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Resilient forest-based value chains? Econometric analysis of roundwood prices in five European countries in the era of natural disturbances

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ABSTRACT

Climate change poses a growing threat to European forests due to the increasing frequency and severity of storms, insect outbreaks, and other natural disturbances. Natural disturbances affect both the volume and the quality of harvested wood and increase the tendency of increased salvage loggings, reducing roundwood prices over the short-term. The increase of unexpected inflow of wood resources prompted by disturbance-induced salvage logging can undermine the stability of forest-based value chains. In addition to supply shocks, rebuilding can increase the demand for wood products in regions affected by storms. This study assesses the impact of supply and demand shocks on roundwood prices. An econometric analysis was performed focusing on five forest-rich European countries (Austria, Czechia, Germany, Finland, and Sweden), applying the theory of price transmission and using a set of candidate resilience predictors that were expected to moderate shock impacts. We used annual time series data in differenced form on salvage logging, forest products production and trade, and roundwood prices. We found that disturbances tend to increase the domestic prices of sawlogs, suggesting a shortage effect on high-quality wood. The effect is less pronounced when country-level sawlog exports are high, implying that mainly high-quality sawlogs are exported in the cases in question. For pulpwood, supply shocks tend to decrease pulpwood prices. Strategic logging management and international trade are possible resilience predictors, but their potential is limited and should not be overestimated. Since it is difficult to assess the magnitude by which the changing climate will affect the already increasing disturbance regimes, the results only allow indirect projections to be made about future and larger magnitude events.

1. Introduction

European forests cover over one-third of the land area and are critical to Europe's environment, economy and society (European Commission, 2021). Climate change poses a growing threat to European forests as evidenced by the increasing frequency and severity of storms and other natural disturbances over an increasingly larger scale (Patacca et al., 2023). As a result, forest ecosystem dynamics, ecological resilience and tree species suitability are altered (Seidl et al., 2017). As climate change unfolds, forest management has to cope with short-term and likely long-term impacts on the stability and the capacity to deliver ecosystem services, including wood provisioning (Sousa-Silva et al., 2018). As an indication, income from wood harvests is declining and the forestry-based industry is challenged by unpredictable wood flows and declining wood quality, especially in those regions most vulnerable to climate change (Hetemäki and Hurmekoski, 2016).

Resilience can be understood as the capacity of a social-ecological system to reorganise, adapt and continuously provide ecosystem services in the face of unexpected shocks as well as under gradual, ongoing changes (Folke et al., 2002; Quinlan et al., 2016; Walker et al., 2004) such as climate change (Hurtado et al., 2022). Resilience obeys the basic scheme of "what to what", i.e., it refers to the change in the performance of a system in coping with given disturbances or stressors (Biggs et al., 2012). Little experience and knowledge exist on how to increase climate resilience and the adaptive capacity to cope with climate change-related disturbances in the forest and forest value chains (Seidl et al., 2017).

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Over the last decade, forest owners have increasingly recognised that climate change impacts their forests, yet only one-third reported adapted management practices (Sousa-Silva et al., 2018). This can be ascribed to the fact that forests are often managed on long time scales making it difficult to respond fast to changing environmental conditions (Seidl et al., 2017).

Natural disturbances affect both the volume and the quality of the harvested wood. A disturbance may first cause a supply shock of wood due to salvage logging ("market effect") (Fuchs et al., 2022; Ning and Sun, 2014; Prestemon and Holmes, 2000; Schwarzbauer, 2007; Sun, 2016; Zhai and Kuusela, 2020; Zhou and Buongiorno, 2006) and the wood quality due to damage ("quality effect") (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). The quality can be lowered by broken logs, boreholes from insects, or secondary fungal infection, and lead to alterations in assortment composition from logs to pulpwood (Loeffler and Anderson, 2018). Both the oversupply and the lowered quality reduce the price of roundwood in the short-term (Fuchs et al., 2022; Loeffler and Anderson, 2018). On the other hand, roundwood and stumpage prices are affected by demand shocks such as abrupt changes in the market conditions of the construction sector as a result of derived demand (Banaś and Utnik-Banaś, 2022; Brown et al., 2012; Hood and Dorfman, 2015; Kożuch and Banaś, 2020; Malaty et al., 2007). It has been hypothesized further that interregional and international roundwood trade (Malaty et al., 2007) and prices in other regions have an effect on local prices (Chudy and Hagler, 2020; Hänninen et al., 2007; Malaty et al., 2007; Mei et al., 2010; Prestemon and Holmes, 2000).

The present study follows on from this, but incorporates interaction effects to investigate the extent to which international trade and assortment composition mitigate the impact of supply and demand shocks on roundwood prices. This allows the interpretation of these factors as potential predictors of resilience, assuming that roundwood short-term price stability is critical for the functioning of forest-based value chains. Furthermore, voluntary logging (in distinction from salvage logging) is explicitly included, a predictor that has received only little attention in previous research on roundwood and stumpage prices (for an example see Schwarzbauer, 2007). The objective of this study is to identify predictors of roundwood price resilience with respect to supply and demand shocks and to find the extent to which their effect varies across national forest-based value chains in Europe. We examined short-term value chain resilience in case of (1) supply shocks through salvage logging after a disturbance (windthrow event or bark beetle outbreak) and (2) the price fluctuation through demand changes. We analysed the extent to which the impact of shock events is contingent upon international trade, voluntary logging, and the changes in the composition of harvested roundwood assortments. We employed a time series econometric model for two forest-based value chains (saw milling, pulp milling) in five EU countries (Austria, Czechia, Germany, Finland and Sweden).

Applying the model at the macro-economic scale allows for the assessment of the socio-economic landscape a forest enterprise operates in and adapts its resilience strategy to. On one hand, disturbances are expected to cause short-term oversupply and price reductions in domestic roundwood supply which are most problematic for the upstream part of the value chain (forest owners). On the other hand, demand shocks can cause short-term shortages and price spikes in domestic roundwood supply, which negatively impacts mostly the downstream part of the value chain (consumers).

2. Data and methods

2.1. Data

The data sources and data processing are described below, with a breakdown by data on roundwood and wood-based product flows and unit values, data on domestic roundwood prices, and data on climate-induced natural disturbances. In a number of cases, data gaps existed for single values or periods. To fill these data gaps, imputations were carried out using the value of the first forthcoming year for which data were available to substitute for the missing information.

Data on roundwood and wood-based product flows and unit values were sourced from FAOSTAT (2021), a database with a high temporal and spatial coverage, and uniformity across the national European data. The database contains data on imports, exports, and production of roundwood and derived products for all countries that are subject of this study during the period 1990 to 2020. FAOSTAT includes the relevant roundwood inputs and wood-based product outputs of the value chains studied (Table 1). The data were compiled in a two-step process including (1) the exclusion and harmonisation of FAO classification items and (2) the disaggregation of roundwood trade flows.

First, the FAO classification items were harmonised to resolve issues arising from splits and mergers of items over time and to avoid double-counting of values reported at multiple levels of aggregation. Second, COMTRADE (United Nations, 2021) data were used to obtain sawlog and pulpwood shares of the roundwood trade reported by FAO (SITC Rev.2, exports of commodities 2471, 2472, 246). As COMTRADE reports data in mass units while the FAO statistics present roundwood trade flows in terms of volumes, the data were converted accordingly. We assumed that the shares of sawlogs and pulpwood measured in mass units equal the volume-based shares. Since the SITC Rev.2 classification does not distinguish between coniferous and non-coniferous pulpwood flows, equivalence between pulpwood and sawlogs was further assumed with regard to their proportion of coniferous and non-coniferous wood. The sawlog and pulpwood shares in monetary terms were determined separately.

To compile domestic sawlog and pulpwood prices, we used the average values of all reported periodicities (e.g., annual, quarterly, monthly) from various data sources. Data for Austria, Germany, and Finland originate from the UNECE/FAO price data base (UNECE/FAO, 2021), data for Czechia was sourced as part of the RESONATE project (H2020-RUR-2020-2 Grant n. 101,000,574) and data for Sweden were retrieved from the Swedish Forest Agency (Skogsstyrelsen, 2017). For data sources which provided price data separately for hardwood and softwood, we have only considered softwood prices.

To construct disturbance national time-series, we retrieved data from

Table 1
Studied forest-based value chains with their respective roundwood inputs and wood-based product outputs.

Forest-based value chain	Roundwood inputs (assortments)	Wood-based product outputs
Sawmills	Sawlogs and veneer logs, coniferous Sawlogs and veneer logs, non-coniferous Sawlogs and veneer logs (export/import)	Wood chips and particles Wood residues Sawnwood, coniferous Sawnwood, non-coniferous all Veneer sheets Plywood
Pulp mills	Pulpwood, round and split, coniferous (production) Pulpwood, round and split, non-coniferous (production) Pulpwood, round and split (export/import)	Mechanical wood pulp Semi-chemical wood pulp Chemical wood pulp, sulphite, unbleached Chemical wood pulp, sulphite, bleached Chemical wood pulp, sulphate, unbleached Chemical wood pulp, sulphate, bleached Dissolving wood pulp Pulp from fibres other than wood Mechanical and semi-chemical wood pulp Chemical wood pulp, sulphite

Table 2
Expected effect directions (signs) of explanatory variables on roundwood prices (10^6 LCU/10^6 m^3) and interactions.

Explanatory variable	Expected sign	Expectation reasoning	Sources supporting expectation
Product unit value (10^6 LCU†/10^6 PU††)	+	Indicates demand shocks; increases demand for domestic roundwood and thus increases domestic roundwood prices.	Banaś and Utnik-Banaś, 2022; Brown et al., 2012; Hänninen et al., 2007; Hood and Dorfman, 2015; Kożuch and Banaś, 2020; Malaty et al., 2007; Tomek and Kaiser, 1999; Zhou and Buongiorno, 2006
Salvage logging (10^6 m^3)	–	Indicates supply shocks; increases domestic roundwood supply and thus reduces domestic roundwood prices.	Fuchs et al., 2022; Ning and Sun, 2014; Prestemon and Holmes, 2000; Schwarzbauer, 2007; Sun, 2016; Zhai and Kuusela, 2020; Zhou and Buongiorno, 2006
Roundwood imports (10^6 PU)	no expectation		
Roundwood exports (10^6 PU)			
Voluntary logging (10^6 m^3)			
Assortment share (10^6 m^3/10^6 m^3)†††			
Product unit value * Roundwood imports	–	If demand shocks are accompanied by increased roundwood imports, the demand for domestic roundwood is reduced; thus, the positive effect of demand shocks on domestic roundwood prices is mitigated.	Deduced from previous findings, according to which roundwood imports reduce domestic roundwood prices (Malaty et al., 2007); thus, the effect of demand shocks on domestic roundwood prices may be moderated by imports.
Salvage logging * Voluntary logging	+	If roundwood supply shocks due to salvage loggings are accompanied by increased voluntary logging, the total supply of roundwood to domestic markets is increased; thus, the effect of supply shocks on domestic roundwood prices is reinforced.	Deduced from previous findings, according to which voluntary logging partly compensates for the amount of salvage logging (Schwarzbauer, 2007) and thus may moderate the effect of the latter with respect to domestic roundwood prices.
Salvage logging * Roundwood exports	–	If roundwood supply shocks due to salvage loggings are accompanied by increased roundwood exports, the supply of roundwood to domestic markets is reduced; thus, the negative effect of supply shocks on domestic roundwood prices is mitigated.	Deduced by analogy with the Product unit value * Roundwood imports hypothesis.
Salvage logging * Assortment share	+	If roundwood supply shocks due to salvage loggings are accompanied by an increased share of sawlogs (pulpwood) in total industrial roundwood supply, the supply of sawlogs (pulpwood) to domestic markets is increased; thus, the negative effect of supply shocks on the domestic sawlog (pulpwood) price is reinforced.	Deduced from previous findings, according to which salvage logging may be associated with a deterioration in the quality of roundwood supply (e.g., less sawlogs, more pulpwood) (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); thus, the assortment composition is hypothesized to moderate the effect of salvage logging on domestic roundwood prices.

† LCU = Local Currency Unit.
†† PU = Physical Unit.
††† The share of the harvest of the respective assortment (e.g., sawlogs for the sawmill value chain) compared to the total harvest.

the Database of Forest Disturbances in Europe (Patacca et al., 2023; Schelhaas et al., 2020). First, we extracted all records of wood volumes damaged by disturbances at national or sub-national levels for Austria, Czechia, Germany, Finland and Sweden. Thereafter, we selected the detailed records of damage caused by wind (including cyclonic storms, thunderstorms and tornadoes) and spruce bark beetles (Ips typographus, L. feeding on *Picea abies*, L., H. Karst) following (Patacca et al., 2023). Second, we cleaned the data to arrive at a single reported value for each year, each country and each disturbance agent. For this purpose, we removed duplicate data points (e.g., where a report from an individual region was also included in a nationally reported summary). Thereafter, we selected peer-reviewed scientific papers and (inter)national reports or databases. When several values were reported for the disturbance event, we selected the value from the most consistent source in terms of continuity and applied method. This means that we gave preference to longer time-series to ensure consistency in the analysis across years. In cases when two or more sources had the same reporting length, we investigated further the method applied for assessing and reporting the damages, and selected the source with the most comprehensive method description (see Patacca et al., 2023 for further details). When needed, timber volume under bark was converted to timber volume over bark following Schelhaas et al. (2003).

2.2. Methods

The demand side was considered by using the theory of derived demand and price transmission between market levels (e.g., Tomek and Kaiser, 1999; Zhou and Buongiorno, 2006). A positive demand shock for wood-based products (e.g., sawnwood) increases roundwood (e.g., sawlogs) demand and price until a new market equilibrium is reached (see, e.g., Hänninen et al. (2007) in European markets). While the effect may not be entirely exogeneous, end product prices can be expected to drive the roundwood prices rather than vice versa (Sun, 2016). To a lesser extent, the roundwood assortment price is also driving the product price as this one is dependent on the cost of labour, material inputs, capital (interest rate) the cost of energy and other production costs.[1] Assuming that the wood-processing industry strives to minimise its costs, on the one hand, the expected consequences of demand shocks may be counteracted by increased roundwood imports and intensified wood storage exploitation. On the other hand, a positive supply shock (e.g., due to salvage logging following a windthrow event) is expected to increase domestic roundwood supply (combined of salvage and voluntary logging) and thus reduce roundwood prices (e.g., Schwarzbauer, 2007). The forest-based sector may respond to expected consequences of supply shocks with reduced voluntary logging, increased roundwood exports, increased storage,[2] and changed assortment composition (i.e., increased shares of pulpwood in total industrial roundwood removals). Table 2 provides a full overview of the expected effects.

The OLS (ordinary least squares) estimation of the effect of potential

[1] A 2SLS estimation was carried out in addition to the OLS estimation. For this purpose, instrument variables were formed from lagged wood-based product unit values and voluntary logging levels. However, it was found that this approach did not produce useful results. Due to the lack of suitable instrument variables, we do not report 2SLS estimates in this study.

[2] Changes in roundwood storage cannot be included in the analysis due to lack of data availability.

reactions of market actors on demand and supply shocks was performed separately for each forest-based value chain (Table 1) and country according to Eq. (1),

$$y_t = \beta_0 + \beta_1 x_{t1} + \ldots + \beta_6 x_{t6} + u_t \tag{1}$$

in which the domestic roundwood price (y_t) at year t is explained by a constant (β_0), the wood-based product export unit value (henceforth product unit value) (x_{t1}), roundwood imports (x_{t2}), roundwood exports (x_{t3}), voluntary logging (x_{t4}), salvage logging (x_{t5}), the share of roundwood used in the value chain under study in total logging (x_{t6}) and an error term (u_t) (the units are displayed in Table 3).

Product unit values (x_{t1}) reflect demand-side effects including demand shocks, while salvage loggings (x_{t5}) indicate disturbance-induced supply shocks. The potential reactions on supply and demand shocks were captured by the four remaining independent variables (x_{t2}, x_{t3}, x_{t4}, x_{t6}). It is hypothesized that these predictors mitigate the negative effects of disturbances. To account for the moderating nature of reactions on demand and supply shocks with regards to domestic roundwood prices, four interaction terms were added (Eq. (2)).

$$y_t = \beta_0 + \beta_1 x_{t1} + \ldots + \beta_6 x_{t6} + \beta_7 x_{t1} x_{t2} + \beta_8 x_{t5} x_{t4} + \beta_9 x_{t5} x_{t3} + \beta_{10} x_{t5} x_{t6} + u_t \tag{2}$$

We used the first differences of the log-transformed data as Augmented Dickey-Fuller and Phillips-Perron test results have shown a clear improvement in the stationarity of time series (see the Supplementary Information for further details). The interaction variables were formed by multiplying the log-transformed sub-variables before differencing.

The analysis included estimation of the full OLS models (without [Eq. (1)] and with interaction terms [Eq. (2)]) and model selection based on Akaike Information Criterion (AIC) (Akaike, 1974). Combinations of predictors were tested and the model with the lowest AIC score was selected as the best model. This ensures a balance between a high goodness of fit of the models on the one hand, and a low number of predictors on the other. For the best models that include interaction terms, all involved sub-variables (i.e., main effects and moderating effects) were included in the specification. On this basis, the significant (1%, 5%, 10%) OLS estimates were interpreted if the respective model was significant overall.

In order to determine the extent to which an oversupply situation with roundwood volumes is responded to by means of a reduction in imports, an estimate of the Armington elasticities of substitution (hereafter referred to as Armington elasticities) is useful to complement to the main analysis. Adopting an approach described by Lundmark and Shahrammehr (2012), Armington elasticities measure the degree of substitutability between domestically harvested and imported roundwood. A high Armington elasticity indicates a high degree of substitutability and thus a role for roundwood trade as a resilience predictor.

The OLS estimations of the Armington elasticities were conducted separately for each forest-based value chain (Table 1) according to Eq. (3),

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + u \tag{3}$$

where roundwood imports per unit of consumption of domestic roundwood (y) (i.e., domestic roundwood production less roundwood exports) are explained by a constant (β_0), the domestic roundwood price divided by the roundwood import unit value (x_1), a time variable (x_2), and an error term (u). The estimated coefficient for x_1, β_1, is the Armington elasticity. The variables y and x_1 were subjected to a log-transformation.

Along with all model parameter estimates, we report results from a number of diagnostic tests (Durbin-Watson, Jarque-Bera, Breusch-Pagan, Rainbow) to test the residuals for the absence of serial correlation and for normal distribution and homoscedasticity, as well as the model specification for linearity. All OLS estimates and diagnostic tests were conducted using the Python module statsmodels (Seabold and Perktold, 2010).

3. Results

Table 3 summarises the significant ($p < 0.1$) coefficient estimates originating from the AIC-selected reduced model solutions. The model has a log-log functional form, i.e., the coefficients can be directly interpreted as elasticities (a 1% increase in the annual change in x_1 increases the annual change in the domestic roundwood price by β_1%). More detailed result tables including the diagnostic tests can be found in the Supplementary Information.

3.1. Sawlog market

Demand shocks were positively associated with sawlog prices with significant effects for Czechia, and, if interaction effects are omitted, also for Austria and Finland. Supply shocks presented positive effects on sawlog prices in some countries (Germany and Sweden, and, if interaction effects are included, also Czechia). If interaction effects are not considered, supply shocks exhibited a negative effect on sawlog prices in Austria. Sawlog imports (exports) tended to be positively (negatively) associated with sawlog prices (Czechia and Germany). For supply shocks, both positive (Finland, Sweden) and negative effects (Czechia) on sawlog prices were found. The share of sawlogs in total logging volume inclined towards a positive effect on sawlog prices (Austria, Germany). As for the interaction effects, roundwood imports increased the (insignificant negative) effect of demand shocks on sawlog prices in Finland. Voluntary logging and sawlog exports tended to mitigate the (positive) effect of supply shocks on sawlog prices (Sweden, partly Czechia), while the share of sawlogs in total harvest amplified the (positive) effect of supply shocks (Czechia).

Significant positive Armington elasticities have been identified in two countries (Czechia, Finland), indicating substitutability between domestically harvested and imported sawlogs.

3.2. Pulpwood market

Demand shocks did not have significant effects on pulpwood prices. Supply shocks negatively affected pulpwood prices in Sweden, when interaction effects are taken into account. If interactions are omitted, for pulpwood exports and voluntary logging, we found a positive effect on pulpwood prices in Finland. The assortment share was positively associated with pulpwood prices in Finland and Sweden. Considering interaction effects, roundwood imports increased the (insignificant negative) effect of demand shocks on pulpwood prices in Sweden. No significant moderating effect was shown for voluntary logging. Pulpwood exports tended to mitigate the (negative) effect of supply shocks on sawlog prices (Sweden).

A positive and significant Armington elasticity was found in Czechia, where pulpwood imports may be a substitute for pulpwood from domestic origins to some degree. A significant negative Armington elasticity was shown in Sweden, suggesting that a high price for domestic or imported pulpwood had a positive effect on roundwood consumption from the respective origin (Lundmark and Shahrammehr, 2012). However, this is not an intuitive result and instead points to the presence of possible measurement errors.

4. Discussion

Estimation of the econometric models was more successful in sawlog markets than it was for pulpwood. The reason for this may be found in the different characteristics of the related value chains, i.e., pulpwood market seems inherently more resilient due to a broader industry raw material base (including also use of recycled fibre in paper production), which better accommodates managing supply-side shocks.

A number of effects turned out as anticipated in the majority of cases

Table 3

Quantities of roundwood logging, processing and international trade (mean and standard deviation [sd] of level data, i.e., non-log-transformed, non-differenced), and significant (1% [***], 5% [**], 10% [*]) OLS estimates of effects on roundwood prices (10^6 LCU/10^6 m^3) (considering interaction effects, best log-log model estimates) and Armington elasticities.

	Austria		Czechia		Finland		Germany		Sweden	
	1990–2019		1998–2019		1998–2019		1994–2019		1995–2019	
	n = 28		n = 20		*n* = 20		*n* = 24		*n* = 23	
Logging	*mean*	*sd*								
Voluntary logging (10^6 m^3)	12.17	2.05	11.14	2.90	54.16	5.89	57.46	13.43	62.95	10.64
Salvage logging (10^6 m^3)	4.36	2.79	6.05	6.93	1.18	1.61	7.99	11.34	6.57	15.09
Sawlogs processing and trade	*mean*	*sd*								
Processed roundwood (10^6 m^3)	22.19	3.18	14.76	2.03	62.12	5.78	65.75	12.61	74.65	7.95
Import share (of total logging)	0.37	0.08	0.07	0.03	0.13	0.08	0.05	0.02	0.09	0.03
Export share (of total logging)	0.02	0.01	0.19	0.08	0.01	0.00	0.05	0.02	0.02	0.01
Sawmills significant OLS estimates										
Interaction effects not considered										
Product unit value (10^6 LCU†/10^6 PU††)		*** 0.5165		*** 0.3591		*** 0.7637				
Salvage logging (10^6 m^3)		** -0.0815						** 0.0162		** 0.0179
Roundwood imports (10^6 PU)				*** 0.1530				* 0.1118		
Roundwood exports (10^6 PU)				*** -0.1763				* -0.0950		
Voluntary logging (10^6 m^3)				*** -0.2097		* 0.3434				*** 0.3784
Assortment share (10^6 m^3/10^6 m^3)†††		* 0.5832						* 0.4124		
Interaction effects considered										
Product unit value (10^6 LCU†/10^6 PU††)				* 0.3144						
Salvage logging (10^6 m^3)				* 1.5624				** 0.0890		** 0.4863
Roundwood imports (10^6 PU)						* -6.2382				
Roundwood exports (10^6 PU)										
Voluntary logging (10^6 m^3)						** 1.0573				*** 0.8317
Assortment share (10^6 m^3/10^6 m^3)†††				* -2.1722						
Product unit value * Roundwood imports						* 1.1521				
Salvage logging * Voluntary logging										** -0.1094
Salvage logging * Roundwood exports				* -0.1483						* -0.0185
Salvage logging * Assortment share				* 1.6584						
Armington elasticity				*** 1.6413		*** 1.0211				
Pulpwood processing and trade	*mean*	*sd*								
Processed roundwood (10^6 m^3)	17.40	2.71	16.93	4.15	56.95	5.58			70.87	8.54
Import share (of total logging)	0.08	0.03	0.01	0.01	0.03	0.02			0.02	0.01
Export share (of total logging)	0.03	0.00	0.03	0.01	0.00	0.00			0.01	0.00
Pulp mills significant OLS estimates										
Interaction effects not considered										
Product unit value (10^6 LCU†/10^6 PU††)										
Salvage logging (10^6 m^3)										
Roundwood imports (10^6 PU)										
Roundwood exports (10^6 PU)						** 0.1117				
Voluntary logging (10^6 m^3)						*** 0.6832				
Assortment share (10^6 m^3/10^6 m^3)†††						*** 1.1987				* 0.7761
Interaction effects considered										
Product unit value (10^6 LCU†/10^6 PU††)										
Salvage logging (10^6 m^3)										** -0.0634
Roundwood imports (10^6 PU)										** -7.4461
Roundwood exports (10^6 PU)										
Voluntary logging (10^6 m^3)						** 0.6825				
Assortment share (10^6 m^3/10^6 m^3)†††										
Product unit value * Roundwood imports										** 0.8881
Salvage logging * Voluntary logging										
Salvage logging * Roundwood exports										* -0.0574
Salvage logging * Assortment share										
Armington elasticity				*** 1.3295				** -0.2651		

† LCU = Local Currency Unit.

†† PU = Physical Unit.

††† The share of the harvest of the respective assortment (e.g., sawlogs for the sawmill value chain) compared to the total harvest.

with significant results. A price transmission from sawmill products to sawlogs could be detected as a tendency for the sawmill industry in line with, e.g., Hänninen et al. (2007). Supply shocks tend to have a negative effect on pulpwood prices, as expected. It is also in line with theory that high levels of roundwood exports alleviate the effect of supply shocks. This could be observed in Czechia where towards the end of the study period, high levels of salvaged wood saturated the domestic market and the surplus of harvested roundwood was exported at low export prices (Committee on Forests and the Forest Industry, 2020).

We found only two publications in the body of literature of the last 20 years investigating the effect of salvage logging on roundwood market prices in Europe. While Fuchs et al. (2022) examined German roundwood prices using supply-side predictors only (annual proportion of salvage logging in total harvest and harvest volume), Schwarzbauer (2007) included both supply-side (amount of salvage logging) and demand-side factors (e.g., sawnwood price) to explain variations in Austrian roundwood prices. We are not aware of previous attempts to identify moderating factors for supply- and demand-side effects on roundwood market prices.

Therefore, while numerous studies provided inspiration during model specification, only parts of the results of the present work can be compared to the literature. For the period of 1990–2004, Schwarzbauer

(2007) found Austrian sawlog prices affected by sawnwood prices (*** 0.99) and salvage logging volumes (*** -0.09), while wood imports did not present a significant effect. Our results related to Austria show a relationship between sawlog prices and product unit values (a proxy for sawnwood prices) of *** 0.52 and salvage loggings of ** -0.08. Furthermore, we found an effect of assortment shares of * 0.58, a factor not considered in the estimates of Schwarzbauer (2007). With respect to pulpwood prices, Schwarzbauer (2007) only identified a significant effect (* 0.41) of lower-grade sawlog prices for the period 1990–2003. Since our data sources do not include prices for lower-grade sawlogs, we did not include such a variable in our analysis. However, the fact that Schwarzbauer (2007) found insignificant results for pulp import prices, salvage logging and wood imports as well as a relatively low coefficient of determination ($R^2 = 0.29$) compared to the sawlog price-related estimates ($R^2 = 0.77$) lends support to our finding that with the data and model specifications used, no reasonable estimates for Austrian pulpwood prices are possible.

Given the different data sources, temporal scopes and data transformations (relative differences vs. absolute differences of log-transformed values), the agreement in significance levels, signs, and magnitudes indicates consistency of our results with previous findings, as far as they can be compared.

4.1. Unexpected results

The analysis also revealed some unexpected results. First, supply shocks caused by disturbances indicated increasing sawlog prices, which we did not foresee. An explanation is that windthrow events affected particularly high grades of sawlogs and thus triggered shortages in the (higher-grade driven) sawmill industry. In Czechia and Sweden, this effect is less pronounced when roundwood exports are high, presumably because better qualities are more likely to be exported and the domestically consumed, lower-grade wood is less susceptible to shortage. A “shortage effect” of supply shock events on high-grade sawlogs would also plausibly explain why large proportions of sawlogs in the total harvest go in parallel with particularly large sawlog price increases as a consequence of supply shocks, which has been observed in the case of Czechia. Moreover, in Sweden, voluntary logging was found to mitigate the increase of sawlog prices occurring in the aftermath of supply shocks. This is only plausible if supply shocks result in shortages of high-quality sawlogs that can only be alleviated with increasing voluntary logging.

Second, roundwood imports were found to reinforce the effects of demand shocks in the two Nordic countries Finland and Sweden. Both countries have in common that roundwood prices were negatively affected by demand shocks. However, it must be doubted that demand shocks actually reduce roundwood prices, as this would contradict the theory of derived demand and is also contrary to the results shown in other countries. More likely, this is a result arising from unobserved quality differences or variations in other unobserved factors. Whatever the reasons, it seems then consistent that roundwood imports in these countries have amplified the impact of shocks in demand. Another explanation could be the fact that Finland and Sweden traditionally have a self-dependent forest sector producing sufficiently for the domestic market. In this regard, both countries might be opportunistic and import more wood at comparably low import prices when the demand for wood-based products is high (Finnish Forest Industry Federation, 2014, 2019). From this perspective, the finding suggests that the Swedish and Finnish wood processing industries are able to overcompensate for the effects of demand shocks via alterations in roundwood imports.

4.2. Strategic logging management and international trade as resilience predictors

The adaptation of voluntary logging volumes does play a role for forest-based value chain resilience. While the reduction of voluntary (normal market) logging in the event of a high incidence of salvage logging is one of the core means to absorb price instabilities, the results also indicate that voluntary logging may be managed to mitigate shortage situations with regard to high-quality sawlogs. Large shares of sawlogs in the total harvest go hand in hand with particularly large sawlog price increases (and probably also shortage situations), while higher shares of pulpwood may lessen the impact of supply shocks. The optimisation of assortment structures thus seems to represent a potential resilience predictor with a more long-term orientation. To this end, forest-based value chain stakeholders could cooperate more closely with each other to exchange information on how supply of and demand for specific assortments are expected to change in the face of increasing forest disturbances over the longer term.

Based on the results, market dynamics at the national level, as measured by the changes in the price of sawlogs and pulpwood, have not been heavily affected by disturbance shocks in the last two decades. This can be ascribed to the fact that disturbance shocks may have dominantly local effects that can be adjusted in the domestic market, especially in larger countries such as Germany and Sweden. For example, in Germany, after the Lothar storm, which mainly affected the south of the country, all means of transport and transport capacities were mobilised to balance wood supply between the regions (Federal Ministry of Consumer Protection, Food, Agriculture, 2001). In addition, with the exception of Czechia, where high proportions of salvage logging have been recorded in the recent years, historically observed forest disturbances exhibited only a limited potential to trigger severe market distortions. This is especially true for the Nordic countries in the sample, which (with few exceptions) were affected only marginally. Therefore, it remains unclear the extent to which strategic logging management can help to promote value chain resilience in the sense of roundwood price stability if stronger and more frequent disturbance events would arise.

Owing to their tendency to alleviate the effects of supply and demand shocks, exporting roundwood may contribute to increased value chain resilience. In the case of pulpwood, it is obvious that higher exports lead to lower domestic wood availability and thus mitigate oversupply and price declines after forest disturbances. In contrast to this, the results for sawlogs suggest that supply shock effects were moderated via quality differences in wood flows: if highest qualities are mostly exported, shock-induced shortages in premium grade sawlogs in the domestic market are less pronounced. There are indications that in the event of possible negative effects of demand shocks on roundwood prices, high roundwood imports can have an additional price-dampening effect. However, since a negative correlation between demand shocks and roundwood prices in a normal situation cannot be assumed, roundwood imports are likely to be of only secondary importance as a resilience predictor for forest-based value chains. Regardless of whether roundwood exports or imports are considered, the scope of international trade as a resilience predictor should not be overestimated. It is clear that low trade volumes limit the effectiveness of trade as a means to foster value chain resilience by stabilising domestic roundwood prices. Of the countries studied, only Austria and Finland are exhibiting larger sawlog import volumes over time and Czechia is the only country with considerable sawlog exports. In addition, there are technical, economic and political conditions that may further limit the substitutability between internationally traded and domestic roundwood such as lacking technical flexibility or short-term trade barriers (Lundmark and Shahrammehr, 2012).

4.3. Limitations

The main challenge faced in this research was the low number of observations per country compared to a relatively large number of predictors, especially for full models with interaction effects. However, more comprehensive data or longer time series on disturbances were not available on roundwood prices and respective voluntary and salvage logging volumes. To alleviate the issue, reduced form (best fit) models were reported separately, and in many cases, they also indicated slightly different results compared to the full models. By following the principle of parsimony, in most cases we have relied on the best fit estimates using reduced sets of predictors.

The data quality for the single time series variables might also leave room for improvement. There might be inconsistency in measuring salvage loggings, due to heterogeneity in (user supplied) definitions between countries. Similarly, the "quality effect" of disturbances on roundwood prices is captured by the assortment share variable, which covers only very drastic reductions in the quality of logs (downgrading of sawlogs to pulpwood). While disturbances did not seem to affect the roundwood assortment shares in most cases, they may have impacted the quality within the assortment instead. A more direct predictor could have captured the different rates of damage, which makes catching the reduction in quality within the roundwood assortments possible.

Also, the model could have benefitted from including the energy wood share from total roundwood supply if such data were available, as some share of salvage logging may also go directly to energy production. However, improving the models depends on the availability and quality of data, as well as balancing between the length of the time series and the number of resilience predictors. Furthermore, there is rationale in considering aggregate pulpwood and sawlog markets in the analysis, and hence, differences across wood species (spruce, pine, hardwoods) could be additional relevant factors. However, this breakdown could not be incorporated in the core variables dealing e.g., with salvage loggings.

Furthermore, policy decisions were made in the countries studied that may have had moderating effects on supply and demand shocks, but for which it was not possible to construct time series. For example, the Austrian Federal forests used wet storage after storms to reduce market fluctuations and maintain wood quality after the 2008 Paula and Emma storm events. In addition, only the most urgent harvesting activities were allowed to be carried out and sawmill production was curbed (Federal Ministry of Agriculture, Forestry, Environment and Water Management, 2008). Following the economic crisis in 2007/2008, the Finnish government decided on tax exemptions that would extend for two years to boost roundwood trade (Timber Committee, 2012). As a result, the Finnish roundwood market experienced a slight revival as the prices increased (Finnish Forest Industry Federation, 2012). In Germany, tax reductions were offered for 2018 for those forest enterprises hit hard by storm events.

Finally, it may depend on the perspective of whether it is price fluctuations or price stability that measures value chain resilience. The literature offers inconclusive evidence on the matter. On one hand, price reductions allow the market to absorb increased amounts of roundwood in the absence of parallel demand shocks (Loeffler and Anderson, 2018). On the other hand, price stability points to less insecurity for forest owners to lose profit due to an unfavourable reduction in the prices. The endogeneity of markets allows for different interpretations, depending on the context and perspective. However, in this study, we emphasise the power of moderating factors in stabilising prices, such as increased trade, reduced voluntary logging and shifts in roundwood assortment shares. Such factors help to alleviate the price volatility in cases of major oversupply or undersupply caused by disturbances. Thus, price stability can also be a measure of resilience in the roundwood market.

5. Conclusions & outlook

This study provides a pioneering attempt for time series econometric modelling of five European forest rich countries' value-chain resilience. The selected countries have highest relevance with their large geographical spread and in covering different forest types and market structures. Based on the findings, we could outline priorities that potentially strengthen the stability of forest value chains across Europe and help the forest-based sector identify more efficient and robust disturbance adaptation measures. By capturing realised market dynamics, the results of the analysis contribute to a body of literature dedicated to facilitating forest sector resilience in face of the changing climate.

Based on the results, a few suggestions for future research can be outlined. First, depending on the availability of data, future work should consider that quality deterioration may also take place within assortments (e.g., high quality sawlogs to low quality sawlogs). Second, a range of disturbance types have historically been part of forest management, but it is plausible they will increase in intensity and frequency due to climate change. Hence, the opportunities to investigate econometrically whether the resilience of forest-based value chains, as captured by roundwood market adjustment, is also sufficient to moderate larger-scale disturbance events are limited. A way forward could be to analyse whether the impact on roundwood price stability also depends on the frequency (and not only on the magnitude) of disturbances. Lastly, an important direction for future work will be to include simulation methods in forestry value chain research to estimate the future impact of disturbances and identify thresholds when resilience has severely deteriorated (e.g., when salvage logging has exceeded voluntary logging). This would contribute to a better understanding of the potential of existing resilience measures to cope with more frequent and more severe disturbances that are looming in the changing climate.

CRediT authorship contribution statement

Raphael Asada: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Elias Hurmekoski:** Methodology, Writing – original draft, Writing – review & editing. **Annechien Dirkje Hoeben:** Conceptualization, Data curation, Writing – original draft, Writing – review & editing. **Marco Patacca:** Data curation, Writing – original draft, Writing – review & editing. **Tobias Stern:** Conceptualization, Writing – original draft, Writing – review & editing. **Anne Toppinen:** Methodology, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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