TYPE Original Research
PUBLISHED 17 November 2025
DOI 10.3389/ffgc.2025.1653665

OPEN ACCESS

EDITED BY
Astrid Moser-Reischl,
Technical University of Munich, Germany

REVIEWED BY
Basanta Lamsal Basanta Lamsal,
Michigan State University, United States
Xiangyu Huang,
Central South University of Forestry and Technology, China

*CORRESPONDENCE
Sandra Paola García-Jácome
✉ garcia_jacome@fld.czu

RECEIVED 25 June 2025
ACCEPTED 16 October 2025
PUBLISHED 17 November 2025

CITATION
García-Jácome SP, Brudermann A, Stern T, Lindner M, Lloret F, Uzquiano S, Asada R, Picos J, Nuhlíček O, Vuletić D, Peltoniemi M, Baumbach L and Jankovský M (2025) Factors affecting the forest value chain resilience—a local economic perspective in five European countries.
Front. For. Glob. Change 8:1653665.
doi: 10.3389/ffgc.2025.1653665

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

Sandra Paola García-Jácome[1]*, Annechien Brudermann[2], Tobias Stern[2,3], Marcus Lindner[4], Francisco Lloret[5,6], Sara Uzquiano[4], Raphael Asada[2], Juan Picos[7], Ondrej Nuhlíček[1], Dijana Vuletić[8], Mikko Peltoniemi[9], Lukas Baumbach[10] and Martin Jankovský[1]

[1]Department of Forestry Technologies and Construction, Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Prague, Czechia, [2]Department of Environmental Systems Sciences, University of Graz, Graz, Austria, [3]Kompetenzzentrum Holz GmbH, Linz, Austria, [4]European Forest Institute, Bonn, Germany, [5]Centro de Investigación Ecológica y Aplicaciones Forestales (CREAF), Edifici C, Universitat Autònoma Barcelona (UAB), Barcelona, Spain, [6]Ecology Unit, Department of Biologia Animal, Biologia Vegetal i Ecologia, Universitat Autònoma Barcelona (UAB), Barcelona, Spain, [7]Escola de Enxeñaría Forestal, Universidade de Vigo, Pontevedra, Spain, [8]Department for International Scientific Cooperation in Southeast Europe, Croatian Forest Research Institute, Jastrebarsko, Croatia, [9]Natural Resources Institute Finland (Luke), Helsinki, Finland, [10]University of Freiburg, Freiburg, Germany

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

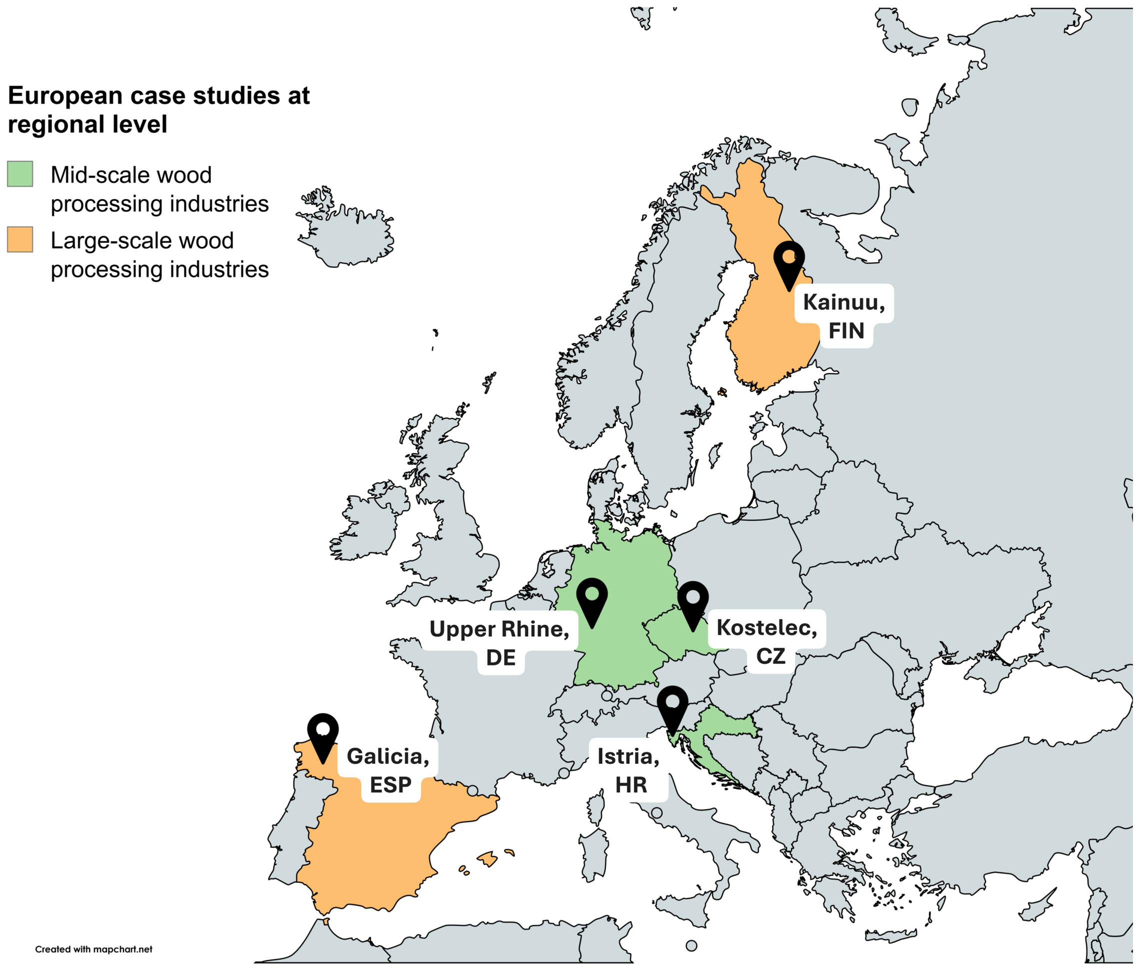

FIGURE 1
Five European case studies by wood processing industry scale: Mid-scale: Kostelec, Czechia (CZ), Upper Rhine Valley, Germany (DE), Istria, Croatia (HR), Kainuu. Large-scale: Finland (FIN), and Galicia, Spain (ESP). Map created with MapChart (https://www.mapchart.net). Licensed under CC BY-SA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

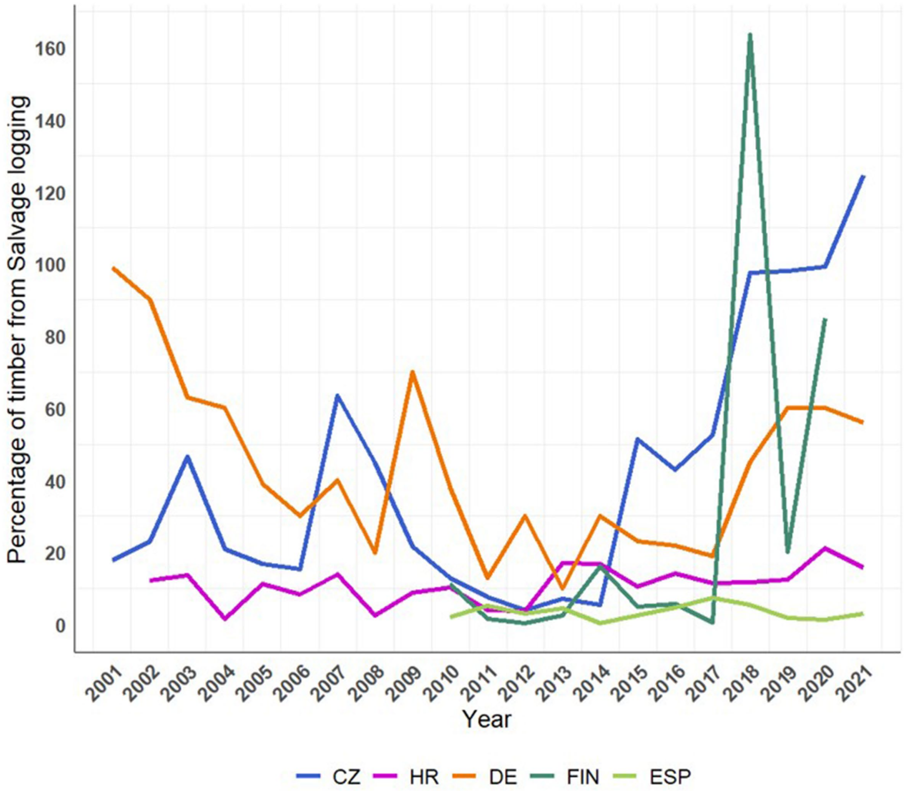

FIGURE 2
Percentage of salvage logging (m^3) related to timber supply, in the five case studies (CZ, HR, DE, FIN, and ESP). When the percentage of salvage logging to timber supply is close to 100, it indicates that a larger portion of timber is from salvage logging likely due to disturbances (e.g., bark 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.

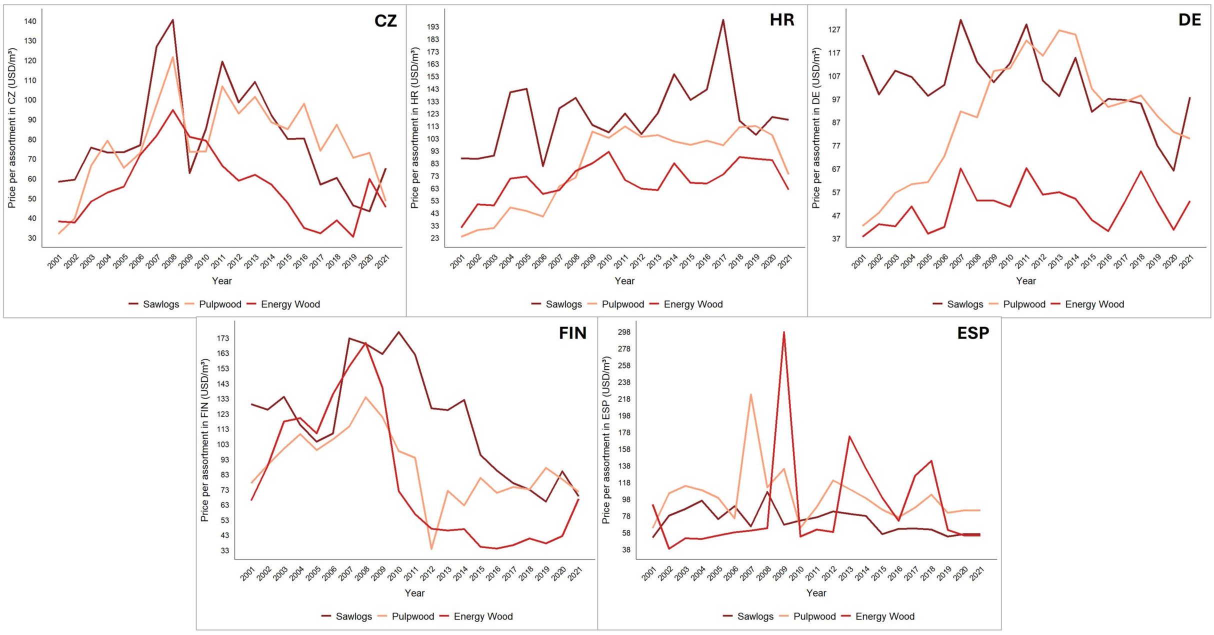

FIGURE 3
Inflation-adjusted price per cubic meter (USD/m3) for sawlogs, pulpwood and energy wood in each case study (CZ, HR, DE, FIN, and ESP) from 2001 to 2021. These metrics provide insights into the economic dynamics of the forest value chain and their resilience to market and environmental disturbances.

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.

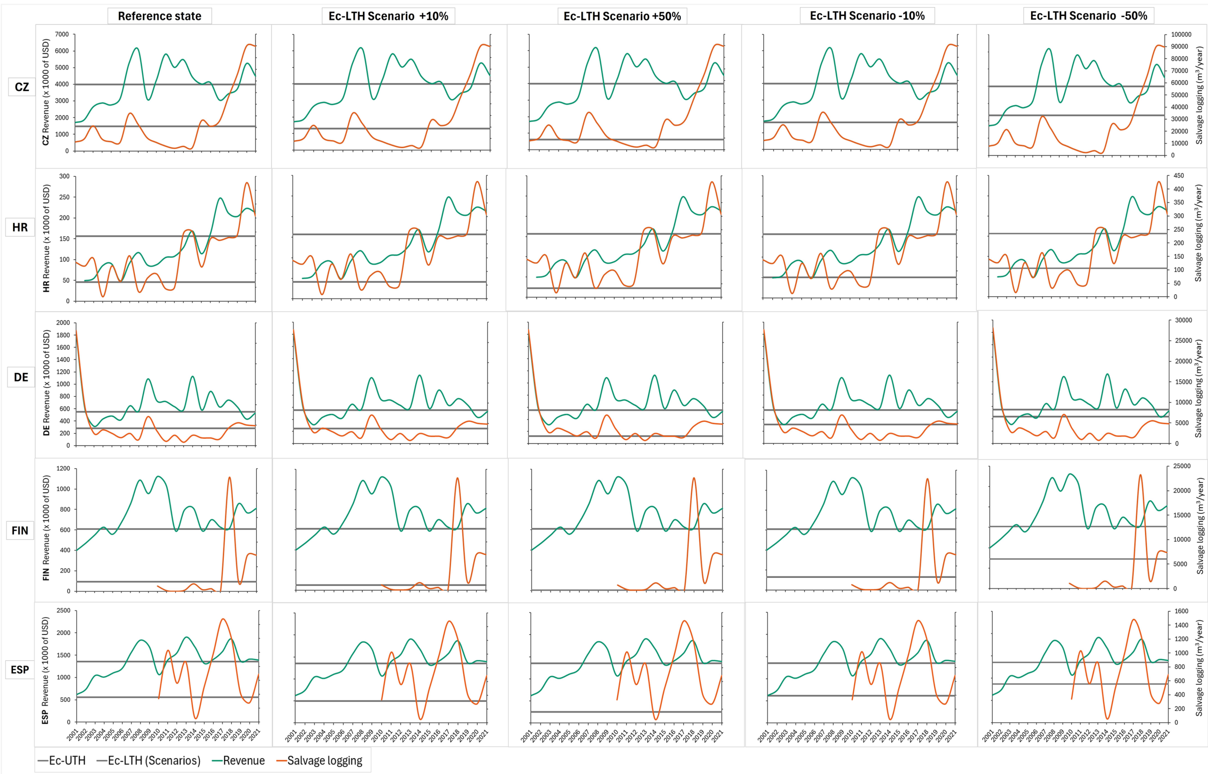

FIGURE 4
Resilience assessment for CZ, HR, DE, FIN, and ESP from 2001 to 2021. The green line shows the revenue; the orange line represents salvage logging volume, a proxy of disturbance level, and the grey lines indicate the upper (Ec.UTH) and lower thresholds (Ec. LTH), specific for each case study, 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

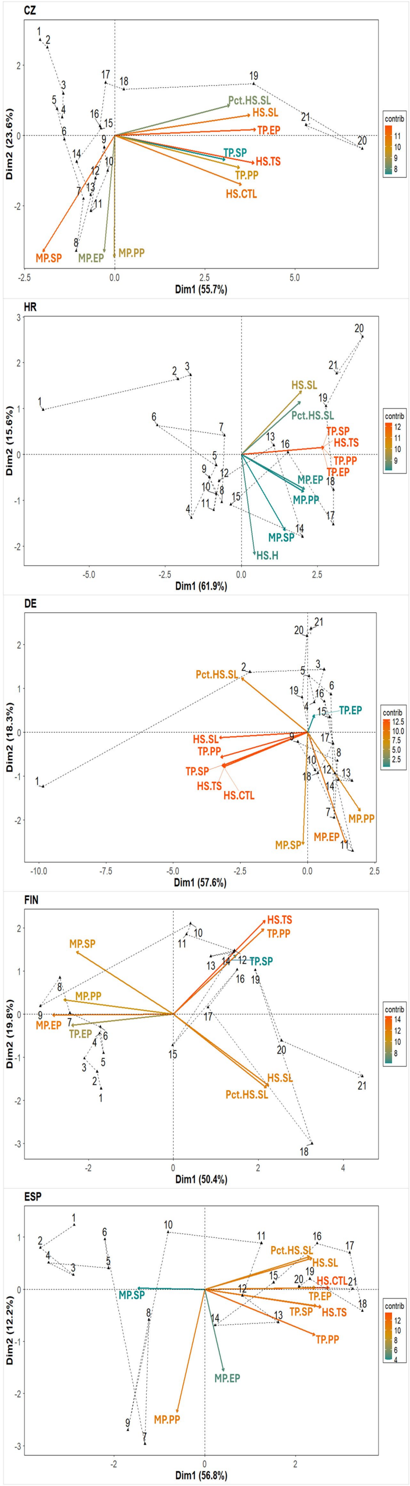

FIGURE 5
Biplot of principal component analysis (PCA), for each case study (CZ, HR, DE, FIN, and ESP) considering predictors of revenue (represented by arrows). Arrows illustrate the direction and the magnitude of each variable's influence. The respective contributions of these variables to revenue are 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.

10.3389/ffgc.2025.1653665

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.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. The research was supported by the RESONATE Project funded by the European Union's Horizon 2020 research and innovation programme under grant agreement number 101000574 and the of the Faculty of Forestry and Wood Sciences of the Czech University of Life Sciences in Prague.

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.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

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

References

Asada, R., Hurmekoski, E., Hoeben, A. D., Patacca, M., Stern, T., and Toppinen, A. (2023). Resilient forest-based value chains? Econometric analysis of roundwood prices in five European countries in the era of natural disturbances. *Forest Policy Econ.* 153:102975. doi: 10.1016/j.forpol.2023.102975

Baho, D. L., Allen, C. R., Garmestani, A. S., Fried-Petersen, H. B., Renes, S. E., Gunderson, L. H., et al. (2017). A quantitative framework for assessing ecological resilience. *Ecol. Soc.* 22:1. doi: 10.5751/ES-09427-220317

Baumgärtner, S., and Strunz, S. (2014). The economic insurance value of ecosystem resilience. *Ecol. Econ.* 101, 21–32. doi: 10.1016/j.ecolecon.2014.02.012

Blattert, C., Mönkkönen, M., Burgas, D., Di Fulvio, F., Caicoya, A. T., Vergarechea, M., et al. (2023). Climate targets in European timber-producing countries conflict with goals on forest ecosystem services and biodiversity. *Commun. Earth Environ.* 4:119. doi: 10.1038/s43247-023-00771-z

Březina, D., Michal, J., and Hlaváčková, P. (2024). The impact of natural disturbances on the central European timber market—an analytical study. *Forests* 15:592. doi: 10.3390/f15040592

Buras, A., Rammig, A., and Zang, C. S. (2020). Quantifying impacts of the 2018 drought on European ecosystems in comparison to 2003. *Biogeosciences* 17, 1655–1672. doi: 10.5194/bg-17-1655-2020

Butry, D. T., Mercer, D. E., Prestemon, J. P., Pye, J. M., and Holmes, T. P. (2001). What Is the price of catastrophic wildfire? *J. For.* 99, 9–17. doi: 10.1093/jof/99.11.9

Christopher, M. (2000). The agile supply chain. *Ind. Mark. Manag.* 29, 37–44. doi: 10.1016/S0019-8501(99)00110-8

Croissant, Y., and Millo, G. (2008). Panel data econometrics in R: the plm package. *J. Stat. Softw.* 27, 1–43. doi: 10.18637/jss.v027.i02

D'Amours, S., Ouhimmou, M., Audy, J., and Feng, Y. (2017). *Forest value chain optimization and sustainability*. Boca Raton, FL: CRC Press.

Ferreira, J., Delgado-Serrano, M. M., and Carmenta, R. (2025). "Relationships between forests and social and economic resilience" in Forests as pillars of social and economic resilience, vol. *45*. (eds.) C. R. Allen, N. Grima, V. Belohrad, and B. Fisher. (Vienna: IUFRO), 43–86.

Ficko, A., Lidestav, G., Dhubháin, Á. N., Karppinen, H., Zivojinovic, I., and Westin, K. (2019). European private forest owner typologies: a review of methods and use. *Forest Policy Econ.* 99, 21–31. doi: 10.1016/j.forpol.2017.09.010

Fuchs, J. M., Bodelschwingh, H. V., Lange, A., Paul, C., and Husmann, K. (2022). Quantifying the consequences of disturbances on wood revenues with impulse response functions. *Forest Policy Econ.* 140:102738. doi: 10.1016/j.forpol.2022.102738

García-Jácome, S. P., Jankovský, M., Hoeben, A. D., Lindner, M., Uzquiano, S., Stern, T., et al. (2025). Forest value chain resilience from a local perspective in five European countries: analysis of predictors and co-drivers. *Front. For. Glob. Change* 7:1461932. doi: 10.3389/ffgc.2024.1461932

González-Gómez, M., Álvarez-Díaz, M., and Otero-Giráldez, M. S. (2013). Estimating the long-run impact of forest fires on the eucalyptus timber supply in Galicia, *Spain. J. For. Econ.* 19, 149–161. doi: 10.1016/j.jfe.2012.12.002

Gower, J. C., Lubbe, S. G., and Le Roux, N. J. (2011). Understanding Biplots. Hoboken, NJ: John Wiley and Sons.

Hanewinkel, M., Cullmann, D. A., Schelhaas, M. J., Nabuurs, G. J., and Zimmermann, N. E. (2014). Climate change may cause severe loss in the economic value of European forest land. *Nat. Clim. Chang.* 3, 203–207. doi: 10.1038/nclimate1687

Hansen, E., and Juslin, H. (2005). Marketing of forest products in a changing world. *N. Z. J. For. Sci.* 35, 190–204.

Henderson, J., and Weiler, S. (2010). Entrepreneurs and job growth: probing the boundaries of time and space. *Econ. Dev. Q.* 24, 23–32. doi: 10.1177/0891242409350917

Hetemäki, L., and Hurmekoski, E. (2016). Forest products markets under change: review and research implications. *Curr. For. Rep.* 2, 177–188. doi: 10.1007/s40725-016-0042-z

Hlásny, T., Krokene, P., Liebhold, A., Montagné-Huck, C., Müller, J., Qui, H., et al. (2019). Living with bark beetles: impacts, outlook and management options, vol. *8*. Joensuu: EFI.

Hoang, N. T., and Kanemoto, K. (2021). Mapping the deforestation footprint of nations reveals growing threat to tropical forests. *Nat. Ecol. Evol.* 5, 845–853. doi: 10.1038/s41559-021-01417-z

Hoeben, A. D., Lautrup, M., Willig, J., García-Jácome, S. P., Jankovský, M., Toppinen, A., et al. (2025). Stakeholder views of adaptation measures to improve climate resilience: case study evidence from European wood value chains. *Forest Policy Econ.* 170:103379. doi: 10.1016/j.forpol.2024.103379

Holmes, T. P., Prestemon, J. P., and Abt, K. L. (eds.). (2008). The Economics of Forest Disturbances: Wildfires, Storms, and Invasive Species, 167–190. Dordrecht: Springer. doi: 10.1007/978-1-4020-4370-3

IPCC, (2022). Climate change 2022. Mitigation of climate change: J. P. R. Shukla, R. Skea, R. Slade, A. Al Khourdajie, R. van Diemen and D. McCollum and et al. (eds.). Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change Cambridge University Press, Cambridge, UK and New York, NY, USA.

Jugovic, R.. (2021). Strategic segmentation of sustainable wood production and processing, World Bank Group. United States of America. Available online at: https://coilink.org/20.500.12592/rc9cbp (Accessed April 23, 2025).

Knoke, T., Paul, C., Gosling, E., Jarisch, I., Mohr, J., and Seidl, R. (2023). Assessing the economic resilience of different management systems to severe forest disturbance. *Environ. Resour. Econ.* 84, 343–381. doi: 10.1007/s10640-022-00719-5

Koch, S., Stern, T., and Schwarzbauer, P. (2012) The influence of seasonality on the wood supply from an Austrian forest association. Available online at: http://oega.boku.ac.at/fileadmin/user_upload/Tagung/2012/Band_22_1/02_Koch_et_al_OEGA_Jahrbuch_2012.pdf

Kristöfel, C., Strasser, C., Morawetz, U. B., Schmidt, J., and Schmid, E. (2014). Analysis of woody biomass commodity price volatility in Austria. *Biomass Bioenergy* 65, 112–124. doi: 10.1016/j.biombioe.2014.03.010

Latta, G. S., Sjølie, H. K., and Solberg, B. (2013). A review of recent developments and applications of partial equilibrium models of the forest sector. *J. For. Econ.* 19, 350–360. doi: 10.1016/j.jfe.2013.06.006

Leverkus, A. B., Buma, B., Wagenbrenner, J., Burton, P. J., Lingua, E., Marzano, R., et al. (2021). Tamm review: does salvage logging mitigate subsequent forest disturbances? *For. Ecol. Manag.* 481:118721. doi: 10.1016/j.foreco.2020.118721

Liubachyna, A., Secco, L., and Pettenella, D. (2017). Reporting practices of state forest enterprises in Europe. *For. Policy Econ.* 78, 162–172. doi: 10.1016/j.forpol.2017.01.019

Lloret, F., Hurtado, P., Espelta, J. M., Jaime, L., Nikinmaa, L., Lindner, M., et al. (2024). ORF, an operational framework to measure resilience in social–ecological systems: the forest case study. *Sustain. Sci.* 19, 1579–1593. doi: 10.1007/s11625-024-01518-1

MapChart. (2025). Available online at: https://www.mapchart.net/europe.html

Messier, C., Bauhus, J., Doyon, F., Maure, F., Sousa-Silva, R., Nolet, P., et al. (2021). The functional complex network approach to foster forest resilience to global changes. *For. Ecosyst.* 8, 1–16. doi: 10.1186/s40663-019-0166-2

Nabuurs, G. J., Delacote, P., Ellison, D., Hanewinkel, M., Lindner, M., Nesbit, M., et al. (2015) A new role for forests and the forest sector in the EU post-2020 climate targets. From Science to Policy 2. European Forest Institute.

Nikinmaa, L., Lindner, M., Cantarello, E., Gardiner, B., Jacobsen, J. B., Jump, A. S., et al. (2023). A balancing act: principles, criteria and indicator framework to operationalize social-ecological resilience of forests. *J. Environ. Manag.* 331:117039. doi: 10.1016/j.jenvman.2022.117039

Nikinmaa, L., Lindner, M., Cantarello, E., Jump, A. S., Seidl, R., Winkel, G., et al. (2020). Reviewing the use of resilience concepts in forest sciences. *Curr. For. Rep.* 6, 61–80. doi: 10.1007/s40725-020-00110-x

Nunes, L. J. (2023). Effects of climate change on temperate forests in the Northwest Iberian Peninsula. *Climate* 11:173. doi: 10.3390/cli11080173

Park, J., Cho, J., and Rose, A. (2011). Modeling a major source of economic resilience to disasters: recapturing lost production. *Nat. Hazards* 58, 163–182. doi: 10.1007/s11069-010-9656-9

Pinto, L. C., Sousa, S., and Valente, M. (2022). Forest bioenergy as a land and wildfire management tool: economic valuation under different informational contexts. *Energy Policy* 161:112765. doi: 10.1016/j.enpol.2021.112765

Prestemon, J. P., and Holmes, T. P. (2004). Market dynamics and optimal timber salvage after a natural catastrophe. *For. Sci.* 50, 495–511. doi: 10.1093/forestscience/50.4.495

Puettmann, K. J., Wilson, S. M., Baker, S. C., Donoso, P. J., Drössler, L., Amente, G., et al. (2015). Silvicultural alternatives to conventional even-aged forest management–what limits global adoption? *For. Ecosyst.* 2:8. doi: 10.1186/s40663-015-0031-x

Rametsteiner, E., Nilsson, S., Böttcher, H., Havlik, P., Kraxner, F., Leduc, S., et al. (2007) Study of the Effects of Globalization on the Economic Viability of EU Forestry. Final Report of the AGRI Tender Project: AGRI-G4-2006-06, EC Contract, 97579.

Riccioli, F., Fratini, R., Marone, E., Fagarazzi, C., Calderisi, M., and Brunialti, G. (2020). Indicators of sustainable forest management to evaluate the socio-economic functions of coppice in Tuscany, Italy. *Soc. Econ. Plann. Sci.* 70:100732. doi: 10.1016/j.seps.2019.100732

RStudio Team (2020). RStudio: Integrated development for R. Boston, MA: RStudio, PBC.

Rubaratuka, D. K., Abdallah, J. M., Gesase, L., and Kitasho, N. M. (2024). The roles of the small and medium enterprises along the forest-based value chain in ruvuma Region, Tanzania. *East African Journal of Forestry and Agroforestry*. 7, 188–199. doi: 10.37284/eajfa.7.1.1950

Scharte, B. (2024). The need for general adaptive capacity—discussing resilience with complex adaptive systems theory. *Risk Anal.* 45, 1443–1452. doi: 10.1111/risa.17676

Schelhaas, M. J., Nabuurs, G. J., and Schuck, A. (2018). Natural disturbances in the European forests in the 19th and 20th centuries. *Glob. Change Biol.* 9, 1620–1633. doi: 10.1046/j.1365-2486.2003.00684.x

Schipfer, F., Kranzl, L., Olsson, O., and Lamers, P. (2020). The European wood pellets for heating market-price developments, trade and market efficiency. *Energy* 212:118636. doi: 10.1016/j.energy.2020.118636

Seidl, R., Spies, T. A., Peterson, D. L., Stephens, S. L., and Hicke, J. A. (2016). Searching for resilience: addressing the impacts of changing disturbance regimes on forest ecosystem services. *J. Appl. Ecol.* 53, 120–129. doi: 10.1111/1365-2664.12511

Senf, C., and Seidl, R. (2021). Storm and fire disturbances in Europe: distribution and trends. *Glob. Chang. Biol.* 27, 3605–3619. doi: 10.1111/gcb.15679

Sever, S., and Horvat, D.. (1999). From centrally planned forest operations to market oriented enterprise (s) in Croatia. In Proceedings of the FAO/Austria expert meeting on environmentally sound forest operations for countries in transition to market economies (pp. 18–23). Rome: FAO.

Sheffi, Y. (2001). Supply chain management under the threat of international terrorism. *Int. J. Logist. Manag.* 12, 1–11. doi: 10.1108/09574090110806262

Spittlehouse, D. L., and Stewart, R. B. (2004). Adaptation to climate change in forest management. *J. Ecosyst. Manag.* 4, 1–11.doi: 10.22230/jem.2004v4n1a254

Standish, R. J., Hobbs, R. J., Mayfield, M. M., Bestelmeyer, B. T., Suding, K. N., Battaglia, L. L., et al. (2014). Resilience in ecology: abstraction, distraction, or where the action is? *Biol. Conserv.* 177, 43–51. doi: 10.1016/j.biocon.2014.06.008

Suchomel, J., Gejdoš, M., Ambrušová, L., and Šulek, R. (2012). Analysis of price changes of selected roundwood assortments in some Central Europe countries.

Sujova, A. (2015). Influence of the economic crisis in 2008 on the performance of companies in wood-processing industry. *Procedia Econ. Financ.* 34, 581–586. doi: 10.1016/S2212-5671(15)01671-8

Svensson, G. (2000). A conceptual framework for the analysis of vulnerability in supply chains. *Int. J. Phys. Distrib. Logist. Manag.* 30, 731–750. doi: 10.1108/09600030010351444

Tampekis, S., Kantartzis, A., Arabatzis, G., Sakellariou, S., Kolkos, G., and Malesios, C. (2024). Conceptualizing forest operations planning and management using principles of functional complex systems science to increase the forest's ability to withstand climate change. *Land* 13:217. doi: 10.3390/land13020217

Toppinen, A., and Kuuluvainen, J. (2010). Forest sector modelling in Europe—the state of the art and future research directions. *Forest Policy Econ.* 12, 2–8. doi: 10.1016/j.forpol.2009.09.017

UNECE/FAO (2021) Price Database. Available online at: https://unece.org/sites/default/files/2021-09/PriceOutputTable.xls

United Nations (2021) UN COMTRADE. International Trade Statistics Database. Available online at: http://comtrade.un.org/

Verkerk, P. J., Delacote, P., Hurmekoski, E., Kunttu, J., Matthews, R., Mäkipää, R., et al. (2022). Forest-based climate change mitigation and adaptation in Europe. From science to policy 14. *Eur. For. Inst.* doi: 10.36333/fs14

Vuletić, D., Kauzlarić, Ž., Balenović, I., and Krajter Ostoić, S. (2014). Assessment of forest damage in Croatia caused by natural hazards in 2014. *South-East Eur. For.* 5, 65–79. doi: 10.15177/seefor.14-07

Walker, B., Holling, C. S., Carpenter, S. R., and Kinzig, A. (2004). Resilience, adaptability and transformability in social–ecological systems. *Ecol. Soc.* 9. Available at: http://www.jstor.org/stable/26267673

Washaya, P., Modlinger, R., Tyšer, D., and Hlásny, T. (2024). Patterns and impacts of an unprecedented outbreak of bark beetles in Central Europe: a glimpse into the future? *For. Ecosyst.* 11:100243. doi: 10.1016/j.fecs.2024.100243

Wooldridge, J. M. (2010). Econometric analysis of cross section and panel data. Cambridge, Massachusetts: MIT press.

World Bank. (2025) World Bank national accounts data, and OECD National Accounts data files. Inflation, GDP deflator (annual %) [Data set]. The World Bank. Available online at: https://databank.worldbank.org/source/world-development-indicators/Series/NY.GDP.DEFL.KD.ZG (Accessed February 18, 2025).

Xu, M., Allenby, B. R., and Crittenden, J. C. (2011). Interconnectedness and resilience of the U.S. economy. *Adv. Complex Syst.* 14, 649–672. doi: 10.1142/S0219525911003335

Zsidisin, G. A., Panelli, A., and Upton, R. (2000). Purchasing organization involvement in risk assessments, contingency plans, and risk management: an exploratory study. *Supply Chain Manag. Int. J.* 5, 187–198. doi: 10.1108/13598540010347307