depict the resilience metric, and horizontal double arrows (orange) represent the resilience measure, illustrating the system's ability to stay within thresholds despite disturbances.

3.3 Quantitative data analyses

All statistical work was conducted in R (version 4.3.1) using RStudio, adopting a 0.05 significance level where relevant. The analytical procedure began with descriptive statistics to summarize baseline conditions in each region, followed by bivariate correlation analyses (Spearman's rank) to identify relationships between performance variables and predictors. Principal Component Analysis (PCA, Papers III & IV) was then applied to reduce dimensionality and uncover covarying patterns among drivers of resilience and vulnerability.

At the enterprise scale, the investigation turned to more detailed economic behaviour in Paper IV. A notable indicator was the share of salvage logging in total harvest volume, reflecting the proportion of disturbance-driven activities. Monitoring this ratio offered insight into the degree of dependency on post-disturbance wood flows. In parallel, long-term price data for key wood assortments were examined in inflation-adjusted terms, tracing how markets responded to ecological shocks and shifting demand.

At the enterprise scale, the analysis turned to the mechanisms underlying resilience and vulnerability. Here, the aim was not to replicate the regional assessment but to understand why certain enterprises maintain stability under disturbance while others falter.

Particular attention was paid to the share of salvage logging within total timber harvests, a proxy for disturbance. A high proportion of salvage harvests indicated systems increasingly governed by unplanned interventions. Market dynamics were also examined through inflation-adjusted timber prices, tracing their evolution over two decades and their reaction to ecological shocks. This approach provided a bridge between ecological and economic dimensions, revealing how biophysical disturbances intertwine with market volatility.

3.4 Extended statistical framework

Subsequent analyses expanded the quantitative design for the revenue resilience (Paper IV). A sensitivity test of profitability thresholds adjusted the lower resilience boundary (EC.LTH) by ±10% and ±50%, simulating moderate and extreme profitability shifts. This allowed the evaluation of how such variations affected the classification of resilient and non-resilient case studies. A two-way fixed effects panel model was then applied to examine the influence of predictors on forest-based revenue, accounting for unobserved heterogeneity across countries and years.

Finally, a complementary study (Paper V) added a stakeholder dimension to examined how different actors in the European wood value chain view climate-change adaptation by conducting an online survey from mid-April 2023 to February 2024 in LimeSurvey (2023). The survey targeted forest managers and experts from primary, secondary and tertiary wood-processing industries. It was available in seven languages and distributed across nine diverse case study regions, covering coniferous, deciduous and mixed forest systems in countries including New Forest in the UK, Catalonia and Galicia in Spain, Bauges in France, Finland, Ireland, Istria in Croatia, Kostelec in the Czech Republic, the Upper Rhine Valley in Germany, and Austria. In total, 182 participants were recruited through researcher networks, email outreach, social media, and snowball sampling.

The questionnaire included four parts: an ethics statement, demographic questions, items measuring climate-change concern, and a set of adaptation measures tailored to the respondent's role in the value chain. Climate concern was measured for both the present and 30 years in the future, reflecting the construal-level theory that people perceive distant climate impacts as more abstract. Respondents also rated a series of adaptation measures, ranging from established practices like shifting from monocultures to mixed forests to more innovative options such as investing in engineered wood products, on how feasible and how effective they considered each measure to be.

Additional information on forest type and the share of coniferous roundwood in each respondent's country was added afterwards using FAOSTAT data (2021). Forest managers described how climate change affects their management, while processors described impacts on their business models. Data were analysed in R (4.3.1). Missing values were imputed using PCA-based methods to avoid excluding responses. The analysis included descriptive statistics, correlations between adaptation-measure assessments and variables such as concern level and forest composition, and ANOVA tests to examine differences across country groups and industry roles, followed by Tukey post hoc tests. Paired t-tests were used to detect gaps between perceived feasibility and effectiveness, and for forest managers, between present and future priorities.

Through this approach, the study combined wide European participation with structured quantitative analysis to understand how adaptation is viewed across the forest-based sector.

4 Results

The sequence of results follows the same progression as the methodology: from the conceptual mapping of forest bioeconomy research to the regional and local assessments of resilience, ending with the perceptions of stakeholders directly engaged in the wood value chain. Each stage of analysis adds a different layer to the analysis, and together they form a composite view of how innovation, market behaviour, and governance intersect in shaping the resilience of European forest systems.

4.1 Innovations in forest bioeconomy: a bibliometric analysis (Paper I)

4.1.1 Bibliometric analysis of scientific literature on innovations and technological trends in forest bioeconomy

The bibliometric analysis of 161 papers on innovations in the forest bioeconomy showed a steadily growing yet fluctuating research output, with an average of 13 papers per year and a total of 2,953 citations. Citation patterns were highly skewed, with the ten most cited papers accounting for 42% of total citations, while 13% of papers remained uncited. Research was generated by a relatively small group of highly productive authors, mostly affiliated with universities, although government agencies, research institutes, and private companies also contributed. Authors came from 43 countries, with a strong dominance of European institutions, particularly Germany, Finland, and Sweden, followed by North America and Oceania. Publications appeared in 59 journals, with nearly two-thirds concentrated in twelve journals, reflecting a clear focus on forestry, environmental sciences, and sustainability. Overall, the findings indicated that forest bioeconomy innovations are gained traction, with research clustered in regions with strong forestry traditions and a focus on natural and technological sciences, while the community of researchers was increasingly adopting forest bioeconomy terminology.

4.1.2 Innovations in forest bioeconomy

Innovation in the forest bioeconomy is a key driver in transforming traditional forestry and related industries toward sustainable, bio-based production systems. It encompassed a wide range of innovation types, including substitute products, new processes, new products, and new behaviors, each requiring interdisciplinary collaboration, stakeholder engagement, and active participation from entrepreneurs and industrial actors. Advances in biorefining and industrial biotechnology enabled efficient conversion of forest biomass into high-value products, while cross-sector cooperation with industries such as food, textiles, and construction fostered knowledge sharing, market access, and reduced environmental impact. Policy support, financial incentives, and public-private partnerships were critical for scaling up innovations and creating resilient value chains. By integrating ecological, economic, and social considerations, innovation in the forest bioeconomy not only enhanced sustainability and ecosystem service contributions but also strengthened regional "economies of scale," promoted job creation, and ensures long-term competitiveness despite challenges such as limited biomass, high production costs, and market uncertainties. Yet, the pace of this growth invited reflection on how economic ambition aligned with ecological and social accountability. The map of collaborations and thematic clusters thus served as both a picture of current knowledge and a signal of the normative tensions shaping the sector.

4.2 The role of bioeconomy in the Czech national forest strategy: a comparison with Sweden (paper II)

4.2.1 State of forestry and sustainability trends

The comparison between Sweden and the Czech Republic demonstrated clear structural contrasts in forest resources and sustainability pressures. Sweden manages approximately 30 million ha of forests, with long-term net annual increment consistently exceeding harvested volume. Only exceptional disturbance events, most notably storm Gudrun in 2005, which caused an unprecedented surge in roundwood removals, temporarily pushed harvesting above increment levels. The Czech Republic, where forest cover represents around one-third of the national territory, displays a markedly different pattern. After 2018, large-scale bark beetle outbreaks and drought-related mortality caused total felling to surpass net annual increment for several consecutive years. This shift reflects the structural vulnerability of its predominantly spruce monocultures, which have contributed to localised declines in forest area.

Both countries maintain certification rates of roughly 70%, signalling strong commitments to recognised standards of sustainable forest management. However, ownership structures, predominantly private in Sweden and largely state-managed in the Czech Republic, shape distinct strategic responses to ecological stress and economic opportunity.

4.2.2 Alignment with the European bioeconomy strategy and industrial orientation

The comparison of national forest strategies showed clear differences in how Sweden and the Czech Republic integrated the European Bioeconomy Strategy. Sweden's NFP strongly embedded bioeconomy principles, emphasising innovation, competitiveness, and a shift toward fossil-free growth, supported by a liberal forestry model and a technologically advanced forest sector. In contrast, the Czech Forest Policy was shaped by ongoing ecological crises and focused primarily on forest health and resilience, with only partial bioeconomy integration due to the absence of a broader national bioeconomy strategy. As a result, Sweden already utilised high-value wood products and bioenergy, while the Czech Republic retained significant untapped potential in upgrading raw wood use and improving research–industry links.

These policy differences reflect deeper structural contrasts. Sweden's largely private 30-million-hectare forest estate supported outward-looking goals such as employment and global competitiveness, whereas the Czech Republic's mostly state-managed forests centred on societal and ecological needs. Although certification rates were similar (≈70%), Sweden aligned far more closely with the 2012 Bioeconomy Strategy across multiple dimensions, while the Czech approach remained mainly confined to the forest sector.

4.3 Forest value chain resilience from a local perspective in five European countries: analysis of predictors and co-drivers (Paper III)

4.3.1 Harvesting patterns and timber supply dynamics

The five case studies showed strong differences in harvesting modes and timber supply. The CZ and DE relied heavily on both planned and salvage logging and made extensive use of mechanised cut-to-length (CTL) harvesting systems. Croatia stood apart as the only case using animal-powered harvesting, reflecting distinct management traditions. Finland and Spain, supported by larger and more diverse industries, consistently produced substantial volumes of sawlogs, pulpwood, and energy wood.

Timber supply correlated strongly with salvage logging in most countries. Mechanisation played a central role in the CZ, DE, and ESP, whereas Croatia's supply patterns were more closely tied to silvicultural limits and long-term sustainability goals. Resilience assessments (Figure 3) show that HR and CZ generally operated within sustainable thresholds except during major disturbances, while Germany and Finland more frequently exceeded their limits due to disturbance-driven surges. Spain remained largely resilient, though its patterns showed a mix of wildfire impacts and market-driven harvesting.

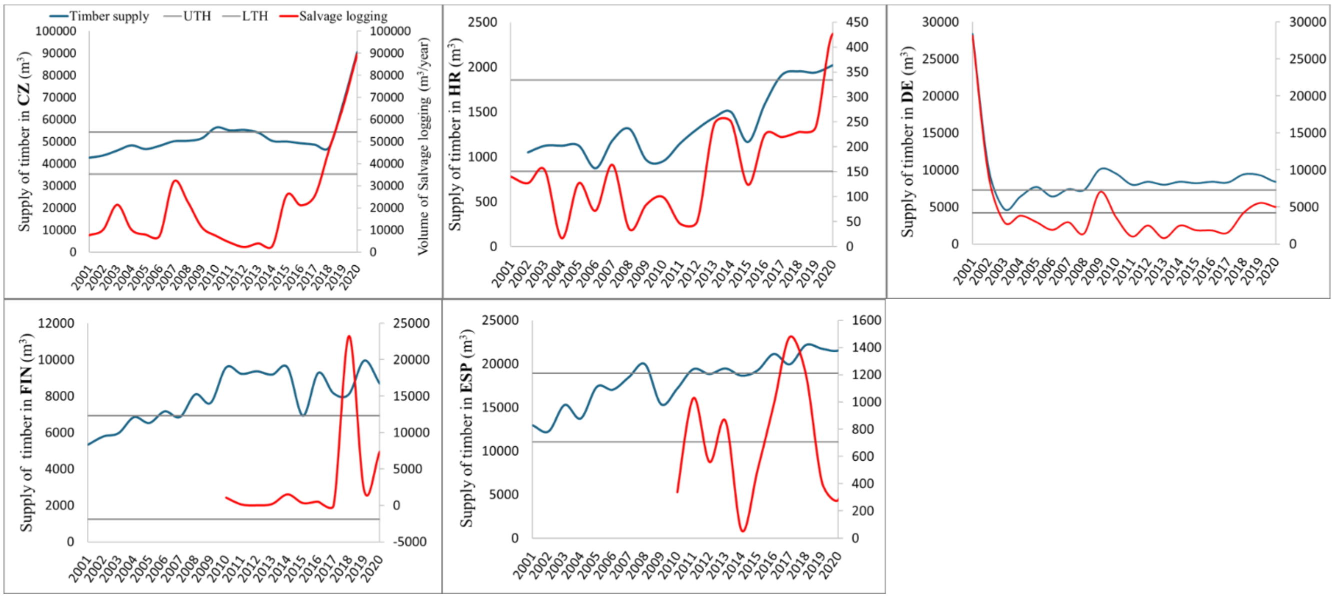

Figure 3. Resilience metrics for CZ, HR, DE, FIN, and ESP from 2001–2021. The blue line shows timber supply, the red line indicates disturbance levels (salvage logging), and the grey lines represent each case study's upper (UTH) and lower (LTH) thresholds. The figure illustrates how well timber supply remains within these thresholds despite natural disturbances (Paper III).

4.3.2 Multivariate patterns and key predictors

The PCA results revealed structured temporal shifts corresponding to decadal forest management planning cycles. The first principal component captured dominant long-term developments, including rising mechanisation, evolving harvesting strategies, and increasing production volumes. The second component accounted for disturbance-responsive or context-specific variability.

Variance explained was consistently high, ranging from 72.7% in FIN to over 87% in DE and ESP, indicating well-defined multivariate structures. Sawlog production emerged as a consistent predictor across all countries. Additional key drivers differed by context: CTL mechanisation dominated in CZ, DE, and ESP; salvage logging shaped trends in all countries but with varying intensity; and HR's dynamics were primarily governed by sustainable resource availability.

Later years, across all cases, studies were characterised by intensified salvage activity, greater mechanisation, and stronger market influence, whereas earlier periods reflected more stable management and less disturbance-driven variability.

4.4 Factors affecting the forest value chain resilience–a local economic perspective in five European countries (Paper IV)

4.4.1 Salvage dependence, price behaviour, and economic resilience

Economic patterns showed clear differences across the five forest value chains. After 2015, CZ and DE became increasingly dependent on salvage logging, reflecting the severity of bark beetle outbreaks and drought-induced mortality. FIN experienced a shorter but intense salvage peak around 2018, while HR and ESP maintained relatively low and stable salvage shares.

Price developments varied. Sawlogs were the most stable assortment, particularly in HR and ESP. In contrast, CZ and FIN showed substantial price volatility, especially during major disturbance periods. Energy wood consistently remained the lowest-priced product in all countries.

The resilience assessment (Figure 4) showed that CZ and ESP had the highest number of UTH/LTH exceedances, indicating strong but disturbance-driven economic activity. For DE and FIN displayed more moderate but sustained deviations, whereas HR showed the lowest sensitivity to disturbance shocks. Sensitivity tests confirmed the robustness of the resilience thresholds: only extreme adjustments resulted in reclassifications, primarily in the systems already near threshold margins.

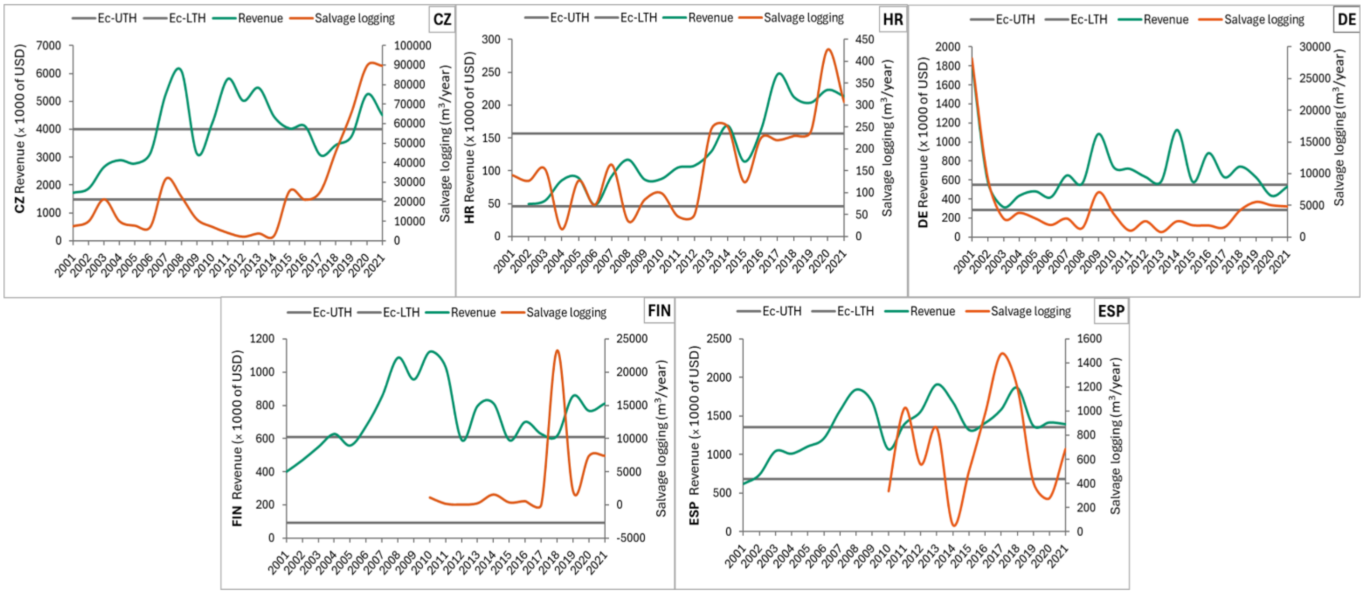

Figure 4. Economic resilience assessment for CZ, HR, DE, FIN, and ESP from 2001–2021. The green line shows revenue, the orange line represents salvage logging volume as a proxy for disturbance, and the grey lines denote each case study's upper (Ec.UTH) and lower (Ec.LTH) thresholds. The figure illustrates how well revenue stays within these limits despite natural disturbances (Paper IV).

4.4.2 System dynamics and adaptive pathways

Correlation analysis and PCA results highlighted distinct national trajectories. Revenue was most strongly linked to total timber supply in HR, moderately related to CZ and FIN, and only weakly tied to salvage logging, except again in HR, where salvage contributed meaningfully.

Sawlog production was a major revenue driver in HR, DE, and FIN. Mechanisation (particularly CTL systems) was strongly associated with revenue performance in CZ and DE. PCA trajectories pointed to convergence toward disturbance-driven dynamics across countries, but with divergent patterns: rapid system shifts in CZ and ESP, cyclical disturbance–recovery sequences in DE, clearer product differentiation in FIN, and alternating market- vs. disturbance-driven years in HR.

Fixed-effect models confirmed that harvesting volume and market prices were the strongest determinants of revenue. Once these variables were included, assortment composition added limited explanatory power. Mechanisation consistently enhanced revenue stability, underscoring its role as an economic buffer under increasing disturbance pressure.

4.5 Stakeholder views of adaptation measures to improve climate resilience: Case study evidence from European wood value chains (Paper V)

4.5.1 Expert characteristics and main adaptation preferences

From 182 expert responses, mainly from conifer-dominated Central Europe, clear different regional, forest-type, and value-chain set up emerged in perceived adaptation options. Manager of coniferous forest viewed most measures as more feasible and effective than managers of non-coniferous forest, especially infrastructure investment and converting monocultures to mixed forests. Processing-sector experts favoured efficiency, storage, infrastructure, flexible machinery, and innovative procurement, while shifting away from wood and expanding engineered wood products were least supported, particularly in softwood chains. Southern European and Scandinavian experts rated several measures on flexible machinery or marketing innovations more positively than Central Europeans. Countries with a high share of coniferous in the mix rated silvicultural transformations as more feasible. Downstream processors consistently perceived adaptation options as less feasible and effective than upstream actors.

4.5.2 Changes over time and feasibility–effectiveness gaps

Experts generally expected most adaptation measures to become more feasible and effective in the future, indicating confidence in technological and organizational improvements. Present-day gaps showed where barriers remained in coniferous forestry, improvement of storage capacity was seen as more feasible than effective, while infrastructure investment was more effective than feasible. Future assessments narrowed most gaps, though shorter rotations of harvesting, and species transformation remained challenging. In non-coniferous forestry, uneven-aged management and transforming monocultures were currently viewed as more effective than feasible, with feasibility expected to improve. In the processing sector, infrastructure investment and flexible machinery or marketing innovations were considered more effective than feasible, especially in hardwood processing. Most of these discrepancies diminished in the future, though PI3 remained partly constrained. Overall, while future expectations were optimistic, persistent gaps indicated practical limitations in species transformation, rotation changes, and certain processing innovations.

5 Discussion

This dissertation set out to assess the resilience of FVCs across selected European regions and to present approaches to their strengthening by integrating social–ecological, economic, and institutional perspectives within the framework of a forest-based bioeconomy. The research pursued this goal through three main objectives: mapping the research and policy landscape of forest bioeconomy innovation, operationalising resilience assessment at regional and local scales, and identifying the economic and market factors that sustain resilience in the face of climate and disturbance pressures. The following discussion revisits each of these aims, drawing together the results and reflecting on their broader implications.

The first objective, to map the current landscape of forest bioeconomy research and policy, revealed an expanding but still concentrated field of study. As the bibliometric analysis showed, most innovation efforts clustered around technological and engineering domains, notably biorefineries, biotechnological processes, and bio-based business models (Jankovský et al., 2021). This pattern mirrored what Bugge et al. (2016) described as the biotechnology and bio-resource visions of the bioeconomy: an orientation toward productivity, material efficiency, and industrial competitiveness.

While such focus propelled technical advancement, it also left less room for the bio-ecological vision concerned with ecosystem integrity, community agency, and social well-being. This imbalance has consequences. A bioeconomy rooted primarily in technological substitution may achieve short-term efficiency but will likely remain vulnerable to systemic shocks. The findings across Papers I and II underscored that resilience could not emerge from technical innovation alone; it depended equally on inclusive governance and on innovation processes that integrate ecological limits and local knowledge.

The four innovation types identified through literature, substitute products, new processes, new products, and new behaviours, further illuminate this point. The preponderance of technological innovations contrasts with the relative absence of new behaviours, which involves behavioural and institutional change. Yet, as Asveld (2019) and Šūmane et al. (2018) remind, the new behaviour is the sphere in which adaptability and collective learning take root. In this light, resilience in forest value chains depends on how deeply innovation processes incorporate these social and institutional shifts.

The comparative policy analysis (Paper II) pursued the first objective further by examining how national strategies mediated the bioeconomy transition. The contrast between Sweden and the Czech Republic illustrated the role of governance structures in shaping innovation trajectories. Sweden's National Forest Programme integrated the European Bioeconomy Strategy as a central reference point, embedding bioeconomy principles within a broader industrial and sustainability agenda. The Czech Forest Policy, by contrast, mentioned the same strategy only in passing, limiting its application to the forest sector itself.

This divergence reflected deeper institutional differences: Sweden's extensive privately owned forest base and tradition of coordinated industrial policy supported an integrated bioeconomy model, whereas the Czech system's fragmentation and predominant state ownership constrained such alignment. As Purwestri et al. (2021) noted, national governance frameworks can either facilitate or hinder transitions toward socially and ecologically balanced innovation. The present results echo that view and also suggested that moving toward the bio-ecological vision requires more than economic incentives; it requires institutional continuity, participatory decision-making, and long-term policy coherence.

The second objective was to apply a quantitative framework capable of measuring and comparing FVC resilience under climate-related disturbances. At the operational level, the analysis confirmed that proactive forest management and adequate processing capacity are central to resilience. Regions where monitoring, planning, and responsive silviculture were integrated tended to recover faster from climate-related disturbances. Across case studies, the frequency and intensity of such disturbances (windstorms, ice damage, bark beetle outbreaks, and wildfires) have clearly increased, consistent with broader global patterns reported by Bauhus et al. (2017), Johnstone et al. (2016), and Patacca et al. (2023).

The data showed that enterprises capable of adapting operations under stress were those with flexible harvesting systems, established contractor networks, and sufficient mechanisation. In such cases, salvage logging was used strategically rather than reactively, avoiding large market imbalances. Mechanised systems (including CTL harvesting) improve extraction efficiency and reduce quality deterioration, particularly when deployed rapidly after disturbance (Udali et al., 2022; Mederski et al., 2022). Yet in parts of Central and Eastern Europe, as Dvořák et al. (2020) observe, limited capital and rugged terrain restrict mechanisation's spread, leaving many enterprises exposed to prolonged recovery periods.

Forest management strategies that combine ecological foresight with operational readiness, such as diversifying tree species, adjusting rotation lengths, or incorporating early-warning indicators, have demonstrated clear benefits (Braatz, 2012; Hörl et al., 2020). Nonetheless, adoption remained uneven. Economic hesitation, uncertainty over market acceptance of alternative species, and weak coordination along the value chain often delay implementation (Knoke, 2017; Zamora-Pereira et al., 2021). This misalignment between ecological potential and market logic was a recurrent bottleneck in the resilience cycle.

The third objective concerned the economic dimension of resilience, identifying which factors underpin market stability and recovery capacity. The study identified three interlinked mechanisms related to value chain economic resilience: resistance to immediate disturbances, recovery capacity over time, and transformation potential through adaptive management. The results indicated that total timber supply and market prices were the most influential predictors of revenue stability, yet their effects were mediated by management choices and market structure. Salvage logging, as shown by Prestemon and Holmes (2008), played a dual role. It compensated for losses by monetizing damaged timber but often produced temporary oversupply, depressing prices and degrading ecological functions (Leverkus et al., 2021). The pattern observed in the study echoed that trade-off: rapid salvage stabilised revenues in the short term but eroded ecosystem services when repeated excessively. Regions with less reliance on salvage tended to sustain moderate yet stable revenues (Vuletić et al. 2014), that balanced harvesting strategies provide greater long-term resilience.

Mechanisation, particularly through CTL systems, improved extraction efficiency and reduced timber deterioration in concerned with on comes of other studies (Mederski et al., 2022; Hansen & Juslin, 2005), though adoption remains uneven, especially in regions with difficult terrain or limited capital (Dvořák et al., 2020). Market resilience also depended on the ability to balance high-garde sawlog production with lower-grade assortments, an approach consistent with Březina's (2024) theory of market saturation. Regions that staggered timber releases rather than flooding the market-maintained price stability and allowed ecological recovery, in line with Sanginés de Cárcer et al. (2021). This adaptive balance, between economic return and ecological regeneration, embodied the multifunctional forestry advocated by Puettman et al. (2025) and Messier et al. (2022).

The study presented in Paper V confirmed that while technical improvements were valuable, governance and knowledge-sharing measures were equally decisive. Managers of conifer forests viewed adaptation options more favourably than managers of non-conifer forests and overall, future measures were rated as more feasible and effective than current ones. It is important to remember the fact that measures such as mixed-species conversion or improved infrastructure succeed only when supported by cooperative networks and trust among actors. Stakeholder agency, local knowledge, and participatory governance emerged as indispensable conditions for resilient transformation. These perspectives reinforced the central argument of this dissertation: resilience depends on both technical innovation and the social frameworks that sustain it. Nonetheless, limitations such as narrow geographic coverage, short observation periods, and reliance on revenue-based metrics restrict the ability to capture long-term trends or broader economic and social dimensions of resilience. Data inconsistencies in salvage logging and limited consideration of policy instruments like subsidies or insurance further constrain the comprehensiveness of resilience evaluations. An additional limitation arises from the model's assumption of a linear, optimally cascading wood flow within the value chain, progressing from high-value to lower-value applications across successive processing stages. In practice, the system functions in a more parallel manner, with various wood assortments entering sawmills, pulp mills, and bioenergy facilities simultaneously, and only a minimal proportion of high-quality timber being used for energy generation in Europe.

5.1 Study limitations and recommendations for practice and policy

Broaden innovation beyond technology to include social and governance dimensions

- ➔ Practice: Encourage and support innovations (new behaviours, collaborative networks, and social innovations) alongside technological one. This means embedding co-creation, local knowledge, and participatory governance into innovation processes.
- ➔ Policy: create funding schemes and regulatory frameworks that value not only technical efficiency but also inclusive, ecosystem-based approaches, ensuring that local actors and forest communities have agency in shaping bioeconomy transitions

Align national strategies and policies with resilience goals

- ➔ Practice: FVC actors should integrate adaptive management strategies to increase resilience against climate shocks and market volatility.
- ➔ Policy: Governments should embed resilience principles into national forest and BE strategies, moving beyond industrial competitiveness alone. Instruments that reward ecosystems-based management, risk sharing mechanisms, and cross-sector partnerships can align economic incentives with long-term sustainability.

Strengthen local capacities and institutional diversity

- ➔ Practice: Invest in capacity building for forest owners, managers, and local communities to improve adaptive responses.
- ➔ Policy: support institutional diversity by linking global market opportunities with locally governance systems. Policies should encourage decentralized decision making, promote markets for alternative species, and ensure that processing/manufacturing infrastructure is accessible across regions.

6 Conclusions

This dissertation examined the resilience of European FVCs through the lens of social–ecological systems theory and forest bioeconomy innovation, providing insights relevant to both academia and practice. The analysis demonstrated that fostering resilient FVCs requires a shift from purely technology-driven economic optimization toward approaches that integrate social–ecological dynamics and long-term sustainability.

While innovation in the forest bioeconomy is expanding, current trajectories remain concentrated on technological and market-based solutions, such as biorefineries, biotechnologies, and efficiency improvements, reflecting the biotechnology and bio-resource visions of the bioeconomy. Innovations emphasizing ecosystem integrity, local knowledge, and participatory governance, which are essential for long-term resilience, remain underrepresented. Expanding the innovation portfolio to include social and governance solutions contributing to environmental stability is therefore critical for embedding resilience principles into forest bioeconomy transition. Comparative policy analysis showed that governance structures shaped the capacity for bioeconomic transformation. Sweden's flexible, owner-driven forestry model operationalized bioeconomy principles through voluntary measures and soft regulations, while the Czech Republic's state-centered framework highlighted the need for cross-sectoral coordination to support entrepreneurship and diversification of ecosystem services.

Complementary evidence from FVCs resilience assessments highlighted that sustainable timber supply, market stability, and technological modernization; particularly precision harvesting, assortment diversification, and strategic storage, proved critical for buffering against ecological and economic disturbances. In this dissertation, resilience was conceptualized as the capacity of forest value chains to remain within defined ecological and economic thresholds, with attention given to both the extent of deviation and the time required for recovery. As an initial step in operationalising resilience, a qualitative, descriptive approach was used, providing a foundation for future, more detailed analyses. Operational frameworks, such as the ORF approach, further support linking ecological and economic thresholds, identifying key predictors of adaptive capacity, and guiding proactive management strategies.

Stakeholder perspectives on climate adaptation revealed that the feasibility and effectiveness of measures varied across the value chain, with differentiation between softwood and hardwood systems and cascading wood use enhancing resource efficiency. These insights underscored that resilient FVCs require coordinated innovation in products, processes, governance, and stakeholder collaboration, integrating technological progress with ecological integrity and social responsibility.

By connecting conceptual research with operational evidence, this dissertation demonstrates that resilience is not a fixed state, but a dynamic process sustained through cooperation, flexibility, and adaptive stewardship. Strategic policy alignment, investment in local capacities, and co-created adaptive solutions will be essential if FVCs are to withstand systemic shocks while contributing to a sustainable European bioeconomy.

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8 Appendix

Paper I

Innovations in forest bioeconomy: A bibliometric analysis.

Jankovský, M., **García-Jácome, S. P**., Dvořák, J., Nyarko, I., & Hájek, M. (2021). Innovations in forest bioeconomy: A bibliometric analysis. Forests, 12(10), 1392.
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Review

Innovations in Forest Bioeconomy: A Bibliometric Analysis

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Abstract: Innovations are a key component of the forest bioeconomy. Many types of innovations are needed for an efficient forest bioeconomy to be deployed. This article aimed to analyze the scientific literature on the topic of innovations in the forest bioeconomy, to understand where we are and where we are likely to be in the future, considering technologies, business models, etc. First, the scientific literature, in the form of peer-reviewed articles indexed in the Web of Science, was compiled in a comprehensive dataset, on which we analyzed the most important authors, their affiliations, regions they come from, journals where papers were most commonly published, and under which categories the papers were indexed. The total number of papers matching the keywords was 161. We found that the number of papers published on the topic is increasing and that, on average, each paper was cited 18 times. A total of 504 authors dealt with the topic, presenting a rather small community. This finding was reinforced by the outcomes of the analysis of regions where the authors of the papers were affiliated—Europe being the region to which most papers were affiliated. We conducted a qualitative synthesis of the literature on forest bioeconomy innovations. We found that authors dealt with the necessary adaptation of policies, while innovations were mainly focused on biorefining, biotechnology, production of various biomaterials, as well as innovations of business models and stakeholder interactions.

Keywords: innovation types; biorefining; cascading use of wood; wooden buildings; bibliometric analysis

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1. Introduction

Environmental damage has gradually become one of the common concerns worldwide, and topics such as climate change, food and energy security, resource scarcity, and industrial restructuring have been brought to the attention of governments, industries, and academic circles which are trying to avoid the increasing repercussions in nature and society [1]. With a better understanding of environmental issues, public awareness of environmental protection is increasing. The only relatively effective efforts towards a partial solution to these challenges resulted in a focus on sustainable development and holistic strategies to tackle them. Not long ago, new concepts were proposed which integrate economic, environmental, and social aspects of sustainable development [2], one of them is the bioeconomy. The concept of the bioeconomy plays a significant role in a novel solution for old problems [3]. It encompasses all activities related to the production, use, and transformation of renewable biological resources (bioresources). These activities aim at sustainably meeting food needs and some of the material and energy needs of societies while preserving natural resources and ensuring good quality environmental services through innovation [4].

Being a knowledge-driven concept [5], the bioeconomy has the potential to substantially contribute to solving global problems in an integrated framework [6]. It relies on strong science and technology bases and a dynamic and innovative approach, supported by the public sector, market, and social pull, encouraged by industry and investors as well as by policymakers and civil society [3]. A whole spectrum of innovations is needed to deploy a functioning and efficient bioeconomy. They range from (i) product-based innovations that enable the private sector to offer products that tackle the global challenges; (ii) optimization of the use of biomass as feedstock; (iii) innovations in the supply chains to increase the efficiency of production and decrease the pressure on land; (iv) innovative cooperation between previously segregated sectors; (v) social innovations that change the way consumers use things and services and many others [6]. In short, the change from a fossil-based economy to a bioeconomy carries the need for profound innovations.

Innovation, thus, plays a central role in the transition towards a sustainable bioeconomy both on the supply side (new technology and products) and the user side (consumption and waste patterns) [7]. The rather complex transition will require an interplay between multiple innovative technologies that use bioresources as feedstock and innovative modes of consumption, resulting in the need for close cooperation of a multitude of actors from multiple sectors [8]. The open innovation approach [9,10] seems appropriate for use in the conditions of increasing globalization, intensifying technology, new business models, and the radical and disruptive innovations associated with bioeconomy transition. Open innovation can be defined as the purposive inflow and outflow of knowledge to accelerate internal innovation and expand the markets for external use of innovation [11]. According to [12], successful adoption of the open innovation approach necessitates (i) choosing relevant stakeholder groups that are important in innovation processes; (ii) having a well-developed and managed innovation strategy; and (iii) matching organizational prerequisites that facilitate open innovation.

As can be seen, innovation is not, as traditionally perceived, a simple, linear process, where fundamental research is followed by applied research, followed by market deployment [13]. Instead, innovation systems research describes it as an intricate collaboration between multiple actors, such as firms, research institutions, government bodies, associations, NGOs, entrepreneurs, and users, who develop networks, enabling the transfer of knowledge, beliefs, and visions [14]. Among other vital components, knowledge transfer and close cooperation are likely to play a key role, creating a need for new formal networks, as classic sectors (in this case forestry, wood processing, or agriculture) are expected to shift, allowing new cross-sectoral actors to cooperate, form networks, and reveal emerging interest groups [7,15]. Because of the complexity of the innovation process and the associated networks and institutions, each phase has its own pitfalls that can prohibit the innovation from market success. So, it does not come as a surprise that many new technologies did not surpass the so-called "valley of death"—a phase between a successful demonstration and introduction to market [14]. Besides the new technology itself, its adoption depends on many factors, such as cognitive and social lock-in to well-known solutions, the alignment of the innovation to existing regulatory frameworks, technical constraints, or other socio-political and economic factors [16,17]. This points to a need to prepare the current policy and regulatory frameworks for the transition to a sustainable bioeconomy.

With this paper, we aim to identify the main clusters of researchers dealing with innovations needed for the deployment of an effective forest bioeconomy, where they are located and what the trends are in publication numbers. Therefore, we conducted a bibliometric analysis of the available peer-reviewed literature that deals with forest bioeconomy innovations (Section 3). The section identifies countries, institutions, persons, and publications important to the field of innovations in the forest bioeconomy. Additionally, we supplemented the bibliometric analysis with a qualitative synthesis of the literature, on which the bibliometric analysis was based. The synthesis served to provide a more in-depth view into the literature, describing the policy changes, stakeholder involvement, focal areas of innovations in the forest bioeconomy, as well as the modes and types of innovations that we found in the analyzed studies.

2. Materials and Methods

Bibliometric Analysis

To provide the readers with a broader outlook on the state of innovation in the forest bioeconomy, we conducted a bibliometric analysis of the papers contained in the Web of Science. We chose to limit the bibliometric analysis to papers included in the Web of Science database for the sake of comparability of results. Web of Science is a comprehensive database that covers multiple fields of study. It includes multiple journals deemed the most prestigious in their respective fields and provides a common ground for comparisons of papers, authors, and institutions through simple and well-known metrics, such as the number of citations.

To create the dataset, we researched the keywords: bioeconomy innovation, bio* innovation, bio-based economy innovation, bioeconomy technology innovation, forest technology innovation, and their truncated and hyphenated versions. We included papers in all research areas that fit the keywords. Besides author keywords, we included papers that contained the keywords from the list above within the article title, its abstract, or, after close inspection of the abstract of the papers for appropriateness, the "keywords plus," as generated by the Web of Science. The papers included were restricted to the year range 2010–2021. Citation data were obtained from Web of Science in June 2021.

Based on the papers included in the dataset, we calculated the following indicators:

- Number of papers per year;
- Total number of citations;
- Citations per paper;
- Mean citations per paper and year since publishing;
- Number of papers published per journal;
- Number of paper citations per journal;
- Number of papers published per author;
- Counts of affiliations of authors;
- Counts of papers related to the type of institution, divided to (i) University; (ii) Research Institute; and (iii) Other institutions (e.g., Government agencies, Ministries, Private companies, etc.), based on the affiliations of the authors;
- Counts of papers published by authors from particular countries based on the affiliations of the authors;
- Counts of papers published by authors from particular world regions based on the affiliations of the authors.

The overall approach to the dataset consisted of the following steps: (i) identification of records in the database (n = 203); (ii) removal of duplicate records (n = 161); (iii) screening of records for the bibliometric analysis (n = 161); (iv) full-text assessment of studies for eligibility (n = 161); (v) exclusion of studies for the qualitative synthesis; (vi) synthesizing the contents of eligible studies in the qualitative synthesis (n = 47).

The qualitative synthesis part of the paper focused on identifying the most important innovation areas, as provided in articles used within the bibliometric analyses. Papers that met the following criteria were included in the qualitative synthesis: (i) the studies addressed innovations related to the forest bioeconomy; (ii) the study adopted an empirical approach; (iii) they discussed the subject of innovation pathways in the forest bioeconomy. The papers were read by at least two co-authors in their entirety, and their outcomes, conclusions, and implications were discussed by the authors. Subsequently, the information gathered from the papers was synthesized into a coherent text.

3. Bibliometric Analysis of Scientific Literature on Innovations and Technological Trends in Forest Bioeconomy

The Web of Science Core Collection contained 161 papers for the specified temporal range and keyword combinations that deal with technological innovations in the field of the forest bioeconomy. The mean number of papers published and included in the Web of Science database per year was 13, with an increasing trend, though, as Figure 1 shows, the trend is erratic and contained several decreases in the number of papers published per year.

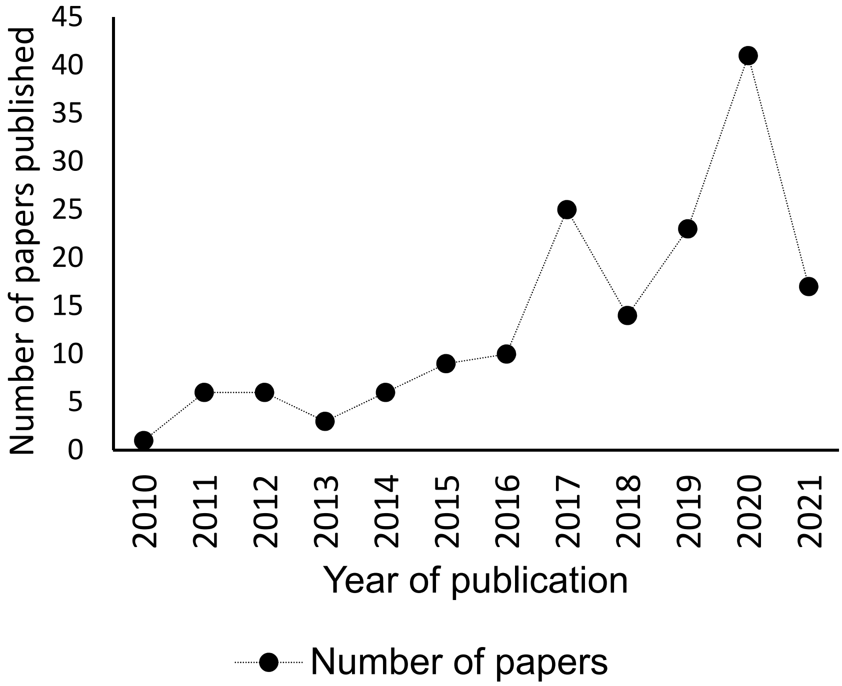

Figure 1. Number of papers per year included in the Web of Science database (n = 161).

In total, the papers included in our dataset were cited 2953 times. On average, each paper was cited 18 times, though the distribution was uneven—the ten most cited papers were cited 1232 times (42%) (Table 1), while 21 papers (13%) were uncited and the bottom 50% (80 papers) were each cited up to six times. The number of citations a paper achieved per year was six, with the number of citations of the top 10 most cited papers reached 27 citations per paper and year.

Table 1. Ten most cited papers and top 10 papers with most citations per year.

Most Cited Papers		Most Cited Papers Per Year	
Reference	**Times Cited**	**Reference**	**Times Cited**
[2]	338	[2]	85
[1]	221	[1]	44
[18]	148	[19]	41
[20]	96	[21]	30
[21]	91	[22]	29
[23]	88	[24]	25
[25]	66	[18]	25
[26]	64	[27]	23
[28]	63	[29]	23
[30]	57	[23]	22

There were some differences between the lists of most cited papers overall and those most cited per year since publication, with five papers appearing in both lists (Table 1). This had to do with the age of the papers—on average, the ten most cited papers overall were published two years before the ten papers with the most citations per year—as older papers had more time to gather citations than newer papers. On the other hand, a small core of impactful publications was visible.

Although a total of 504 authors were listed in the dataset, the impactful publications were written by a rather compact group of 26 (most cited papers overall) or 36 authors (papers with most citations per year), many of whom have contributed to several papers (Table 2). On the other hand, almost 87% (438) of authors in the dataset contributed to one paper.

Table 2. Eleven authors with more than three publications in the dataset.

Author	Number of Papers
Toppinen, A.	10
Stern, T.	6
Hellsmark, H.	5
Bauer, F.	4
D'Amato, D.	4
Hansen, T.	4
Korhonen, J.	4
Ladu, L.	4
Ludvig, A.	4
Soderholm, P.	4
Weiss, G.	4

The authors of papers focused on the forest bioeconomy innovations primarily came from universities. Of the 255 institutions listed in the dataset, 133 were universities, 82 were other types of institutions, such as government agencies, government bodies, international organizations, companies, etc., and 40 were research institutes. In the top ten institutions, considering the number of papers in the dataset, only the European Forest Institute was a non-university type of institution (Table 3).

Table 3. Institutions with the most papers in the dataset.

Institution	Number of Papers
University of Natural Resources and Life Sciences Vienna	11
University of Helsinki	10
Lund University	8
European Forest Institute	7
University of Freiburg	6
Swedish University of Agricultural Sciences SLU	5
University of Graz	5
Oregon State University	5
University of Eastern Finland	5
University of Canterbury	4

The authors of the papers included in the dataset were affiliated with institutions from 43 different countries. Considering the countries to which the authors were affiliated (Table 4), most were European, with Germany (33; 15%), Finland (28; 13%), and Sweden (18; 13%) leading the list. Overall, authors affiliated with European institutions contributed to 66% of the papers, followed by authors affiliated to institutions from North American (14%), Oceanian (8%), South American (6%), African (3%), and Asian (3%) regions.

The 161 papers dealing with innovations in the forest bioeconomy were published in 59 journals. Almost two-thirds of all papers were published in twelve journals that contained at least three papers, and more than three-quarters of all citations were of papers that were published in these journals (Table 5). This shows that authors focus on publishing in a rather specific group of journals that attract considerable attention of the scientific community dealing with innovations in the field of the forest bioeconomy.

Table 4. The ten countries with the most authors of the papers included in the dataset.

Country	Number of Papers
Germany	33
Finland	28
Sweden	18
USA	18
Austria	16
Canada	10
Italy	8
New Zealand	8
Spain	8
UK	7

Table 5. Journals with at least three papers published.

Journal Title	Number of Papers	Share of All Papers	Number of Citations	Share of All Citations
Forest Policy and Economics	28	17%	352	12%
Sustainability	22	14%	686	23%
Journal of Cleaner Production	17	11%	740	25%
Forests	8	5%	38	1%
Croatian Journal of Forest Engineering	5	3%	98	3%
New Biotechnology	5	3%	123	4%
Environmental Innovation and Societal Transitions	5	3%	85	3%
Biofuels Bioproducts and Biorefining	3	2%	94	3%
Environmental and Climate Technologies	3	2%	44	1%
International Journal of Forest Engineering	3	2%	15	1%
Technological Forecasting and Social Change	3	2%	17	1%
International Forestry Review	3	2%	8	0%

A similar focus can be seen when looking at the Web of Science publication categories (Figure 2). Though journals are often listed in several categories, only 25 unique categories were identified for papers included in the dataset. Naturally, most papers were published in journals categorized under Forestry (25%), followed by Environmental studies (17%), Environmental Sciences (14%), Green and Sustainable Science and Technology (13%), while journals categorized under Textile, Ecology, Science, and Technology or Developmental studies only had one paper published in them. A clear focus on natural and technological sciences can therefore be seen.

Our analysis showed that innovations in the forest bioeconomy are gaining traction in the scientific community, and the community of researchers connected to forestry and forest-based industries is beginning to adopt the terminology related to the concept of the forest bioeconomy. We found that while higher education institutions, i.e., universities, hosted the most authors, a considerable portion of authors were affiliated with other types of institutions, such as government agencies, private companies, associations, etc., as well as research institutes. Moreover, much of the research was conducted in distinct regional clusters located in Europe (mainly North and Central Europe), North America (mostly USA), and Oceania (New Zealand), where forestry research is traditional and strong. As with the whole concept of the forest bioeconomy, the research is strongly topical, and the authors published their papers mostly in journals dealing with matters of forestry, the environment, sustainability, or economy, and to a smaller extent with biotechnology, engineering, material sciences, all of which are at the core of the focus of forest bioeconomy innovations.

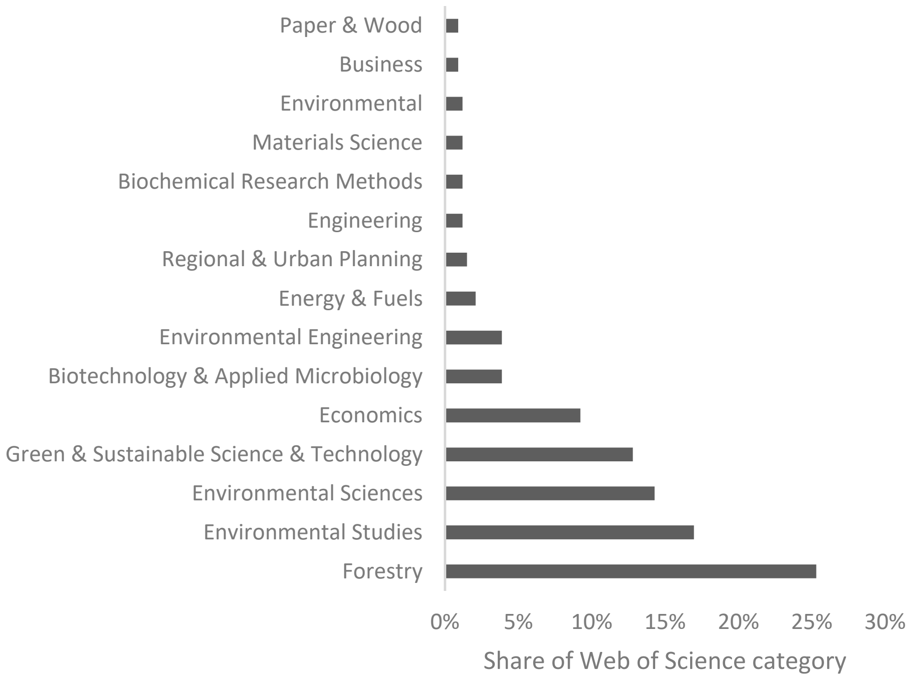

Figure 2. Share of papers published in journals listed in Web of Science categories; 15 most prominent categories listed.

4. Innovations in Forest Bioeconomy

The bioeconomy, as a novel and integrative concept, covers a variety of fields and disciplines, from health and the chemical industry to agriculture, forestry, bioenergy, and more. Engineering and natural science have a central role in the bioeconomy, generating a strong impact in the three types of bioeconomy visions, as identified by [1]. First, the biotechnology vision is based on the importance of the application and commercialization of biotechnology in different sectors of the economy. Second, the bio-resource vision focuses on processing and upgrading bioresources coming from forestry, agriculture, and fisheries that establish new value chains. Finally, the bio-ecology vision highlights sustainability and ecological processes. These visions present a complementary strategy resulting in synergies in terms of research and innovation. However, it is important to consider the societal and economic implications following the principles of regional and national context [1].

Although the bioeconomy is based on using bioresources in manufacturing and services, it is not inherently sustainable and brings new challenges to face. To make the bioeconomy sustainable, it needs a strong social and ecological perspective, though this is frequently not sufficiently addressed in the connected strategies. Ecological viability, economic feasibility, and social acceptance are the sustainability targets that can be achieved through economic growth and innovation. Albeit, this last statement is difficult to accomplish without decoupling economic growth from environmental degradation [21,29,31]. For instance, the increasing demand for bioresources will put a lot of pressure on the limited biomass and land resources, potentially causing several sustainability problems. Here, using novel technologies can reduce the negative impact of the large-scale use of biomass. On the other hand, these innovative technologies should not be taken as an immediate solution to this problem. Innovation needs to go hand in hand with ecological and social responsibility in optimal combination and implementation to alleviate the competition for land use, as well as deforestation, water, and land footprints, and others [2,31].

Innovations function as one of the most important drivers to foster more political and environmental support needed to meet the sustainability embedded in the bioeconomy. Although many national strategies stress the ecological benefits of bioeconomy innovation, not all innovations lead to intended improvements in terms of sustainability. This is a result of a substantial number of uncertainties that go along with the design and implementation of innovations. Therefore, innovations require a gradual, adaptative, and credible commitment plan to approach this transition in the best way. Innovation is, thus, a double-edged sword—partly the problem, partly the solution to reaching sustainability of the forest bioeconomy [2,31].

To provide sustainable alternatives for technologies and products, as well as adjustments to the consumption and waste generation patterns, a range of innovation types are needed [8,32]. The literature distinguishes four distinct innovation types (IT), classified by their development status, in the bioeconomy [32]. Innovation type 1: “Substitute products” is based on the replacement of fossils-based products by bioresources. Innovation type 2: “New processes” promotes bio-based production and value chains. Innovation type 3: “New products” focuses on bio-based materials with new functions. Finally, IT4: “New behavior” describes a new way of doing things, either concerning interactions or actions of the customers, or new ways of collaborating with stakeholders, etc. (Appendix A). To succeed, ITs require combining different knowledge areas and overcoming challenges concerning interdisciplinary development, such as market uncertainties, value chains, resources, innovation capacities, knowledge integration, or attracting end-users/consumers. So, innovations require anticipation, reorganization, and, related mainly to the IT4, balancing their economic and ecological benefits. To figure out their dynamics and understand what policy measures result in noticeable improvements or fill an existing gap, monitoring the activity for particular ITs is also needed. From an economic systems perspective, systems undergoing broad, disruptive innovations need a high degree of resilience to adapt to the associated disruption accompanying innovations, especially when the bioeconomy competes with the established economic systems dependent on fossil resources and products [3,12].

In addition, the specific situation of technology and innovation management (TIM) transcends national, regional, and sectoral boundaries, thus encompassing IT2. In line with this, [8] lists bio-based chemicals and wooden-based buildings, categorized as complementary and competing TIMs. Aside from the requirement to anticipate and reorganize the market or integrating knowledge, TIM also stresses that the need to support niches and indirect demand-pull is essential in bringing technologies forward, as is the use of large-scale deployment support for creating new bridging markets. In addition, it is necessary to keep in mind that networks, public-private intermediaries, or other stakeholders can ease the transition while innovations are being implemented. Thus, proving the need for proper planning and preparation in the complex innovation implementation process [12].

Aside from political vision and innovative technology, the role of actors from the private sector, especially innovative entrepreneurs, is crucial for the transition. Entrepreneurs enable transformation not only through introducing new products and services but also through reestablishing the process of value creation and redesigning business models for enhanced efficiency and sustainability. Interaction of activities on a micro-, meso- (entrepreneurial ecosystems or clusters), and macro- (governmental vision) levels result in acknowledging the importance of entrepreneurship perspectives. The interaction also serves as an essential resource for societal and economic transformation, motivated by creating and reconfiguring value chains while seeking stable solutions [33].

Considering the crucial role of entrepreneurs and industrial stakeholders in bioeconomy innovations, they should be incentivized to opt-in on a long-term scale. However, this is often not the case. Lovric et al. [34] found that most innovations are far from a market application, and the organizations that participate in the European forest bioeconomy projects only participate once. After the initial, low technological readiness level innovations, no project follows up to bring the innovation to the market, and there are few innovation cases in the later stages of development. Furthermore, innovations in several Central European countries are seldom funded; the support was given by different external stakeholders, which shows a lack of finances [34]. Finally, the authors [34] concluded that different from “routine and safe” types of innovation, bioeconomy innovation should be backed by policy spheres.

Several authors have recognized the need for more investment in research and development, policy strategies, and incentives to boost the bioeconomy [32,35]. However, great care should be given to developing political frameworks because if inappropriately deployed, overuse of bioresources can have severe negative environmental impacts, resulting in unsustainability and possible political conflicts. Despite a considerable body of literature on bioeconomy policies, more research is needed, focusing on the analysis and concrete comparisons of cases and emerging policies in this field to strengthen transition-oriented innovation systems [8,36]. According to [36], there is a need to identify key causal mechanisms in bioeconomy politics to reveal underlying power relations, conflicts of interest, and relevant impacts on the environment and more consistent, homogeneous, and less fragmented policies.

Bioeconomy strategies often describe the roles of entrepreneurs in detail. Nonetheless, the level of detail, as well as the definition and the focus on products and market, found in a strategic document will vary depending on the scale (e.g., national or regional) of the implementation [37]. Most of the bioeconomy strategies were made in the EU, and the most recent were proposed by UK, Finland, Czech Republic, France, Italy, Latvia, Norway, and Spain. Despite the different approaches in different parts of the world, whether it is related to bio-based buildings (The Netherlands), using biomass for energy, wood-based biorefining (Italy), or macro-regional bioeconomy policies (Latin America and Eastern Africa), the aim of the strategies is alike. The strategies aim to promote collaboration between similar regions (in terms of resource availability and economic power), increase the value of local bioresources, create job opportunities, and improve regional innovation systems as a base for sustainability [37]. Bezama et al. [37] promoted the concept of "economies of scope", in which bioeconomy regions could have a wide range of bio-based industries cooperating within networks and clusters while having a diversified product basket, based on a regional smart specification strategy, thus creating a region of collaborators.

Another study in the area of forest-based bioeconomy focused on the services and activities that cover primary production and manufacturing–processing, service outputs from tangible products, and services as strategies (business model with value creation) [38]. The analysis was conducted at the European level, not national and regional strategies. According to the authors, most of the bioeconomy strategies mention the importance of natural ecosystem services and their contribution to society. The strategies will improve the contribution of the ecosystem services to resource efficiency and solving the challenges associated with climate change, land use, and global food security. For example, to unlock the potential of the UK's bioeconomy, innovation efforts are needed in the country [39]. These include amending the public procurement guidelines to promote biobased products, promoting joint public–private investments with an emphasis on attracting large innovative companies into the UK, and achieving wider public consensus and support. Biotechnology and innovation were identified as the main drivers of the development of the Czech forest bioeconomy. Still, the country needs to ramp up funding and financial and political support to increase the efficiency of bioeconomy deployment in the country [24].

Outside the EU, innovations being implemented are focused differently, as in the US, where the bioeconomy has gained interest too recently. In contrast to the EU, which emphasizes sustainability, the trend in the US includes genomic sequencing for individuals and a stronger focus on life science [33]. In 2012, the government released a document, "National Bioeconomy Blueprint" recognizing biotechnological innovation as a strong driver of bioeconomy growth. The document focuses on the necessity to develop more efficient biorefining technologies and co-producing fuels, chemicals, fibers, polymers, heat, and electricity. Thus, commercial production of bioethanol, biodiesel, biogas, bioheat, and biopower, as well as manufacturing commercial bioproducts, such as biopolymers, biochemicals, biopharmaceuticals, and bio-adhesives, are to be widely practiced. Commercial production of lignocellulosic ethanol, renewable diesel, green jet fuel, and other advanced biofuels is at the demonstration stage, demanding improved cost-effectiveness and economic viability. On the other hand, barriers, such as the high cost of biomass feedstock, lack of cost-competitive bioproducts that function at least as well as their petrol-based counterparts, and unstable biofuel and bioproducts market, still need to be overcome. Thus, it is crucial to integrate biorefining processes (bioenergy and bioproducts) under one roof [40].

The innovations listed (Appendix A) are similar in involving a variety of industries in leading to specific changes that improve the various sectors of the bioeconomy. They often focus on biotechnology as a substantial part of the engine that drives growth, innovation, and increases productivity. Products or processes from other branches of the bioeconomy need to pass through some form of biotechnological or biorefining process to generate the final product [41,42]. In short, industrial biotechnology and biorefinery go hand in hand with the use of bioprocesses for greener products and are interconnected [41].

The biotechnology area involves novel sources of biomass and blue technology, where terrestrial and marine-derived materials need to be co-bioprocessed. Industrial biotechnology (or biorefining) is applied in segments that range from specialty chemicals, bio-based plastics, biolubricants, biosurfactants, to biofuels, bioenergy, and other biomaterials. High-value products are always the preferred outputs of biorefining, so a boom in new enzymes with applications in the medical, environmental, food, and chemical sectors is expected [14,41].

These new products are to be produced by resource-efficient biotechnological methods rather than conventional ones. The fact is, however, that there are only a handful of operational biorefineries capable of production of these products, and their value chains differ from one to the other in aspects such as volume/price, potential advantages, product characteristics, maturity, and sector [42]. In this, industry partnerships will help, by allowing more combinational and recombinational modes of innovation, though interdisciplinary and intersectoral collaboration will be required as well [14].

An example of a sector well underway of transitioning from fossil-based products to bioproducts is food packaging, with evidence backed by research [43,44]. The bioplastics used for food packaging are compostable and could be used circularly. This serves as a model for other industries, such as textile and technics, to pursue this transition. A recent study [45] suggested that textile manufactures should transition in cooperation with the retailers, thus providing better market access. Whether the textile industry cooperates in price or cost, both should increase the average clothing sustainability. Furthermore, cooperation between the textile and food sector constitutes a win–win situation, where new knowledge and new models to be implemented are acquired, as well as the ability to put less pressure on the environment by removing the trend of fast fashion.

Cooperation, support, and learning from other sectors is a circular experience that makes the bioeconomy transition smoother and friendlier. For instance, the forest bioeconomy is an important sub-sector of the overall bioeconomy, under which forests are managed in a sustainable mode. They are projected to provide a significant contribution of biomass and have “classic” applications, such as wood processing or pulp and paper [7,46]. However, the forest sector was perceived as a conservative industry, with traditional business culture and little experience collaborating with other industries, unlike the companies they partnered with. Recently, this perception of forestry has shifted towards an image of a welcoming industry, which may lead to the incorporation of forest-sector companies into other supply chains, creation of new partnerships, sharing best practices, and facilitating innovation. Ultimately, collaborating with firms from other industries may lead to an improved capitalization of forest companies in the growing bioeconomy [18,47,48].

To reach collaboration between the sectors, an innovative process was needed to realize the future bioeconomy of products. Though any sector welcomes new ideas being introduced, these frequently underdeliver, regardless of how good they seemed to be on paper. A key could be to ensure adequate extension amongst the target audience. This fosters a requirement for a successful implementation of innovation and encourages the forestry community to engage in innovation [46]. The innovations summarized in

Appendix A show that innovations in the forest bioeconomy range from 'classic products', passing through improvements in forest data management and usage, harvesting both timber and non-timber forest products, to biorefining. Some of these products are more familiar than others. In summary, this set of innovations served as a reference point to analyze all possibilities that forest-based sectors offer to our society.

5. Concluding Remarks

This paper focused, first and foremost, on analyzing the state of innovations in the forest bioeconomy in scientific literature. Besides the unsurprising high share of papers being published in journals related to the forestry category, many were published in journals that deal with environmental studies and sciences. This points to the prominent role of sustainability and environmental responsibility associated with the bioeconomy. Another encouraging fact was that green and sustainable science and technology or other technical publication categories were among those with high publication numbers. This points to concrete technological innovations being reported in the literature. On the other hand, though the increasing interest of the scientific community in the topic is laudable, we found that most papers were published in just a few regional and institutional clusters. Further efforts are therefore needed to increase the output and improve its quality in regions outside Europe and North America.

From the literature analyzed, it was apparent that the transition to the forest bioeconomy will be accompanied by substantial innovation efforts. Besides their more talked about benefits, these innovations will likely cause disruptions and, as any substantial economic shift, will create a complex web of winners and losers. To minimize these negative effects, bioeconomy transition will require not only profound technological innovations but also adapted policies and strategic documents, as well as innovations of the way stakeholders collaborate. The scientific community is aware of the necessity to precede innovations with appropriate and complex adaptation of policy frameworks based on science, which can be seen in the number of papers dedicated to changes of policies and strategic documents connected to bioeconomy transition.

Concrete innovations will likely cover all innovation types, ranging from substitute products through new processes, new products to new behaviors. Such innovations were already introduced to certain sectors, e.g., the case of bioplastics in packaging and their introduction in the textile and technics industries. Another example of an ongoing shift to bio-based solutions can be seen in the construction sector and the increasing share of wooden buildings in Europe. Biorefining, on the other hand, represents a case with slower uptake. This is caused by the complexity of the case regarding technologies, supply chains, inadequate regulatory frameworks, or lock-ins to existing solutions from potential consumers of biorefining products. In short, the transition to the bioeconomy is a complex issue, with numerous bottlenecks and problems that need to be solved. However, with well-devised regulations, resilient economies, and innovation-driven industries, the efforts will ultimately lead to the deployment of an efficient and sustainable forest bioeconomy.

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

Appendix A

Table A1. Summary of forest bioeconomy innovations across their different areas.

Area	Location, Reference	Materials	Description
Based on "classic" products (woodwork, pulp and paper)	Europe [22]	Pulp and paper industry (PPI) and other cellulose-based products.	Transformation of the actual business model to increase its profitability with value-added bio-based products, while contributing to climate change mitigation. Potential strategies that are proposed: Evaluation of strategic options; Marketing to address new customers; Optimization of biomass; Research cooperation and new value chain; Policy support.
	World [49]	Lignocellulose-based products; Cellulose chemical; Cellulose textile fibers	Substitution of fossil-based materials with lignocellulose-based products in the chemical and textile industries. Inclusion of lignocellulosic products into global forest sector scenario modeling. The elasticity estimates the import demand and consumption can be used synonymously as, e.g., demand elasticities for adaption of economic equilibrium models for the forest products market.
	Germany [7]	Lignocellulose biorefinery	TIS approach, only an exploratory work. Main importance to actors' perception (forest and wood industry, chemical industry, and energy sector). Policy integration issue is one of the biggest obstacles due to cross-sectorial concepts, such as biorefinery. Forest biorefineries are still far from competitiveness in Germany. Technology readiness is crucial for the transition.
	US [50]	Cellulosic biofuel pathways	Hypothetical future containing additional cellulosic ethanol produced from two-near commercial pathways. Cellulosic biofuel pathways may not be environmentally beneficial across all metrics but are likely to provide net socioeconomic benefits. The associated relatively higher costs and lower sugars yields hinder the adoption of these lignocellulosic biomass pretreatment technologies.
Biorefinery	Sweden [28]	Biorefinery development	TIS approach and four policy measures are the following: Implementation of deployment policy for creating domestic niche markets; Enhanced policy timing and more structured coordination among governmental agencies. Stronger incentives for mature industries to invest in R&D and improve their absorptive capacity. Improved organization and financing of existing research infrastructure.

Table A1. *Cont.*

Area	Location, Reference	Materials	Description
	Pan-European [51]	Emerging Biorefinery technologies	Knowledge developed at Pilot and demonstration projects (PDPs) is very important for emerging biorefineries technologies. Innovating actors active in biorefinery TIS create and shape the sustained change in a forest-based circular bioeconomy with strategies directed at the construction and operation of PDPs. Actor strategy could be the link between organizations and innovation systems. The PDPs have a strong technological focus on chemical and biochemical conversion as well as on biopolymers processing in high-profile plants.
Bionergy	Italy Norway Sweden Finland [52]	Biogas	ER fast processes of biogas adoption, but they experience harmful consequences despite "good" expectations. When the actors involved do not fully cooperate or coordinate their actions–decisions to reach common goals and issues, then an active role of municipalities and knowledge centers can foster learning processes, the inclusion of better conflict resolution. Exploited their knowledge of local economic and social base to include a variety of actors. Foster links between old and new industries (industrial symbiosis).
Data	World [53]	Big data and remote sensing	Big data make easier to monitor forest and make informed decisions over their use and management, at lower cost, user-friendly formats, actionable and timely. There are many ways that forest data can be generated: from high-resolution satellite images to the mining of the "Twittersphere", and genetic fingerprints, and it is harder to keep information hidden. Tools for forest monitoring are spatial resolution, temporal resolution, repeatability, and affordability. Augment geospatial data gathered through remote sensing.
	Ontario, Canada [54]	Remote sensing	Site: Petawawa Research Forest (PRF) Supersite Data records are digital terrain model, canopy height model, airborne imagery, satellite remote sensing time series, and ground plot data, among others. Public data allow more users to directly access and use the data for further research and education purposes, also addressing new questions not previously conceived. Supersites can foster increased collaboration, sharing resources in the development of remote sensing applications. Benchmarking is one of the key applications, enabling efficiencies and reducing investment risk for stakeholders.
Harvesting	Europe New Zealand North America Other parts of the world [55]	Winch-assist harvesting	Winch-assist system is considered as a major innovation in steep terrain harvesting. In steep terrain, harvesting operations have increased by removing workers from the hazard of manual and motor-manual work. It is considered more productive than conventional steep terrain harvesting and economic viable It could be a solution to shortening operating seasons and soil impact concerns. It is a relatively young technology, and the system productivity seems to be good but is often limited in their scope systematic comparison of productivity and costs. This is the first step to follow with the next stages in the forest bioeconomy.

Table A1. *Cont.*

Area	Location, Reference	Materials	Description
Non-timber	China [56]	Non-timber products	There is a trend of feminization in forest management, and it is more common in developing countries. This is because of the migration of rural male laborers for off-farm work. Feminization has affected rural households' decisions, and they are inclined to adopt labor-saving technologies (LSTs) and less inclined to adopt labor-intense technologies in forest production. Due to the new technology adopted, new seedlings technology increases the non-timber forest products (NTFP) outputs due mainly to the higher quality of seeds, and that it requires less labor input than the other two labor-saving technologies. Government supportive policies can improve households' adoption of new technologies; the subsidies are for machinery and seedling purchases and continued investment in forest production.

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Paper II

The Role of Bioeconomy in the Czech National Forest Strategy: A Comparison with Sweden.

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The role of Bioeconomy in the Czech national forest strategy: a comparison with Sweden

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HIGHLIGHTS

- The Czech Forest Policy denotes the 2012 European Bioeconomy Strategy as one of the reference documents, while the Swedish National Forest Programme (NFP) positions the Bioeconomy Strategy as its core value.
- The principles of the 2012 European Bioeconomy have not been officially transposed by the Czech government, and therefore their application in the forestry sector is limited.
- Differences in the initial situation between the Czech Republic and Sweden now may result in various foci on the strategic measures in the 2020 Czech Forest Policy compared to Sweden.
- The adoption of the 2012 European Bioeconomy to uplift the bio-based manufacturers in the Czech Republic is carefully being examined through the lens of Sweden's experiences
- The main challenges for the Czech forest-based sector are to fulfil the need for sustainable forest biomass and high added-value products.

SUMMARY

The 2012 European Bioeconomy Strategy has been adopted in some European countries' national policies. However, it has not been officially included in the Czech Republic's national policy. In Sweden, the Bioeconomy Strategy has been adopted in the national policy and the National Forest Programme (NFP). The paper reviews the current forest policy in the Czech Republic in meeting the purposes of the forest-based bioeconomy by performing a comparative study between the Czech Republic and Sweden. As bioeconomy principles are core values in the Swedish NFP it aims not only to deliver sustainable forest products and ecosystem services to support forest enterprises but also to achieve a fossil-fuel-free Sweden. Although the Czech Forest Policy denotes the European Bioeconomy Strategy as one of the reference documents, it does not directly relate to shifting from fossil fuels to bioenergy. The implementation of the Czech document is limited to the forest-based sector. Bioeconomy principles are expected to be included in inter-ministerial committees at the government level in the Czech Republic. The challenges faced by the country include fulfilling the provision of sustainable forest biomass and high added-value products while harmonising forest policies and regulations.

Keywords: forest strategy, forest policy, forest bioeconomy, sustainable forestry, Czech Republic, Sweden, comparative analysis

Rôle de la bio-économie dans la stratégie nationale forestière tchèque: une comparaison avec la Suède

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La stratégie bio-économique européenne de 2012 a été adoptée dans les politiques nationales de plusieurs pays européens. Elle n'a toutefois pas été inclue officiellement dans la politique nationale de la République Tchèque. En Suède, cette stratégie bio-économique a par contre été adoptée dans la politique nationale et dans le Programme de foresterie national (NFP). Le papier examine le succès de la politique forestière actuelle dans la République Tchèque quant à son intégration dans les fins de la bio-économie basée sur la forêt, en conduisant une étude comparative entre la République Tchèque et la Suède. Alors que les principes de la bio-économie sont des valeurs centrales dans le NFP suédois, ce dernier vise à non seulement produire des services d'écosystèmes et des produits forestiers durables pour soutenir les entreprises forestières, mais à également parvenir à une Suède libérée des combustibles fossiles. Bien que la Politique forestière tchèque cite la Stratégie bio-économique européenne comme l'un de ses documents de référence, elle ne fait directement allusion à la transition des combustibles fossiles à la bio-économie. La mise en application du document tchèque est limitée au secteur basé sur la forêt. Il est attendu que les principes de bio-économie soient inclus dans les comités interministériels au niveau gouvernemental dans la République Tchèque. Les défis auxquels le pays fait face comprennent assurer la provision d'une biomasse forestière et de produits à forte valeur ajoutée durables, tout en harmonisant les politiques forestières et les règles.

El papel de la bioeconomía en la estrategia forestal nacional checa: una comparación con Suecia

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La Estrategia Europea de Bioeconomía de 2012 ha sido adoptada en las políticas nacionales de varios países europeos. Sin embargo, no se ha incluido oficialmente en la política nacional de la República Checa. En Suecia, la Estrategia de Bioeconomía ha sido adoptada en la política nacional y en el Programa Forestal Nacional (PFN). Este artículo revisa la política forestal actual de la República Checa con relación al cumplimiento de los objetivos de la bioeconomía forestal, para lo cual se realiza un estudio comparativo entre la República Checa y Suecia. Dado que los principios de la bioeconomía son valores fundamentales en el PFN sueco, su objetivo no es sólo ofrecer productos forestales sostenibles y servicios ecosistémicos para apoyar a las empresas forestales, sino también lograr una Suecia sin combustibles fósiles. Aunque la política forestal checa incluye la Estrategia Europea de Bioeconomía como documento de referencia, no se menciona directamente el cambio de los combustibles fósiles a la bioenergía. La implementación del documento checo se limita al sector forestal. Se espera que los principios de la bioeconomía se incluyan en los comités interministeriales a nivel gubernamental en la República Checa. Los retos a los que se enfrenta el país son, entre otros, lograr un suministro de biomasa forestal sostenible y productos de alto valor añadido a la vez que se armonizan las políticas y normativas forestales.

INTRODUCTION

Environmental problems due to climate change and their consequences (Intergovernmental Panel on Climate Change (IPPC) 2015), combined with European Union (EU) climate and energy targets (European Environment Agency 2017a), have challenged European countries to direct their strategies towards bioeconomy. Bioeconomy is defined as an economy emphasizing the sustainable production of renewable bio-based resources and their transformation into food, feed, bio-based products, and bioenergy to replace fossil-based fuels (European Commission/EC 2012, 2018), which promotes the creation of new biological products and business activities (EC 2012, 2018, Sillanpää and Ncibi 2017). The re-established bio-based industries are also expected to improve the quality of life and environmental conditions by reducing the exploitation of natural resources (Sillanpää and Ncibi 2017, Aguilar *et al*. 2018). The expected measures include the extended life cycle of products, their parts, and/or materials, while reducing the amount of energy utilisation and pollution generated by the products (Cristóbal *et al*. 2016, Hildebrandt *et al*. 2019).

Based on its vital contribution to biomass and sustainable production, forestry is considered to be one of the pillars of the bioeconomy (Giurca and Späth 2017, Hetemäki *et al*. 2017). Forestry provides a climate benefit through its substantial contribution in the provision of carbon stock (indicated by the above- and below-ground mass) (Millennium Ecosystem Assessment 2005, Pan *et al*. 2011), higher utilisation of sustainable and carbon-neutral fuelwood (Food and Agriculture Organisation/FAO 1997), and substitution of wood for steel, concrete, and other products that require more energy in their manufacturing to reduce the fossil fuel use and, consequently, CO2 emissions (Hurmekoski 2017). Hence, the inclusion of bioeconomy principles in the national forest strategies in several European countries has strengthened the forest policy implementation (Federal Ministry of Food, Agriculture and Consumer Protection 2011, Ministry of Agriculture and Forestry 2015, Nordic Council of Ministers 2016, Department of Agriculture, Food and the Marine 2015, Ministry of Enterprise and Innovation of Sweden 2018, Federal Ministry for Sustainability and Tourism 2018). The national forest strategies in Europe have been largely influenced by international, pan-European, EU, and other relevant policies. Simultaneously, the external and internal occurrences, and the related national policies also shape the respective forest strategies (Aggestam and Pülzl 2018, Edwards and Kleinschmit 2013). Following the goal of bioeconomy in sustainable development aimed at replacing fossil-based energy sources, the EC also introduced the European forest strategy in 2013 to respond to the recent challenges faced by forests and the forest-based sector, and denoted the importance of documents related to the European forestry (EC 2013, Aggestam and Pülzl 2018). The implementation of the bioeconomy principles in the forest-based sector supports the development of less popular forest products and other ecosystem services other than wood. At the same time, it is expected to foster economic growth and create new job opportunities. Also, the production of high added-value renewable resource products and the utilisation of long-life products from the forest-based sector are being promoted (EC 2012, 2013, 2018, Wolfslehner *et al*. 2016a).

In 2018, the German bioeconomy council reported that nine European countries had officially adopted bioeconomy as their national strategies, and six other countries had acknowledged the Strategy on an industrial level (German Bioeconomy Council 2020). However, to date, no distinctive bioeconomy strategy is officially stated in Czech policies. The Czech national government is supportive of the Bioeconomy implementation (Hájek *et al.* 2021a). General bioeconomy principles were mentioned in rural development policy documents, in the 2018 draft strategy of the Ministry of Agriculture (MoA) of the Czech Republic (Langeveld 2015), and, more recently, in the 2020 State Forest Policy (The Government of the Czech Republic 2020). The Czech Republic is currently in the middle of the Bioeconomy adoption process, taking advantage of learning from other European countries' existing models. A comparison of the German national forest strategy and the Czech Republic's was recently studied. The lessons learned from the German forest strategy are the commitment to sustainable production, promotion of high added-value products, and policies and society's support to bioeconomy (Purwestri *et al*. 2020). The results have encouraged the country to implement further reviews based on Sweden's forest-based bioeconomy industrial sectors and forestry contribution to its environmental conditions. Nordic countries, including Sweden and Finland, have acknowledged the European Bioeconomy principles in their forest strategies (Nordic Council of Ministers 2016, Ministry of Enterprise and Innovation of Sweden 2018).

The paper aims to review the current forest policy in the Czech Republic in meeting the purposes of the forest-based bioeconomy by performing a comparative study of the Czech Republic and Sweden. A review of the forest strategies was performed based on the following research questions: 1) How are the Bioeconomy core values and precedences present in the Czech forest strategy? 2) How does the Czech forest strategy in contrast to that in Sweden? A comparison of selected indicators in forest-based sectors of the studied countries is also presented for a better understanding of the forestry situation. The analysis results will provide essential information for the Czech Republic in adopting the European Bioeconomy principles.

METHODS

Selection of countries for the comparison

In this paper, Sweden was selected as a comparison country to the Czech Republic in the Bioeconomy principles implementation in the forest-based sector. Firstly, we listed the European countries that consider forestry as a bioeconomy hub, based on the existence of forested regions and roundwood production. Sweden is dominated by forested regions (70%) (Ministry of Enterprise and Innovation of Sweden 2018), slightly less than Finland (76%) (Ministry of Agriculture and Forestry Finland 2015). Czech forests occupy about 33.7% of the country's total area with 71.0% and 27.7% of coniferous and deciduous trees, respectively. About 1.3% is forest land without trees. Regarding conifers, 49.5% are Norway spruce (Picea abies), followed by pine (16.1%). Deciduous trees in the Czech forests consist of beech (8.8%), oak (7.8%), birch (2.8%) and others (0.6%) (MoA the Czech Republic 2020). Three major Swedish tree species, namely spruce (42%), pine (39%), and birch (12%) dominate in the Swedish forests, followed by 7% of other deciduous trees (Swedish Wood 2021). In 2020, Sweden had the largest forested landscape in Europe (about 30.3 million ha), followed by Spain (± 28.0 million ha) and Finland (about 23.2 million ha). Sweden and Germany have the highest share (13.3%) of growing stock equally for timber in forests and other wooded lands among the EU member states (Eurostat 2020a).

Secondly, with the current global challenges in climate change and bio-based market, the country takes an opportunity to learn different forestry and forest management models from the neighbouring European countries. Based on the forest ownership, 48% and 24% of Swedish forests are owned by private person and forest companies, 13% by state-owned limited liability companies, and 6% by other private owners (e.g. organisations), which makes it possible that the management of the forest-based sector is geared towards profitable forest enterprises. The state also has a minor portion of the forests (7%), and further 2% are owned by other shareholders (Swedish Forest Agency 2019). In contrast, more than a half of 2.6 million ha of Czech forests are owned by the state (54.09%, of which 44.71% are state forest enterprises), followed by private individuals (19.27%), municipal forests (17.17%), religious associations/churches (5.0%), legal persons (3.27%), forest cooperatives and companies (1.19%) (MoA the Czech Republic 2020).

Within its neighbouring Central European countries, the Czech Republic was placed at the first position for wood exports, together with Slovakia, in contrast to the negative balance of Austria and Germany in 2018 and 2019 (FAO 2021). The high number of wood exports indicates the low added-value transfer (Berankova and Polášek 2017). Thus, the third reason for conducting the comparison was concerning the provision of sustainable wood production and high added-value products from the Swedish forestry. In 2018, Sweden became the leader in total roundwood production among the EU countries with approximately 75.1 million m^3, followed by Germany (about 71.8 million m^3), Finland (± 68.3 million m^3), and France (about 48.2 million m^3), while the Czech Republic contributed by nearly 22 million m^3 (Eurostat 2020a). Thus, the Swedish forests supplied the highest amount of industrial roundwood (68.3 million m^3) compared to the other EU member states.

As the forest is also an essential source for diverse economic activities in rural areas in Europe, the fourth reason was in relation to employment in the bio-based economy and in forest-based sector. Sweden is categorised as a country with an above EU average labour productivity in the bioeconomy and with an above EU average employment share in sectors with partial biomass manufacturing together with, e.g., Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Italy, Luxembourg, the Netherlands, and Spain. In particular, Sweden, Luxembourg, and Finland report having the highest levels of turnover per person employed in the manufacturing of wood and wooden furniture (> EUR 270,000 per person employed) (Ronzon *et al*. 2017). Sweden was also among the top three of the highest workforces in forestry after Poland and Romania, with an approximately 20% increase of persons employed in 2008 to 2018, by contrast to the Czech Republic with a decrease of about 20% (Eurostat 2020a).

Based on the characteristic similarities (e.g., tree species composition, economic objectives) and differences (share of forest over total land, forest ownership, industrialisation) of forest-based sector between the studied countries, the comparison of the Czech Republic and Sweden was made. The results of this paper are expected to provide essential information and knowledge gained from the implementation of the sustainable forestry and forest-based enterprise in

Sweden, as part of the process in embracing the European Bioeconomy into the Czech national strategy.

Forestry characteristics compilation in Sweden and in the Czech Republic

Selected forestry indicators based on the conformity of data available in Sweden and the Czech Republic were compiled, analysed to present baseline information of the Czech forestry before and after the introduction of the 2012 European Bioeconomy Strategy, as well as the current situation and then compared with the forestry situation in Sweden. The forestry characteristics data were gathered from the FAO Global Forest Resources Assessments (FAO 2020a, 2020b), and the studied countries' forestry reports and statistical data (Royal Swedish Academy of Agriculture and Forestry 2015, MoA the Czech Republic 2020, The Swedish Forest Agency 2020). The presented information includes the proportion of industrial roundwood compared to the fuelwood production and the relationship between the forests' net annual increment and felling. Data on both countries' total roundwood production in 2000–2018 are from Eurostat (Eurostat 2020). The net annual increment data in 2000 and 2010 were gathered from Eurostat (Eurostat 2019). The increment data in 2015 and 2018 in Sweden were collected from the Swedish forest and forestry report (Royal Swedish Academy of Agriculture and Forestry 2015), while those in the Czech Republic were compiled from two forestry reports (MoA of Czech Republic 2017, 2018), respectively.

Document review analysis of the studied national forest strategies

The conceptual framework followed the research questions of the paper. The core document under review in the Czech Republic was the 2020 State Forest Policy, which was recently introduced by the MoA (The Government of the Czech Republic 2020). The 2020 Czech Forest Policy consists of the vision, four long-term objectives, and 20 measures. Meanwhile, a primary forest strategy document in Sweden is the 2018 Swedish National Forest Programme (NFP) from the Ministry of Enterprises and Innovation. The Swedish NFP covers five foci and 13 strategic measures (Ministry of Enterprise and Innovation of Sweden 2018).

A document review approach for assessing interlinkage and coherence between the policies was used and modified to answer the paper's research questions (Miola *et al*. 2019). The review analysis carried out a keyword extraction to classify the vision, goals, or objectives of the studied forest strategies. Rapid Automatic Keyword Extraction (RAKE) algorithm method was used to extract the candidate keywords and phrases (Anjali *et al*. 2019).

At the first stage of the keyword extraction, the single keywords and frequency mentioned in each forest strategy were listed. In the 2020 Czech Forest Policy 14 potential single keywords were defined, meanwhile, 15 keywords were incorporated from the Swedish NFP. At the second stage, a score-weight matrix was developed to calculate the potential keywords degree (number of two-words co-occurred in the selected text or document) and frequency (number of occurrences in the selected text or document), and the word degree ratio to frequency. The selected essential keywords (single or two words) were 'forest*' AND/OR 'sustain*', 'society', 'function' OR 'ecosystem' OR 'multifunction', 'innovation' OR 'knowledge', 'national' OR 'regional' OR 'the country'. Furthermore, the 2018 Swedish NFP included several additional single keywords with similar scores of RAKE values with 'innovation' OR 'knowledge'. They were 'bio*economy' OR 'fossil-fuel-free', 'global' OR 'international' OR 'the world', 'growth', 'development', 'job' OR 'employment'. The third stage of the keyword extracting calculated the final score for each candidate keyword, which was determined by adding all member potential keyword scores. Afterwards, at the final stage of the analysis, the keyword phrases of the studied forest strategies were then compared using the RAKE values to check the frequency or order of priorities.

In this article, bioeconomy refers to "the production of renewable resources and the conversion of these resources and waste streams into high added-value products, such as food, feed, bio-based products, and bioenergy" (European Commission 2012). In the forest-based sector, the term forest bioeconomy is defined as "all activities in the forest-based sector (comprising forestry, forest-based industries, forest-related ecosystem services) that are based on biomass, instead of non-renewable materials" (Toppinen *et al.* 2018, Lovrić *et al.* 2020). In addition to the present sustainable forest-based indicators introduced by the pan-European process for the protection of forests in Europe, the European Forest Institute has added some other measures to forest bioeconomy along the value chain, e.g., roundwood production and wood processing, carbon stock, and emission, and wood consumption (Wolfslehner *et al*. 2016). Hence, the second step was to review the relationship between the studied forest strategy's objectives in the Czech Republic and Sweden with the 2012 European Bioeconomy Strategy. Data analysis of the RAKE algorithm and grouping themes were accomplished using Microsoft Excel 2016 (corp. Microsoft, Redmond, WA, USA).

The strategic measures and challenges mentioned in the studied forest strategies were analysed using thematic analysis (Braun and Clarke 2006) by compiling and then grouping them based on the themes. Thereafter, the strategic measure thematic groups of the studied forest strategies were also compared to the 2012 European Bioeconomy objectives and plan of actions. A modified scoring system (Nilsson *et al.* 2016) was used to review the relationship between the studied forest strategies and the 2012 European Bioeconomy. The scoring system is consisted of (++, double plus): reinforcing, promotes the achievement of another goal/priority; (+, plus): enabling, creates conditions that support another goal/priority; (0, zero): consistent, no significant positive or negative interactions; (–, minus): constraining, limits options on another goal/priority; and (—, double minus): counteracting, clashes with another goal.

RESULTS AND DISCUSSION

Forestry situation in Sweden and in the Czech Republic

Figure 1 depicts the forest cover in Sweden and the Czech Republic based on the CORINE land cover in 2018, of which the forested regions combined the areas of coniferous, broad-leaved and mixed-forest classes (European Environment Agency 2019). In Sweden, forested landscapes cover the majority of the country's size, in contrast to about one-third of the Czech Republic. Due to the vast forested region in Sweden compared to the Czech Republic (Figure 1), the selected forestry data were divided by forested land area in each studied country (Table 1).

As to the ratio of total felling to the net annual increment at the EU level, less than 80% of the forest stock was harvested in 2010 (European Environment Agency 2017b), similar to most of the observed years in the studied countries. There were exceptions, especially in 2005–2010 in Sweden and 2019/2020 in the Czech Republic. Until 2017, the total annual felling (final and sanitary) was not higher in the Czech Republic than the net annual increment. However, from 2018, the whole felling slightly rose above the entire net annual increment, because the bark beetle attack drove the forest owners to process the calamity-affected timber hastily. The situation resulted in a decrease in the country's current forested landscapes (Holusa *et al.* 2010, MoA of the Czech Republic 2019, Huertas Bernal *et al.* 2021) and forced the forest owners to diversify their forest products and services. Most of the Czech forests are production forests with mainly homogenous spruce stands (FAO 2017), making them more susceptible to bark beetle attack.

Table 1 also shows that in 2005, Swedish forestry experienced a similar situation to the Czech Republic. The 2005 peak of roundwood production in Sweden was due to hurricane Gudrun, which resulted in massive wind throws of timber in southern Sweden and overproduction of wood to replace the loss and scarcity of fuelwood in the country (Olsson 2006, Jonsson 2011). Hurricane Gudrun and infestation with the bark beetle are two examples that have pointed to the importance of climate change mitigation, which is also one of the key objectives in forest bioeconomy and in the studied national forest strategies. Currently, Sweden is a top roundwood producer in the EU countries (Eurostat 2017), and

FIGURE 1 *Forest cover in Sweden and the Czech Republic*

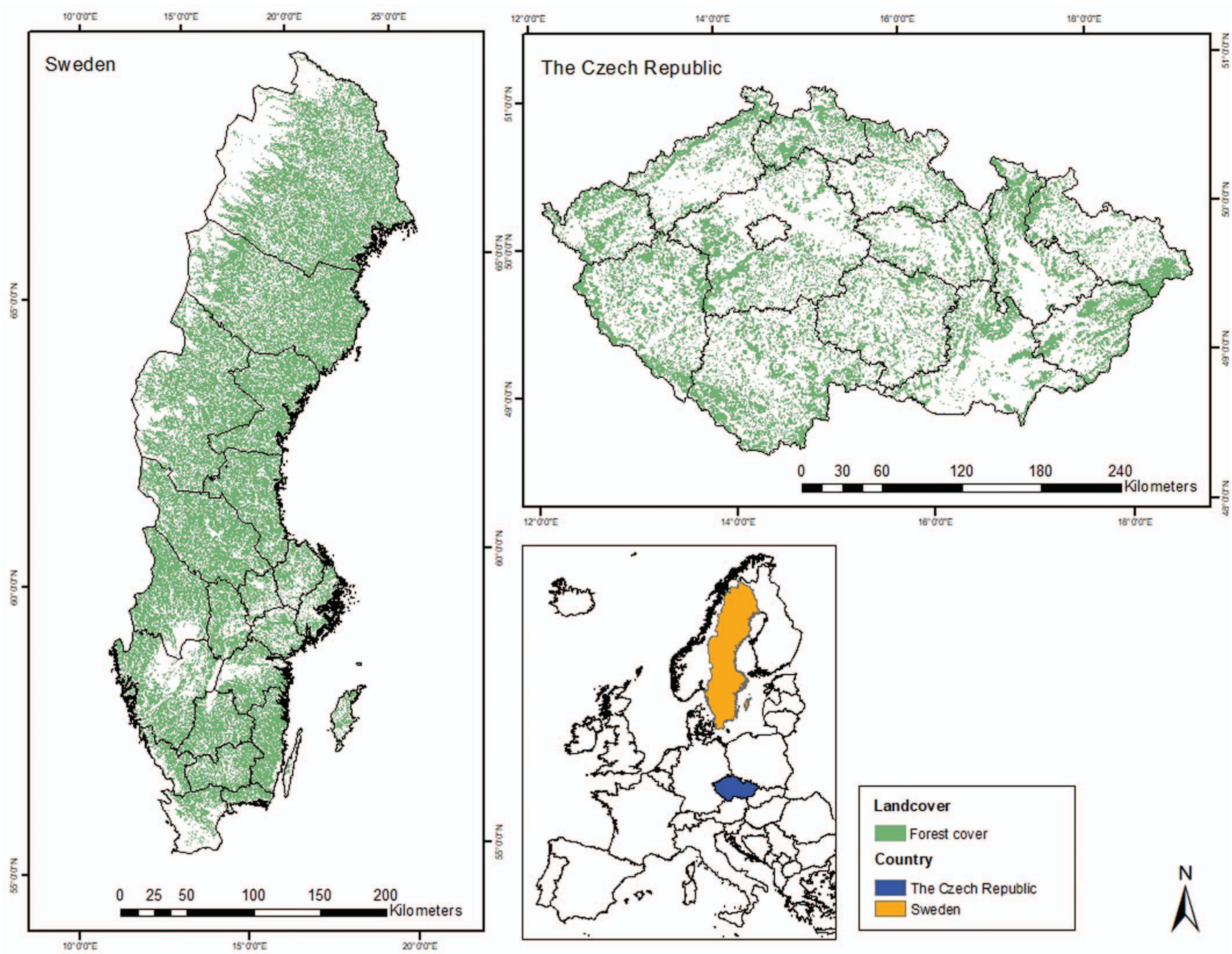

TABLE 1 *Development of selected forestry characteristics in the Czech Republic and Sweden before and after the introduction of the Bioeconomy Strategy*

Characteristics	Year				
	2000	2005	2010	2015	2019/2020
Forest area (thousand ha)[a,b]					
Czech Republic	2,637	2,647	2,657	2,667[c]	2,667
Sweden	28,163	28,218	28,073	28,073[c]	27,980
Growing stock of forests (million m^3 over bark)[a,b]					
Czech Republic	698.7	735.1[c]	754.6	768.15	790.7
Sweden	3,184.7	3, 154.8[d]	3,294.7	3,477.6	3,653.9
Growing stock of forests (m^3/ha)[a,b]					
Czech Republic	264.9	277.7[§]	284.0	287.9	295.4
Sweden	113.1	111.8[§]	117.4	124.3	130.6
Total carbon stock (ton/ha)[a,b]					
Czech Republic	150.78	160.89	167.81	172.26	150.78
Sweden	123.46	123.46	127.66	132.96	123.46
Wood production, m^3/ha (%)[e,¶]					
Czech Republic					
Industrial roundwood	5,119.8 (93.5)	5,396.7 (92.1)	5,559.3 (88.3)	5,184.5 (85.5)	9,960.4 (91.8)
Fuelwood production including charcoal	356.5 (6.5)	462.8 (7.9)	739.6 (11.7)	875.9 (14.5)	887.6 (8.2)
Sweden					
Industrial roundwood	2,038.1 (90.7)	3,271.0 (94.0)	2,361.7 (91.8)	2,397.3 (90.6)	2,502.2 (92.8)
Fuelwood production including charcoal	209.5 (9.3)	209.1 (6.0)	210.2 (8.2)	249.3 (9.4)	195.1 (7.2)
Annual felling and net increment of forest					
Czech Republic					
Net annual increment (m^3/ha)	7,508.5[f]	7,744.6[f]	7,701.5[g]	8,286.5[h]	8,367.6[i]
Felling (m^3/ha)	5,460.8[j]	6,309.0[j]	6,300.3[j]	6,040.5[h]	9,596.6[i]
Forest utilisation (%)[£]	72.7	81.5	81.8	72.9	114.7
Sweden					
Net annual increment (m^3/ha)	3,221.4[f]	3,237.5[f]	2,826.4[g]	4,407.4[k]	4,288.8[k]
Felling (m^3/ha)[l]	2,773.1	4,323.5	3,166.7	3,227.3	3,363.1
Forest utilisation (%)[£]	86.1	133.5	112.0	73.2	78.4

[a](FAO, 2020a), [b](FAO, 2020b), [c](FAO, 2017), [d](FAO, 2004), [e](Eurostat, 2020), f(Eurostat, 2009), [g](Eurostat, 2018), [h](MoA the Czech Republic, 2017), [i](MoA the Czech Republic, 2020), [j](MoA the Czech Republic, 2013), [k](Official Statistics of Sweden and Swedish University of Agricultural Sciences, 2020), [l](Swedish Forest Agency, 2020)
[§]Calculated from growing stock/forest area in m^3/ha, [¶]Calculated as wood production/forest area (m^3/ha), and proportion of wood production utilisation from industrial roundwood and fuelwood (%), [£]Calculated as annual felling as a percentage of net annual increment

the forests presented a higher net annual increment compared to the total roundwood production in 2015 onwards.

The Czech forests had similar total carbon stock (in ton/ha), and higher growing stock (in m3/ha) compared to the Swedish forest area (Table 1). Carbon sequestration in forest biomass, soil, deadwoods, or harvested wood products contributes to climate change mitigation (Karjalainen *et al.* 2003). Land-use, land-use change, and forestry (LULUCF) take part in the mitigation of climate change by increasing the removals of greenhouse gas emissions (Jia *et al.* 2019). Harvest rate, and the area affected by fires and storms correlated to the net CO_2 emissions from living biomass (Pilli *et al.* 2016), while deforestation and forest degradation release between 10% and 15% of global greenhouse gas emissions (Van der Werf *et al.* 2009); which implies the essential role of forest management in climate change mitigation. Subsequently, certification for sustainable forest management was introduced and implemented in both countries to promote sustainable forest management.

A set of predetermined environmental standards implemented in managing the forests is used to assess the quality of forest management. If a product or process conforms to the standard requirements, a written assurance will be given by a third party. Currently, approximately 1.8 million ha (± 70%) forests in the Czech Republic are certified by the Programme for the Endorsement of Forest Certification (PEFC) schemes (MoA of the Czech Republic 2020), comparable to more than 60% of certified Swedish forests (Royal Swedish Academy of Agriculture and Forestry 2015). Participation in forest certification is voluntary; a market-driven benefit generally follows the owner's decision to get the certificate. Therefore, participation on sustainable forest management is not necessarily due to the high conservation values or environmental benefits (Mikulková *et al.* 2015, Villalobos *et al.* 2018). In addition, the forest ownership structure in both countries also differentiates the management of the forests, of which Czech forests are mainly owned by the state (50%), while 48% and 24% of Swedish forests are owned by private individual or companies, respectively.

Relationship between the 2012 European Bioeconomy Strategy and the national forest strategies in the Czech Republic and Sweden

In this paper, the core document under review in the Czech Republic was the 2020 Czech Forest Policy, which was recently introduced within the competence of the MoA. The main driver of the 2020 Czech Forest Policy development is the forests' dire situation, which is mostly caused by the rapidly changing environmental conditions. The Czech forests are finding it difficult to adapt to these conditions, which induces their throwback and reduced resilience of forest ecosystems, resulting in the development of insect and harmful agents with catastrophic impacts on the forestry and downstream sectors (Thuiller *et al*. 2005, Cudmore *et al*. 2010, Holusa *et al*. 2010). The Czech Republic respects the nature's limits; hence, the adoption of bioeconomy principles to uplift the bio-based manufacturing forest industries in the Czech Republic is carefully examined through the experiences of other EU countries, especially Sweden.

Presence of the 2012 European Bioeconomy principles in the studied national forest strategies

The vision of the 2020 Czech Forest Policy is to achieve "Forests for Society": sustainable multifunctional forests and forest management, reflecting the current and expected needs of society. Sustainable forest management provides ecosystem services such as environmental, economic, social, and cultural resources for the community. Meanwhile, the central concept of the 2018 Swedish NFP is "Forest, the green gold, will contribute with jobs and sustainable growth throughout the country, and to the development of a growing bioeconomy." The visions of the studied forest strategies were elaborated further in the objectives.

Of the defined keywords of the objectives in the 2018 Swedish NFP, the top five most mentioned identified words were 'forest*' AND 'sustain*' (eleven times), 'global' OR 'international' OR 'the world' (six times), 'national' OR 'regional' OR 'the country' (five times). Meanwhile, the keyword 'innovation' OR 'knowledge', 'bio*economy' OR 'fossil-fuel-free, 'growth', 'development', 'job' OR 'employment', each was mentioned four times. From the total essential keywords in the 2020 Czech Forest Policy, three keywords were mentioned more than once; they were 'function' OR 'ecosystem' OR 'multifunction' (four times), 'forest*' AND 'sustain* (three times), and 'society' (two times).

The thematic groups of the 2018 Swedish NFP's objectives (from the highest to lowest RAKE value) were: 1) forestry in a growing bioeconomy at the international level; 2) multifunctional forests for regional development and providing jobs; 3) sustainable forests for climate and environmental benefits; 4) improving knowledge and innovation in forestry, respectively. Differences in the thematic group's order in the 2018 Swedish NFP and those of the 2020 Czech Forest Policy were found. The Czech document does not include the first rank of the thematic groups. Furthermore, the second and third ranks in the Swedish forest strategy were found to be a reversal for the 2020 Czech Forest Policy under the position of the first and the second rank.

The principal dissimilarities between the studied forest strategies were in the documents' scope of work and support to the 2012 European Bioeconomy (Table 2 and A.1). Implementation of the 2020 Czech Forest Policy is limited to the forest-based sector and the related regional/provincial development, since the Bioeconomy Strategy has not been embraced nationally. Hence, the implementation is limited in the forest-based sector. To expand the implementation of the European Bioeconomy Strategy in their country, the scope of work of the Bioeconomy Strategy is expected to be broadened to multi-sectoral and inter-ministerial levels by the government. In comparison, the 2018 Swedish NFP is applied throughout Sweden, especially in the rural regions; and can also be seen by its large forest area.

Although the national forest strategies in the studied countries formulate different strategic measures to achieve their objectives, both documents mostly agree with the objectives and areas of actions of the 2012 European Bioeconomy Strategy (Table A.1). The Policy was developed by referring to the 2008 Czech NFP (MoA of the Czech Republic 2008), the earlier forest policy in the country. In this regard, the 2020 Czech Forest Policy is the first forest policy that explicitly denotes the European Bioeconomy Strategy documents. The objectives and strategic measures of the 2020 Czech Forest Policy enable but does not directly relate with the target to shift from fossil fuels to bioenergy (Table 2 and A.1). On the contrary, the strategic measures in the Swedish NFP reinforced the objectives of the 2012 European Bioeconomy, except for the first objective ('Ensuring food security'). The first objective was not strategically mentioned in the two studied national forest strategies, because the role of the European forests is generally not for food production. The European Bioeconomy Strategy is the core value in the 2018 Swedish NFP, as also can be seen in the position based on the keywords RAKE value. Furthermore, the NFP agrees with the country's mission of achieving a fossil-fuel-free Sweden.

TABLE 2 *Comparison of principal themes of in the studied forest strategies and the coherency with the 2012 European Bioeconomy*

Grouping themes of the objectives	The 2020 Czech Forest Policy	The 2018 Swedish NFP	The 2012 European Bioeconomy
Sustainable forests for climate and environmental benefit	Given the ongoing climate change, increase the biodiversity and ecological stability of forest ecosystems while maintaining the production function (p. 6)	Sustainable forestry with an increased climate benefit is to achieve the sustainable forest growth with adequate and secure access to the national biomass from the Swedish forest, within the framework of achieving the national environmental goals (p. 13)	Objective 4: Mitigating and adapting to climate change
Multifunctional forests for regional development and providing jobs	Ensure the full, balanced performance of all forest functions for future generations (p. 6). Ensure the competitiveness of forestry and downstream sectors and their importance for regional development (p. 6).	The multi-use of forests for more jobs and sustainable growth throughout the country to increase employment, strengthen the sustainable growth and rural development, by taking into account the social values of the forest (p. 18)	Objective 5 Creating jobs and maintaining European competitiveness
Sustainable forestry in a growing bioeconomy at the international level		Innovations and refined world-class forest raw materials to position the Swedish forest industry as a world leader when it comes to creating and utilising innovations and to produce refined forest raw materials for a growing bioeconomy sustainably and to satisfy the demand for sustainable, fossil-free goods and services in global markets (p. 22)	Objective 3: Reducing dependence on non-renewable resources Objective 5: Creating jobs and maintaining European competitiveness
		The sustainable use and conservation of the forest as a profile issue in Swedish international cooperation aims are: 1) The forest and its value chain shall contribute to global sustainable development and implementation of Agenda 2030. 2) The forest shall be included as a profile issue in Swedish international cooperation. 3) Export and investment promotion should be strengthened, and synergies should be utilised with development where appropriate within the forest area. 4) The national self-determination of forest issues must be safeguarded within the EU. (p. 25)	
Improving knowledge and innovation in the forestry	Strengthen the importance of advice, education, research, and innovation in forestry (p. 6).	A knowledge for sustainable use and conservation of the forest is to increase the knowledge and innovation about all the values of the forest and the entire value chain for a sustainable and growing bio-based economy (p. 28)	Objective 2: Managing natural resources sustainably

The Czech Forest Policy also does not explain the position of Czech forestry at a global level (Table 2 and A.1). However, the international and EU strategies listed as referral documents showed their strong influence in the 2020 Czech Forest Policy development. In contrast, the Swedish NFP presented less interaction with international policies, and showed strong self-determination towards its national forest territory. The Swedish NFP lies on the Swedish forestry model (Royal Swedish Academy of Agriculture and Forestry 2009, Lindahl *et al*. 2017). The country's forestry model is mainly characterised by the strength and constraints of the country's natural conditions, historical background, knowledge and experience of forest owners, and the tradition of consensus policies derived from mutual respect, understanding, and compromise (Royal Swedish Academy of Agriculture and Forestry 2009). Additionally, Sweden safeguards its national self-determination over forest issues within the EU, following the earlier national forest strategy (Lindstad and Solberg 2012). Sweden believes that forest policy should not be a standard policy applicable to all states. Despite finding a lesser influence of global and EU documents, the Swedish NFP still emphasises the relationship with the other national policies and implementation on bio-based economy and industries.

The Swedish NFP connects the forestry and bioeconomy in the form of neo-industrialisation (Ministry of Enterprise and Innovation of Sweden 2018, Fischer *et al*. 2020). The bioeconomy principles in the Swedish NFP also follow the Swedish Bioeconomy strategy in the industrial sector. The principles focus on the production and increased consumption of biomass within different social areas and on the reduced utilisation of the fossil-based raw materials, thus reducing the climate effects, and achieving a fossil-fuel-free Sweden. Furthermore, the Swedish Bioeconomy also emphasises optimisation of the value and contribution of ecosystem services to the national economy, which includes the forest ecosystem services (Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning, 2012, Antikainen *et al*. 2017).

Sustainable forestry, opportunities, and challenges of the forest industry in the studied countries

The studied forest strategies described current challenges which the countries have to face comprehensively (Table A.2). The theme groups of the respective constraints included 1) national forest contributions to climate change mitigation; 2) maintaining the forest's health for enabling its ecosystem services to function adequately; 3) increase national support and motivation on competitiveness and sustainability of the forestry and forest-based industries, bio-energy, and production of high added-value forest-based products, to reduce the risks that threaten jobs and increasing economic strength particularly in rural areas (the 2018 Swedish NFP included the statement for the global competitiveness and in a growing bioeconomy); 4) legislation for forest management bureaucracy, and coordination; 5) public awareness of sustainable forestry production and ecosystem services, and their utilisation.

Every country experienced a unique situation and managed the challenges differently. The share of net annual increment and wood production, the proportion of industrial roundwood and fuelwood production, became an essential indicator of forest production sustainability (Eurostat 2018a). Forest biomass is considered to be carbon neutral and therefore may substitute fossil fuels (FAO 1997).

An increase demand of fuelwood has been observed in the Czech Republic over the years (Table 1). On the one hand, this situation showed an increased bioenergy consumption in the country; on the other hand, this should be carefully interpreted that the wood is used as a less added-value product. In 2015, approximately 25% of utilised energy was from renewable resources. Of the total bioenergy users, 66.5% were mainly at a household level (Czech Statistical Office 2017), and preferably in the form of firewood (Purwestri *et al*. 2020). Furthermore, the current share of bioenergy users from industries and other sectors (25.2% and 8.3%, respectively) (Czech Statistical Office 2017) still allows the country to increase its consumption. The recent trend of fuelwood type consumption also shows that the share of firewood has stagnated in recent years, in contrast to the slightly increased consumption of wood chips (post-harvest waste treatment) in the Czech Republic. Thus, the production of high added-value forest biomass products in the Czech Republic is still expected for both heat production and to generate electricity. In this respect, the collaboration gap between forestry science, research, and industry innovation is expected to be reduced or diminished to hasten the adoption of technology into the production of high added-value products (Pacourek *et al*. 2003, Purwestri *et al*. 2020). In Sweden, the proportions of the fuelwood production have been relatively stable after 2000 (around 8%-9%), except in 2005 (6%). By number, the amount of fuelwood production in 2000 and 2015 was similar (5.900 thousand m^3). In the Czech Republic, the share of fuelwood over the industrial roundwood production increased from 10% (1992) to 12% (2010) and continued to rise to 17% in 2018 (Eurostat 2020).

Focusing on the Swedish forest industry's growth and position at the global level is included in one of the objectives and key strategic measures in the Swedish NFP. The country also actively supports its forest-based production by creating the product's demand on the market. Wood consumption, aimed at high added-value products, besides paper and printing, has been suggested for Swedish forestry, because of the decreasing demand for paper over electronic material (Jonsson *et al*. 2011). Sweden is also aware of the value of their natural and innovative products, and the importance of keeping the wood flowing and planning future processes to meet market demands and create more jobs (Royal Swedish Academy of Agriculture and Forestry 2015). For instance, the country further processed the wood into bioenergy. Research in biomass usage in Sweden reported that 46% of total bioenergy used in the district heat sector in 2013 was generated predominantly from forest biomass. The types of wood fuels are mainly wood chips and sawdust (70%), followed by wood pellets and briquettes (16%), and various wood waste (3%). Also, the use of bioenergy included bio-oil (5%), tall oil – a by-product of pulp production (2%), and unspecified biomass fuels (4%) (Ericsson and Werner 2016). In 2016, Sweden was the second-highest wood pellet producer after Germany (European Pellet Council 2017). In this case, the main drivers of the pellet production in Sweden are to fulfil the national demand and provide it from the domestic production (Björheden 2006, Trømborg *et al*. 2013, European Pellet Council 2017).

The promotion and growth of forest bioenergy utilisation in Sweden were in agreement with the efforts to achieve the 2017 EU climate and energy targets (to increase the national bioenergy share by up to 49% of total energy sources) (European Environment Agency 2017a) and was also part of the vision for a fossil-fuel-free Sweden (Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS) 2012, Ministry of Enterprise and

Innovation of Sweden 2018). In 2018, Sweden not only surpassed the goal, but also the country had, by far, the highest share (54.6%), being followed by Finland (41.2%) and Latvia (40.3%) (Eurostat 2018b). In this case, the bioeconomy principles are reinforced by the EU climate and energy targets policy, which, in return, influence the development and implementation of the studied national forest strategies. In the Czech Republic, the country has committed to increasing the national bioenergy share by up to 13% of total energy sources by 2020, and the share of bioenergy in the Czech Republic exceeded the target (15.1%) in 2018 (Eurostat 2018b).

Another example was the sawn woods in Sweden were further processed into construction materials, which are considered a new market for wood export products (Antikainen *et al*. 2017, Ministry of Enterprise and Innovation of Sweden 2018). Sweden promotes more wood construction materials and substitution of wood for other non-wood materials due to the reduction of CO_2 emissions, shorter construction time, and, therefore, less disturbance to the society (Hurmekoski 2017, Swedish Wood 2020). In contrast, the composition of the forests and the subsequent wood flow in the Czech Republic are governed more from the outside (demand, needs of neighbouring states, and the path of least resistance) than from the inside (resources and needs of the country) (Dřevařský ústav (Timber Institute) 2015).

The Swedish forestry has applied a more liberal approach in the forest-based sector for almost three decades and at the same time more attention to conservation in forestry; thus, the forest-based sector is also strongly influenced by the environmental policy. In this regard, the Swedish forestry model gives the owners an immeasurable opportunity to make silvicultural decisions while concurrently paying more attention to societal needs and environmental considerations (Royal Swedish Academy of Agriculture and Forestry 2009, Wallin 2017). For the sake of forest management guiding principles, the model introduced slogans such as “freedom under responsibility” and “sectorial responsibility”. Also, as a consequence of the privatisation of Swedish forests, the levy and related subsidies on forestry have been abolished (Royal Swedish Academy of Agriculture and Forestry 2009). In principle, the Swedish Forestry Model applies ‘soft’ policy instruments, collaborative approaches, and voluntary measures (Wallin 2017). Wallin (Wallin 2017) and Brukas *et al*. (Brukas *et al*. 2013) explained further that the ‘soft’ policy instruments provided information and communication to the sector, forest owners, and managers. The guided policy expresses the silvicultural or environmental targets in terms of a minimum standard of forest management practices. It rarely defines the quantitative thresholds, except for the forest regeneration (every three years after the final felling), the lowest acceptable age for the final felling, and prescribing a clear-cut size limit in specific forest areas. Since the legislation sets a minimum value, the implementation of forest owner strategies often relies upon voluntary participation, initiative and dialogue (Royal Swedish Academy of Agriculture and Forestry 2009). In addition, the freedom to pursue the profit of Swedish forests for individual forest owners and the national economy could result in prioritising the economic aspect over the aspects of environment and society (Brukas *et al*. 2013), which was considered as the drawback of this model.

In the Czech Republic, the political transformation and transition from one central government to a more market-oriented approach have also influenced its forest-based sector. Czech forests are characterised by a predominant proportion (more than 50%), of state-owned forests; most of which were state-forest enterprises; with bureaucratic forest management procedures (Pacourek *et al*. 2003). About 19% of private forest owners and other legal entities, such as legal persons (3.27%), churches (5%), cooperatives and companies (1.19%) occupy about 700,000 ha; nearly 90% of them possess less than two ha, which makes it difficult to properly manage the forest (Pacourek *et al*. 2003, MoA of the Czech Republic 2020). Regulations currently applied by the Czech forest management are expected to be reduced to some extent to accommodate the immediate needs of private forests and forest enterprises, while maintaining public access rights. At the moment, the Czech Forest Law still forbids the privatisation of Czech state forests. Thus, the possibility of collaboration among state and private entities in the country could be explored in the form of a pilot study.

Nevertheless, the surplus of total roundwood production in the Czech Republic indicates a potential for the creation of high added-value products (Jankovský *et al.* 2021), such as the possibility of creating a new product to have a higher market value (e.g., furniture, etc.), instead of only raw wood materials, or to produce the wood waste for further utilization, like bioenergy source. Results of current and available public surveys on wood product utilisation and preferences can be used as baseline information for selecting potential products to be promoted and manufactured. The State Environmental Fund, and the European Structural and Investment Funds have financed different projects for the creation of capacities, identification of possible local, regional and transnational alliances, promotion of the use of renewable raw materials and research of specific initiatives on the use of biomass, all to identify and publicise the opportunities that the bioeconomy may represent for the country and the society (European Commission 2017, BIOEASTsUp 2019, Danube Transnational Programme 2021, Hájek *et al.* 2021, Mainar-Causapé *et al.* 2021). In this respect, the Czech Republic realises the critical role of policy harmonisation in forestry, similar to Sweden. The Czech Republic is also considering a reduction in land taxation to promote the potential of other forest ecosystem services (The Government of the Czech Republic 2020); the aim is to promote the other ecosystem services in bringing the economic value, without neglecting the public rights in accessing the forests. In Sweden, forestry is categorised as a commercial sector; therefore, no existing direct subsidies for wood production, besides some state subsidies for forestry measures to enhance environmental protection, are available now. It means the net income taxation in forestry uses the same system as other economic branches with a progressive tax scale (Royal Swedish Academy of Agriculture and Forestry 2015). In addition, public funding or stimulus packages, i.e., grants and risk capital, are provided for entrepreneurs to enter the new forest-based market in Sweden (Björheden 2006, Ministry of Enterprise and Innovation of Sweden 2018). The wide spread benefit and wood utilisation have allowed greater technological advancement and public acceptance through considerable project optimisation and initiatives that are partially financed with funds and environmental subsidies to support the growing forest bioeconomy in Sweden (Hodge *et al.* 2017, Toppinen *et al.* 2018).

The differences in both countries' initial situation may result in different proposed measures (e.g., selecting high added-value products) and policies (e.g., tax and subsidies). The Czech policymakers need to consider a pilot project for implementing the model of forest-based privatisation, e.g., by sharing responsibility and management between the state and private forests. A market study on potential customers for Czech-made high added-value products, for instance, in the furniture sector, both domestically and internationally, is proposed to encourage the respective forest manufacturers.

CONCLUSIONS

Bioeconomy principles are the core values of the Swedish National Forest Programme (NFP). Thus, the NFP aims are not only to supply sustainable forest products and ecosystem services to support forest enterprises but also to attain a fossil-fuel-free Sweden. Meanwhile, the Czech Forest Policy denotes the Bioeconomy Strategy as one of the reference documents. Still, it does not directly relate to shifting from fossil fuels to bioenergy. Different foci on the strategic measures were found in the 2020 Czech Forest Policy compared to Sweden, such as supporting the development of forest enterprises. The adoption of the 2012 European Bioeconomy to uplift the bio-based manufacturers in the Czech Republic is carefully being examined through the lens of Sweden's experiences. Since the 2012 European Bioeconomy principles have not been adopted at a national level, their application is limited in the forest-based sector. The Bioeconomy Strategy is expected to be extended into multi-sectoral and inter-ministerial levels to expand the implementation of the Strategy in the Czech Republic. By doing so, policy coordination and harmonisation in supporting forest manufacturing can be expected at a national level, including the promotion of other forest ecosystem services.

The Swedish NFP applies the country's forestry model that gives the owners a vast opportunity to make silvicultural decisions while simultaneously paying more attention to society's environmental considerations, including the participation in forest certification. The Swedish Forestry Model principally applies 'soft' policy instruments (by setting a minimum acceptable value), collaborative approaches, and voluntary measures. The country's experience that the freedom to pursue a profit could also encourage the forest owners to prioritise economy over the environment and society, which should be dealt with wisely by the policymakers. Nevertheless, the European Bioeconomy Strategy is supported by other policy measures in the environmental dimension and climate change mitigation has encouraged the country to implement these principles. On the other hand, the Czech forests are characterised by the predominant share of state-owned forests with strict forest management procedures and regulations. The present rules employed in the Czech forest management administration, especially in the state forests, are expected to be reduced to some extent to accommodate the immediate needs of private forests and forest enterprises. Some private owners and other legal entities (e.g., legal persons, churches, cooperatives, and associations) have less than two ha of forest property, making it challenging to manage their forests properly. Collaboration between state and private institutions is recommended, and a pilot project is encouraged to be undertaken to create a forestry model that fits the Czech Republic. The efforts imply that the promotion of the forest ecosystem services other than wood products is awaited to bring economic value to the owners/managers without neglecting the public right to access the forests.

Sustainable forest-based production supports forest-based enterprises in Sweden (as indicated by the proportion of industrial roundwood compared to the fuelwood production, the relationship of the net annual increment and roundwood production), besides the demand from inside and outside the country. In this respect, the main challenges for Czech forest-based sector are to fulfil the need for sustainable forest biomass and high added-value products. Furthermore, the Czech forestry also faces problems caused by climate change; hence, any strategy supporting the mitigation measures should be encouraged, e.g., policy harmonisation, greater species diversity, innovation in afforestation technique, etc.

AUTHOR CONTRIBUTIONS

Ratna C. Purwestri: Conceptualisation, methodology, validation, formal analysis, writing—original draft, writing—review and editing, visualisation. **Miroslav Hájek:** Conceptualisation, methodology, validation, formal analysis, writing—original draft, writing—review and editing, visualisation, supervision, project administration, funding acquisition. **Miroslava Hochmalová:** Writing—original draft, writing—review and editing. **Petra Palátová:** Writing—review and editing. **Diana Carolina Huertas-Bernal**: Visualisation, writing—review and editing**. Sandra Paola García-Jácome:** Writing—review and editing. **Vilém Jarský:** Writing—review and editing. **Jan Kašpar:** Writing—review and editing **Marcel Riedl:** Writing—review and editing. **Róbert Marušák:** Writing—review and editing. All authors have read and approved the published version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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Appendix A.1 *Connection between the strategic actions of the 2012 European Bioeconomy Strategy and the strategic measures in the Czech Republic (CZ) and Sweden (SE)*

The 2012 European Bioeconomy	**The Czech forest policy**	**The Swedish NFP**	**Note[1]:**
Objective 5: Creating jobs and maintaining European competitiveness	Objective C. Competitiveness of the forestry and downstream sectors, and their importance for regional development - Measure 1: Reduce the number of **legislative restrictions** on forest management (p. 11) - Measure 2: Implement a **fundamental reform** of the state administration of forests (p. 11) - Measure 3: Support the process of forest consolidation to improve the **structure of forest assets** (p. 11) - Measure 4: Maintain the general use of forests by the public and **financial payment of the ecosystem services** provided to the public by forest owners (p. 11) - Measure 5: **Promote the use of wood** as a renewable raw material (p. 11) - Measure 6: **Unify the system of support** for forestry at the level of the Czech Republic (p. 11) - Measure 7: Strengthen **the importance of forestry in the regions** (p. 12) - Measure 8: Promote the development of the **wood processing industry** and other downstream sectors (p. 12)	Focus 2. Multi-use of the forest for more jobs and sustainable growth throughout the country (p. 18) - Measure 1: Make visible and develop all the values of the forest (p. 19) - Measured 2: Regional opportunities and resources for raising all the values of the forest (p. 21)	CZ+: scope of work is within the country (for rural development) SE ++
Objective 3: Reducing dependence on non-renewable resources	Objective C. Competitiveness of the forestry and downstream sectors and their importance for regional development - Measure 1: Reduce the number of **legislative restrictions** on forest management (p. 11) - Measure 2: Implement a **fundamental reform** of the state administration of forests (p. 11) - Measure 3: Support the process of forest consolidation to improve the **structure of forest assets** (p. 11) - Measure 4: Maintain the general use of forests by the public, and **financial payment of the ecosystem services** provided to the public by forest owners (p. 11) - Measure 5: **Promote the use of wood** as a renewable raw material (p. 11) - Measure 6: **Unify the system of support** for forestry at the level of the Czech Republic (p. 11) - Measure 7: Strengthen **the importance of forestry in the regions** (p. 12) - Measure 8: Promote the development of the **wood processing industry** and other downstream sectors (p. 12)	Focus 3. Innovations and refined world-class forest raw materials (p. 22) - Measure 1: Communicate the **importance of forest raw materials** and the **forest industry** in a growing bioeconomy (p. 23) - Measure 2: Create **good framework conditions for refining world-class forest raw materials** (p. 23) - Measure 3: Stimulate **increased industrial wood construction** (p. 24)	CZ+: focuses less on broader bioeconomy SE++
Objective 4: Mitigating and adapting to climate change	Objective A. Full balanced performance of all forest functions for future generations (p. 6) - Measure 1: Develop sustainable forest management as part of the protection of values, care, and use of the landscape (p. 7) - Measure 2: Motivate and financially support forest owners to manage their forests on a sustainable basis and to deliver services to the public (p. 7) - Measure 3: Promote positive water and carbon balance of the landscape (p. 7)	Focus 1. Sustainable forestry with increased climate benefit (p. 13) - Measure 1: A growing and sustainable forest production with increased climate benefits and a sustainable society (p. 14) - Measure 2: Variety-rich forest landscape for forest ecosystem services (p. 16)	CZ and SE ++

The 2012 European Bioeconomy	The Czech forest policy	The Swedish NFP	Note[1]:
	Objective B. Given the ongoing climate change, an increase in the biodiversity and ecological stability of forest ecosystems while maintaining production function (p. 6) - Measure 1: Promote the increase in species, age, and spatial forest structure to ensure long-term forest stability, including increasing the proportion of suitable trees in forest stands (p. 6) - Measure 2: Promote forest management to preserve and increase the biodiversity of forests (p. 6) - Measure 3: Promote the abandonment of a reasonable proportion of rotting wood, harvesting residues and habitat trees in the forest (p. 6)	Focus 1. Sustainable forestry with increased climate benefit (p. 13) - Measure 1: A growing and sustainable forest production with increased climate benefit and a sustainable society (p. 14) - Measure 2: Variety-rich forest landscape for forest ecosystem services (p. 16)	
Objective 2: Managing natural resources sustainably	Objective D. Strengthening the importance of advice, education, research, and innovation in forestry (p. 6) - Measure 1: Strengthen the importance and role of science, research, and innovation in forestry (p. 14) - Measure 2: Improve the content and quality of all levels of forestry education, including lifelong learning (p. 14) - Measure 3: Develop counseling and awareness (p. 14) - Measure 4: In line with the concept of updating/ defining research, development, and innovation priorities in the forestry sector (p. 14) - Measure 5: Significantly improve the position of Czech forestry research at the international level (p. 15)	Focus 3. Innovations and refined world-class forest raw materials (p. 22) - Measure 1: Communicate the importance of forest raw materials and the forest industry in a growing bioeconomy (p. 23) - Measure 2: Create good framework conditions for refining world-class forest raw materials (p. 23) - Measure 3: Stimulate increased industrial wood construction (p. 24) Focus 5: A knowledge or sustainable use and conservation of the forest (p. 28) - Measure 1: Research and innovation (p. 28) - Measure 2: Attractive education (p. 29) - Measure 3: Information, dissemination of knowledge, and data collection (p. 29)	CZ and SE ++
Objective 5: Creating jobs and maintaining European competitiveness	*Significant relevance with the international strategy documents (see also Appendix A)*	Focus 4: Sustainable use and conservation of the forest as a profile issue with Swedish international cooperation (p. 25) - Measure 1: Prioritise the forest with Swedish international cooperation (p. 25) - Measure 2: Develop export and investment promotion and increase synergies with development cooperation (p. 26) - Measure 3: Protect national self-determination over forest issues (p. 27)	CZ+: acknowledges the connection with the other relevant international and national policy documents SE ++

[1] Explanations and score of relationship; ++ Reinforcing; + Enabling.

Appendix A.2 *Challenges faced by forestry in the Czech Republic and Sweden based on the studied national forest strategies*

Theme groups of challenges	The Czech forest policy	The Swedish NFP
The contribution of forests in climate change mitigation	- Reduced resilience and deteriorating health of forest ecosystems with the catastrophic occurrence of harmful biotic (insects, fungi, etc.) and abiotic (drought, storms, etc.) factors - Drying of the landscape as a whole - in addition to climate change, also due to insensitive management of the landscape, the interaction of the forest with the surrounding environment and the impacts of the surrounding landscape on the forest - Extent and forms of ensuring the production of timber in the future concerning climate change - Significant ownership fragmentation of forest assets, which reduces the economic efficiency of forest management and reduces the ability to respond to the risks associated with climate change	- Meeting the climate goals and achieving a fossil-free Sweden with net negative emissions. - Challenges in digitalisation, life science, and environmental and climate technology
Maintaining the forest's health for enabling its ecosystem services to function adequately	- Restoration of the forests from catastrophic occurrences - Absence of standard forestry procedures for dealing with crises - Insufficient species and structurally rich forest ecosystems, insufficiently adapted composition of forest stands risks associated with changes in natural conditions in the context of the dynamics of environmental change - Increased numbers of ungulates, especially those with a significant negative impact on the restoration of forest stands - Poor condition of forest soils - Endangerment of the forest tree gene pool and disruption of ecosystem links - Setting the age parameters of forest stands concerning climate change	- Increased production of forest raw materials is important in a transition to a bio-based society, but protection and environmental considerations must increase to achieve the environmental goals - Insect and other pest-induced damage - Climate change and growing global trade increase the risk of problems with plant pests, and the need to clarify the division of responsibilities concerning pests - Grazing damage
Increased national support and motivation on competitiveness and sustainability of the forestry and forest-based industries, bio-energy, production of high value-added forest-based products, and to reduce the risks that threaten jobs and increased economic strength, particularly in rural areas (the 2018 Swedish NFP included the statement for the global competitiveness and in a growing bioeconomy)	- Low degree of positive motivation of forest owners to maintain and develop services of societal demand - Insufficient preferential state support aimed at increased consumption of wood as a renewable raw material for society	- Sweden has high ambitions in its efforts to meet the global goals of sustainable development and wants to show that it is possible to implement them while maintaining global competitiveness - Targeting fossil-free Sweden by replacing fossil-based fuels - Increase research efforts in the area of sustainable use and conservation of the forest and its entire value chain - Effective collaboration between universities, colleges, and other research actors, the business sector, and the rest of society, strengthening Sweden's competitiveness - Ongoing work to increase industrial wood construction in Nordic countries - Increased export and internationalisation of forest products and ecosystem services because of the limited domestic market

Theme groups of challenges	**The Czech forest policy**	**The Swedish NFP**
	- Export of timber without added value abroad, instead of domestic processing of raw materials - Insufficient share of private capital to finance applied research	- Collaboration between the forest industry (knowledge and innovation) and decision-makers, or between public and private actors, and cross-industry collaborations
	- Low competitiveness of forestry compared to other industries and agriculture - Low-income diversification of forestry enterprises - Insufficient financial reserves of the sector linked to natural conditions to overcome emergencies - Lack of professional forestry workers, little interest in working in the field	- Lack of a trained workforce despite increasing demand for qualified personnel due to low interest from young people in education within the green industries, including forestry - Open recruitment of forest education across genders and society structures
Legislation for forest management bureaucracy and coordination	- Complex legislative conditions for forest management, characterised by a high degree of regulation and insufficient use of motivational tools - No comparable legal terms have been created for the application of the selective economic method, especially from forest management - Problematic (time and administratively demanding) procurement of works in forestry through public procurement - A complex and not very clear system of support for forest management - Low degree of coordination of individual policies in the field of forestry, wood processing industry, and environmental protection - Insufficient interdisciplinary cooperation at the level of "landscape management" - Significant ownership fragmentation of forest assets, which reduces economic efficiency of forest management and reduces the ability to respond to the risks associated with climate change - Complicated and confusing system for the owners, and performance of state administration concerning forestry economy - Conflict of interests of state forest administration (performed in the delegated competence) and self-government	- Develop a national forest policy that is predictable and can be managed by the individual forest owner so that the various benefits of the forest can be developed and profited in the best possible way. - Reduce the risks of loss of incentives due to changes in policy instruments that are introduced quickly for the long-term sustainable use of the forest - Develop measures that affect the distribution of responsibility between society and forest owners, requiring careful impact assessments and broad consultation - Involvement of the state, civil society, the forest industry, and actors in the forestry's entire value chain to develop policy instruments and incentives that support increased refinement and conversion to bioeconomy - Coordination between forestry and other ministries concerning climate action, biodiversity, export strategy, industrialisation, and rural policy - A coherent and integrated promotion is needed, which increases the synergies between aid strategies, export, and investment promotion
Public awareness of sustainable forestry production and ecosystem services and their utilisation	- Insufficient public awareness of the complexity and importance of forests for society - Insufficient support for forest pedagogy as an important communication tool - Insufficient preferential state support aimed at increased consumption of wood as a renewable raw material for society	- To increase the knowledge of the values of the forest, as well as public access and ownership in society for the forest to be used in a versatile, active, and sustainable way, - To design a relevant data collection that facilitates the efforts of forestry actors to increase competitiveness, sustainable use and conservation of forests, and a growing bio-based economy

Paper III

Forest value chain resilience from a local perspective in five European countries: analysis of predictors and co-drivers.

García-Jácome, S. P., Jankovský, M., Hoeben, A. D., Lindner, M., Uzquiano, S., Stern, T., Nuhlíček, O., Vuletić, D., Marjanović, H., Picos, J., Peltoniemi, M., Baumbach, L., & Lloret, F. (2025). Forest value chain resilience from a local perspective in five European countries: analysis of predictors and co-drivers. Frontiers in Forests and Global Change, *7*, 1461932. https://doi.org/10.3389/ffgc.2024.1461932

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Forest value chain resilience from a local perspective in five European countries: analysis of predictors and co-drivers

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Climate change-associated disturbances such as storms, wildfires, and pest outbreaks increasingly destabilize forest systems, threatening their ecological, economic, and social functions. These disruptions impact the forest value chain (FVC) by causing fluctuations in timber supply, from a quantity and quality perspective. This study employed the operational resilience framework (ORF) to assess FVC resilience in five European case studies (CZ, HR, DE, FIN, and ESP), focusing on timber supply as a key system variable. A resilience assessment was conducted using resilience thresholds, considering sustainability from both ecological and economic perspectives. Principal component analysis (PCA) identified three predictor groups that influenced FVC resilience: wood production (WP), harvesting systems (HS), and management and silviculture (MS). Findings revealed that regions with proactive management and sufficient processing capacities (CZ, HR, and ESP) maintained relative stability despite natural disturbances, while others (DE and FIN) experienced prolonged instability due to market-driven logging practices and limited adaptive measures. The study highlighted the frequent breaching of resilience thresholds, particularly during high-volume salvage logging following disturbances such as bark beetle outbreaks, windstorms, and wildfires. The results emphasized the importance of integrating adaptive and proactive strategies to mitigate these impacts. The ORF demonstrated potential for operationalizing FVC resilience and provided guidance for improving preparedness against future disturbances.

KEYWORDS

disturbances, timber supply, social-ecological systems, forest management, thresholds, wood production

1 Introduction

Climate change increasingly threatens the stability of forest social-ecological systems, as the frequency and severity of natural disturbances such as storms, wildfires, and pest outbreaks intensify across broader regions (Seidl and Senf, 2024). The changes alter forest dynamics, decreasing forest health, and weakening ecosystem resilience, with cascading effects on the forest value chain (FVC; Patacca et al., 2023; Nikinmaa et al., 2024). Issues such as inconsistent timber supply, fluctuating wood quality, and market instability challenge stakeholders in maintaining steady operations. While substantial research exists on resilience frameworks at national and international levels (Seidl et al., 2017; Messier et al., 2019; Asada et al., 2023), local-scale operations need context-specific strategies to optimally adapt to disruptions and ensure long-term sustainability of their FVCs, which is an under-researched outlook on value chain resilience.

According to Porter (1985) a value chain "is a series of activities that create value at each step, with the total value being the sum of all contributions throughout the company." In the context of forest social-ecological systems (forest systems), the FVC refers to a sequence of activities that use forest-based resources as inputs for processing and production of goods and services that are delivered to final consumers and ultimately disposed. Primary activities include harvesting, logistics, and packaging while supporting activities include marketing, planning, and managing (Kaplinsky and Morris, 2000; D'Amours et al., 2017). The FVC is vital for sustainable resource management, economic growth, and ecosystem service provisioning. Besides the usefulness of the value chain approach in optimizing the systems for their performance or efficiency of resource use, FVCs can be used to provide useful insights into the resilience of the forest-based industries and their constituent parts. Resilience of European FVCs needs to be considered for a diverse set of stressors, e.g., the disturbances in Central Europe, such as prolonged droughts, are causing widespread tree mortality, partly due to bark beetle outbreaks (Schuldt et al., 2020). These outbreaks have led to extensive salvage logging of spruce forests in the Czechia and Germany, saturating wood markets and collapsing sawlog prices (Hlásny et al., 2021; Sommerfeld et al., 2021). Coniferous species, which dominate the region, are more vulnerable to climate-induced disturbances than broadleaf and mixed forests (Seidl et al., 2017; Steckel et al., 2020). Moreover, in the Mediterranean region, wildfires are becoming larger and more severe, causing direct damage to the existing forest stock (De Rigo et al., 2017; López-Rodríguez et al., 2021). These challenges underscore the importance of improving resilience, not only in forest ecosystems but also across the FVC, to sustain operations and minimize cascading impacts.

Ensuring adaptability in forest systems depends on proactive measures that synergistically enhance their resilience, enabling them to withstand and recover from disturbances (Pingoud and Wagner, 2006). The widespread use of resilience has led to various definitions and approaches in the context of the forest system, and three key levels can be distinguished: engineering, ecological, and social-ecological resilience (SER) (Nikinmaa et al., 2020, Lindner et al., 2020). Engineering resilience refers to a system's ability to return to its equilibrium state after a disturbance (Holling, 1996; Pimm, 1984). Ecological resilience, on the other hand, is defined as a system's ability to withstand disturbances from its equilibrium state (Holling, 1996; Scheffer et al., 2015). Finally, SER represents the capacity of the system to continue providing ecosystem services while undergoing disturbances (Biggs et al., 2015).

Based on the concept of SER, Lloret et al. (2024) proposed a novel approach for operationalizing the resilience of forest systems, termed the operational resilience framework (ORF). This approach incorporates various system boundaries, disturbances or stressors, resilience descriptors (so-called system variables) and resilience indicators in the form of predictors or co-drivers to quantitatively assess the resilience levels of forest systems at different scales. Specifically, in this context, operationalization involves analyzing the performance of system variables (i.e., characteristics of ecosystem services or the FVC) and describing the state of a system in response to disturbances, relative to some reference state (Lloret et al., 2024). The performance of the system variable considered, along with the relevant disturbances, is observed over a specific period relative to a reference state (i.e., which may correspond to the hypothetical absence of stressors or to a desired state of the system variable) and pertinent environmental, climatic or management changes, thus enabling the comparison of resilience across various contexts such as regions, management practices, and policies (Cantarello et al., 2024). Following this, the relationships between system variables, resilience predictors (i.e., variables that can be manipulated), and co-drivers (i.e., variables that cannot be manipulated meaningfully, but provide valuable information about the context) are observed, thus enabling an operational assessment of the system's resilience (Lloret et al., 2024).

The system variable that reflects resilience in both forest as ecosystem and their related FVCs is timber supply—the volume of harvested timber available for supply to the market (Prestemon and Wear, 1999). Timber supply depends on market and nonmarket factors, including the merchantable stock of standing timber and stakeholder-specific circumstances (Tian et al., 2017; Hurmekoski et al., 2018). In literature, various resilience predictors and co-drivers can be found that impact FVCs, some of which apply to international or national levels, while others are region-specific (e.g., harvesting technologies, processing capacities, tree species composition, etc.). Moreover, strengthening local forestry networks can enhance resilience by reducing costs, improving resource access, and adapting to market trends (Macqueen, 2010), so variables connected to network structure, performance or efficiency can work as effective resilience predictors or co-drivers.

Value chain actors need concrete, operational decision-making support to enhance FVC resilience. However, there is a lack of integrated operational assessment strategies tailored to regional-level actors. This study aims to fill this gap with two main objectives, (1) integrate an operational resilience assessment to natural disturbances based on quantitative analysis which could help regional-level actors in mitigating and adapting their operations to the changing disturbance regimes, and (2) provide a (non-exhaustive) list of resilience predictors and co-drivers based on their relationship with the supply of timber to the market, considered as system variable.

2 Materials and methods

The research focused on the assessment of FVC resilience based on historical, regional data. Because we researched resilience from a regional perspective, the study was conducted using a case study approach (which encompasses the entire region, including other actors within it), covering five introducing European countries: Kostelec, Czechia (CZ), Upper Rhine Valley, Germany (DE), Istria, Croatia (HR), Kainuu, Finland (FIN), and Galicia, Spain (ESP; Figure 1). These case studies were selected to cover major bio-geographic regions and exemplars (the specific company which we are studying in each region) were chosen to represent diverse forest management systems and FVC setups across Europe. For instance, CZ, DE, and HR had mid-scale wood processing industries, in which the use of timber and forest products was mostly confined to the regional level due to the limited export capabilities of the forest-based industries. In contrast, FIN and ESP had more diverse processing industries with broad access to international markets, though in the case of FIN, the industry was driven by large companies while in ESP, the industry consisted of a large number of small-scale community driven companies. Given these regional differences, the species composition varied across the studied regions. In CZ, the forests were predominantly composed of Norway spruce, with overall low species diversity. In HR, the forests exhibited high diversity, with broadleaved species dominating, followed by beech, oaks, and conifers. Then in DE, forests managed by the case study featured primarily beech, along with fir and Norway spruce; however, conifer dominance has declined due to repeated disturbances. In FIN, forests were predominantly coniferous, mainly pines, with a preference for harvesting softwood species. Finally, in ESP, broadleaved species dominated, particularly eucalyptus, followed by pine and other softwoods. Also, the main disturbances during the study period varied across countries, with bark beetle outbreaks playing a prominent role in CZ, windstorms in DE and FIN, ice storms and windstorms in HR, and wildfires in ESP.

Within each country, a forest enterprise was selected as an exemplar (Figure 2). To ensure comparability between the case studies, exemplars were selected based on the spatial range of forests they managed—between 500 and 5,000 ha. The spatial range allowed the integration of smaller case studies characterized by lower processing capacities while incorporating larger enterprises with greater economic capacities, all representing key aspects of the forest-based industries. If an exemplar that fit the spatial range could not be found within a case study, a suitable and cooperative exemplar enterprise was selected and the spatial range of its operation was scaled up or down by multiplying the original size of forests managed by an exemplar by the ratio of the lower or upper bound of the spatial range to the original size of the area of the forests managed by said exemplar. The case studies which did not need readjustments were CZ and DE while HR, FIN, and ESP needed a downscaling in their data.

Two formats for primary data collection were used: a standardized dataset template and a survey. To streamline the data collection process, we began by establishing a common dataset structure. Working closely with case study representatives, we developed a standardized dataset template, containing a unified list of variables to be gathered, thus ensuring consistency and reliability of collected data (Supplementary Annex I). Additionally, each topic was further elaborated into specific questions, case study reports, related to resilience predictors and co-drivers to accompany the gathered data and provide context. These case study reports were specifically tailored to the unique conditions and characteristics of each case study, ensuring filling information gaps and ensured that the collected data remained relevant and informative. Primary data collection included gathering operational data from the exemplar and operational and industrial data from stakeholders through case study reports. If primary data was not sufficient to satisfy data needs, secondary data was obtained through reviews of literature, databases, and gray literature.

Annual data were collected for the period from 2001 to 2021, the following topics we covered: regulatory frameworks, forest management practices, business models, resource availabilities, technologies, harvesting and storage capacities, network properties, particularly wood processing capabilities (such as sawmilling, wood-based panels, pulp and paper, downstream industries, and bioenergy production) of the exemplars or their networks. Additionally, we gathered data on disturbances, expressed as annual volumes of salvage logging (m^3 $year^{-1}$) and disturbance agents, such as wildfires, windstorms, and insect outbreaks, which impacted the volume and quality of salvaged timber.

We chose the annual supply of timber to the market (henceforth timber supply) as the system variable. The system variable was formulated as the sum of the annual provisioning of timber (i.e., voluntary and salvage logging) by the forest enterprise to other value chain actors involved in the timber processing, i.e., lumber and other sawmill producers, pulp and paper producers, and heat and power producers (Supplementary Annex II, correspondence of the components of the assessment of the FVC with the ORF).

2.1 Resilience assessment

In our study, we defined a forest enterprise as sustainable and resilient when it was able to maintain operations without depleting the forest it managed—establishing an upper resilience threshold (UTH)—while also generating stable revenues that exceed costs, thereby setting a lower resilience threshold (LTH). Resilience in this context aligned with sustainability but emphasized the impact of disturbances, such as bark beetle outbreaks in Central Europe (quantified in our case through salvage logging, Figure 3), as potential disruptors of system functioning. To support regional value chain actors, we developed a resilience assessment.

Resilience was assessed by comparing the observed development of the system variable, timber supply, over time against a reference state framed by upper (Eq. 1), and lower (Eq. 2) thresholds. That meant that the enterprise–based system was considered to be fully resilient if its related timber supply remained within these thresholds defined by sustainable timber extraction from the forest (UTH) and sustainable enterprise operation (LTH).

$$UTH = \frac{\sum_{1}^{n} Prescribed\ Logging\ Volume}{Number\ of\ years} \tag{1}$$

Where, UTH is the upper resilience threshold, defined as the mean annual logging prescriptions according to forest management plan

FIGURE 1
Five European case studies: Kostelec, Czechia (CZ), Upper Rhine Valley, Germany (DE), Istria, Croatia (HR), Kainuu, Finland (FIN), and Galicia, Spain (ESP). Illustration by Gabriela Rueda, EFI (adapted by Rueda, 2022).

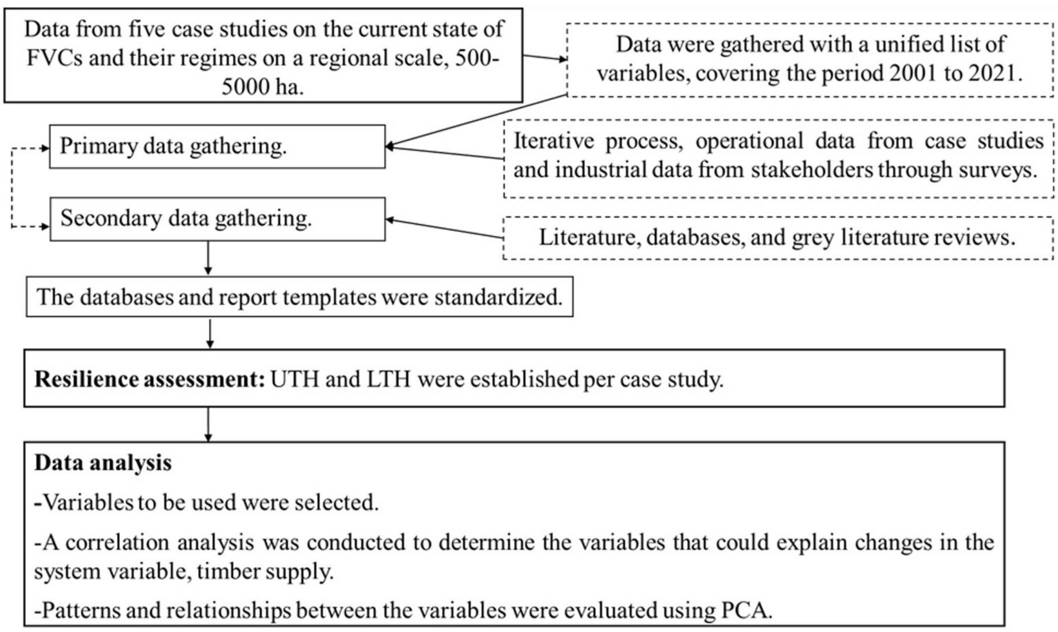

FIGURE 2
Workflow of the data gathering and analysis as outlined in the methodology of this study.

TABLE 1 Profitability and LTH per case study.

Country	Profitability of forest enterprises (X%)	LTH per case study	Reference
CZ	14.05%	86%	MZe, 2021
HR	4.11%	96%	Motik et al., 2005; Posavec et al., 2021
DE	10%	90%	Kovalčík, 2011; Eurostat, 2023
FIN	77.46%	23%	Saramäki, 2012; Luke, 2021
ESP	10%	90%	Instituto Galego de Estatística, 2021; Eurostat, 2023; Picos, 2023

from year 1 (2001) to year n (2021) of the observed period; and n is the number of years within the observed period.

$$LTH = Minimum\ of\ TS\ for\ the\ observed\ period \times (x\%) \quad (2)$$

Where, LTH is the lower resilience threshold, defined as the minimal annual timber supply by the exemplar, expressed as the profitability of forest enterprises (x%) in particular case study country based on literature, since empirical data on the profitability of the exemplars were not available.

The LTH was defined in terms of the exemplar's capacity to generate profit (Table 1). So, the LTH then considers the exemplar's financial performance in relation to its lowest level of timber supply.

The calculation of the system variable referred to the annual values of the timber supply during the observed period. We devised a resilience metric, given by the vertical distance between timber supply and the UTH or LTH in a given year. The measure of the resilience of the exemplar was then assessed based on both the vertical distance between timber supply and UTH/LTH as well as the time lapse between the year when the system variable breached the reference state (i.e., UTH or LTH) and the year when it returned to the reference state. If a exemplar was able to promptly return the system variable to its reference state, it likely demonstrated greater resilience compared to a situation when the exemplar continuously operated so that its system variable was outside of its reference state, as exemplified in Figure 3.

2.2 Data analysis

An exploratory overview of all variables collected (Supplementary Annex I) in the standardized data set took place to select meaningful variables for quantitative analysis and to ensure applicability across all countries (Table 2). We identified 11 variables explaining the resilience dynamics of timber supply in each case study (resilience predictors, which correspond to actions suitable to be implemented, and co-drivers, which correspond to contextual variables, sensu Lloret et al., 2024). It is important to note that due to the challenges they posed from an analytical point of view, binary variables were omitted from analyses (e.g., species presence). Variables with minimal variation or limited data availability throughout the observed period were also omitted. Nonetheless, excluded variables were leveraged to contextualize the selected variables, contributing to the holistic narrative for each case study.

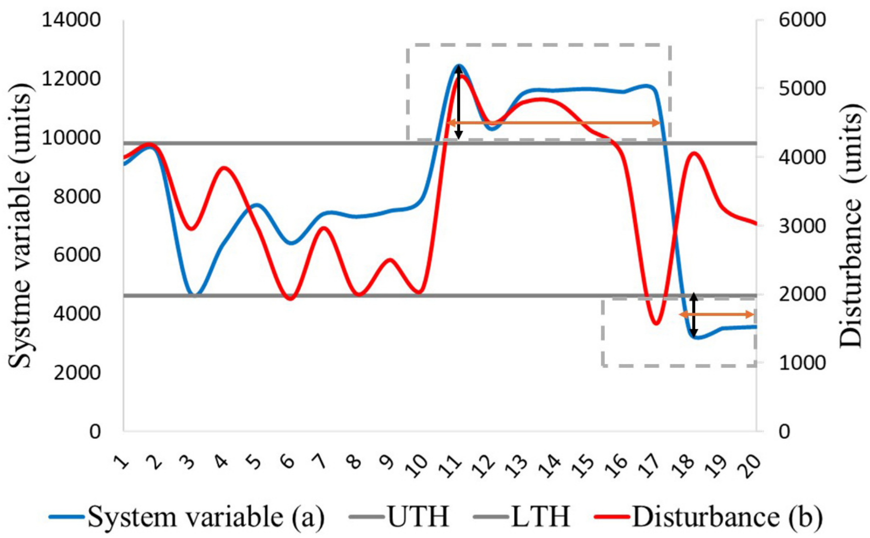

FIGURE 3
Representation of resilience metrics and measurement for resilience assessment. The blue line represents the System variable (a), which in this case is timber supply, the red line represents the Disturbance (b), summarized as salvage logging in this study, and the gray straight lines are upper (UTH) and lower thresholds (LTH). The time series from 1 to n, corresponds to a selected number of time intervals (e.g., years). In this example, the dotted gray rectangles highlight periods where the system exhibits a lack of resilience, i.e., when timber supply exceeds both UTH and LTH. A vertical double arrow (black) is used to depict the resilience metric, and horizontal double arrows (orange) represent the resilience measure, illustrating the system's ability to stay within thresholds despite disturbances.

TABLE 2 List of resilience predictors and co-drivers.

Variable cluster	Variables	Code	P/C	Units
Harvesting system (HS)	Annual volume of prescribed logging	HS.PL	P	(m^3 year^{-1})
	Annual volume of salvage logging	HS.SL	P	
	Usage of cut-to-length harvesting systems	HS.CTL	P	
	Usage of skidders for timber extraction	HS.S	P	
	Usage of motor-manual (chain saw) logging	HS.CS	P	
	Usage of animals for timber extraction	HS.A	P	
Management and silviculture (MS)	Harvestable timber stock[a]	MS.HTS	C	(m^3 ha^{-1})
	Total resource availability[b]	MS.TRA	C	
Timber production (TP)	Volume of sawlogs	TP.SP	P	(m^3)
	Volume of pulpwood	TP.PP	P	
	Volume of wood for energy production	TP.EP	P	

C, resilience co-driver; P, resilience predictor. [a]Indicate the amount of timber in the exemplar's forests eligible for harvesting. [b]Indicate the total amount of timber in the exemplar's forests.

First, descriptive statistics were computed to provide a summary of the main aspects of the dataset. Spearman correlation analyses were conducted to assess the strength of the associations between the timber supply and the resilience predictors and co-drivers in the different case studies. These correlations were used to interpret timber supply resilience, according to its dynamics referred to UTH and LTH boundaries.

Following the correlation analysis, we employed a biplot principal component analysis (PCA), as a dimensionality reduction technique (Gower et al., 2011) adopted in several analytical settings in forestry (Liubachyna et al., 2017; Ficko et al., 2019; Riccioli et al., 2020). The PCA enabled the identification of factors driving variation in each case study, revealing patterns and correlations within the dataset by showing the tendencies of variables to move in similar directions. Importantly, PCA facilitated the visualization of temporal impacts by observing data points representing different periods, tracking shifts over time, and identifying trends. An integrated vision of the various predictors created a multivariate space, allowing us to visualize their characteristics and patterns of change over time, thus helping to understand the temporal sequence and interactions among the predictors. The PCAs were conducted using R Studio, with R version 4.3.1 utilized for the analyses (RStudio Team, 2020).

3 Results

The findings showed notable trends concerning harvesting systems across different case studies. Cases such as CZ and DE showed higher volumes in both HS-PL (54,195 and 7,310 m^3 year^{-1}, respectively) and HS-SL (24,483 and 4,580 m^3 year^{-1}, respectively). The CZ demonstrated the highest mean volume of harvested timber using the cut-to-length (CTL) logging method (16,789 m^3 year^{-1}), while HR was the only country where animals were used in forest harvesting (1,283 m^3 year^{-1}). On the other hand, FIN and ESP, with their complex forest industries, showed high production volumes, especially evident from the mean volumes of produced sawlogs (2,942 and 11,928 m^3 year^{-1}), pulpwood (44,773 and 3,561 m^3 year^{-1}, respectively) and energy wood (2,794 m^3 year^{-1} in ESP). These significant production volumes likely contributed substantially to the output of the forest-based sectors of these countries. Further details of the descriptive statistics of each case study can be found in Supplementary Annex III.

3.1 Relationship between timber supply and resilience predictors

To uncover the relationships between timber supply and the 11 predictors and co-drivers, a Spearman correlation analysis was performed for each case study (Table 3). Timber supply was significantly positively correlated with salvage logging (HS-SL) in all case studies except for the CZ. The use of cut-to-length harvesting systems (HS.CTL) showed a strong positive correlation with timber supply in CZ, DE, and ESP. In contrast, only HR exhibited a significant positive correlation between timber supply and the management and silviculture co-drivers (MS.HTS and MS.TRA). Timber production (including sawlogs, pulpwood, and energy wood) showed moderate to strong significant correlations with timber supply across all case studies.

3.2 Resilience assessment

Figure 4 illustrates the outcomes of resilience assessments for case studies. Beginning with the first block of countries, CZ, HR, and DE were categorized within the mid-scale wood processing industry. In the CZ (Figure 4, CZ), timber supply remained mostly within resilience thresholds during the first decade of the study. In 2015, salvage logging increased to about 50% of total felling (50,051 mł year^{-1}), rising to 99% between 2018 and 2021 due to a large-scale bark beetle outbreak. This peak reached 72,000 mł year^{-1}, exceeding resilience thresholds and signaling unsustainable operational mode if continued. Under the Forestry Act of 1995, salvage logging is mandatory and reforestation must occur within 2 years. Thus, regulation, coupled with market pressure often required rapid timber sales to avoid fines and degradation of timber.

TABLE 3 Correlation analysis for each case study between system variable, timber supply, and resilience predictors and co-drivers.

		HS.PL	HS.SL	HS.CTL	HS.S	HS.CS	HS.A	MS.HTS	MS.TRA	TP.SP	TP.PP	TP.EP
CZ	ρ	**0.427**	0.131	**0.942**	−0.301	−0.305	NA	0.427	0.250	**0.557**	**0.799**	**0.744**
	p-Value	**0.05**	0.57	**1.74e−10**	0.19	0.179	NA	0.053	0.275	**0.009**	**1.42e−05**	**1.10e−04**
HR	ρ	**0.773**	**0.66**	NA	**0.83**	NA	0.08	**0.78**	**0.85**	**1.00**	**1.00**	**1.00**
	p-Value	**4.03e−05**	**0.001**	NA	**3.27e−06**	NA	0.74	**3.39e−05**	**8.07e−07**	**0.00e+00**	**0.00e+00**	**0.00e+00**
DE	ρ	0.194	**0.630**	**0.959**	NA	NA	NA	NA	0.279	**0.714**	**0.764**	**0.528**
	p-Value	0.399	**0.002**	**7.50e−12**	NA	NA	NA	NA	0.221	**02.74e−04**	**5.55e−05**	**1.39e−02**
FIN	ρ	0.372	**0.125**	NA	NA	NA	NA	0.319	NA	**0.596**	**0.944**	**−0.582**
	p-Value	9.61e−02	**4.16e−04**	NA	NA	NA	NA	0.159	NA	**0.0040**	**5.30e−11**	**0.006**
ESP	ρ	**0.990**	**0.743**	**0.914**	**0.729**	NA	NA	NA	NA	**0.987**	**0.897**	**0.756**
	p-Value	**0.00e+00**	**1.16e−04**	**7.31e−09**	**1.79e−04**	NA	NA	NA	NA	**0.00e+00**	**3.54e−08**	**7.41e−05**

Significant correlations are highlighted. ρ represents the Spearman correlation coefficient and α = 0.05. NA indicates that the data for this variable is not available for the given case study; CZ, Czechia; HR, Croatia; DE, Germany; FIN, Finland; ESP, Spain. Predictors and co-drivers: according to the cluster harvesting system (HS): HS.PL, the annual volume of prescribed logging; HS.SL, the annual volume of salvage logging; HS.CTL, usage of cut-to-length harvesting systems; HS.S, usage of skidders for timber extraction; HS.CS, usage of motor-manual (chain saw) logging; HS.A, usage of animals for timber extraction. Management and silviculture (MS): MS.HTS, harvestable timber stock; and MS.TRA, total resource availability. Finally, timber production (TP): TP.SP, the volume of sawlogs produced; TP.PP, the volume of pulpwood produced; TP.EP, the volume of energy wood produced.

Similar to CZ, HR stayed within its thresholds in years with low disturbance occurrence, due to its adherence to forest management plans (Figure 4, HR). However, disturbances in 2016 and 2020 caused timber supply to exceed thresholds, with salvage logging reaching 1,590 and 2,021 mł year^{-1}, respectively. Sustained high salvage logging volumes, similar to those in CZ, could pose risks to long-term sustainability.

The German case study (DE) frequently exceeded its UTH throughout the observed period, reflecting high logging activity driven by frequent disturbances (Figure 2, DE). Notably, salvage logging accounted for 99% of timber supply in 2001 after the Lothar windstorm. From 2009 to 2021, timber supply consistently exceeded thresholds, with reductions only to compensate for earlier overharvesting. This underscores a reactive rather than preventive approach to forest management.

Then FIN and ESP were characterized by a diverse industry. Finland (FIN) exhibited a distinct trend, with a dramatic spike in timber supply in 2018 driven by a large-scale disturbance. During said year, salvage logging exceeded 100% of timber supply (Figure 4, FIN), which means that the exemplar was able to store the surplus salvaged timber and supply it to the market in later years. While historically affected by windstorms and snow damage, the impacts of these disturbances were relatively limited. Nevertheless, timber supply consistently exceeded UTH since 2006, likely due to increased timber supply driven by market demand. Notably, FIN provided indirect data, but national disturbance trends reflected the case study's performance.

In ESP, timber supply showed a sharp increase from 2018 onward, with a peak at 22,134 mł year^{-1}, corresponding to wildfire-driven logging in Galicia (Figure 4, ESP). With the exception of 2007, the earlier increases in timber supply (2000–2010) were likely driven by market demand rather than disturbances, though the 2006 fire season was particularly severe. In the Spanish region of Galicia (ESP), the Forestry Act of 2012 introduced Forest Management Plans to enhance sustainable forestry practices. However, due to the predominance of communal-private ownership and fragmented family forests, by 2022, only 20.6% of the forest area was covered by such plans. Moreover, most of these plans were advisory in nature, significantly limiting their impact on forest management practices.

Overall, CZ and HR demonstrated effective disturbance management, enabling them to maintain a resilient timber supply within their resources. In contrast, DE and FIN faced challenges due to disturbance-driven logging, which undermined long-term stability. Finally, ESP appeared resilient, but additional context is needed to confirm whether its situation was primarily driven by market demand rather than disturbances. Thus, these insights provide a broader understanding of resilience of forest systems over time.

3.3 Multivariate analysis of resilience predictors and co-drivers through time

The PCA for the case studies highlighted similarities and differences in forestry practices, temporal trends, and responses to disturbances across the regions (CZ, HR, DE, FIN, and ESP). Dim1 represented the most significant patterns in the data. The

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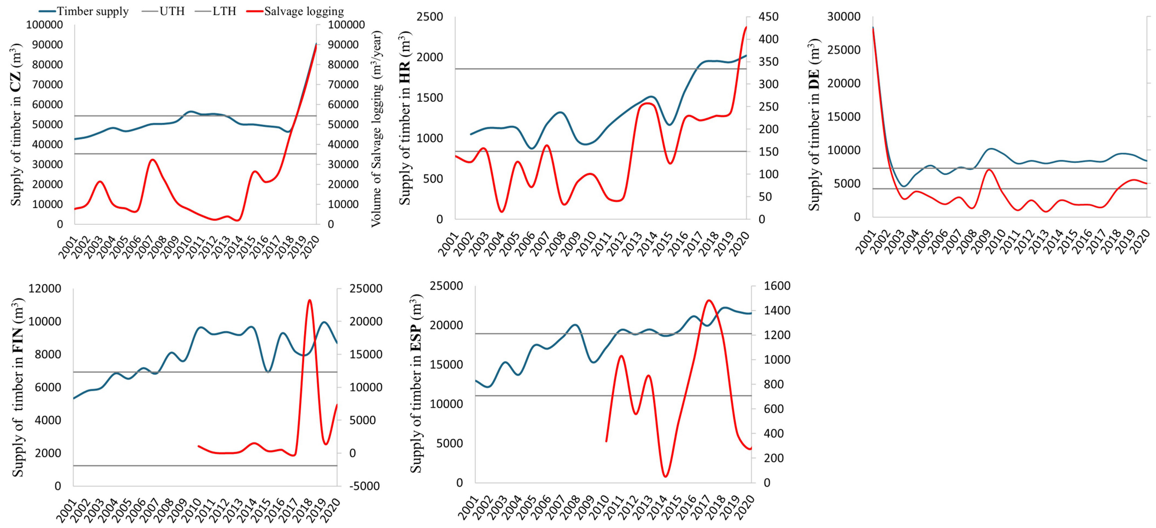

FIGURE 4
Representation of resilience metrics for assessment CZ, HR, DE, FIN, and ESP from 2001 to 2021. The blue line shows the timber supply; the red line represents the disturbance (salvage logging volume), and the gray lines indicate the upper (UTH) and lower thresholds (LTH) specific for each case study. It highlights each case study's ability to maintain timber supply within these thresholds despite natural disturbances.

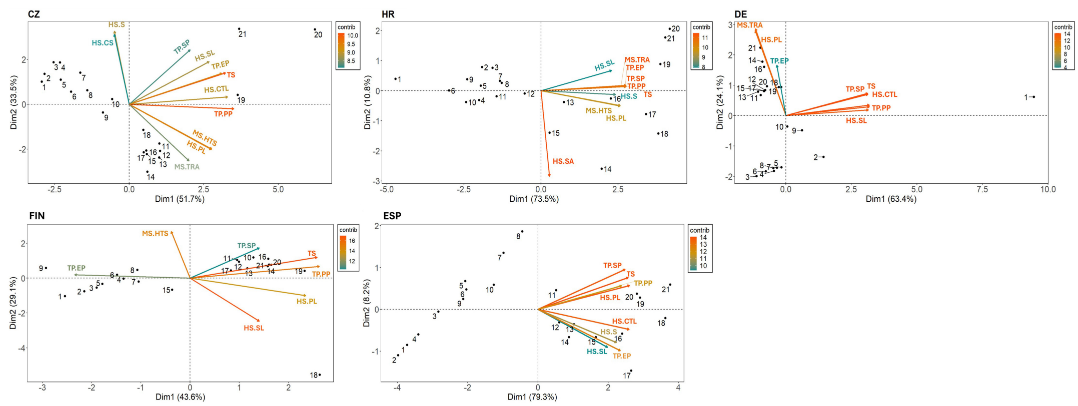

FIGURE 5
In principal component analysis (PCA) biplot, variables per case study – CZ, HR, DE, FIN, and ESP – are represented by arrows within dimension 1 (Dim1) and dimension 2 (Dim2). These arrows illustrate the direction and the magnitude of each variable's influence. The respective contributions of these variables to the timber supply (TS) are indicated by a color gradient. The observations, depicted as dots, correspond to different time periods, where "1" signifies the year 2001 and "21" represents 2021. The complete names of the variable abbreviations are provided in Table 2 of the section "2 Materials and methods."

distribution of dots (observed years) across the quadrants (Figure 5) reflected temporal trends, highlighting shifts in forestry practices and resource usage over time.

First, temporal trends aligned with the resilience assessment graphs and revealed two distinct periods, each lasting around 10 years, consistent with the typical duration of forest management plans. These changes reflected modifications in voluntary logging, harvesting systems, and timber production practices. However, deviations in specific years are evident, likely caused by external market disturbances or other contextual factors.

Second, the explained variance reflected a substantial portion of the variability in the data, ranging from 72.7% in FIN (Figure 5, FIN) to 87.5% in DE and ESP (Figure 5, DE and ESP). Dim1 consistently captured the dominant trends in forestry practices and resource usage, while Dim2 explained additional variability. In CZ, HR, DE, and ESP (Figure 5), the PCA explained over 84% of the variance, reflecting well-defined patterns in forest operations and responses to disturbances. While for FIN, with 72.7%, Dim1 and 2 explained slightly less variance, suggesting that additional factors (not captured in the PCA) may have played a more significant role in this case study.

About key predictors (Dim1 Drivers), a consistent pattern was observed across all case studies: TP.SP (Volume of Sawlogs Produced) was a common contributor to Dim1. However, additional predictors varied among region, reflecting differences in management priorities and regional contexts. For instance, CZ, DE, and ESP emphasized mechanized operations and market demand, with HS.CTL (cut-to-length harvesting) playing a key role. HS.SL (salvage logging) contributed either positively or negatively to Dim1 and 2 across all case studies, but FIN stood out with a negative loading, suggesting challenges related to overexploitation during periods of disturbance. In ESP, HS.PL likely reflected an increase in logging operations over time due to market demand. Lastly, in HR, MS.TRA (total resource availability) contributed positively to Dim1, indicating that sustainable resource management was a central strategy.

The PCAs revealed consistent patterns of adaptation and change in forestry practices over the studied period. Later years were characterized by increased mechanization, salvage logging, and market-driven shifts in timber production, while earlier years reflected a combination of less-intensive practices, species composition, and external factors not fully captured by the PCA.

4 Discussion

Based on our observation, the frequency and severity of natural disturbances increased in all case studies over the observed period, which is in line with reporting in the literature (Bauhus et al., 2017; Johnstone et al., 2016; Patacca et al., 2023). Figure 4 showed that case study representatives reacted to the occurrence of natural disturbances by increasing the amount of salvage logging and consequently the amount of timber supply to the market (Table 2), though the changes in total timber supply were relatively small in most cases. On the other hand, we observed several instances of substantial natural disturbances across all case studies, which caused swings in timber supply beyond the resilience thresholds. For example, DE and CZ experienced significant disruptions to normal operation from windstorms like Lothar and Kyrill, both followed by secondary biotic disturbances, especially in the case of CZ. Also, FIN dealt with windstorms coupled with snow damage, HR faced challenges from ice storms and drought, while in Spain, wildfire activity was rising over the observed period.

Besides their quantitative effects, disturbances also influence the quality grades of timber harvested and supplied to the market, with timber downgrading varying based on the type and severity of the disturbances (Gunnarsson et al., 2004; Hlásny et al., 2019). Moreover, excess salvage logging involves hiring more people, increasing harvests, and reestablishing forest stands thus incurring excessive costs on the exemplars. The joint effects of oversupply and degraded quality of salvaged timber likely caused the enterprises to operate with lower profit margins per unit of timber sold (Fuchs et al., 2022; Greenwood et al., 2023). The combined effects of natural disturbances, therefore, posed a substantial challenge to the resilience of the operations of the case studies.

The resilience assessment (Figures 3, 4) showed that CZ and HR largely operated within resilience boundaries, only breaching the UTH under severe disturbances occurring toward the end of the observed period. In ESP, the timber supply had a relatively stable increasing trend throughout the observed period as can be seen in Figure 4. In ESP, however, the lack of peaks in timber supply when disturbances occurred was likely due to the nature of the disturbance agent (wildfire), which limits the amount of timber available for salvage logging (De Rigo et al., 2017). In the DE and FIN cases the UTHs were consistently exceeded by the companies, the breach was spanning 12 and 13 years, respectively. The duration of the breach hints at the lower ability of these exemplars to mitigate the effects of windthrow by decreasing voluntary logging (Kärhä et al., 2018; Sanginés de Cárcer et al., 2021).

In addition to the disturbance agent, factors such as exemplar size, its processing capacities and network size can substantially influence the ability to absorb disturbances through decreasing the amount of voluntary logging, as demonstrated by CZ, HR and to some extent, ESP. For instance, CZ leveraged its sawmill to efficiently process timber in-house and sell finished lumber products instead of supplying timber to the market. Similarly, the acquisition of a sawmill in 2020 in HR marks a step toward enhancing local processing capacity. In the case of ESP, even if the community-oriented forest sector relied on small-scale processing within the region, having a complex network of small players promoted the regional capacity to process excess timber. Conversely, DE's limited processing capabilities hindered its ability to stabilize timber supply during disturbances. Indeed, the data showed that being able to process timber and having a well-developed network played a role in mitigating disturbance impacts and maintaining supply stability.

To further investigate relationships between timber supply, disturbances and the mode of operation of particular exemplars, we used a PCA-based procedure, which led to the identification of three clusters of variables that could serve as predictors or co-drivers of FVC resilience: timber production (TP), harvesting systems (HS), and management and silviculture (MS). The TP cluster, encompassing sawlogs, pulpwood, and energy wood, underscores the dual importance of monitoring routine timber production and the system's responses to disturbances (Pettenella and Maso, 2011; Badini et al., 2018). In line with these findings, our study showed (Figure 5) that increased salvage logging goes hand in hand with a change of assortment structure (the share of pulpwood and energy wood produced). Therefore, the companies can increase their preparedness for disturbances by adapting their network structures and sawmill capacities.

In synergy with the adaptation of the customer base, companies can also increase their preparedness by introducing high productivity harvesting systems either by expanding their network of harvesting contractors or by increasing their own capacity to harvest more efficiently. For example, using a CTL system in favor of conventional logging systems can enhance extraction efficiency in regions with favorable terrain and species composition (Mederski et al., 2022; Udali et al., 2022). Still, fully mechanized harvesting systems are less common in more complex landscapes, such as Croatia (Vuletić et al., 2014) or countries where forestry is undercapitalized such as the Central and Eastern Europe region (Dvoøák et al., 2020). Rapid salvage logging operations can substantially limit the deterioration of the quality of timber supplied to the market in the case of disturbance and coupled with other recovery techniques—such as debarking, treatment and adequate storage—are essential for maintaining FVC resilience (Pischedda, 2004; Hlásny et al., 2019; Greenwood et al., 2023).

Finally, variables within the MS cluster, i.e., Harvestable timber stock (MS.HTS) and Total resource availability (MS.TRA) connected to forest growth and as such their change was gradual. Their sudden change would point toward a devastating extent of a disturbance event (or substantial malpractice); therefore, they were considered co-drivers. We observed no such instances in the data, and the behavior of MS.HTS and MS.TRA showed that they had a small immediate effect on timber supply. Even so, Braatz (2012) and Hörl et al. (2020) state that proactive and adaptive management strategies enhance long-term sustainability. Another important co-driver connected to the resource base (the resilience of forest ecosystems) is the tree species composition or biodiversity in general. Mixed-species stands have demonstrated better resilience to natural disturbances (Muñoz-Gálvez et al., 2021; Jactel et al., 2017; Pukkala, 2018) through the reduced susceptibility to windthrow and pest infestations (Thom et al., 2017; Romeiro et al., 2022). The challenges in improving FVC resilience lie also in the coordination of tactical to operational level measures with strategic level measures related to forest ecosystems and their resilience.

Indeed, diversifying forest structure and species composition is widely recognized as a key strategy for enhancing the ecological resilience of forests to climate change and related stressors (Pretzsch et al., 2021; Messier et al., 2022). Forest owners are often hesitant to implement measures such as replacing vulnerable species with more resilient variants or introducing alternative management systems due to perceived economic trade-offs of these measures (Knoke et al., 2017; Zamora-Pereira et al., 2021). While these approaches can strengthen forest resilience, many forest owners perceive that downstream industries are not yet adequately prepared to take the timber in quantities sufficient for the sustainable operation of timber producers (Lawrence, 2020; Mazziotta et al., 2023). Adopting a participatory networking structure integrating diverse expertise and stakeholder input can foster better information-sharing (Nikinmaa et al., 2023) and goal alignment along the FVC. Additionally, promoting innovation can support diversification, enhance efficiency, and improve flexibility in forest management and the processing industry while strengthening communication between these stakeholders (Hoeben et al., 2023). Furthermore, providing economic incentives (Juutinen et al., 2022; Haeler et al., 2023) can address forest owners' short-term financial concerns, enabling them to sustain operations while markets for alternative timber species continue to develop, thus promoting long-term ecological and value chain resilience. The predictors and co-drivers of resilience identified within this study are tied within the broader scope of the ORF (Lloret et al., 2024) which provides a comprehensive multiscale resilience assessment of forest social-ecological systems. Literature provides insights into FVC resilience at national and international levels (Fuchs et al., 2022; Loeffler and Anderson, 2018; Seidl et al., 2017), methods focusing on resilience assessment on a local level are scarce and do not cover the variability of how companies operate in different world regions. For example, European FVCs are much more industry-driven and frequently companies are connected to well-integrated markets (Toivonen et al., 2002; Toppinen and Kuuluvainen, 2010; Dzian et al., 2019). In contrast, the more community-oriented approaches observed in Asia and Latin America create an environment where small- and medium-sized enterprises can grow and compete with larger enterprises through policy setting. These approaches often prioritize long-term resource management, balancing the goals of generating employment with conserving the diverse services provided by forests that sustain local communities and ecosystems (Molnar et al., 2007; Hajjar et al., 2013; Baynes et al., 2015). Understanding these structural differences highlights opportunities for developing context-specific strategies that align with economic, social, and operational needs.

This study focused on the local-level resilience assessment of five European case studies. Aside from its geographical focus, it also focused on the interface between forest management and first-stage timber processing of the FVC. Furthermore, the observed period was limited from the point of view of our ability to observe long-term trends connected mainly to forest management and silvicultural data. However, this was a trade-off necessitated by the use of exemplar operational records. Despite these limitations, our findings emphasize that by integrating adaptive management practices and strategies, the FVC can become more sustainable and better equipped to address evolving environmental challenges.

5 Conclusion

This study provides a methodical framework for the operationalization of FVC resilience. We proposed using timber supply as a system variable because, on the one hand, it relates to an essential provisioning ecosystem service, and on the other hand, it provides information about the amount of timber available as input material for value chain actors. We also proposed thresholds of resilience based on the sustainability of exemplar operations, from both ecological and economic perspectives. The resilience metric was defined by the system's ability to remain within thresholds, while its measurement focused on the magnitude of breaches and the time required for recovery to the reference state set by the thresholds. Since this study represents an initial step in developing this type of resilience assessment, we chose not to establish specific criteria for evaluating resilience levels and instead provided a qualitative, verbal assessment. Aside from the resilience assessment itself, we identified key predictors and co-drivers based on our analysis. These findings support companies in enhancing their preparedness for future disturbances by connecting key operations to adaptive and proactive management strategies. Literature suggests additional potential predictors and co-drivers, however, testing their viability requires adapting data-gathering methods and extending observation periods, which poses a challenge due to the limited availability of past operational records of companies.

Future studies of local-level FVC resilience should incorporate additional predictors, such as tree species composition and storage capacity, and examine later stages of the value chain. Moreover, the ORF approach developed within the RESONATE project and first used here in this setting, has the potential for broader global application and can be adapted to assess resilience across different regions and systems. In this sense, future research should test its applicability across scales and explore its integration into other social-ecological systems.

Data availability statement

The original contributions presented in this study are included in this article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SG-J: Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. MJ: Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. AH: Methodology, Investigation, Visualization, Writing – original draft, Writing – review & editing. ML: Project administration, Supervision, Validation, Writing – review & editing. SU: Methodology, Visualization, Writing – review & editing. TS: Conceptualization, Writing – original draft. ON: Data curation, Methodology, Writing – original draft. DV: Data curation, Writing – review & editing. HM: Data curation, Writing – review & editing. JP: Data curation, Writing – review & editing. MP: Data curation, Writing – review & editing. LB: Data curation, Writing – review & editing. FL: Conceptualization, Formal analysis, Methodology, Supervision, Visualization, Writing – review & editing, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2024.1461932/full#supplementary-material

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Paper IV

Factors affecting the Forest value chain resilience-a local economic perspective in five European countries

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Factors affecting the forest value chain resilience–a local economic perspective in five European countries

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This study investigates the economic resilience of Forest Value Chains (FVC) at the local level through five European case studies: Kostelec, Czechia (CZ), Upper Rhine Valley, Germany (DE), Istria, Croatia (HR), Kainuu, Finland (FIN), and Galicia, Spain (ESP). Using an operational resilience framework (ORF) and a resilience assessment centered on revenue as a system variable. A sensitivity analysis of profitability thresholds confirmed the robustness of the results. Principal Component Analysis (PCA) was applied to examine market price fluctuations across various timber types, market trends and salvage logging practices from 2001 to 2021. Two-way fixed-effects panel regression models revealed that planned harvested volume, mechanization, and market prices were significant predictors of enhanced economic resilience. The analysis revealed three interrelated dimensions of FVC resilience: resistance to market shocks, recovery following disturbances, and capacity for transformation via adaptive management. Two predominant adaptation strategies emerged: a market-driven approach, characterized by product diversification and price stability, and a disturbance-driven strategy, focused on reactive harvesting and technological innovation. While salvage logging offered short-term economic relief, excessive dependence undermined long-term stability. The findings highlight the need to balance short-term recovery with long-term sustainability in managing Europe's FVCs.

KEYWORDS

salvage logging, timber assortments, technology, market approach, harvesting strategies

1 Introduction

Forest-based value chains (FVCs) play an important role in regional and global economies, linking forest product harvesting, processing, and marketing (Henderson and Weiler, 2010; Rubaratuka et al., 2024). They provide income for forest owners, employment in local communities, and raw materials for industry (D'Amours et al., 2017), playing a key role in supporting sustainable local development. Forest enterprises, which are central to managing and processing resources, depend on the stability and productivity of the forest system (Nabuurs et al., 2015; Liubachyna et al., 2017). However, enterprises and the broader FVC, are increasingly threatened by the impacts of climate change.

A key aspect of how climate change affects FVCs stability are natural disturbances. Bark beetle outbreaks, windstorms, droughts and wildfires are becoming more frequent and severe, directly affecting forest ecosystems, their productivity and therefore, the value chain and forest-based industries (Buras et al., 2020; Senf and Seidl, 2021; Nunes, 2023; Washaya et al., 2024). These disruptions often lead to unplanned salvage logging and a decline in timber quality, thereby reducing revenues for forest owners and undermining the financial viability of forest enterprises (Fuchs et al., 2022). The ability to respond to and recover from such shocks is becoming a central concern for those managing and depending on FVCs (Spittlehouse and Stewart, 2004; Verkerk et al., 2022; IPCC, 2022).

In this context, the concept of resilience has gained increasing attention. Generally, resilience can be described as the capacity of a system to absorb disturbances while recovering and maintaining its essential functions and structure in a timely and efficient manner (Lloret et al., 2024; Walker et al., 2004). For forest owners and enterprises, this means being able to continue operations, sustain livelihoods, and plan for the future despite environmental and market disruptions. Therefore, building resilience requires not only ecological management but also socio-economic planning and governance (Nikinmaa et al., 2020).

The resilience concept is often applied in different ways according to the system boundaries and specific goals (Nikinmaa et al., 2020). Engineering resilience, for example, refers to the ability to recover to a state equivalent to the undisturbed one (e.g., before disturbance). Ecological resilience focuses on maintaining key ecosystem processes and functions within a system's domain (i.e., avoiding shifts to alternative states). Considering the context of forest systems, economic resilience refers to the capacity of economic actors to absorb shocks and adapt to changing ecological or market conditions and transform, when necessary, to sustain functionality and competitiveness (Pinto et al., 2022; Ferreira et al., 2025). On a higher level, social-ecological resilience is defined as the capacity of systems confronting stress or disturbance to reorganize and adapt through interactions between ecological and social components (Seidl et al., 2016; Nikinmaa et al., 2023), thereby recognizing the possibility of shifting to another (potentially more resilient) system state.

For this study, we have adopted the social-ecological resilience approach given that complex FVCs involve diverse social and economic stakeholders and address the delivery of multiple ecosystem services across various scales. This approach captures the importance of adaptability, cross-scale dynamics, and system-wide interactions to ensure long-term functionality of FVCs. Particularly, this study extends the resilience concept to the economic domain through the consideration of recovery speed (Knoke et al., 2023), which is defined as "the ability of a business to recapture lost production" (Park et al., 2011). In this context, economic processes such as market access, price stability, harvesting capacity, and diversity of forest management strategies are suited to assess the system's resilience.

Building on this economic perspective, according to Knoke et al. (2023) and Tampekis et al. (2024) highlight the influence of forest management and operational strategies on economic resilience. For example, continuous cover forestry was more economically beneficial and more resilient in terms of recovery after disturbances compared to the clear-fell system. Xu et al. (2011) have emphasized the importance of understanding how disruptions propagate through the entire value chain, from harvesting to processing to end-users. Similarly, Baumgärtner and Strunz (2014) conducted an economic analysis on the insurance value of resilience, quantifying the contribution of ecological resilience value by measuring the reduction in risk premium as resilience increases. In addition, studies have examined how factors such as supply chain disruptions, vulnerability and volatility affect resilience (Christopher, 2000; Sheffi, 2001; Svensson, 2000; Zsidisin et al., 2000) Market interactions and management efforts to support adaptation to forest disturbances further complicate resilience dynamics. For instance, Asada et al. (2023) demonstrated that large-scale disturbances at the national level in European countries lead to a reduction in value added within the lower-quality segments of the FVC, as high-quality sawlogs are downgraded to low-quality fuelwood. However, mechanisms such as increased salvage logging and import and export on the international market partially offset these losses.

While aggregated market-level studies provide insights on global drivers of FVC resilience, they cannot fully account for the role of local actors in responding to disturbances and ensuring FVC resilience. Despite its importance, the local perspective remains underexplored, particularly within a social-ecological and economic context. The complex interplay between natural disturbances, adaptation behavior and market dynamics in forest value chains at the local level is not yet fully understood. Moreover, the multi-regional approach allows us to identify generalized resilience patterns and context-specific adaptations, which would not be evident in a single-region analyses. This study aims to address this gap by examining the economic effects of natural disturbances on FVC at the local level across diverse biogeographic regions and forest management systems. By identifying key resilience predictors (Lloret et al., 2024) and evaluating how market dynamics influence operational resilience across different wood assortments, this research provides valuable insights for enhancing the adaptive capacity of forest-dependent economies.

2 Methods

2.1 Data gathering

This study applies a case study approach at regional level, with one case per region, located five in European countries: Kostelec in Czechia (CZ); Upper Rhine Valle in Germany (DE); Istria in Croatia (HR); Kainuu in Finland (FIN); and Galicia in Spain (ESP; Figure 1). This procedure captures specific contexts and practices, allowing to explore how they influence enterprise operations and decision-making processes across Europe. These CSs were selected to cover

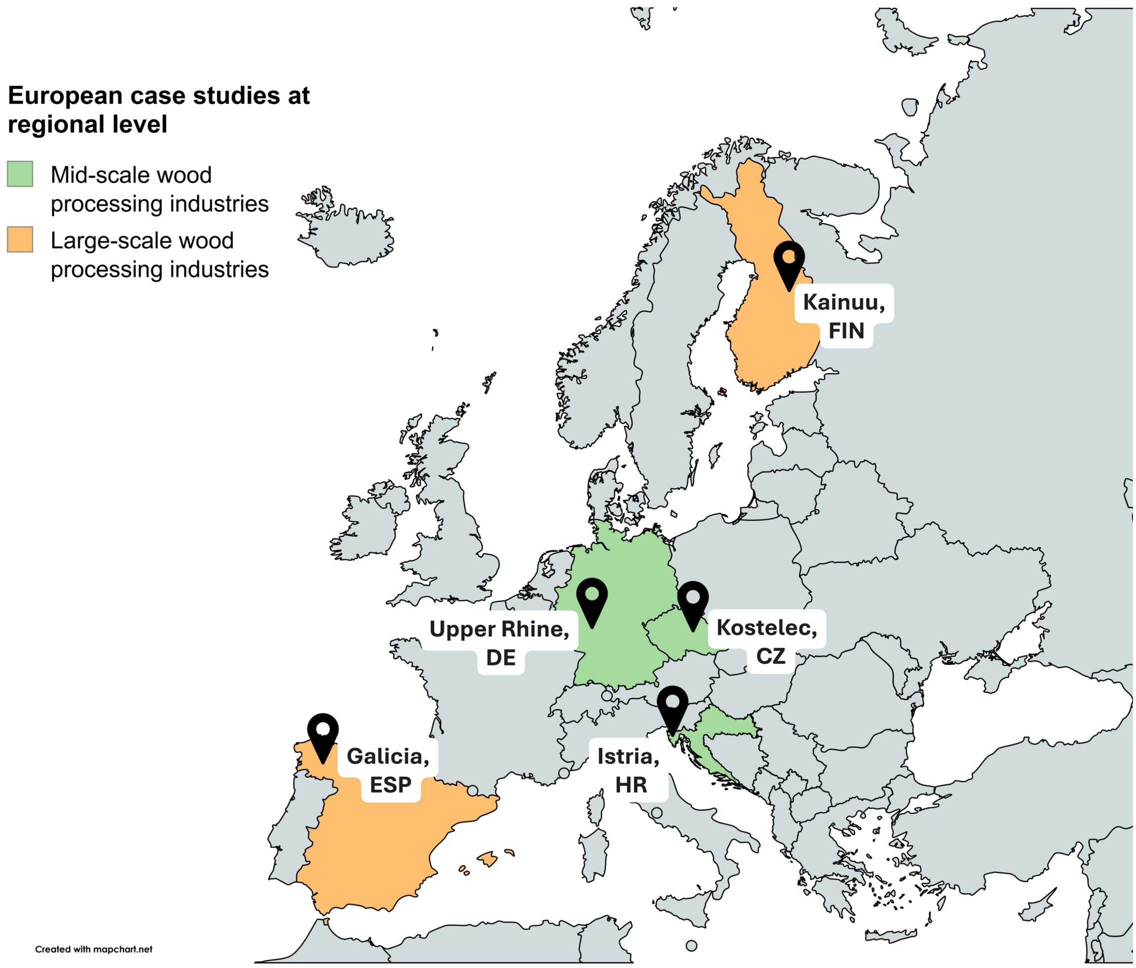

FIGURE 1
Five European case studies by wood processing industry scale: Mid-scale: Kostelec, Czechia (CZ), Upper Rhine Valley, Germany (DE), Istria, Croatia (HR), Kainuu. Large-scale: Finland (FIN), and Galicia, Spain (ESP). Map created with MapChart (https://www.mapchart.net). Licensed under CC BY-SA 4.0. MapChart (2025).

major biogeographic areas, and diverse forest management systems and FVC structure across Europe. In each country, a representative forest enterprise was selected as an exemplar, taking into account the processing capacities, which reflect the distinct structure and scale of the forest-based enterprises. Considering that, CZ, DE, and HR have mid-scale wood processing industries, where the use of timber and forest products is mostly confined to the region, and the export capabilities of the forest-based industries are limited. These forest-based sectors often served domestic or nearby markets, constrained by logistical infrastructure and certain production technologies. While FIN and ESP feature as large-scale wood processing industries, they showcased diverse processing industries and greater integration with international markets. The main disturbances varied between case studies along the considered period, with a prominent role of bark beetle outbreak in CZ, windstorms in DE and FIN, ice-storm and windstorms in HR and wildfires in ESP. The disturbances were reflected in the salvage logging volume, which was used as a proxy of the volume of damaged timber. The volume and quality of damage timber was affected by disturbance agent prevalent in particular regions. This approximation is commonly used in literature (Butry et al., 2001; Prestemon and Holmes, 2004; González-Gómez et al., 2013). The type of processing capacity and its versatility not only increases the potential for value recovery after disturbances, but also market outlets and the recovery of damaged timber.

Data was gathered according to García-Jácome et al. (2025), considering annual data for the period 2001 to 2021. The dataset included information on case studies in terms of harvesting systems, technologies, timber production and market price of sawlogs, pulpwood and energy wood.

In this study, revenue was used as a system variable, representing a quantitative indicator of the performance of the FVCs social-ecological system in response to disturbances. A system variable is a measurable attribute that responded to external pressures and characterizes the system's structure and function over time (Nikinmaa et al., 2023; Baho et al., 2017). We followed Asada et al. (2023) to obtain the system variable, the revenue for sawlogs, pulpwood and energy wood, where the source of the data was UNECE/FAO (2021) and United Nations (2021). However, to ensure cross-country comparability, all prices were kept in USD. Additionally, we applied inflation corrections using the World Bank (2025), allowing us to isolate real price changes from general inflation or currency effects and ensure an accurate reflection of economic trends over time.

To assess the resilience dynamics of revenue across the case studies, we identified 11 key resilience predictors (sensu Lloret et al., 2024; Table 1). These predictors offer insight into specific mechanisms or components that enhance a system's ability to absorb disturbances and adapt to change (Standish et al., 2014). This approach will help tailor to local needs while informing broader European strategies for sustainable forest-based economies.

2.2 Resilience assessment

For the resilience assessment, a forest enterprise was considered sustainable and resilient when it was able to generate stable revenue over time while remaining within ecological limits, represented by the economic upper threshold (Ec.UTH). In turn, consistently generating revenues covered operational costs, defined by the economic lower threshold (Ec.LTH).

The Ec.UTH was calculated by first determining the total available timber supply at the upper threshold level (TS.UTH). As it is described in García-Jácome et al. (2025) "UTH is the upper resilience threshold, defined as the mean annual logging prescriptions according to forest management plan rom year 1 (2001) to year n (2021) of the observed period; and n is the number of years within the observed period."

First, the Timber supply UTH was calculated as:

TABLE 1 List of resilience predictors.

Variable cluster	Variables	Code	Units
Harvesting system (HS)	Annual volume of total timber supply	HS.TS	$m^3\ year^{-1}$
	Annual volume of salvage logging	HS.SL	
	Percentage of salvage logging relative to total timber supply	Pct.HSL.SL	
	Usage of Cut-to-length harvesting systems	HS.CTL	
	Usage of horses for timber extraction	HS. H	
Timber Production (TP)	Volume of sawlogs	TP. SP	m^3
	Volume of pulpwood	TP. PP	
	Volume of wood for energy production	TP. EP	
Market price (MP)	Price per m^3 at which sawlogs are sold	MP. SP	USD/m^3
	Price per m^3 at which pulpwood is sold	MP. PP	
	Price per m^3 at which wood for energy is sold	MP.EP	

$$UTH = \frac{\sum_{1}^{n} Prescribed\ Logging\ Volume}{Number\ of\ years}$$ (García-Jácome et al., 2025).

This volume was then divided into different assortments (sawlogs, pulpwood and energy wood) based on their respective shares obtained from appropriate timber yield tables. Each assortment's volume is multiplied by its mean annual market price (MP.SP, MP.PP and MP.EP), and the results are summed up to calculate the total economic value, referred to as Ec.UTH.

While Ec.UTH provides a guideline for sustainable revenue, it should not be considered as a strict rule. Factors like price fluctuations can temporarily increase revenue without necessarily leading to overexploitation.

Then, the Ec.UTH was then calculated by:

$$Ec.UTH = UTH * (Share.SP * mean\ MP.SP + Share.PP * mean\ MP.PP + Share.EP * mean\ MP.EP)$$

The Ec.LTH represents the minimum total revenue required for a forest enterprise to sustain its essential operations. It was calculated by taking the minimum observed annual revenue (Min Revenue) and the expected profitability ratio for each case study, according to literature-based values (Annex I).

The Ec.LTH was calculated as

$$Ec.LTH = (\min Revenue) * (1 - x\%)$$

where x% denotes the expected profitability (expressed as a decimal). This formulation assumes that when total revenue falls below Ec.LTH, the enterprise becomes economically unsustainable, that is, unable to cover its essential operating costs once profit margins are accounted for.

If the system variable, revenue, stays within the defined economic upper and lower thresholds, then the exemplar can be considered economically resilient. This means it's generating enough revenue to cover costs without exceeding ecological limits.

To assess the robustness of the Ec.LTH estimates, a sensitivity analysis was performed by adjusting the Ec. LTH values by ±10 and ±50%. These scenarios tested the influence of moderate and extreme deviations in the profitability assumptions that would affect the classification of resilience states across the case studies.

2.3 Data analysis

We evaluated the role of salvage logging on the operational economies of forest enterprises. So, we calculated the proportion of salvage logging relative to total timber supply from 2001 to 2021. This metric allows us to identify and quantify long-term trends in salvage logging dependence and its impact on forestry markets.

The proportion of salvage logging was calculated as:

$$Pct.HS.SL = \frac{Salvage\ logging}{Total\ timber\ supply}$$

Where the percentage of salvage logging is relative to total timber supply (Pct.HS.SL) represents the share of volume of unplanned timber extraction due to disturbances. The total timber supply was used as the denominator because the goal was to show the proportion of salvage logging within the total volume extracted, regardless of planning. This approach helped to assess the relative impact of disturbances on overall supply. However, in some case studies, salvage logging even exceeds the reported total timber supply, suggesting it may not have been completely placed on the market within that year, thus spilling over to subsequent year.

We also analyzed the price trend for sawlogs, pulpwood and energy wood adjusted for inflation and expressed in USD per CS. This analysis helped track long-term price dynamics, detecting market disruptions, and allowed exploring links with revenue fluctuations.

We used Spearman correlations to explore the bivariate relationship between economical revenue and the different predictors (Table 1), Then we employed PCA to reduce the dimensionality of predictors (Gower et al., 2011; Ficko et al., 2019; Riccioli et al., 2020) in order to visualize regional economic patterns and detect temporal trends in economic resilience, in terms of economic revenue. The PCA was conducted using data from 2001 to 2021, and its Dim1 accounted for 70% of the total variability. This PCA was performed by R Studio (version 4.3.1).

Following the explanatory PCA that identified general spatial and temporal trends, we employed a panel regression model to estimate the specific effects of the predictors on forest based economic revenue, while controlling for unobserved heterogeneity across countries and years.

We estimated a two-way fixed effects panel regression, which controls for both country-specific (μ_i) and year-specific (λ_t) effects. On one hand, country fixed effects capture time-invariant characteristics of each national forestry system, such as forest resource, management structure, or institutional condition. On the other hand, year fixed effects absorb external shocks common to all countries (e.g., economic shocks, disturbance years, pandemic). This specification isolates the within-country, overtime variation in the explanatory variables that drives changes in real timber revenue.

With many related predictors, multicollinearity was a major concern. To minimize this and ensure stable estimation, variables were pre-processed (Annex II), and the transformed variables were used in the subsequent models.

Model A "Scale model," examined how total planned harvest, salvage intensity, mechanization and overall market price influenced revenue:

$$Revenue_{it} = \alpha + \beta_1 HS\_Planned_{it} + \beta_2 Pct\_HS\_SL01_{it} \\ + \beta_3 HS\_CTL_{it} + \beta_4 Price\_Index_{it} + \mu_i + \lambda_i + \varepsilon i$$

Where revenue ($Revenue_{it}$) in country i in year t is explained by the volume of planned harvested ($HS\_Planned_{it}$), the proportion of salvage logging to total supply ($Pct\_HS\_SL01_{it}$); the degree of mechanization (HS_CTL_{it}), and the aggregate price level for timber assortment ($Price\_Index_{it}$).

Log-transformed variant was also estimated to interpret coefficients as elasticities and to reduce heteroscedasticity:

$$lnRevenue_{it} = \alpha + \beta_1 \ln\left(1 + HS\_Planned_{it}\right) \\ + \beta_2 Pct\_HS\_SL01_{it} + \beta_3 HS\_CTL_{it} \\ + \beta_4 Price\_Index_{it} + \mu_i + \lambda_i + \varepsilon i$$

- $\beta_1 \approx$ revenue elasticity w.r.t. planned harvest
- $\beta_2 \approx$ % change in revenue per unit (or 10 pp) change in salvage share
- β_3, β_4= semi-elasticities (since not logged)
- Using ln (1 + x) allows zero values of harvest or volume.

Model B "Composition model," replaced total harvest with type of assortments volume of sawlogs, pulpwood and energy wood to test whether changes in harvest composition affected revenue:

$$Revenue_{it} = \alpha + \beta_1 TP\_SP_{it} + \beta_2 TP\_PP_{it} + \beta_3 TP\_EP_{it} \\ + \beta_4 Pct\_HS\_SL01_{it} + \beta_5 HS\_CTL_{it} \\ + \beta_4 Price\_Index_{it} + \mu_i + \lambda_i + \varepsilon it$$

Model significance was tested using F-statistics for joint significance of regressor and Wald Test for time and group effects. The models were estimated using the plm package (Croissant and Millo, 2008) in RStudio (version 4.3.1) (RStudio Team 2020). Heteroscedasticity-robust standard errors were computed and clustered by both country and year to ensure inference robustness with a small cross-sectional sample (five case studies). The FE was used because unobserved structural characteristics of each country are likely correlated with the explanatory variables (Wooldridge, 2010).

3 Result

3.1 The proportion of salvage logging relative to timber supply

Figure 2 illustrates the percentage of timber supply sourced from salvage logging across the five case studies. A higher proportion of salvage logging indicates a stronger reliance on reactive harvesting rather than planned timber extraction. The fluctuating trend reflects the severity and frequency of disturbances.

In CZ and DE, there was a clear upward trend in the proportion of timber coming from salvage logging, particularly from 2015 onwards, likely related to the bark beetle crisis in CZ and extreme weather like drought in DE. In DE specifically, this increase represented a shift from the earlier declining trend and was marked by a considerable year-to-year variation, which increased unplanned timber extraction. In FIN, there was a notable spike around 2018, coinciding with a major windstorm and snow damage. In HR, the relative percentage of salvage logging remained consistently low throughout the period under consideration, though it showed some fluctuations. ESP maintained the lower, more stable proportions of salvage logging, indicating that their timber supply was primarily sourced from planned operations.

3.2 Price trends across different wood assortments

For CZ (Figure 3), all prices of timber grades showed an upward trend until around 2007–2008 (global financial crisis), followed by a decline and fluctuations in later years. Sawlog and pulpwood prices followed a similar trajectory, with notable fluctuations occurring

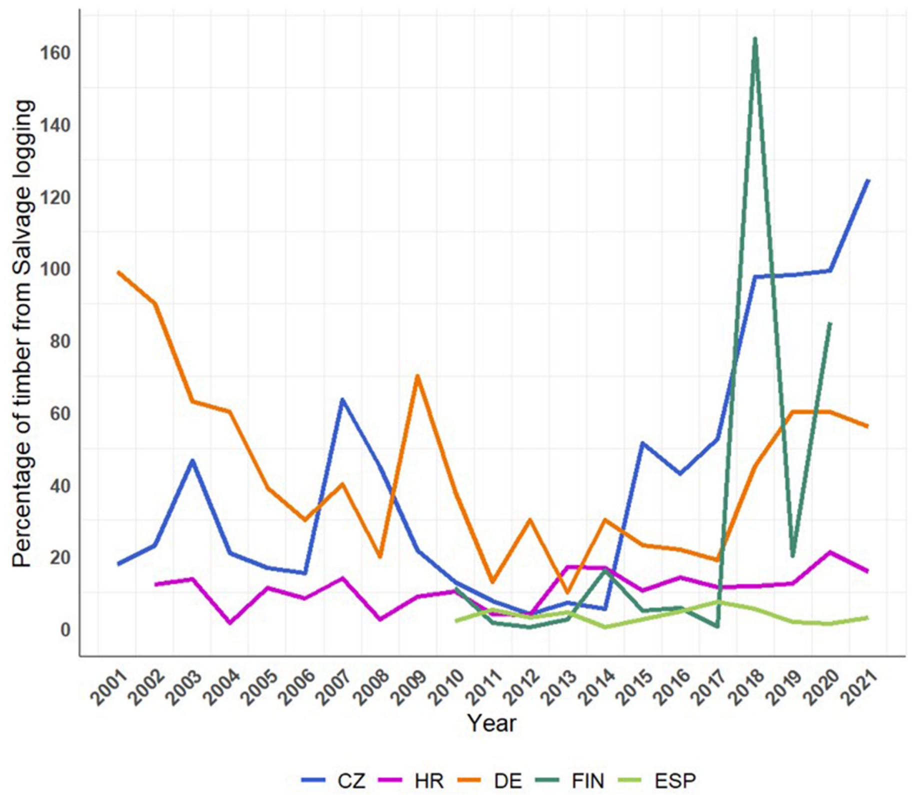

FIGURE 2
Percentage of salvage logging (m^3) related to timber supply, in the five case studies (CZ, HR, DE, FIN, and ESP). When the percentage of salvage logging to timber supply is close to 100, it indicates that a larger portion of timber is from salvage logging likely due to disturbances (e.g., bark beetle, windstorms, fires, snow, etc.) that led to much higher salvage operations than originally anticipated, whereas a percentage close to 0 suggests that the timber supply is largely sourced from the planned logging.

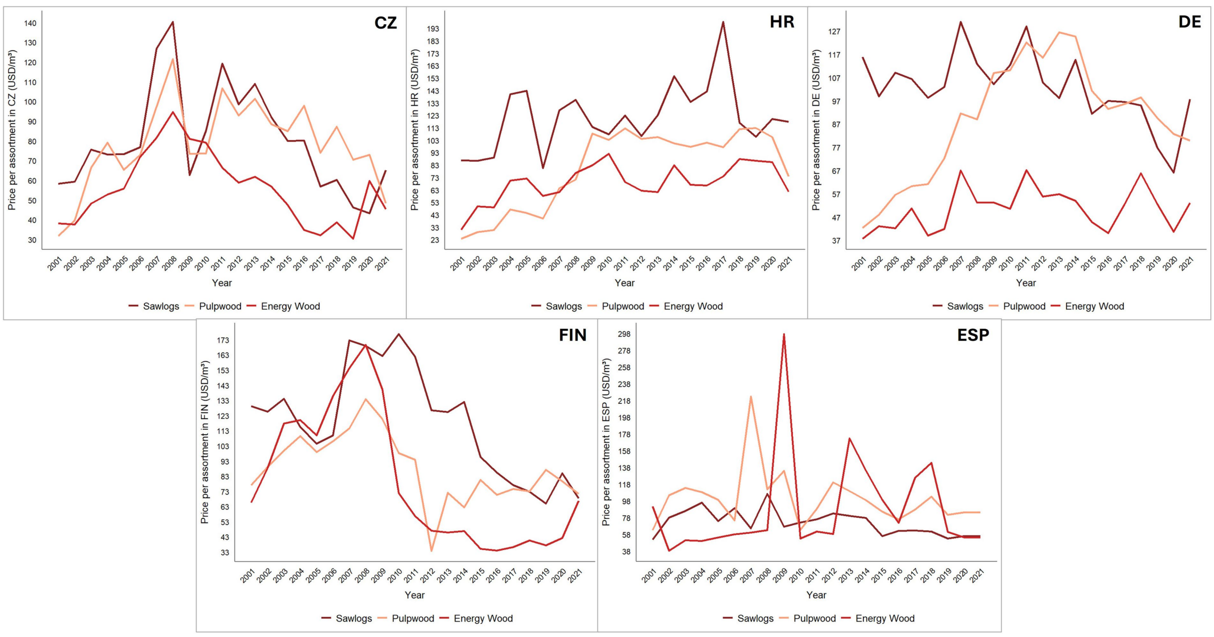

FIGURE 3
Inflation-adjusted price per cubic meter (USD/m3) for sawlogs, pulpwood and energy wood in each case study (CZ, HR, DE, FIN, and ESP) from 2001 to 2021. These metrics provide insights into the economic dynamics of the forest value chain and their resilience to market and environmental disturbances.

from 2010 to 2020, with a slight recovery only for sawlogs in 2021. The energy wood prices were consistently lower than the other two assortments, with a drop in the late 2010s. In contrast, sawlog prices in HR remained relatively stable when considering the whole 2001–2021 period, but experienced periodic peaks, possibly reflecting sporadic market disruptions. As for pulpwood, there is an increase from 2006 to 2009, where it remained stable and dropped in 2021. In the case of energy wood, the same as in CZ can be observed, it remained lower than the other two assortments but with less fluctuations than CZ. In the case of DE, the sawlog prices declined with fluctuations over time, while pulpwood prices exhibited an increasing trend until 2011–2013, declining again afterwards. Wood energy prices remained relatively low and stable, with some moderate fluctuations. In FIN, price volatility was observed, particularly for sawlogs and pulpwood, with peaks around 2007–2010 and subsequent declines. Energy wood prices remained more stable, but with a remarkable drop after 2007 and recovering by 2020–2021 Finally, in ESP, sawlogs remained relatively stable over the period. However, pulpwood and energy wood showed important fluctuations, with important peaks during 2007–2008 for pulpwood and 2009–2010 for energy wood. Across the observed period, sawlog prices tended to be more stable over the long term (HR and ESP). Notably, CZ and FIN experienced market fluctuations, particularly for sawlogs and pulpwood prices. In contrast, DE and HR exhibited more moderate price movements. Finally, energy wood consistently remained the lowest-priced assortment.

3.3 Resilience assessment

This section evaluates economic resilience by examining revenue behavior relative to the established upper (UTH) and lower thresholds (LTH) in response to natural disturbances, estimated by salvage logging (m3) (Figure 4). In CZ, the revenue exhibited a rather steady behavior after 2007, but presented several notable breaches over the UTH, with a maximum value of 6.1 million USD. Although salvage logging fluctuated, and followed peaks of revenue in 2007 and 2021, it does not appear to significantly buffer revenue losses, such as in 2009 or after 2011. In HR, the revenue initially remained within the thresholds, but it rose over the UTH after 2016, reaching a peak of 247.07 million USD, indicating a temporary surge in activity, likely as a compensatory harvesting following disturbance events. However, the moderate previous levels of salvage logging suggests that additional economic or policy mechanisms likely played a role in stabilizing revenue.

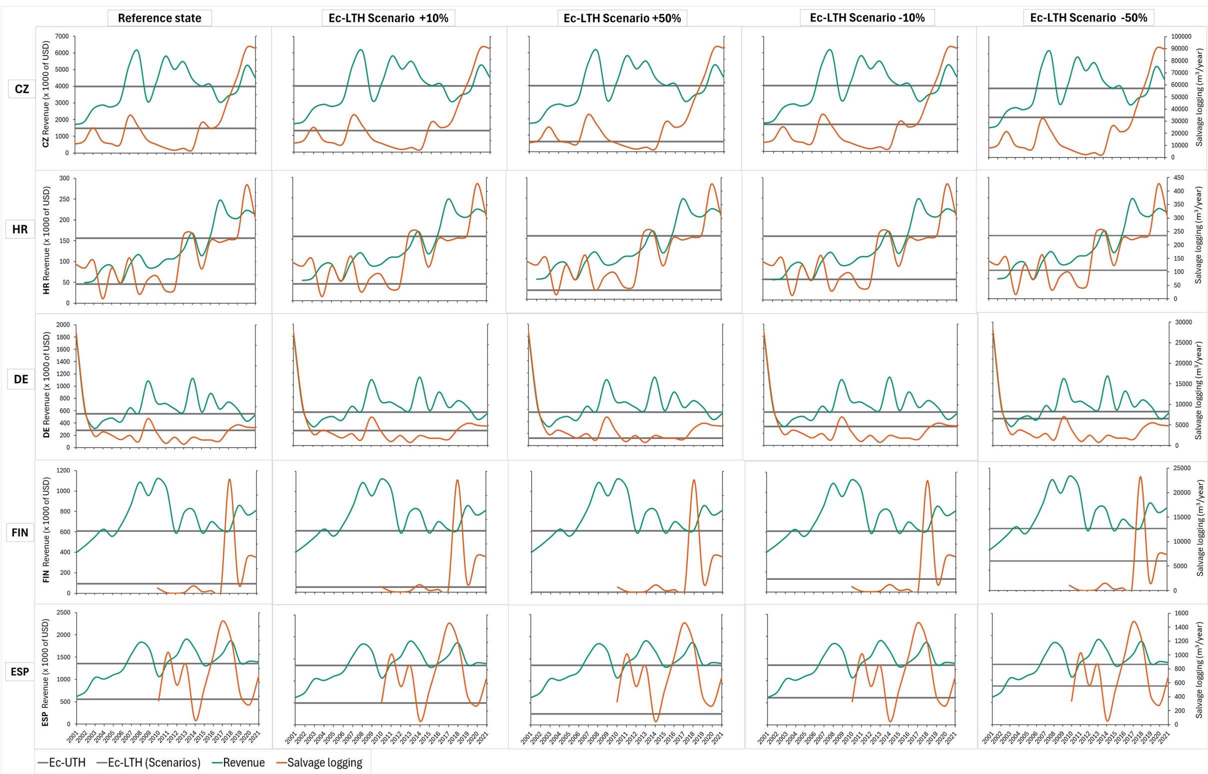

FIGURE 4
Resilience assessment for CZ, HR, DE, FIN, and ESP from 2001 to 2021. The green line shows the revenue; the orange line represents salvage logging volume, a proxy of disturbance level, and the grey lines indicate the upper (Ec.UTH) and lower thresholds (Ec. LTH), specific for each case study, which depicts each case study's ability to maintain the revenue within certain levels (see Methods) thresholds despite natural disturbances. The first column "Reference state" displays the baseline thresholds, while the subsequent columns illustrate the sensitivity scenarios, where the Ec. LTH was adjusted by ±10 and ±50% to test the robustness of profitability assumptions.

The German case study exhibited prolonged breaches of the UTH. It was significantly affected by Storm Lothar in 1999/2000, which led to a substantial reduction in timber stock. This decline resulted in a situation where standard harvesting levels necessitated an increase in harvesting intensity beyond sustainable limits. This disruption is reflected in the highest observed deviation from the UTH, reaching 1.8 million USD, which coincides with a peak in salvage logging following the storm event. Overall, sustained high revenue suggests a robust market response, supported either by increased timber prices or intensified harvesting efforts.

In FIN, the revenue showed dramatic spikes, from 2006 to 2012, peaking at 1.12 million USD. After this period, fluctuations were less extreme but still generally remained above the UTH. In contrast, the largest spike in salvage logging occurred in 2018, driven by a major disturbance event involving ice and storm damage. This disturbance resulted in only a moderate increase in revenue in 2019. However, the delayed revenue response in subsequent years suggests that surplus salvage timber was stored and gradually introduced to the market, contributing to a more stable revenue stream over time.

Finally, ESP presented multiple breaches of the UTH; particularly a sharp increase in 2018 coincided with major disturbance events, likely linked to 2017 wildfire season in Galicia as reflected in the peak of salvage logging. The highest revenue exceeded 1.9 million USD. Salvage logging events in ESP in the study period (2001–2021) were often followed by a slight increase in revenue, however, these increases were typically temporary, with revenues declining in the years that followed.

ESP and CZ experienced the highest exceedances, suggesting that strong economic activity followed disturbance events. In contrast, DE and FIN showed moderated but sustained deviations, likely reflecting market adjustments such as increased salvage logging, changes in harvesting intensity, or pricing strategies to mitigate revenue losses. Finally, HR showed the lowest revenue exceedances, suggesting a more stable structure with less dependence on disturbance-driven harvesting.

The sensitivity analysis (Figure 4) tested how adjustments of the Ec.LTH by ±10 and ±50% influenced the classification of economic resilience across the five case studies. Results showed that moderate deviations (±10%) had minimal effect on the resilience status, as revenue trends generally remained within the defined Ec.UTH and lower bounds. In contrast, extreme adjustments (±50%) meaningfully affected the classification only in case where revenues were consistently near the lower threshold, such as HR and ESP, where minor declines pushed revenues below sustainability limits. The overall shape of the trajectories and distance between Ec.UTH and Ec.LTH remained stable, confirming that the threshold definition is robust under realistic profitability assumptions.

TABLE 2 Spearman correlation between the system variable revenue and significant resilience predictors for each case study during the considered period.

Case study	Strong correlation ($\rho > 0.5$)	Moderate correlation ($0.3 < \rho < 0.5$)
CZ	HS.CTL (0.633)	HS.TS (0.445)
	MP.SP (0.552)	
HR	HS.TS (0.957)	–
	TP.SP (0.949)	
	TP.PP (0.949)	
	MP.PP (0.613)	
	MP.EP (0.609)	
	HS.SL (0.594)	
	MP.SP (0.541)	
	Pct.HS.SL (0.516)	
DE	MP.EP (0.667)	TS.SP (0.318)
		MP.SP (0.307)
	MP.PP (0.580)	HS.CTL (0.295)
FIN	TP.SP (0.633)	HS.TS (0.445)
	MP.SP (0.552)	
ESP	MP.EP (0.667)	–
	MP.PP (0.580)	

Significant correlations between the system variable, revenue, and predictors. ρ represents the Spearman correlation coefficient, and α = 0.05. The table is organized from highest ρ to the lowest, to easily identify the strongest correlation in terms of effect size. The case studies are: CZ, Czechia; HR, Croatia; DE, Germany; FIN, Finland; ESP, Spain. Predictors: according to the clusters (Table 1): Harvesting system (HS): HS-TS, Timber supply; HS.SL, the annual volume of salvage logging; Pct.HS.SL, the proportion of salvage logging relative to timber supply; HS.CTL. Timber production (TP): TP.SP, the volume of sawlogs produced; TP.PP, the volume of pulpwood produced. Finally, the market prices, MP. SP, price of sawlogs USD/m3; MP. PP, price of pulpwood USD/m3 and MP.EP, price of energy wood USD/m3.

3.4 Relationship between revenue and resilience predictors

The Spearman correlation (Table 2) showed that revenue had a strong positive correlation with timber supply (HS.TS) in HR and a moderate correlation in CZ and FIN. Salvage logging only had a weak but significant correlation in HR. The percentage of salvage logging (Pct.HS.SL) showed significance only in HR, indicating this predictor had limited direct influence on revenue across most regions. For harvesting systems, the use of cut-to-length harvesting systems (HS. CTL) showed a strong positive correlation with revenue in the CZ and a moderate correlation in DE.

Regarding timber production variables, sawlog volume (TS.SP) displayed a strong positive correlation with revenue in HR and a moderate correlation in DE and FIN. Pulpwood volume (TP.PP) showed a significant correlation in HR. Market prices demonstrated significant correlations across several regions. Sawlog prices (MP.SP) showed a strong positive correlation in CZ and HR. Pulpwood prices (MP.PP) and Energy wood prices (MP.EP) were significantly correlated with revenue in HR, DE and ESP. For more detailed information about the correlation between the system variable, revenue, and the predictors, please go to Annex III.

3.5 Multivariate analysis of revenue of resilience predictors through time

The PCA results across the five CS reflect varying levels of integration between disturbance-driven harvesting, silvicultural practices and market dynamics, offering insight into how each region responds to economic incentives and ecological pressures. The first two principal components explained substantial variance in each country (CZ: 79.3%, HR: 77.5%, DE: 76.1%, FIN: 70.2%, ESP: 69.0%; Figure 5), allowing for robust interpretation of the underlying resilience mechanisms affecting revenue streams. A table summarizing the PCA loadings for each case study is provided in Annex IV to highlight the relative importance of each variable and to support the interpretation of the results.

According to the temporal patterns, CZ and ESP showed a transition from conventional forest management to a disturbance-driven system. Both countries exhibited a gradual shift where early years were market-oriented, while later years became increasingly dominated by salvage logging operations. Then, HR exhibits a divergent trajectory, some years strongly influenced by market prices while others are dominated by salvage logging, suggesting potentially competing management strategies. DE showed a cyclic pattern where salvage logging was important in the early years, followed by a regular period, and then intensification of salvage operations in the last years. Finally, FIN showed a distinct multi-phase pattern with an initial year's focus on energy wood, followed by a conventional sawlog orientation, then product-oriented practices with increased salvage logging, and finally, intensified salvage operations.

Regarding the market dynamics and price relationships, CZ and ESP showed sawlog price (MP.SP) separated from pulpwood and energy wood prices (MP.PP and MP.EP) likely reflecting market saturation from salvage logging volume depressing sawlog values. Then, HR showed market prices clustering together but somewhat separated from timber production variables, indicating distinct market dynamics that maintained partial independence from disturbance-driven production changes- a potential buffer against revenue volatility. The DE case study has market prices clustered in one quadrant during middle years and reduced influence during intensified salvage periods. FIN maintained more coherent market price dynamics despite changing production patterns. Potentially due to well-established international trade relationships and industrial capacity to absorb varying product qualities.

The disturbance response mechanisms are different in each of the case studies, CZ showed disturbance-driven harvesting as the primary structuring force with tight integration between salvage operations and production systems; HS.SL, HS.TS and HS.CTL, cluster together, indicating a unified response to disturbances. The salvage logging (HS.SL) in HR aligned with sawlog volume (TP.SP), suggesting salvage operations focus on recovering sawlog material, while total timber supply (HS.TS) aligned with pulpwood and energy wood production (TP.PP and TP.EP). Then, DE showed early engagement with salvage-focused management, with variables like total timber supply (HS.TS) and cut to length (HS.CTL) closely aligned. Uniquely, FIN separated the total timber supply (HS.TS) from salvage logging (HS.SL), indicating different dynamics in how disturbances affect total supply versus focused salvage operations.

From the technological adaptation, CZ, ESP and DE showed strong contribution of cut-to-length (HS.CTL) with disturbance vectors, implying technological adaptation optimized for efficiency in degraded stands. The HR case study with the use of horses (HS.H) was correlated with sawlog prices.

Finally, all five case studies have experienced shifts toward disturbance-driven forest management, but with distinct trajectories and adaptation mechanisms. However, the economic implications of this convergence varied considerably in the last years: CZ showed an association with energy wood, indicating a shift toward lower-value

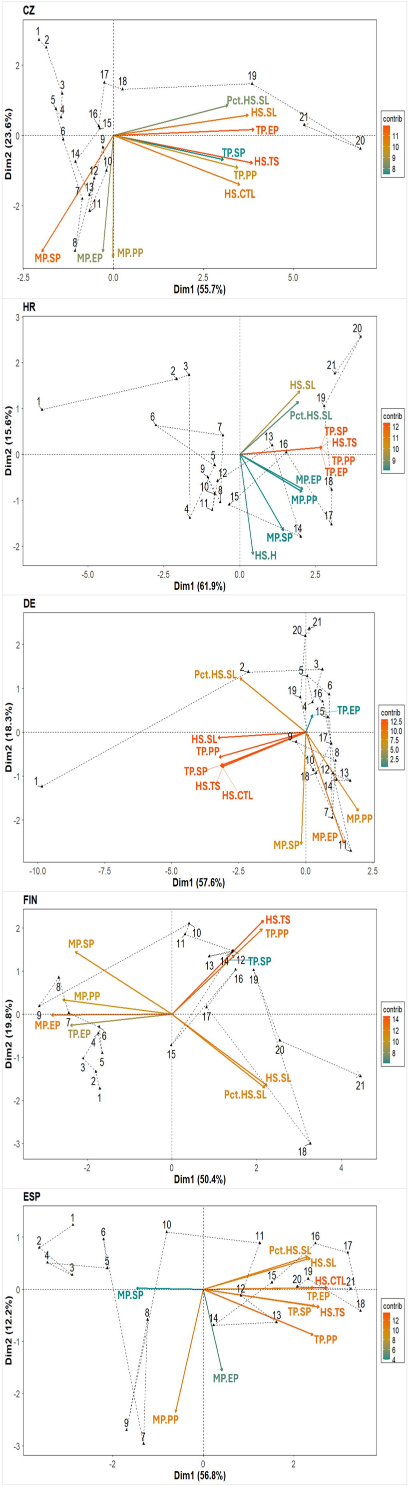

FIGURE 5
Biplot of principal component analysis (PCA), for each case study (CZ, HR, DE, FIN, and ESP) considering predictors of revenue (represented by arrows). Arrows illustrate the direction and the magnitude of each variable's influence. The respective contributions of these variables to revenue are indicated by a color gradient. The observations, depicted as dots, correspond to different years, where "1" corresponds to the year 2001 and "21" to 2021. Temporal trajectories are shown by chronologically connecting yearly points to highlight transitions within their respect case study over time. The complete names of the variable abbreviations are provided in Table 1 of section "2".

products, but maintained revenue streams. The patterns in HR diverge and suggest regional or operational differences in economic adaptation strategies. Due to the longer-term engagement with disturbance management in DE, it showed a cyclic pattern rather than a single transformation. FIN maintains more separation between different product categories despite increasing disturbance influence, and ESP demonstrated a strong-salvage logging focus without clear product differentiation.

The two-fixed effect models were estimated to explain within-country variation in the revenue across the five European case studies from 2001 to 2021 (Table 3). Model A "Scale effects" (Table 4) explained 56% of within-country variation in revenue ($R^2 = 0.562$). All coefficients were positive and statistically significant ($p < 0.01$). Planned harvest volume had the strongest impact: each additional cubic meter increased annual revenue by about 42 USD (±10). A 10 percentage-point rise in the proportion of salvage logging increased revenue by approximately 189,000 USD, indicating that large disturbance events temporarily boost output and sales. Mechanization (use of cut-to-length) also raised revenue, adding about 50 USD per additional percentage-point increase. Price index showed a strong positive effect (≈ 0.5 million USD per unit change), confirming the central role of market conditions. The variance inflation factor (VIF) below 2 indicated no multicollinearity.

Model B "Composition effects" (Table 3) replacing total harvest with the volume of each assortment the explanatory power decline ($R^2 = 0.46$). Volumes of sawlogs, pulpwood and energy wood were not statistically significant once price and mechanization were controlled for ($p > 0.10$). Only the price index remained significant ($\beta = 509403$; $p < 0.001$), suggesting that short-term revenue fluctuations are driven mainly by market prices rather than shifts in harvest composition. VIFs (≤9) confirmed moderate correlation among product categories but acceptable model stability.

The log-scaled version of Model A (Table 4) yielded consistent results and interpretable elasticities: a 1% increase in planned harvest raised revenue by 0.22%, a 10 pp. increase in salvage share by ≈ 11%, and a one-standard deviation rise in the price by ≈ 30%. All effects remained significant at $p < 0.01$, confirming the robustness of the results. Then, across all specifications, harvest scale and market prices emerged as the dominant drivers of the system variable, revenue. Mechanization contributed positively, while the composition of harvest assortments showed limited influence. These results indicate that maintaining harvesting capacity and stable price levels is more critical to short-term economic resilience. Product composition plays a limited role once a total harvest, and price effects are controlled for.

4 Discussion

Our analysis revealed that FVC resilience across the five case studies (CZ, HR, DE, FIN, and ESP) operated through distinct but interconnected mechanisms. The results demonstrate three core resilience dimensions: (1) resistance to market disruptions, (2) recovery capacity following disturbances, and (3) transformation potential through adaptive management. Two distinct adaptation strategies emerged: market-driven adaptation, characterized by price stability and steady timber assortments, and disturbance-driven adaptation, defined by reactive harvesting and technological optimization. The relative effectiveness of these strategies is shaped by regional contexts and disturbance patterns.

Building on the identified dimensions of resilience, consistent production volumes have been associated with reduced vulnerability to short-term market fluctuations, supporting findings by Nikinmaa et al. (2020). This relationship is evident in both PCA and later in the fixed-effects model, which confirmed a positive correlation between timber supply and revenue. In HR, timber supply showed the strongest correlation with revenue (see Table 2). This could have reflected Croatia's regulated market structure, where Croatian State Forest controls distribution through a structured harvesting plan and fixed pricing mechanisms (Sever and Horvat, 1999; Jugovic, 2021). In contrast, moderate correlations in CZ and FIN suggest that other factors, such as disturbance severity, e.g., the large-scale bark beetle

TABLE 3 Two way fixed-effects panel regression models explaining variation in revenue (2001–2021).

Variable	FE Model A (Scale) Estimate	FE Model A SE (clustered by year)	FE Model A *p*-value	FE Model B (Composition) Estimate	FE Model B SE (clustered by year)	FE Model B *p*-value
HS_Planned, m^3	42.254	10.011	0.0000958	—	—	—
PCT_HS_SL01, 0–1	1889700	526980	0.0007321	188815.333	567121.377	0.7405471
HS_CTL, %	49.715	10.304	1.227E-05	40.056	20.087	0.0514932
Price_Index	501750	102030	8.872E-06	509403.256	131072.306	0.0002947
TP_SP, m^3	—	—	—	20.523	34.967	0.5598431
TP_PP, m^3	—	—	—	35.189	70.035	0.6175131
TP_EP, m^3	—	—	—	14.482	46.677	0.7576275
Observations (N)	80		—	80		—
R^2 (within)	0.562		—	0.463		—

Results from two way fixed-effects panel regression models (Model A and B) testing influence of harvesting, mechanization, and market variables on the system variable, revenue. Model A "Scale model" includes planned harvest volume (HS_Planned), salvage share (PCT_HS_SL01), mechanization (HS_CTL), and the price index (Price_Index), while Model B "Composition model" replaces total harvest with product specific assortments (sawlogs, pulpwood and energy wood). Coefficients represent the estimated effect of each predictor on revenue, with standard error (SE) clustered by year and p-values indicating statistical significance ($\alpha = 0.05$). Both models were based on 80 observations across the five case studies (CZ, HR, DE, FIN, and ESP), capturing the temporal variation from 2001 to 2021. The estimate column shows the direction and magnitude of each variable's effect on revenue. The within R^2 values indicate moderate explanatory power (between 0.3 and 0.6) and this allows the comparison between Model A and B in explaining within-country revenue variation over time.

TABLE 4 Log-transformed two-way fixed-effects panel regression Model A.

Variable	Estimate (log)	SE (clustered by year)	*p*-value	Interpretation
ln (1 + HS_PLANNED)	0.21513	0.072613	0.004591	~0.22% ↑ revenue per 1% ↑ planned harvest
PCT_HS_SL01 (0–1)	1.1513	0.34889	0.001751	~11.5% ↑ revenue per +10 pp. salvage share
HS_CTL (%)	0.000016995	0.000005086	0.00155	Small positive semi-elasticity per 1 pp. ↑ CTL
Price_Index_POS	0.29629	0.059922	8.357E-06	~30% ↑ revenue per +1 SD price index
Observations (N)	79		—	

Results from the log-transformed two-way fixed-effects panel regression model (Model A) examining the effects of harvesting, mechanization, and market variables on forest-sector revenue. The log-transformed model captures proportional (percentage-based) relationships between predictors and revenue. The model includes the natural logarithm of planned harvest volume (LN_HS_Planned), the proportion of salvage logging (PCT_HS_SL01), mechanization level (HS_CTL), and the composite price index (Price_Index_POS). Coefficients represent the estimated elasticities, with standard errors (SE) clustered by year and *p*-values indicating statistical significance ($\alpha = 0.05$). Positive coefficients indicate variables associated with higher revenue growth rates. Based on 79 observations across the five case studies (CZ, HR, DE, FIN, and ESP) from 2001 to 2021.

outbreak in CZ, also play a significant role in shaping economic outcomes.

The fixed-effects model was particularly valuable in isolating within-country temporal variation, thereby minimizing bias from structural differences such as ownership regimes, institutional frameworks, or ecological conditions (Wooldridge, 2010). This approach allowed for more accurate identification of the key dynamic factors influencing revenue stability across time rather than across regions. By controlling unobserved heterogeneity, the model strengthens the robustness of the observed relationship between harvesting intensity, mechanization, and price trends; factors previously highlighted as central to forest sector resilience (Hanewinkel et al., 2014; Blattert et al., 2023). Consequently, the fixed-effects model results provide a solid empirical foundation for linking observed market responses to adaptive management mechanisms within national FVCs.

Price trend analysis also revealed regional and timber assortment variations. In general, sawlog prices exhibited greater long-term stability, particularly in HR and ESP, while pulpwood and energy wood prices were more volatile, reflecting external economic shocks, climate-related disturbances and dynamic markets. This relative stability in sawlog prices can be attributed to well-established market structures, as supported by Toppinen and Kuuluvainen (2010), who emphasized that mature market systems can enhance resilience through improved price transmission. These results challenge simplified assumptions that disturbance events inevitably cause price collapse. Consistent with Asada et al. (2023), disturbances may actually lead to an undersupply of high-quality (sawlogs, either due to a reduction in regular harvesting activities or the downgrading of damaged timber) thereby raising sawlog prices rather than crashing them. Notably, energy wood was consistently priced lower across the case studies, with CZ and FIN experiencing significant energy wood price drops in the late 2010s. This price volatility might reflect seasonal in demand fluctuation of energy wood, as storage facilities primarily meet cold-weather needs rather than maintain strategic reserves. Unlike other timber assortments where storage can serve strategic purposes (allowing purchase when prices are low) (Kristöfel et al., 2014; Schipfer et al., 2020) energy wood cannot be easily accumulated. This leaves its market more exposed to short-term demand swings.

Beyond timber supply and pricing mechanisms, the effect of salvage logging was context-dependent. On the one hand, salvage logging operations provided immediate economic relief by capturing value from damaged timber that would otherwise be lost. In the short-term, this can boost harvested volume and revenue. The fixed-effects model indicated that years with higher proportions of salvage wood were often associated with a bump increase in total revenue, reflecting the influx of additional volume to the market. These findings are consistent with Holmes et al. (2008), who noted that salvage logging tended to coincide with subsequent market instability and longer-term price depression, especially for lower-grade wood, as well as raised concerns about overharvesting.

In CZ and DE, where disturbance-driven management increasingly dominated, a more strategic management can improve their overall outlook. As Leverkus et al. (2021), showed well-implemented salvage operations, alongside mechanized harvesting tailored to local conditions, mitigated short-term economic losses. In contrast, HR's limited reliance on salvage logging corresponded with more stable revenues, aligning with Vuletić et al.'s (2014) recommendation for rapid damage assessment frameworks that enable timely market responses and prevent cascading effects. While salvage logging reflects short-term operational responses, broader patterns in revenue offer insight into how different regions absorb and recover from market shocks.

The resilience assessment showed that revenue patterns further illustrated regional variation. In CZ and ESP, revenue spikes following disturbances indicate a strong price effect, where reduced supply or increased demand temporarily boosted revenues. However, sustained breaches of the upper economic resilience threshold suggest a lack of buffering mechanisms and reliance on reactive strategies (Schelhaas et al., 2018). In contrast, FIN and DE showed delayed but stable responses, reflecting the use of storage and phased market release to maintain price stability (Prestemon and Holmes, 2004; Hanewinkel et al., 2014). While HR exhibited steadier but less extreme fluctuations, likely due to administrative management rather than market-driven adaptation. However, this approach raised sustainability concerns, particularly when harvesting intensity exceeded ecological limits, illustrating the tension between short-term recovery and long-term forest health (Puettmann et al., 2015).

In addition, the technological capabilities of each case study also played a key role in enhancing resilience. Mechanized harvesting systems allowed continued productivity under difficult conditions, supporting Hansen and Juslin's (2005) findings on the value of innovation in supporting value-added forestry. The fixed-effects model including mechanization reinforces that higher levels of mechanized harvesting capacity were associated with a smaller drip in harvested volume during disturbance years, suggesting that technology helped dampen the impact of disturbances on production. Tailored deployment of these technologies proved effective in various disturbance contexts. Notably, traditional methods retained relevance in specific settings: in HR, horse extraction (HS.H) correlated positively with sawlog prices, indicating that selective, high-value timber harvesting remains economically viable in certain contexts. This highlights the need for context-sensitive approaches rather than universal reliance on technology.

Among the mechanisms contributing to market flexibility, timber assortment played a particularly important role, especially during supply fluctuations. The segmentation between sawlogs and lower-value assortment illustrates how markets responded to changing supply conditions. This aligns with Březina et al.'s (2024) market saturation theory, which emphasizes the importance of timber assortments during oversupply to maintain timber value. However, results from the composition model (Model B) showed that changes in the relative volumes of sawlogs, pulpwood, and energy wood were not statistically significant predictors of revenue after controlling for price and mechanization. These findings suggested that short-term economic performance depended more on price dynamics than on shifts in harvesting composition, while long-term resilience was linked to the structural benefits of diversification. Enterprises focusing narrowly on a few assortments are likely to face higher processing and transport costs, reduced market flexibility, and greater exposure to price volatility (Latta et al., 2013; Hetemäki and Hurmekoski, 2016). In contrast, maintaining a balanced assortment mix enables cost efficiency and adaptive relocation among markets when shocks occur (like FIN; Toppinen and Kuuluvainen, 2010; Koch et al., 2012). Thus, even though short-term effects were statistically weak, strategic assortment diversification remains a key determinant of long-term economic resilience for the FVC.

The interplay of the above factors led to distinct regional outcomes that subsequently evolved over time as markets adjusted to repeated shocks. Temporal patterns from PCA revealed evolving market structures, especially in regions with longer disturbance histories have undergone adaptive market development. For example, DE exhibited a cyclical price pattern, with temporary price decoupling during salvage peaks followed by a return to stability, illustrating the market's adaptive adjustments. These findings support the view of markets as dynamic systems capable of evolving resilience through repeated exposure to shocks (Scharte, 2024). These changes are also shaped by external factors, like global market integration. In FIN, international trade linkages helped stabilize prices despite supply fluctuations, extending Rametsteiner et al.'s (2007) work on forest sector competitiveness. However, global integration can also increase exposure to volatility and the risk of overexploitation (Hoang and Kanemoto, 2021), highlighting the need for region-specific strategies. Notably, the long-term impacts of the 2008 financial crisis were particularly notable in some regions (Suchomel et al., 2012; Sujova, 2015), with recovery trajectories shaped by regional industrial structures and international trade connectivity.

Institutional legacies, regulatory mandates, disturbance regimes, and industrial capacities jointly shaped the adaptation pathways across the five cases. In Croatia, a state-led forest governance model with long-term harvested plans and fixed pricing constrained excessive swings in supply and enabled a "market-driven" approach. In the Czech case, severe spruce bark beetle outbreaks, combined with legal obligations for prompt sanitary felling, led to a surge in salvage logging. The prevalence of contractor-based operations and widespread use of CTL systems facilitated rapid extraction that frequently exceeded planned harvested levels (Hlásny et al., 2019). In Germany's Upper Rhine case study, the processing capacity forced the use of external contractors when windstorm damage occurred. Finland's case, rooted in private, cooperative forestry with strong industry integration, allowed flexibility in assortments and smoothed out shock impacts, thereby tempering disturbance-driven pluses. Galicia, the Spanish case study, with fragmented private ownership and frequent wildfires, led to reactive salvage management type, often channeling burnt wood into biomass or pulp markets. In summary, Croatian's configuration favored a stable, market-aligned adaptation; Czechia's policy and disturbance context turned its path into a technology-intensive, disturbance-driven model. The other case lay between these poles: Germany mixed planning with episodic reactions, Finland smoothed over disturbance cycles through industrial leverage, and Spain's wildfire regime pushed it toward a reactive harvesting orientation. Ultimately, these findings highlight that responses to disturbance events were shaped by a combination of disturbance regimes, ownership structure, regulatory frameworks, and local processing capacities, underscoring the need for a context-tailored resilience strategy.

Overall, regions with more regulated and moderate market responses (HR, DE, FIN) achieved more stable revenue trajectories. In contrast, market-driven systems (CZ, ESP) experienced sharper but less durable recoveries. These results underscore the trade-offs between short-term gains and long-term resilience. Effective FVC resilience depends on adaptive management and wood processing that integrates economic stability with ecological sustainability, thereby promoting multifunctional forest systems rather than focusing solely on economic objectives (Messier et al., 2021; Hoeben et al., 2025).

Despite the study's comprehensive scope, several limitations should be noted. It focused on five European regions, limiting generalizability to other ecological or institutional settings. Enterprise-level factors such as labor availability, investment decisions, and operational costs (though influential) were not fully captured, underscoring the need for improved databases. In addition, the resilience assessment relied primarily on revenue as a system variable. While revenue offers a consistent and comparable measure across countries, it does not capture other critical dimensions of enterprise resilience, such as profit margins, liquidity, or employment stability. Future research should therefore incorporate a broader set of economic and social descriptors to complement revenue-based analyses. Furthermore, salvage logging data, while widely used, are subject to reporting inconsistencies and temporal mismatches in how harvested volumes are introduced to markets. These limitations highlight the need for more systematic and harmonized salvage logging records across Europe. Finally, while policy frameworks were acknowledged, they were not analyzed in depth and, the resilience assessment was based primarily on revenue metrics; key economic instruments such as subsidies, taxation, and insurance remain underexplored. Future research should integrate these dimensions to provide a more comprehensive view of FVC resilience.

5 Conclusion

Several key patterns emerged from this analysis. First, across all the case studies, total timber supply and market prices consistently emerged as an important predictor of economic stability. Second, salvage logging played a more complex role, functioning as a short-term stabilizing mechanism while potentially contributing to long-term market disruption when exceeding sustainable limits. Third, technological advancements in harvesting operations served as a resilience booster, allowing forest enterprises to maintain productivity under adverse conditions.

The findings suggest that regional approaches to resilience reflect both structural market conditions and disturbance histories. The analysis also offers valuable opportunities for regions to learn from each other. Regions with more reactive, disturbance-drive systems could benefit from adopting elements of structured pricing, assortment diversification, and market buffering observed in HR and FIN. Conversely, countries with regulated systems may draw on the CZ and DE experience to integrate flexible, technology-supported harvesting strategies, particularly in response to increasing disturbance frequency.

From a policy perspective, several implications emerge. Resilience can be enhanced through targeted support for timber assortment differentiation, storage infrastructure, and price stabilization mechanisms, which help mitigate the economic effects of supply shocks. Furthermore, sustainable salvage logging protocols and investment in harvesting technologies should be embedded with broader forest policy frameworks to avoid long-term market disruption. Improved data availability, particularly regarding timber prices, product flow and resilience indicators, is essential for evidence-based decision-making. Finally, fostering coordination across national and international markets is increasingly important in a globalized context where local disturbances can have transboundary economic effects.

These findings translate into actionable strategies at different scales. At the enterprise level, resilience can be strengthened by investing in flexible processing lines for assortment diversification, establishing on-site or corporative storage yards to buffer market volatility, and adopting precision harvesting systems such as cut-to-length to improve efficiency during salvage logging operations. At the regional level, measures include cooperative storage facilities, coordinated pricing mechanisms, and standardized salvage protocols. At the policy level, empirical results point to specific priorities: in CZ and ESP, the strong correlation of CTL systems with revenue resilience supports financial incentives for precision forestry technologies in disturbance-prone areas; in DE, where salvage logging was noticeable driver, developing strategic wood reserves would help mitigate market gluts; in FIN, the stabilizing role of industrial diversity highlights the importance of policies that supports assortment diversification and export flexibility; and in HR, regulated supply structures suggest that price stabilization schemes embedded in long-term contracts may be particularly effective.

Data availability statement

The original contributions presented in this study are included in this article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SG-J: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing, Visualization. AB: Conceptualization, Visualization, Writing – review & editing, Investigation, Methodology. TS: Validation, Conceptualization, Methodology, Writing – review & editing, Visualization. ML: Validation, Funding acquisition, Project administration, Visualization, Writing – original draft. FL: Conceptualization, Writing – review & editing, Validation, Methodology, Visualization. SU: Methodology, Visualization, Investigation, Writing – review & editing. RA: Writing – review & editing, Methodology, Visualization, Formal analysis. JP: Writing – review & editing, Methodology, Data curation. ON: Methodology, Writing – review & editing, Data curation. DV: Data curation, Writing – review & editing. MP: Data curation, Writing – review & editing. LB: Data curation, Writing – review & editing. MJ: Investigation, Conceptualization, Writing – review & editing, Writing – original draft, Funding acquisition, Supervision, Visualization, Validation, Resources.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2025.1653665/full#supplementary-material

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Paper V

Stakeholder views of adaptation measures to improve climate resilience: Case study evidence from European wood value chains.

Hoeben, A. D., Lautrup, M., Willig, J., **García-Jácome, S. P**., Jankovský, M., Toppinen, A., Vuletić, D., Peltoniemi, M. & Stern, T. (2025). Stakeholder views of adaptation measures to improve climate resilience: Case study evidence from European wood value chains. Forest Policy and Economics, 170, 103379. https://doi.org/10.1016/j.forpol.2024.103379

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Stakeholder views of adaptation measures to improve climate resilience: Case study evidence from European wood value chains

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ABSTRACT

This study examines stakeholders' views of the feasibility and effectiveness of climate change adaptation measures across selected wood value chains in Europe based on survey data from 182 respondents. Respondents view the future implementation of adaptation measures as more feasible and effective than present implementation. Managers of conifer forests see more opportunities for implementing measures than managers of non-coniferous forests. This may be ascribed to the many measures currently being applied in countries with even-aged, non-site-adapted vulnerable coniferous forests. Furthermore, measures that predominantly increase resilience against bark beetle outbreaks and windthrow events are viewed more effective in coniferous forests, where these events are more frequent. Softwood processing experts generally consider implementing measures at processing facilities as less feasible and effective than hardwood processing experts. This may be due to the benefits gained by some softwood value chain segments from lower roundwood prices (which also applies to the lower-quality segments of hardwood processing), the more diversified raw material base in the softwood value chain and in secondary and tertiary processing facilities, and the hardwood industry's dominant reliance on high-quality wood, which cannot be harvested prematurely. Policy implications include prioritising measures with high effectiveness and resolving barriers to their feasibility. The findings highlight the need to invest in infrastructure and transition to mixed-species forests to create and manage climate-resilient forests effectively. Non-coniferous forests also require a shift from even-aged to uneven-aged stands. Respondents from the processing industry prioritise investments in infrastructure and acquiring flexible machinery for processing diverse tree species and damaged wood.

1. Introduction

In recent decades, European forests have faced increased abiotic and biotic disturbances (Hlásny et al., 2021; Senf and Seidl, 2020). Extreme weather events, including storms, heat waves and extended periods of droughts, have led to widespread bark beetle outbreaks, tree mortality and forest decline, which have impacted even several commercially important tree species previously thought to be resilient (Nabuurs et al., 2018; Schuldt et al., 2020; Verkerk et al., 2020). This trend is exacerbated by the use of intensive management practices that have favoured homogenous, even-aged forests since the beginning of the twentieth century (Siiskonen, 2007).

In the past ten years, forest owners have increasingly recognised the need to implement adaptation measures to cope with climate change-induced forest changes. Blennow et al. (2012) found that diverse climate change adaptation strategies were used by private forest owners in Europe that were strongly associated with their beliefs in localised impacts and their personal experiences with climate change effects. A follow-up survey conducted in 2016 extended this knowledge, revealing that forest professionals in South and West Europe will not typically implement adaptation measures unless they identify a 'tipping point' signalling a shift to a climate system that they believe will have consistently negative consequences for the forest. Conversely, professionals in North and East Europe demonstrate a more optimistic approach towards changing climate conditions, suggesting that they believe the transition to a climate system will have more favourable consequences for forest production (Blennow et al., 2020). Findings of a 2018 survey conducted in seven European countries revealed that only about one-third of forest owners and managers had implemented adapted management practices in response to climate change. Notably,

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the adoption rates of such practices significant vary, ranging from 14 % in Portugal to 57 % in Slovakia (Sousa-Silva et al., 2018). Roitsch et al. (2023) examined the perspectives of forestry experts in nine European nations regarding climate change impacts and adaptation strategies. Like Blennow et al. (2020), these authors also noted a trend where Northern European professionals tended to interpret climate change effects as less severe than their Southern counterparts. Additionally, two primary approaches to climate change adaptation in forestry were identified: close-to-nature forestry and intensive forestry. These distinct approaches influence how foresters continue to provide multiple forest ecosystem services and which adaptation measures are likely to be adopted in different ways (Roitsch et al., 2023).

Adaptation strategies aimed at reducing forest fires, windthrows, insect pests, root rot and fungal species may involve altering forest management practices and selecting different tree species (Donis et al., 2018; Nabuurs et al., 2018; Pukkala et al., 2016). For instance, converting single-species coniferous forests to mixed forests with broadleaf tree species can enhance forest resilience (see, e.g. Seidl and Turner (2022)). This may decrease the availability of softwood and increase the availability of small-diameter hardwoods in the medium term (e.g. Astrup et al., 2018; Bäucker and Bues, 2009; Verkerk et al., 2022). Such shifts will ultimately affect the roundwood assortments and prices at local and regional levels. Consequently, wood processing industries must adapt by diversifying species utilization, accounting for transportation costs, and strategically selecting the locations of processing facilities (Verkerk et al., 2022).

Forest disturbances not only affect forest management but also trigger a ripple effect[1] that has a dual impact on the wood value chain: It affects both the quantity and quality of harvested wood. Initially, these disturbances lead to a surge in wood supply due to salvage logging (Fuchs et al., 2022; Ning and Sun, 2014; Prestemon and Holmes, 2000; Schwarzbauer, 2007; Sun, 2016; Zhai and Kuusela, 2020; Zhou and Buongiorno, 2006). The quality of wood deteriorates due to various forms of damage, including drying, breakage, insect infestations and fungal infections (Brown et al., 2012; Fuchs et al., 2022; Kolis et al., 2014; Leefers and Potter-Witter, 2006; Loeffler and Anderson, 2018; Sydor and Mendell, 2008). This decline in quality often alters the quality grade ratios of wood available on the market; fewer sawlogs and more pulpwood become available (Asada et al., 2023; Loeffler and Anderson, 2018). Mostly the oversupply (Fuchs et al., 2022), but also the reduced quality of the salvaged wood lower the price of roundwood in the short term (Loeffler and Anderson, 2018). However, the price for high-quality sawnwood (harvested wood from healthy and mature trees) remains largely unaffected (Asada et al., 2023).

While plummeting wood market prices may offer short-term benefits for the wood processing industry, the long-term outlook presents challenges such as declining wood quality, unpredictable wood flows and a gradual shift in tree species composition (RESONATE, 2021). Still, the issue of climate change adaptation in response to forest disturbances has only been relatively marginally addressed in the wood processing industry. Persson et al. (2020) studied forest professionals and found that professionals in Northern European countries tend to anticipate that climate change will have relatively neutral effects on forests as compared to those in Southern Europe, where the professionals tend to have a more negative outlook. In addition, professionals were predominantly pessimistic about the effects of climate change on timber production and economic returns, but mostly optimistic about bioenergy production. Slavec et al. (2023) found that 18 % of enterprises in the wood industry in Austria and Slovenia introduced innovations related to climate change from 2016 to 2018, and 76 % of these introduced innovations related to climate change mitigation, and 38 %, to climate change adaptation. Importantly, these authors also discussed the fact that respondents were prone to overestimation when asked which innovation strategies they had implemented and how these were related to climate change adaptation or mitigation. The authors speculated that this may have been in part because the respondents had implemented innovations that increased the efficiency of processes as part of standard operations, but also because the outcomes led to improved mitigation or adaptation.

Existing studies of supply chain resilience of natural resource value chains in Europe have examined how companies have generally adapted to climate change (e.g. (Emmanuel-Yusuf et al., 2017; Hoffmann and Schöpflin, 2022; Ivanov and Dolgui, 2019). However, few studies have examined the synergies and trade-offs between adaptation at different stages in the value chain. Hoeben et al. (2023) found a discrepancy between the preferred adaptation measures at the beginning of the wood value chain in forest management and towards the end of the value chain in the processing industry. Specifically, adaptation measures in forest management support tree species diversification, whereas those used in the processing industry support processing efficiency, and these two approaches do not always go hand in hand. Bode and Wagner (2015) and Ivanov (2017) showed for supply chains in general that upstream disruptions are more likely to result in ripple effects in the case of single source policy,[2] but that diversification can simultaneously lead to supply complexities and increasingly frequent supply chain disruptions. Furthermore, Schmitt and Singh (2012) found that upstream disruptions (e.g. forest disturbances) in the supply chain may not be felt as quickly as downstream disruptions (e.g. machinery breaking down), but that these impacts can be amplified, outlasting the disruptions themselves.

Strengthening resilience along the entire wood value chain requires integrating the networks of upstream wood suppliers (the forest owners), downstream processors (the wood processing industry) and consumers, as well as encouraging a high level of collaborative work at stages in value chains (Christopher and Peck, 2004; Paloviita and Järvelä, 2019). In this work, we investigate stakeholder beliefs of the feasibility and effectiveness of various climate adaptation measures in the wood value chain and explore factors that influence these views over time. In this context, the following research questions were proposed: How do stakeholders along the wood value chain (in forest management and the wood processing industry) view different climate adaptation measures in terms of their feasibility and effectiveness for increasing climate change adaptation over time, and what factors influence these views? To answer these questions, we distributed an online survey amongst stakeholders and experts working in the forest value chain in selected regions in Europe and asked them to describe their adaptation preferences.

2. Methods

2.1. Data collection

To answer the research questions, an online survey in LimeSurvey (2023) of stakeholders working in the wood value chain in Europe was conducted from mid-April 2023 to February 2024. These included forest managers (e.g. forest owners, managers and public authorities overseeing the forestry sector) and expert stakeholders from the primary, secondary and tertiary processing industries (e.g. experts working in sawmills, pulpmills and biomass plants and further wood processing facilities, as well as public authorities responsible for this part of the wood value chain) (Aggestam and Giurca, 2022).

[1] This is the phenomenon where a disruption or disturbance at one point in the supply chain network propagates and amplifies, causing subsequent disruptions at multiple stages or nodes of the supply chain (e.g. Akkermans and Van Wassenhove, 2018; J. Han and Shin, 2016; Ivanov, 2017; Liberatore et al., 2012)

[2] A single source policy, in a business or procurement context, refers to a strategic decision by an organisation to procure a particular product or service exclusively from one supplier, rather than from multiple suppliers (Monczka et al., 2021).

The survey was provided in seven languages (English, German, Finnish, French, Croatian, Spanish and Czech) and sent out to the nine case study regions of the H2020 RESONATE project (RESONATE, 2021): New Forest (UK), Catalonia (ES) Bauges, (FR), Galicia – Northern Portugal (ES/PT), Finland (FI), Republic of Ireland (IE), Istria (HR), Kostelec (CZ), Upper Rhine Valley (DE) and Austria. These forests represent major European biogeographic regions and diverse forest management regimes and comprise predominantly coniferous forests (FI, CZ and DE), deciduous forests (ES/PT, IE, HR) and mixed forests (FR, ES, UK). Case studies were selected to balance leveraging the existing resilience assessments and to investigate new cases that present unique regional challenges, thus covering important ecosystem service demands and diverse forest value chains.

Data were collected throughout Europe using a convenience sample by disseminating the survey through the networks of the researchers who are part of H2020 RESONATE project (RESONATE, 2021) by speaking with them directly, e-mail and via LinkedIn. Furthermore, we added a question in the survey to ask for further contacts, and we continued snowball sampling from there.

2.2. Survey design: Variables and measures

The survey consisted of four sections containing: (i) an ethics statement related to the voluntary nature of the survey and our data privacy policy; (ii) questions collecting geographic and demographic information from the respondents; (iii) questions measuring their climate change concerns; and (iv) questions to determine preferences regarding the adaptation measures (Supplementary Materials A). The variables and measures are outlined in more detail below.

Concerning the geographic and demographic information, we only asked the respondent to describe which country they operate in and their position along the value chain (i.e. as experts on forest management, the primary, secondary, or tertiary processing industry). In the case of the primary processing industry, respondents were additionally asked what kind of processing facility applied to them (sawmill, pulp mill, biomass powerplant, or a fourth choice labelled 'other'). Based on their group affiliation, they were presented with a separate set of adaptation measures (see Table 1). The dominant forest type in the country and the share of roundwood were added afterwards and were not derived from the survey responses. The dominant forest type and the share of coniferous roundwood were based on the roundwood production data for each country based on the FAOSTAT data (FAOSTAT, 2021). Regarding the former, if a country produced more than 60 % coniferous wood, it was labelled as 'coniferous'; otherwise, it was labelled as 'non-coniferous'. The only exception was made for the respondents from Galicia: Although Spain has a mix of coniferous and non-coniferous forestry, Galicia predominantly produces non-coniferous wood. These respondents were labelled accordingly.

Forest managers were asked to describe how climate change is impacting and has impacted their forest management. Primary and secondary producers were asked to describe how climate change is impacting their company's business model. The participants' climate change concerns were operationalised on a temporal scale. The participants were asked to describe how worried they are about climate change on a Likert scale (1 meaning not worried at all, and 10 meaning very worried), considering both the present situation and one thirty years from now.

The rationale for including a temporal scale is based on the construal level theory of psychological distance developed by Trope and Liberman (2010, 2012) and used by Huff et al. (2017) to study forest owners. In intertemporal choice situations, human decisions are biased towards the present; benefits and losses occurring in the future are usually heavily discounted (Green and Myerson, 2004; Grüne-Yanoff, 2015). Future climate change impacts are often viewed as temporally distant; thus, the construal level theory argues that these impacts are viewed as more abstract and less relevant (Maiella et al., 2020; Tan and Liu, 2018).

Table 1
Adaptation measures addressed in the survey.

Analysis code	Adaptation measures	Reference
FM1	1. Increase wood storage capacities in the forest	Asada et al., 2023; Federal Ministry of Agriculture, Forestry, Environment and Water Management, 2008; Kolström et al., 2011
FM2	2. Reduce disturbance losses through increased sanitation cuts or controlled burning	Amorini et al., 2001; Ganley and Bulman, 2016; Goodwin et al., 2019; Ma et al., 2004; May et al., 2023; Menkis et al., 2016; Meyer et al., 2007; North et al., 2022; Odland et al., 2021; Ryu et al., 2009; Wayman and North, 2007; Zald et al., 2008, 2024
FM3	3. Investment in human and physical infrastructure that enhances adaptation for climate change-related disturbances	Calders et al., 2020; Ersson et al., 2018; Fol et al., 2023; Hoeben et al., 2023; Näyhä et al., 2015; Nitoslawski et al., 2021; Xanthopoulos et al., 2022
FM4	4. Transform even-aged stands to uneven-aged stands	Antonucci et al., 2021; Honkaniemi et al., 2020; Knoke et al., 2023; Ledermann et al., 2022; Neuner et al., 2015; Pretzsch et al., 2021; Vitali et al., 2018
FM5	5. Reduction in stand density and leaf cover	Aldea et al., 2023; Becs et al., 2024; Brooks and Mitchell, 2011; Cushman and Meentemeyer, 2008; Del Río et al., 2017; Giuggiola et al., 2013; Goheen et al., 2012; Hood and Kimberley, 2009; Jules et al., 2002; Lagergren et al., 2008; Navarro-Cerrillo et al., 2019; Pretzsch, 2019; Robinson, 2003; Rosso and Hansen, 1998; Sohn et al., 2016; Van Der Maaten, 2013; Zald et al., 2024
FM6	6. Shortening rotation period	Brang et al., 2016; Felton et al., 2024; Forzieri et al., 2021; Kolström et al., 2011; Ogden and Innes, 2009; Roberge et al., 2016; Seidl et al., 2017a; Yousefpour and Hanewinkel, 2015)
FM7	7. Transform mono-cultures to mixed species forests	Attocchi and Skovsgaard, 2015; Brabec et al., 2023; Brzeziecki et al., 2018; Giberti et al., 2023; Griess and Knoke, 2011; Larsen et al., 2022; Messier et al., 2022; Neuner et al., 2015; Schmidt et al., 2015
FM8	8. Transformation of forests towards tree species that are better adapted to climate change	Aitken and Bemmels, 2016; Bärmann et al., 2023; Pötzelsberger et al., 2020
PI1	1. Increasing resource efficiency	Bösch et al., 2018; Hurmekoski et al., 2021; Mantau, 2015; Schwarzbauer et al., 2013; Suominen et al., 2017
PI2	2. Increase wood storage capacities at secondary processing facilities	Asada et al., 2023; Kolström et al., 2011)
PI3	3. Investment in human and physical infrastructure that enhances adaptation for climate change-related disturbances	Kogler and Rauch, 2023
PI4	4. Innovative approaches to procurement and marketing	Bode and Wagner, 2015; Ericsson and Nilsson, 2004; Fuhrmann et al., 2021; Ghafghazi et al., 2017; Husgafvel et al., 2018; Ivanov,

(*continued on next page*)

Table 1 (*continued*)

Analysis code	Adaptation measures	Reference
		2017; Kalt and Kranzl, 2012; Mantau, 2015; Schwarzbauer et al., 2013; Sikkema et al., 2017; Suominen et al., 2017
PI5	5. Flexible machinery to better process different wood species and damaged wood	Verkerk et al., 2022
PI6	6. Shift away from wood to other (non-wood) materials[a]	Ivanov and Dolgui, 2019
PI7	7. Investing in engineered wood products to increase flexibility regarding raw materials[a]	Brodin et al., 2017; Hurmekoski et al., 2019; Sandra and Alessandro, 2021; Wenger et al., 2020

[a] Questions about adaptation measures 6 and 7 were only asked of respondents from the secondary and tertiary wood processing industry as these are measures that occur further down the value chain.

The last section of the survey comprised questions about preferences for adaptation measures. In the literature, authors propose that viewed adaptive capacity depends on an individual's belief in the efficacy of adaptation measures and the ability to carry out adaptive responses (Grothmann and Patt, 2005). Therefore, in this study we propose that the interpretation of an adaptation measure is based on its feasibility and effectiveness in terms of enhancing resilience towards climate change. We understand the feasibility of a measure to mean how difficult it is to implement a measure regarding financial, human and time constraints. We understand the effectiveness of a measure to mean the success of a measure in helping humans to cope with climate change-related impacts in the forest-based sector, regardless of financial, human and time constraints. The feasibility and effectiveness of each adaptation measure were measured on a Likert scale of 1–10.

The selected adaptation measures (Table 1) were derived from available studies addressing climate change adaptation and innovation in the forest-based sector (A full literature review can be found in the supplementary materials B). Consequently, some of these measures are already in place, such as the transformation of monocultures to mixed tree forests. In contrast, others are relatively novel, such as the investment in engineered wood products to increase flexibility with regard to raw materials. The latter includes the utilisation of lignin as highlighted by Wenger et al. (2020) for applications such as replacing plastics, petrochemicals and polyester (Skog et al., 2015; Skyrman, 2023). The selected measures have not been inconclusively found to positively enhance resilience and are often still under debate in the literature; therefore, it is important to investigate how experts view their feasibility and effectiveness.

With regard to this analysis, only those measures directly related to wood production are discussed. While numerous measures that enhance the ecological resilience of forests and indirectly impact wood production are discussed in the literature (see, e.g. Juutinen et al. (2020) and Marques et al. (2020)), they are not the primary focus here. For example, several studies have shown a positive relationship between the quality and volume of deadwood and biodiversity (Parajuli and Markwith, 2023), specifically as a predictor linked to the bird, insect and fungal richness (Koivula and Vanha-Majamaa, 2020).

2.3. Data analysis

The statistical analysis was performed using R software (version 4.3.1 (2023-06-16) – "Beagle scouts") (Supplementary material C). To address the posed research questions, the data analysis consisted of three main steps that are described in detail in the sections below: (I) data preparation, (II) a descriptive analysis of how adaptation measures were viewed by deriving the mean score and the standard deviation for each adaptation measure, (III) a statistical analysis of the correlations between the adaptation measures and the qualitative variables (country group, level of concern, share of coniferous roundwood and position along the value chain, e.g. in the case of the wood processing industry), and (IV) a statistical analysis of the gap between the feasibility and effectiveness, and present and feature for each adaptation measures (*t*-tests).

To prepare the data for the analyses, we segmented the original dataset into two distinct subsets: One containing the responses from forest management pertaining to their current preferences for adaptation measures and their anticipated preferences for adaptation measures in the future, and the other one containing the responses from processing industry representatives. Prior to analysis, missing values or questions answered with 'I don't know' for the concern, feasibility and effectiveness variables were imputed using Principal Component Analysis (PCA) and by using the imputePCA function (from the "missMDA" package in R). This was the case for 16.4 % of the processing industry and 5.1 % of the forest managers. This was done to avoid having to exclude further variables in the dataset during analysis.

As part of the statistical analysis, the Pearson correlations were derived between the assessment of adaptation measures and the share of coniferous roundwood and level of concern. For the categorical variables indicating the country group (Central Europe, Scandinavia, Southern Europe, Western Europe) and the position in the processing industry (sawmill, pulpmill, biomass plant, secondary processing industry, other) we conducted ANOVA tests to analyse the variance. To identify the exact differences between country groups and value chain positions, we conducted Tukey's HSD (Honestly Significant Difference) post hoc tests. Thereafter, differences between the mean viewed feasibility and effectiveness for each measure were assessed, by conducting paired *t*-tests separately for each forest type, wood processing type, level of concern and country group (present or future). All tests were carried out using the Base package of R.

3. Results

3.1. Descriptive statistics

A total of 333 experts started the survey, of which 151 provided incomplete responses, had a significantly low response time (time values below half of the median; $t < 5$ min), or were experts from outside of Europe. Consequently, the final sample comprises 182 responses, of which 93 experts in forest management and 89 experts in the processing industry. The respective respondent numbers are included in Table 2. As the final sample was small, we merged the countries into four groups: Central European forestry (Austria, Czech Republic, Germany and Slovenia), Western European forestry (Belgium, France and United Kingdom), Fennoscandian forestry (Norway and Finland), and Southern European forestry (Croatia, Italy and Spain). There were 101

Table 2
Sample descriptive statistics.

Position along the value chain	Coniferous / Softwood value chain		Non-coniferous / Hardwood value chain	
	Frequency	Percentage total	Frequency	Percentage total
Forest management	66	19.8 %	27	8.1 %
Primary processing industry	41	15.3 %	27	11.4 %
Sawmill	5	1.5 %	11	3.3 %
Pulpmill	8	2.4 %	0	0.0 %
Bioenergy plant	2	0.6 %	1	0.3 %
Other	4	1.2 %	6	1.8 %
Secondary and tertiary processing industry	32	9.6 %	20	6.0 %

respondents from Central European forestry, 12 from Fennoscandian forestry, 60 from Southern European forestry, and 9 from Western European forestry. Coniferous forestry countries are overrepresented compared to non-coniferous forestry countries.

Differences were observed in the preferences for adaptation measures between those managing coniferous and non-coniferous forests and those in the softwood and hardwood value chain (Figs. 1 and 2). An overview of mean values and the standard deviation of the feasibility and effectiveness for each variable can be found in Supplementary materials D. Amongst the respondents who identified themselves as experts on forest management, higher values were observed for managers of coniferous forests (i.e. mean values ranging 5.4 to 6.8 across adaptation measures) compared to managers of non-coniferous forests (i.e. mean values ranging from about 3.9 to 6.0). In both types of forest management, FM3 (Investment in human and physical infrastructure) and FM7 (Transforming mono-cultures to mixed species forests) exhibited the highest feasibility and effectiveness values in the present and in the future scenarios. FM5 (reduction in stand density and leaf cover) and FM8 (Transformation of tree species that are better adapted to climate change) showed the lowest values. Furthermore, FM1 (increasing wood storage capacities in the forest) showed a relatively low effectiveness value for coniferous forestry, and FM6 (shortening rotation periods) was evaluated as unsuitable in terms of feasibility and effectiveness for non-coniferous forestry. Although they were evaluated unfavourably, the responses regarding these measures still reach values close to or above 5, and thus were not completely irrelevant for participants.

Furthermore, amongst the respondents identifying as processing industry, we found that softwood processing generally exhibited lower feasibility and effectiveness values than hardwood processing. Along both value chains, PI1 (Increasing resource efficiency), PI2 (Increase wood storage capacities at secondary and tertiary processing facilities), PI3 (Investment in human and physical infrastructure), PI4 (Innovative approaches to procurement and marketing) and PI5 (Flexible machinery to better process different wood species and damaged wood) are equally preferred. In contrast, PI6 (shift away from wood to other materials) and PI7 (Investing in engineered wood products to increase flexibility regarding raw materials) are viewed as less suitable, especially in the softwood value chain.

3.2. Effect of covariables on viewed effectiveness and feasibility of adaptation measures

3.2.1. Country group

Country group-specific analyses uncovered disparities in feasibility and effectiveness values, with Southern European respondents generally evaluating measures more positively than those from other regions (Central Europe in particular) (Table 3). Specific differences were analysed by conducting ANOVA analyses. These differences proved to be only significant for PI6 (Shift away from wood to other materials) and

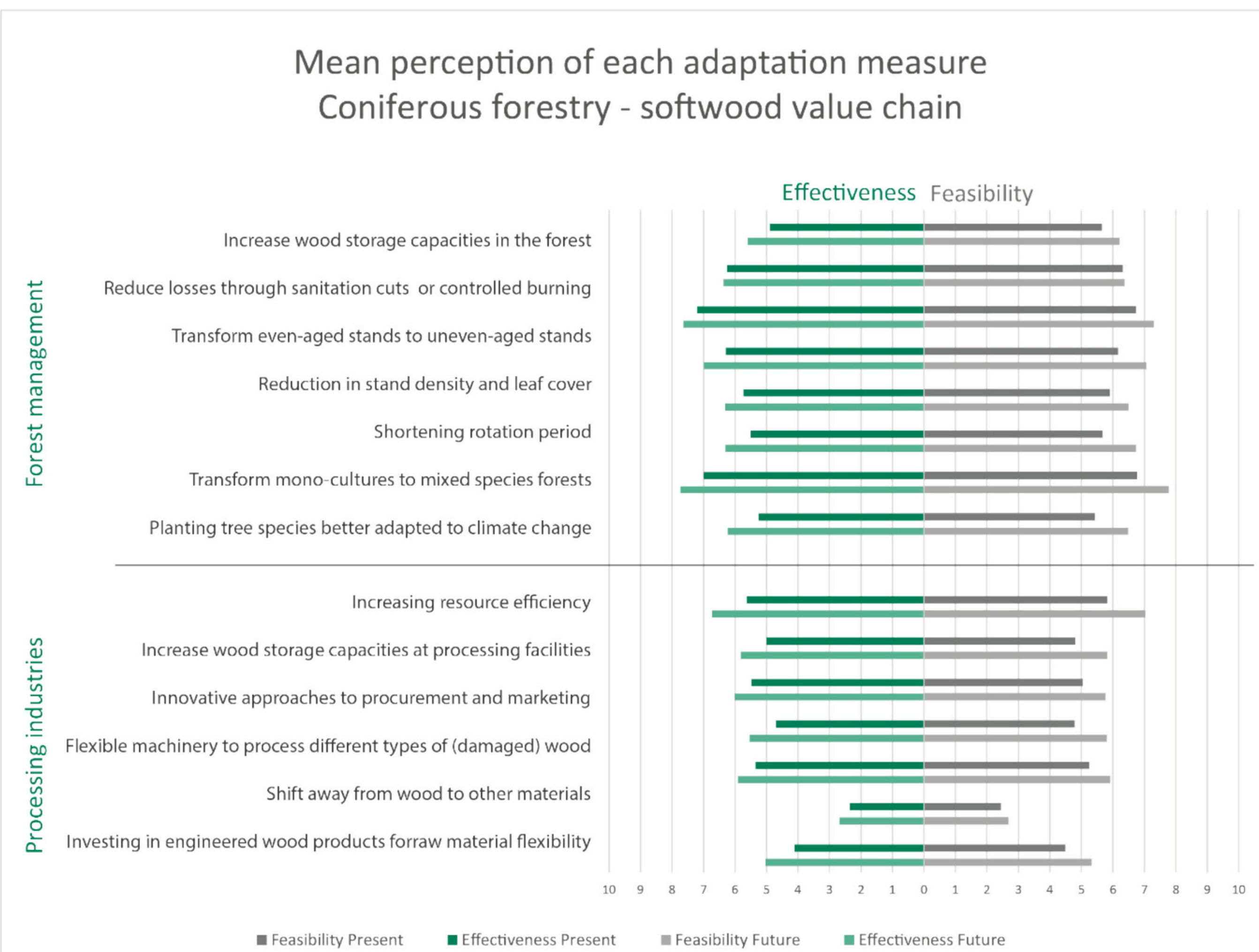

Fig. 1. Mean values for the feasibility and effectiveness of each adaptation measure as viewed by experts on coniferous forest management ($n = 107$) (on a scale from 1 to 10).

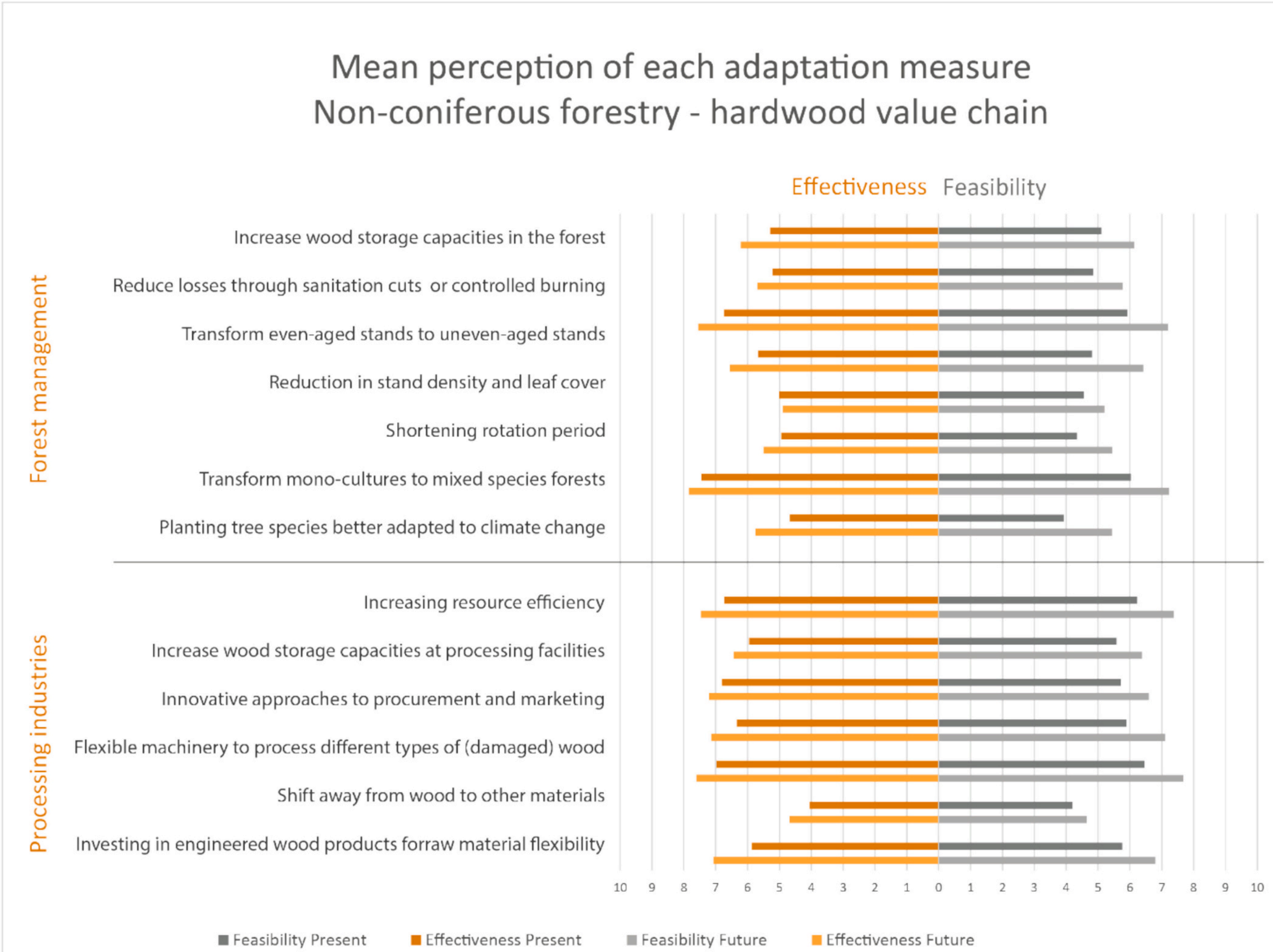

Fig. 2. Mean values for the feasibility and effectiveness of each adaptation measure as viewed by experts on non-coniferous forest management ($n = 65$) (on a scale from 1 to 10).

Table 3
Results of the ANOVA between the country group, and feasibility and effectiveness values in the present and future.

Position	Adaptation measures	Present feasibility		Future feasibility		Present effectiveness		Future effectiveness	
		F-value	*P*-value	*F*-value	*P*-value	*F*-value	*P*-value	*F*-value	*P*-value
Forest managers	FM1	2.173	0.097	1.374	0.256	1.090	0.358	1.306	0.277
	FM2	1.569	0.203	0.575	0.633	0.565	0.639	0.398	0.755
	FM3	0.622	0.603	0.648	0.586	0.079	0.972	0.206	0.892
	FM4	1.832	0.147	0.370	0.775	1.674	0.178	1.286	0.284
	FM5	2.354	0.077	1.461	0.231	0.545	0.653	1.366	0.259
	FM6	1.244	0.299	1.511	0.217	0.243	0.866	0.510	0.676
	FM7	0.716	0.545	0.171	0.916	0.528	0.664	0.356	0.785
	FM8	3.323	0.023	1.470	0.228	2.554	0.060	1.464	0.230
Processing industry	PI1	0.311	0.817	0.339	0.798	1.422	0.242	1.115	0.348
	PI2	2.078	0.109	2.087	0.108	3.420	**0.021***	1.083	0.361
	PI3	2.117	0.104	2.724	**0.049***	2.652	0.054	2.218	0.092
	PI4	2.426	0.071	2.790	**0.045***	6.084	**0.001***	4.170	**0.008***
	PI5	2.362	0.077	4.491	**0.006***	3.156	**0.029***	4.781	**0.004***
	PI6	7.749	**1.24E-04***	6.553	**4.87E-04***	6.808	**3.62E-04***	4.668	**0.005***
	PI7	7.520	**1.60E-04***	6.912	**3.21E-04***	8.916	**3.35E-05***	10.090	**9.35E-06***

PI7 (Investing in engineered wood products to increase flexibility regarding raw materials) in the present scenario and for PI4 (Innovative approaches to procurement and marketing), PI5 (Flexible machinery to better process different wood species and damaged wood) and PI7 in the future scenario.

In a series of Tukey's HSD post hoc tests were conducted to compare the means of different country groups for the adaptation measures that showed significant differences in the ANOVA analyses. In the evaluation of the present situation, we noted that the viewed feasibility and effectiveness of PI6 is significantly higher in Southern European forestry than in Central European forestry. The feasibility and effectiveness of PI7 is viewed as significantly more feasible in both Scandinavian and Southern

European forestry than in Central European forestry. In the evaluation of the future situation, the measures PI4 and PI5 are viewed more feasible and effective by Southern European experts. PI7 is viewed as more feasible and effective by both the Southern European and Scandinavian researchers.

3.2.2. Level of concern

The level of climate change concern amongst forest managers is associated with a higher view of effectiveness for these strategies. However, concern had no significant correlations with the feasibility or effectiveness of any forest management strategies except for FM1 (The increase in wood storage capacities in the forest) and FM2 (Reduce losses through sanitation cuts and controlled burning). The results are slightly different for the processing industry. Significant positive correlations are found between the level of concern and the feasibility and effectiveness of PI1 (increasing resource efficiency), PI4 (Innovative approaches to procurement and marketing) and PI6 (Shift away from wood to other materials) (Table 4).

3.2.3. Share of coniferous roundwood and softwood processing

We explored the Pearson correlations between the mean preference for adaptation measures and the continuous variable share of coniferous roundwood within a country (Table 5). Amongst forest managers, significant outcomes were found between the share of coniferous roundwood within a country and the viewed feasibility of FM4 (Transform even-aged stands to uneven-aged stands), FM5 (Reduction in stand density and leaf cover) and FM8 (Transformation of forests towards tree species that are better adapted to climate change) in the present and of FM6 (Shortening rotation period) in the future, indicating that these measures were regarded more feasible for coniferous forestry than for non-coniferous forestry. Regarding the viewed effectiveness of these measures, only FM1 (Increase wood storage capacity in the forest) and FM5 (Reduction in stand density and leaf cover) proved to be significantly more effective for coniferous forestry.

Amongst responses from the processing industry representatives, significant differences were found between the share of softwood processing within a country and the viewed feasibility of adaptation measures in the present and in the future for PI4 (Innovative approaches to procurement and marketing), PI5 (Flexible machinery to better process different wood species and damaged wood), PI6 (Shift away from wood to other materials) and PI7 (Investing in engineered wood products to increase flexibility regarding raw materials). These results indicate that these measures are viewed as less suitable for the softwood value chain. Concerning the effectiveness of measures, in the present all measures were viewed as being significantly better for non-coniferous forestry by respondents from the processing industries. In the future, this difference decreases for SP1 (Increasing resource efficiency) and SP2 (Increasing wood storage capacities at secondary and tertiary processing facilities), which respondents believed would become more effective over time in both coniferous and non-coniferous forestry.

3.2.4. Position in the value chain

The ANOVA merely revealed statistically significant differences between position and the feasibility and effectiveness of PI5 (Flexible machinery to better process different wood species and damaged wood, and the effectiveness of PI1 (Increasing resource efficiency) (Table 6). A series of Tukey's HSD post hoc tests were conducted to compare the means of different value chain positions for the adaptation measures PI1 and PI5. The secondary and tertiary processing industry consistently views adaptation measures as less feasible and less effective than other segments of the value chain. These findings would suggest that, as one moves along the value chain from sawmilling and pulp production towards downstream processing industries like bioenergy plants and secondary and tertiary processing, the viewed feasibility and effectiveness decrease. However, these results are not statistically significant for bioenergy plants.

3.3. Evaluating the gap between feasibility and effectiveness and present and future

3.3.1. The gap between present and future view

By means of two-sided paired *t*-tests, we found that the view of feasibility and effectiveness is significantly higher in the future than in the present situation for most adaptation measures ($p < 0.05$ except for FM2 (Reduce disturbance losses through increased sanitation cuts or controlled burning)) (Table 7).

3.3.2. The gap between feasibility and effectiveness

T-tests were conducted to explore the differences between viewed feasibility and effectiveness for each measure (Table 8). In the present situation for coniferous forests, significant differences are observed in the assessed feasibility and effectiveness for FM1 (The increase in wood storage capacities in the forest) and FM3 (The investment in human and physical infrastructure). FM1 is considered as more feasible than effective, and FM3 was considered as more effective than feasible. In the future situation, FM1 is still considered as more feasible than effective, which similarly applies to FM6 (Shortening rotation period) and FM8 (Transformation of forests towards tree species that are better adapted to climate change). The difference between the assessed future feasibility and effectiveness for FM3 is not statistically significant; the respondents indicate that it will become more feasible to apply this measure in the future. Regarding non-coniferous forestry, some measures display significant differences, notably FM4 (Transform even-aged stands to uneven-aged stands) and FM7 (Transform mono-cultures to mixed

Table 4
Pearson correlations between the level of concern, and the present and future feasibility and effectiveness values.

Position	Adaptation measures	Present feasibility		Future feasibility		Present effectiveness		Future effectiveness	
		Pearson	*P*-value	Pearson	*P*-value	Pearson	*P*-value	Pearson	*P*-value
Forest managers	FM1	0.135	0.197	0.101	0.334	0.224	**0.031***	0.252	**0.015***
	FM2	0.201	0.053	0.263	**0.011***	0.289	**0.005***	0.287	**0.005***
	FM3	0.01	0.924	0.189	0.069	0.143	0.171	0.142	0.175
	FM4	−0.024	0.820	0.037	0.725	0.125	0.233	0.085	0.416
	FM5	0.058	0.578	0.064	0.540	−0.106	0.311	−0.015	0.889
	FM6	0.05	0.633	0.203	0.051	0.007	0.947	0.162	0.121
	FM7	−0.011	0.916	0.063	0.549	0.109	0.300	0.074	0.481
	FM8	−0.079	0.452	0.07	0.504	0.016	0.880	0.111	0.289
Processing industry	PI1	0.141	0.186	0.245	**0.022***	0.144	0.179	0.246	**0.021***
	PI2	−0.053	0.625	0.09	0.407	0.073	0.496	0.038	0.728
	PI3	0.005	0.963	0.124	0.250	0.155	0.147	0.178	0.097
	PI4	0.239	**0.024***	0.268	**0.011***	0.228	**0.032***	0.304	**0.004***
	PI5	0.187	0.079	0.294	**0.005***	0.192	0.071	0.253	**0.017***
	PI6	0.313	**0.003***	0.343	**0.001***	0.28	**0.008***	0.29	**0.006***
	PI7	0.142	0.184	0.166	0.121	0.198	0.063	0.226	**0.034***

Table 5
Pearson correlations between the share of coniferous roundwood, present and future feasibility and effectiveness values.

Position	Adaptation measures	Present feasibility		Future feasibility		Present effectiveness		Future effectiveness	
		Pearson	*P*-value	Pearson	*P*-value	Pearson	*P*-value	Pearson	*P*-value
Forest managers	FM1	0.014	0.897	−0.049	0.639	−0.15	0.151	−0.18	0.084
	FM2	0.173	0.097	0.034	0.743	0.113	0.282	0.036	0.731
	FM3	0.105	0.318	−0.051	0.627	0.032	0.760	−0.057	0.589
	FM4	0.238	**0.022***	0.089	0.398	0.095	0.366	0.053	0.615
	FM5	0.193	0.063	0.181	0.082	0.111	0.288	0.221	**0.033***
	FM6	0.175	0.093	0.211	**0.042***	0.066	0.532	0.12	0.253
	FM7	0.1	0.340	0.033	0.752	−0.132	0.206	−0.091	0.387
	FM8	0.244	**0.019***	0.133	0.205	0.108	0.304	0.078	0.456
Processing industry	PI1	−0.09	0.400	−0.08	0.454	−0.221	**0.037***	−0.161	0.132
	PI2	−0.137	0.199	−0.103	0.336	−0.217	**0.041***	−0.142	0.185
	PI3	−0.155	0.148	−0.19	0.075	−0.285	**0.007***	−0.256	**0.016***
	PI4	−0.249	**0.019***	−0.271	**0.010***	−0.38	**2.40E-04***	−0.351	**0.001***
	PI5	−0.272	**0.010***	−0.36	**0.001***	−0.338	**0.001***	−0.353	**0.001***
	PI6	−0.45	**9.70E-06***	−0.423	**3.59E-05***	−0.422	**3.73E-05***	−0.366	**4.25E-04***
	PI7	−0.264	**0.012***	−0.301	**0.004***	−0.363	**4.78E-04***	−0.374	**3.10E-04***

Table 6
Results of the ANOVA between the position in the value chain, and feasibility and effectiveness values in the present and future.

Position	Adaptation measures	Present feasibility		Future feasibility		Present effectiveness		Future effectiveness	
		F-value	*P*-value	*F*-value	*P*-value	*F*-value	*P*-value	*F*-value	*P*-value
Processing industry	PI1	1.729	0.151	0.494	0.740	4.874	**0.001***	1.632	0.174
	PI2	1.009	0.408	0.906	0.465	0.301	0.877	0.270	0.897
	PI3	0.263	0.901	0.046	0.996	0.969	0.429	0.322	0.863
	PI4	1.771	0.142	1.026	0.399	0.782	0.540	0.393	0.813
	PI5	2.355	0.060	1.621	0.177	3.082	**0.020***	1.625	0.175
	PI6	0.447	0.775	0.166	0.955	0.272	0.896	0.197	0.940
	PI7	0.271	0.896	0.127	0.972	0.229	0.922	0.171	0.953

Table 7
Results of the *t*-tests between the feasibility and effectiveness values for each adaptation measure in the present and future.

Position	Adaptation measures	Feasibility		Effectiveness	
		T-value	*P*-value	*T*-value	*P*-value
Forest managers	FM1	−4.618	**1.25E-05***	−5.614	**2.08E-07***
	FM2	−1.964	0.053	−1.449	0.151
	FM3	−5.228	**1.07E-06***	−4.119	**8.32E-05***
	FM4	−6.892	**6.75E-10***	−5.325	**7.12E-07***
	FM5	−3.703	**3.64E-04***	−3.093	**0.003***
	FM6	−5.356	**6.24E-07***	−4.311	**4.08E-05***
	FM7	−6.369	**7.40E-09***	−4.544	**1.68E-05***
	FM8	−6.726	**1.45E-09***	−5.598	**2.23E-07***
Processing industry	PI1	−6.778	**1.33E-09***	−5.251	**1.04E-06***
	PI2	−5.214	**1.21E-06***	−4.778	**7.03E-06***
	PI3	−6.319	**1.05E-08***	−3.586	**0.001***
	PI4	−7.657	**2.32E-11***	−5.511	**3.51E-07***
	PI5	−6.317	**1.06E-08***	−4.634	**1.24E-05***
	PI6	−2.821	**0.006***	−2.699	**0.008***
	PI7	−7.946	**5.96E-12***	−7.459	**5.82E-11***

species forests). Both measures are considered as more effective than feasible, but only in a present scenario; their feasibility is expected to increase in the future.

In the softwood processing industry, significant differences between viewed effectiveness and feasibility are detected for PI3 (The investment in human and physical infrastructure) and PI7 (Investing in engineered wood products to increase flexibility regarding raw materials). PI3 is considered as more effective than feasible, whereas PI7 is considered as more feasible than effective. Both statistical differences become unsignificant in the evaluation of the adaptation measures in the future: PI3 is expected to become more feasible, and PI7 is considered to become less effective over time. In the hardwood processing industry, significant differences are found for PI3 (The investment in human and physical infrastructure), PI4 (Innovative approaches to procurement and marketing) and PI5 (Flexible machinery to better process different wood species and damaged wood). Respondents considered all of these to be more effective than feasible. This difference remains statistically significant for only PI3 in the future. Interestingly, PI6 was considered to be more feasible than effective in the future (Shift away from wood to other materials). However, it should be noted that this measure was generally less preferred by the respondents.

4. Discussion

The findings of this study indicate differences between the viewed adaptation potential of coniferous and non-coniferous forests and, consequently, between the softwood- and hardwood value chains. On the one hand, respondents view that it is more feasible and effective to apply measures in coniferous forests than in non-coniferous forests. On the other hand, they also view it as more feasible and effective to apply measures in the hardwood processing industry than in the softwood processing industry. Furthermore, we observe a tendency towards higher predicted feasibility and effectiveness of implementing measures in the future than at present. These results are in agreement with the temporal dimension of the construal level theory of psychological distance (see e.g., Huff et al., 2017 for forest owners and Gifford et al., 2009; Schultz et al., 2014 and Spence et al., 2012 for other

Table 8
Results of the *t*-tests between the feasibility and effectiveness values in the present and future.

Value chain position	Adaptation measures	Coniferous/softwood present		Coniferous/softwood future		Non-coniferous/hardwood present		Non-coniferous/hardwood future	
		T-value	*P*-value	*T*-value	*P*-value	*T*-value	*P*-value	*T*-value	*P*-value
Forest managers	FM1	2.957	**0.004***	2.328	**0.023***	−0.555	0.583	−0.276	0.785
	FM2	0.255	0.800	0.012	0.991	−1.258	0.220	0.221	0.827
	FM3	−2.159	**0.035***	−1.600	0.114	−1.739	0.094	−1.043	0.306
	FM4	−0.619	0.538	0.405	0.687	−2.335	0.028*	−0.589	0.561
	FM5	0.782	0.437	0.861	0.392	−0.973	0.339	0.672	0.507
	FM6	0.907	0.368	2.182	**0.033***	−0.964	0.344	−0.122	0.904
	FM7	−1.070	0.289	0.281	0.780	−2.582	**0.016***	−1.758	**0.090***
	FM8	1.095	0.278	1.850	**0.069***	−1.929	0.065	−0.865	0.395
Processing industry	PI1	0.726	0.471	1.655	0.104	−2.012	0.052	−0.414	0.681
	PI2	−0.726	0.471	0.047	0.963	−1.235	0.225	−0.236	0.814
	PI3	−2.333	**0.024***	−1.222	0.227	−2.992	**0.005***	−2.030	**0.050***
	PI4	0.533	0.597	1.552	0.127	−2.047	**0.048***	−0.239	0.812
	PI5	−0.341	0.734	0.035	0.972	−2.636	**0.012***	0.391	0.698
	PI6	1.268	0.211	0.068	0.946	1.220	0.230	2.208	**0.034***
	PI7	2.305	**0.025***	1.710	0.093	−0.686	0.497	−0.233	0.817

environmental studies).

The findings are interesting in light of current forestry practices. The lower view of the feasibility and effectiveness of the adaptation measures by non-coniferous forest managers might be attributed to different types of disturbances that have occurred and are occurring in coniferous and non-coniferous forests. Coniferous forestry primarily affected by wind and bark beetle disturbances tend to have higher feasibility and effectiveness values across all adaptation measures than non-coniferous forests subjected to forest fires, possibly reflecting the tendency of respondents to assign higher effectiveness to measures that mitigate impacts of bark beetle outbreaks and windthrow events than those that prevent forest fires (Seidl et al., 2017a). Furthermore, converting single-species coniferous forests to mixed forests with deciduous tree species can enhance forest resilience (Bourke et al., 2023; Giberti et al., 2023; Griess and Knoke, 2011; Neuner et al., 2015; Schmidt et al., 2015), and this has been a common practice over the last decade (Forest Europe, 2020). However, integrating coniferous species into a deciduous forest is viewed as more challenging, because the fast-growing coniferous species preferred by the industry are often better adapted to higher altitudes. Furthermore, deciduous trees are generally better adapted to drought, windthrow and bark beetle outbreaks (Verkerk et al., 2022). In this regard, it might be considered as more easy to mix more deciduous tree species (Antonucci et al., 2021; Brzeziecki et al., 2018). However, broadleaved trees may not be inherently better suited to future climates or specific areas, and can be planted in unsuitable habitats, just like conifers can (Carnol et al., 2014; Coll et al., 2018). Furthermore, not all conifer species are alike; some may be well-suited to some regions despite climate change (Cukor et al., 2022; Vacek et al., 2023).

Notwithstanding the above, deciduous forests are increasingly being faced with the consequences of heat and drought (Elizabeth and Arain, 2024). This poses challenges with respect to adaptation efforts for the deciduous forest managers, which may have consequences for the hardwood processing industry in the future (Skog et al., 2015). While the softwood processing industry (and parts of the lower-quality hardwood processing industry) benefits from utilising lower-grade and cheaper timber, parts of the high-quality hardwood processing industry (e.g. the furniture industry) grapples with its reliance on high-quality wood, which cannot be harvested prematurely (Asada et al., 2023). Furthermore, parts of the softwood value chain (e.g. pulpmills and bioenergy production) benefit from lower roundwood prices caused by surges in softwood after salvage logging after major disturbance events (Persson et al., 2020). As an indication, flexible machinery that can be used to more efficiently process different wood species and damaged wood, as well as investments in engineered wood products that allow the more diverse use of raw materials, were found to be less suitable for the softwood value chain than for the hardwood value chain. Moreover, the pulpwood market appears to possess inherent resilience, which is attributed to its diversified raw material base, including the utilisation of recycled fibre in paper production. This broader base facilitates better management of supply-side shocks (Asada et al., 2023).

Moving downstream the value chain, from sawmills and pulpmills to bioenergy plants and secondary and tertiary processing, we find a decrease in both the viewed feasibility and effectiveness of the measures. However, this decrease was not always significant. Nevertheless, it could be attributed to the fact that pulpmills and bioenergy plants often profit from the lowered roundwood prices following a disturbance; therefore, respondents from these sectors viewed the future more optimistically (Persson et al., 2020). It could also be attributed to the diminishing impact of disturbances on processing companies further downstream, where lower-quality wood can be efficiently utilised, reflecting how wood is being downcycled from higher to lower value applications. Another potential explanation could be that the primary processing industry has experienced regional shortages in wood raw material in recent years and is expected to face more in the future (FAO, 2022; Paczkowski et al., 2023). Often this is not the case for the secondary and tertiary processing industries, because they operate on a supra-regional scale (Paczkowski et al., 2023). However, a reduction in sawlog demands or sawlog production has been found to reduce the availability of pulpwood and sawmill by-products (Fuhrmann et al., 2021). In addition, the scarcity of sawmill by-products increases competition between pulp and panel production and energy production (Ericsson and Nilsson, 2004; Ghafghazi et al., 2017; Kalt and Kranzl, 2012).

Our results also seem to indicate that respondents tend to view measures initiated by policy over the last decades more positively, echoing the results of Brunette et al. (2020). Many of the measures surveyed are currently being applied in countries with extensive even-aged coniferous forestry at lower altitudes (e.g. parts of Austria, Germany and Czech Republic) (Forest Europe, 2020). Forest managers, and particularly those managing coniferous forests, tend to view measures that involve, e.g. investments in human and physical infrastructure and the transformation of mono-cultures to mixed species forests as highly feasible and effective. Conversely, measures like reducing stand density and leaf cover were viewed as being less feasible and effective. Therefore, if the adaptation measures that are currently implemented are effective enough, stakeholders might be reluctant to invest in further expensive measures. Additionally, the urgency of climate change effects might also play a significant role in determining the willingness to invest in implementing adaptation measures (Blennow et al., 2012, 2020; Persson et al., 2020; Roitsch et al., 2023).

Another result is that respondents evaluated measures less favourably if there was no unilateral support in the scientific literature that they led to improved resilience against climate change-related disturbances. This was especially the case for forest managers. For example, first, stand density and leaf cover can be reduced to lower competition between trees (i.e. for water and light) (Aldea et al., 2023), lengthen the growing season (Van Der Maaten, 2013), accelerate tree growth (Pretzsch, 2019), maintain mixed species conditions (Becs et al., 2024) and reduce the vulnerability of both coniferous and broadleaved species to forest disturbances (Sohn et al., 2016). On this topic, Giuggiola et al. (2013) has reported findings for dry Scots Pine forests; Aldea et al. (2023), for Scots Pine-Pyrenean Oak forests; Del Río et al. (2017) and Navarro-Cerrillo et al. (2019), for Mediterranean broadleaf environments; and Zald et al. (2024) for mixed-conifer forests. However, numerous studies have indicated adverse effects associated with reducing stand densities, noting a decrease in water availability due to increased transpiration and evaporative losses due to the amplified wind speeds and deeper solar radiation penetration in recently thinned stands (Brooks and Mitchell, 2011; Lagergren et al., 2008). Furthermore, stumps and tree wounds may be prone to infection, and increased traffic in managed areas aids pathogen spread via vectors (Cushman and Meentemeyer, 2008; Goheen et al., 2012; Hood and Kimberley, 2009; Jules et al., 2002; Robinson, 2003; Rosso and Hansen, 1998). Second, regarding the shortening of rotation period, observations indicate that an increasing risk of storm damage correlates with advancing stand age and height (Brang et al., 2016; Forzieri et al., 2021; Seidl et al., 2017b), particularly in Norway Spruce stands (Roberge et al., 2016). However, hydrological integrity, water quality and soil nutrients are sometimes negatively impacted by reducing rotation time (Roberge et al., 2016), and species-specific effects on pest and pathogen resistance are difficult to foresee (Felton et al., 2024). Third, assisted gene flow from populations (from a similar region or regions with the projected future climatic conditions) may increase the resilience of mixed forests to climate change (Aitken and Bemmels, 2016). However, introducing non-native species from distant regions can have adaptation benefits, but can also introduce non-native pests such as fungi and microorganisms and disrupt local food webs (Pötzelsberger et al., 2020).

The findings of this study have important implications for policy and practice in promoting climate adaptation within the forestry sector. Our results indicate that policymakers should prioritise promoting measures with high effectiveness but low feasibility and communicate this to the stakeholders to increase the likelihood of uptake. In the coniferous forestry and the softwood processing industry, this means investing in human and physical infrastructure, e.g. by supporting environmental monitoring and communication, the use of drones, proper road network maintenance (for quicker log transport from affected area) or by training and equipping forest workers properly. In non-coniferous forestry, this involves transforming even-aged stands to uneven-aged stands and transitioning mono-cultures to mixed species forests. Although our respondents believed that these measures would become more feasible in the future, the process urgently needs to be expedited due to the long-time spans involved. In the hardwood processing industry, most respondents seemed to believe that investing in human and physical infrastructure, adopting innovative procurement and marketing approaches and acquiring flexible machinery for processing various wood species and damaged wood made the most sense. This presents a potential win-win situation, as forests can become more diverse, and the industry can prepare by adapting machinery to process new types of wood.

Several limitations should be acknowledged in this study. The sample is small and not representative for the whole of Europe. In addition, a convenience sampling approach was adopted to reach respondents. Both the non-response bias and the convenience sample could have led to a bias towards individuals who are more familiar with climate change, which makes the sample non-generalisable beyond this group. Furthermore, respondents from countries with a dominant deciduous forests and hardwood processing industry were comparatively under-represented. This may have led to a bias in the type of forest owner or processing facility. Moreover, survey-based data collection is subject to a so-called response bias, where participants may provide inaccurate or socially desirable answers. This issue was addressed by ensuring the anonymity of survey responses and emphasizing that the results reflect the respondents' stated preferences, which should be understood as subjective rather than objective facts. Still, these results can be used to detect discrepancies between views and opinions and scientific evidence and guide policymakers towards low-hanging fruits in terms of measures where few monetary incentives are necessary or the uptake is more likely.

Another limitation is the assumption that the value chain operates as a linear system with an optimal cascading of wood use in the primary processing industry from high-value applications to lower-value applications, followed by secondary and tertiary processing. In reality, all types of wood from the forest go to sawmills, pulpmills and bioenergy plants (although very little high-quality wood is burned in a European wood market context) (Aggestam and Giurca, 2022; FAOSTAT, 2021; Wolfslehner et al., 2019). Furthermore, a significant amount of wood (mainly fuelwood) is consumed by landowners and members of forest communities themselves; thus, it never enters the market (Feliciano et al., 2017). Lastly, the size of the forest and the processing facility was not determined after the survey results were received, nor was gender or age of the respondents. Although the results cannot be transferred beyond this sample, our findings indicate that the developed questionnaire can be used in a larger-scale study, and we highly recommend this for future studies.

5. Conclusion

Successful climate change adaptation along the wood value chain requires a better understanding of the feasibility of implementing adaptation measures and their effectiveness for addressing climate change over time. Furthermore, it is critical to understand which adaptation measures are preferred at the beginning of the value chain (amongst forest managers) compared to those at the end (amongst representatives of the processing industry). The study findings uncover stakeholder views on the feasibility and effectiveness of climate adaptation measures applied along the softwood and hardwood value chains in selected cases in Europe, encompassing the beliefs of both forest management and actors at various stages in the processing industry.

While managers of coniferous forests tended to view measures like investment in infrastructure and forest diversification favourably, this study establishes that managers of non-coniferous forests were less optimistic about the feasibility and effectiveness of measures. This may be due to difficulties associated with implementing the measures in non-coniferous forests and differing disturbance regimes. In contrast, adaptation measures applied in softwood processing were considered as less feasible and effective than those applied in hardwood processing. This may be due to the fact that roundwood prices are lower after major disturbance events, benefiting parts of the softwood value chain and parts of the secondary and tertiary wood processing industry. Furthermore, the use of a more diversified raw material base when moving down the value chain and in the lower-grade wood industry facilitates better management of supply-side shocks.

In conclusion, it is essential to understand stakeholders' views about climate adaptation measures along the wood-based value chain in order to design effective policies. By addressing barriers to feasibility and prioritising measures with demonstrated effectiveness, policymakers and practitioners can adapt to the impacts of climate change on forest ecosystems and wood-based industries. To address these aspects, it is critical to foster open innovation activities and raise awareness for the importance of adaptation along the value chain, i.e. in forest management and the processing industries. Our results underline the importance of optimally distributing (especially damaged) wood usage along the wood-based value chain in a cascading manner, enhancing resource efficiency and alleviating pressure on remaining forest stock.

CRediT authorship contribution statement

Annechien Dirkje Hoeben: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marie Lautrup:** Writing – review & editing, Validation, Data curation, Conceptualization. **Julius Willig:** Writing – review & editing, Validation, Data curation. **Sandra P. García-Jácome:** Writing – review & editing, Validation, Data curation. **Martin Jankovský:** Writing – review & editing, Validation, Data curation, Conceptualization. **Anne Toppinen:** Writing – review & editing, Validation, Project administration, Data curation. **Dijana Vuletić:** Writing – review & editing, Validation, Data curation. **Mikko Peltoniemi:** Writing – review & editing, Data curation. **Tobias Stern:** Conceptualization, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve language and readability, minimally and with caution. After using this virtual assistant, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

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The authors declare no conflict of interest.

Data availability

The data will probably be made available in the future in a data sharing repository.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2024.103379.

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