RESONATE

Resilient Forests for Society

Deliverable 3.2

Results of the statistical analysis of national and some regional forest-based value chains regarding historical resilience

Planned delivery date (as in DoA): M20
Due date of deliverable: 30/11/2022
Workpackage: WP3

Workpackage leader: University of Graz
Deliverable leader: University of Helsinki
Version: 1.0
Dissemination level: CO(nfidential)

Grant Agreement number: 101000574

RESONATE — H2020-RUR-2018-2020 / H2020-RUR-2020-2

Project Acronym: RESONATE

Project title: Resilient Forest value chains – enhancing resilience through natural and socio-economic responses

Duration of the project: April 1st, 2021 - March 31, 2025

VERSION HISTORY

Version	Date	Author /Reviewers	Partner	Description
0.1	30.06.2022	Raphael Asada, Elias Hurmekoski, Annechien Hoeben, Anne Toppinen, Marco Patacca & Tobias Stern	UGRAZ, UH, WUR	First efforts to build the deliverable.
0.2	31.07.2022	Elias Hurmekoski & Annechien Hoeben	UH, UGRAZ	Deliverable up until discussion
0.3	31.08.2022	Anne Toppinen, Elias Hurmekoski & Annechien Hoeben	UH, UGRAZ	First full draft deliverable
0.4	20.09.2022	Annechien Hoeben	UGRAZ	Cleaning & editing of the deliverable
0.5	05.10.2022	Raphael Asada, Annechien Hoeben, Anne Toppinen, Elias Hurmekoski & Tobias Stern	UH, UGRAZ	Going over final comments and adding newly learned insights from the Vienna meeting.
0.6	13.11.2022	Jette Bredahl Jacobsen, Tomáš Hlásny	UCPH, CZUP	Review
1.0	29.11.2022	Raphael Asada, Annechien Hoeben	UGRAZ	Final deliverable for submission

REFERENCE

Asada, R., Hoeben, A., Hurmekoski, E., Toppinen, A., Patacca, M., Stern, T. (2022). Results of the statistical analysis of national and some regional forest-based value chains regarding historical resilience. Horizon 2020 project RESONATE, project no. 101000574, [UH].

DISCLAIMER

The information in this document is provided “as is”, and no guarantee or warranty is given that the information is fit for any particular purpose. The above referenced authors shall have no liability for damages of any kind including without limitation direct, special, indirect, or consequential damages that may result from the use of these materials subject to any liability which is mandatory due to applicable law.

The content of this deliverable does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

ACKNOWLEDGEMENT

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement no 101000574

Table of Contents

Executive Summary 3
Keywords 3
1. Introduction 4
1.1 Background 4
1.2 Research gap 4
1.3 Research objective 6
2. Data and methodology 7
2.1 Data 7
2.1.1 Data on roundwood and wood product flows and unit values 7
2.1.2 Data on domestic roundwood prices 9
2.1.3 Data on climate change-induced disturbances 9
2.2 Methodology 9
3. Results 14
3.1 The historical development of the forest-based sector in Europe 14
3.1.1 Austria 1994-2019 14
3.1.2 Czechia 1998-2019 16
3.1.3 Finland 1999-2019 18
3.1.4 Germany 1995-2019 21
3.1.5 Sweden 1995-2019 23
3.2 Descriptive statistics and econometrics analysis of demand and supply shocks 24
3.2.1 Austria 25
3.2.2 Czechia 27
3.2.3 Finland 29
3.2.4 Germany 32
3.2.5 Sweden 34
3.3 Estimation of Armington elasticities 38
4. Discussion and conclusions 39
4.1 Interpreting and generalising of the findings 39
4.2 Validity and reliability of our analysis 42
4.3 Embedding our findings in RESONATE and avenues for future work 43
5. References 46
6. Supplementary materials 54
6.1 Austria 54
6.2 Czechia 55
6.3 Finland 57
6.4 Germany 58

6.5 Sweden..... 59

Executive Summary

Climate change poses a growing threat to European forests through increasing frequency and severity of heat waves, extended periods of drought, storms, insect outbreaks and other natural disturbances. Natural disturbances affect both the volume and the quality of the wood and increase salvage logging, causing reduced roundwood prices in the short-term with possible negative effects on the functioning of forest-based value chains. In addition to the supply shocks, infrastructure renovation can induce higher demand for wood products in a region affected by a storm. This study assesses the impact of supply and demand shocks to roundwood prices through econometric analysis in five forest-rich European countries (Austria, Czechia, Germany, Finland and Sweden), building on the theory of price transmission and selected indicators for natural disturbances. We used annual time series data in differenced form on collected disturbance and price data from national sources. Statistically significant results for all countries were gained only for sawlog price formation. The preliminary results show strong differences between countries: Prices were driven by demand-side effects in the Nordics and supply-side effects in Central Europe, with mixed results for Austria. The results may be affected by moderate disturbances in historical data, so the results can only indirectly inform about the future.

Keywords

Wood value chains, resilience climate change-related disturbances, times-series econometrics modelling

1. Introduction

1.1 Background

The RESONATE project aims at generating the needed knowledge and practices for making European forests, the services they provide, and related economic activities more resilient to future climate change and disturbances. In this regard, WP3 addresses the current resilience of European forest-based value chains to short-term and immediate stressors (e.g., disturbances) and more gradual long-term effects (e.g., climate change). More precisely, the stability of different value chains in terms of product output volumes and service provisioning will be investigated (T3.1). Simultaneously, factors are derived that have a positive effect on value chain resilience from the perspective of a forest enterprise (T3.2). Taken together, these factors will form the basis of a framework dedicated to achieving resilient forest-based value chains (T3.3). As a last step, the framework will be evaluated by forest sector decision makers and stakeholders (T3.4).

In line with these efforts, this deliverable (D3.2) is comprised of a statistical analysis of resilience in national forest-based value chains accompanied with some observations on regional level between Nordic and Central European areas. Following Hurtada et al. (2022), we understand resilience as the capacity of the social-ecological system (SES) to reorganise, adapt and continuously provide ecosystem services in the face of unexpected shocks as well as under gradual, ongoing changes such as climate change.

In forest social-ecological systems we recognise natural- and human-driven subsystems connected by ecosystem services that interact together. On the one hand, the natural-driven system supplies ecosystem services to the human-driven subsystem. On the other hand, the human-driven subsystem strongly influences the development of the natural-driven subsystem through policy and management. The SES is described by system variables. In this context, resilience obeys to the basic scheme of "what to what", i.e., it refers to the change in the performance of a system variable to cope with given disturbances or stressors (Biggs et al., 2012).

1.2 Research gap

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

heat waves, extended periods of drought, storms and other natural disturbances over an increasingly larger scale. As a result, forest ecosystem dynamics, ecological resilience and tree species suitability are altered at minimum and likely deteriorated (Seidl et al., 2017). As climate change continues, forest management has to cope with short-term and likely long-term impacts on the stability and the capacity to deliver ecosystem services (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 & Hurmekoski, 2016).

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 the analogous forest value chains (Seidl et al., 2017). Over the last decade, forest owners increasingly recognise 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). Another reason could be that, in case of forest disturbances, wood-based value chains are characterised by both under- and oversupply (Schwarzbauer, 2007). For example, windthrow increases the supply of wood to the pulp and paper industry and for energy applications, whereas sawmills could face undersupply. Furthermore, wood can be utilised and substituted from higher value applications such as sawnwood to lower value applications such as wood for energy production (Hurmekoski et al., 2021).

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”) and lower the wood quality due to damage (“quality effect”) (Fuchs et al., 2022). The quality is lowered by, e.g., broken logs, boreholes from insects, or secondary fungal infection, and lead to alterations in assortment composition from logs to pulpwood (Loeffler & Anderson, 2018). Both the oversupply and the lowered quality, and the increase in harvest costs, reduce the price of roundwood in the short-term (Fuchs et al., 2022; Loeffler & Anderson, 2018). This allows the market to absorb increased amounts of roundwood in the absence of parallel demand shocks. Disturbances can also increase the price of roundwood in the long term due to reduced stocks, in the case of extreme disturbances (Prestemon & Holmes, 2000).

Previous studies on market effects of forest disturbances find short-term reductions in the prices following a major disturbance (Fuchs et al., 2022; Ning & Sun, 2014; Prestemon & Holmes, 2000; Zhai & Kuusela, 2020; Zhou & Buongiorno, 2006). However, existing papers focus on the impacts of single major disturbance events (operationalised through dummy

variables), rather than the cumulative impact of disturbances over time. As disturbance events are becoming more frequent and severe due to climate change, it is critical to examine the superimposing short-term impacts of disturbance effects over time (IPCC, 2021).

1.3 Research objective

The research objective of the present study is to identify resilience drivers and find to what extent they vary across national forest-based value chains in Europe. We examine 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 aim to explore how the impact of product price and salvage logging rate may be conditional to moderating effects, namely international trade, voluntary logging (which we use as a synonym to planning logging), and the changes in roundwood assortment shares. We employ a time series econometric model of interaction variables in five EU countries (Austria, Czechia, Germany, Finland and Sweden).

We cover the demand side price transmission through the theory of derived demand, stating that the assortment price (e.g., of saw logs) is positively affected by the price of the subsequent product (e.g., of sawnwood) (Zhou & Buongiorno, 2006). While the effect may not be entirely exogeneous, product prices can be expected to drive the assortment prices rather than vice versa (Sun, 2016). However, to a lesser extent, the assortment price is also driving 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.

By applying such an econometric model on a macro-economic scale, we can assess the socio-economic landscape a forest enterprise operates in and adapts its resilience strategy to. On the one hand, disturbances 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 bear the risk for short-term shortages and price spikes in domestic roundwood supply, which negatively impacts mostly the downstream part of the value chain (consumers). In this context, alterations in trade volumes, voluntary logging (as opposed to salvage logging), and shifts in high-quality and low-quality assortments are considered factors that reduce the fluctuation of the roundwood price caused by supply shocks.

2. Data and methodology

2.1 Data

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

To complement the econometrics analysis, we reviewed forest-based sector market reports in the case study countries to provide historical context to the chosen system variables and their potential resilience drivers. In this regard, it is important to mention that in such reports, the supply-side effects are described more in-depth than the demand-side effects, which may amplify or limit the former.

2.1.1 Data on roundwood and wood product flows and unit values

Data on roundwood and wood product flows and unit values were sourced from FAOSTAT. The choice to extract most of the data from the FAOSTAT database stems from the fact that these data have a high temporal and spatial coverage, and are uniform across the national European data. The database contains data on imports, exports, and production of roundwood and derived products for most EU-28 countries 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 database was compiled in a three-step process, which is explained below. The applied method involved a data download using FAOSTAT (step 1), the exclusion and harmonisation of FAO classification items (step 2), and the disaggregation of roundwood trade flows (step 3).

Table 2: 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
Saw mills	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)	Mechanical wood pulp Semi-chemical wood pulp Chemical wood pulp, sulphite, unbleached

	Pulpwood, round and split, non-coniferous (production) Pulpwood, round and split (export/import)	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

In the first step, the data set was extracted from FAOSTAT (2021) using the following parameters:

- Austria, Czechia, Finland, Germany, Sweden
- All Elements
- All Items
- Years 1990-2020
- Output Type: Table
- File Type: CSV
- Thousand Separator in 'Show Data': None

Output Formatting Options: Flags, Notes, Codes, Units, Null Values

As a second step, FAO classification items were harmonized. Occasionally both aggregated and corresponding disaggregated items were found in the FAO Forestry Production and Trade statistics (FAOSTAT, 2021). To avoid double-counting, affected items were assigned a code representing the applicable reason for exclusion.

Since 1989, the FAO trade statistics (FAOSTAT, 2021) no longer distinguish different uses of industrial roundwood; however, a distinction between sawlogs and pulpwood is necessary to meet the requirements of the present analysis. To obtain sawlog and pulpwood shares of the roundwood trade reported by FAO, COMTRADE (United Nations, 2021) data were used in the third step (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 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.

2.1.2 Data on domestic roundwood prices

To determine 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 from the corresponding RESONATE partner and data for Sweden was 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.

2.1.3 Data on climate change-induced disturbances

In the first step towards constructing disturbance national time-series, we retrieved data from the Database of Forest Disturbances in Europe (Patacca et al., 2021; Schelhaas et al., 2020). We downloaded all records of wood volumes damaged by disturbances at national or sub-national level 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). As aforementioned, in this deliverable we assume that the frequency and severity of such disturbances will increase due to climate change (Seidl et al., 2017). Records mentioning bark beetles without a specific insect species or tree species affected were allocated to the agent spruce bark beetles. We note that there are other species of bark beetles that feed on different host tree species throughout Europe, but based on available data in the DFDE those other bark beetle species are contributing less than 5% to the total disturbance caused by bark beetles in Europe.

In the second step, we cleaned the data to arrive at a single reported value for each year, each country and each disturbance agent. First, 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. In cases where several values were reported for the and 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. When needed, timber volume under bark was converted to timber volume over bark following Schelhaas et al. (2003).

2.2 Methodology

The demand side is considered using the theory of derived demand (e.g., Tomek & Kaiser, 1999; Zhou & Buongiorno, 2006). A positive demand shock for wood-based products (e.g.,

wood for construction, paper or heating pellets) increases roundwood demand and price until a new market equilibrium is reached (Hänninen et al., 2006). Assuming that the wood-processing industry strives to minimise its costs, on the one hand, the expected consequences of demand shocks may be counteracted with increased roundwood imports and intensified 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 and thus reduce roundwood prices (Schwarzbauer, 2007). The forest-based sector may respond to expected consequences of supply shocks with reduced voluntary logging, increased roundwood exports, increased storage, and changed assortment composition (i.e., increased shares of pulpwood and energy wood in total wood removals). The expected signs for all predictor effect estimates are shown in In order to determine the extent to which an oversupply situation with roundwood 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 & 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 possible role of roundwood trade as a resilience predictor.

The OLS estimation of the Armington elasticities are conducted separately for each forest-based value chain (Table 2) according to Equation 3,

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + u \quad (3)$$

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 (Table 3). The Durbin-Watson test tests the null hypothesis that there is no serial correlation in the residuals, whereas the Jarque-Bera test tests the null hypothesis that the data is normally distributed. The Breusch-Pagan test for heteroscedasticity tests the null hypothesis that the residual variance does not depend on the predictors, i.e., the residuals are homoscedastic. The Rainbow test for linearity tests null hypothesis that the fit of the model using the full sample is the same as using a central subset, implying that the linear model specification is correct. All OLS estimates and diagnostic tests were conducted using the Python module statsmodels (Seabold & Perktold, 2010).

Table 3: Diagnostic tests used with specification of null hypotheses and aimed result.

Test	Null hypothesis	Aim
Durbin-Watson	No serial correlation in the residuals	dw ~ 2
Jarque-Bera	Residuals normally distributed	Prob > α
Breusch_Pagan	Residuals homoscedastic	Prob > α
Rainbow test for linearity	Linear specification is correct	Prob > α

Table 4.

The OLS (ordinary least squares) estimation of the effect of potential reactions of market actors on demand and supply shocks is performed separately for each forest-based value chain (Table 2) according to Equation 1,

$$y_t = \beta_0 + \beta_1 x_{t1} + \cdots + \beta_6 x_{t6} + u_t \quad (1)$$

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 (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 4).

Wood-based product export 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 mentioned above[1] are captured by the four remaining independent variables (x_{t2}, x_{t3}, x_{t4}, x_{t6}). In principle, these are operational, manageable predictors of forest-based value creation and as such constitute candidates for resilience predictors. The analysis will show, on a case-by-case basis, to what extent the management of these predictors plays a role in terms of mitigating 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 (Equation 2).

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

We used the first differences of the log-transformed data, as previous Dickey-Fuller test results have shown a clear improvement in the stationarity of most variables. The interaction variables were formed by multiplying the log-transformed sub-variables before differentiation. Furthermore, 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)

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

(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.[2]

In order to determine the extent to which an oversupply situation with roundwood 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 & 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 possible role of roundwood trade as a resilience predictor.

The OLS estimation of the Armington elasticities are conducted separately for each forest-based value chain (Table 2) according to Equation 3,

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + u \quad (3)$$

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 (Table 3). The Durbin-Watson test tests the null hypothesis that there is no serial correlation in the residuals, whereas the Jarque-Bera test tests the null hypothesis that the data is normally distributed. The Breusch-Pagan test for heteroscedasticity tests the null hypothesis that the residual variance does not depend on the predictors, i.e., the residuals are homoscedastic. The Rainbow test for linearity tests null hypothesis that the fit of the model using the full sample is the same as using a central subset, implying that the linear model

[2] Since it cannot be ruled out that the domestic roundwood price and the export unit value of the wood-based product are co-determined, a 2SLS estimation was carried out in addition to the OLS estimation. For this purpose, an instrument variable was formed from the lagged wood-based product export unit value. The same applies to voluntary logging, the amount of which is likely to depend partly on the domestic roundwood price. However, it was found that this approach did not produce useful results, which is why they are not reported in this study.

specification is correct. All OLS estimates and diagnostic tests were conducted using the Python module statsmodels (Seabold & Perktold, 2010).

Table 3: Diagnostic tests used with specification of null hypotheses and aimed result.

Test	Null hypothesis	Aim
Durbin-Watson	No serial correlation in the residuals	dw ~ 2
Jarque-Bera	Residuals normally distributed	Prob > α
Breusch_Pagan	Residuals homoscedastic	Prob > α
Rainbow test for linearity	Linear specification is correct	Prob > α

Table 4: Expected signs for predictors and underlying reasoning.

Effect type	Expected sign	Predictor	Predictor short name	Expectation reasoning
Main effects	+	Mills output, Export Unit Value, 10^6 LCU*/10^6 PU**	Product unit value	Increases demand for domestic roundwood and thus increases domestic roundwood prices.
	-	Salvage logging	Salvage logging	Increases domestic roundwood supply and thus reduces domestic roundwood prices.
Moderating effects	-	Mills input, Import Quantity, 10^6 PU	Roundwood imports	Reduces domestic roundwood demand and thus reduces domestic roundwood prices.
	-	Voluntary logging, 10^6 m^3	Voluntary logging	Increases domestic roundwood supply and thus reduces domestic roundwood prices.
	+	Mills input, Export Quantity, 10^6 PU	Roundwood exports	Increases domestic roundwood demand and thus increases domestic roundwood prices.
	-	Assortment share (10^6 m^3/10^6 m^3)***	Assortment share	Tends to increase domestic roundwood supply of the assortment under study and thus to reduce the corresponding domestic roundwood prices.
Interaction effects	-	Mills output, Export Unit Value, 10^6 LCU/10^6 PU * Mills input, Import Quantity, 10^6 PU	Interaction between product unit value and roundwood imports	If sufficiently high, imports can be increased to balance out short-term demand peaks on the domestic market. This mitigates the price-increasing effect of demand shocks (indicated by mills output, export unit values).
	+	Salvage logging, 10^6 PU * Voluntary logging, 10^6 PU	Interaction between salvage logging and voluntary logging	If sufficiently high, voluntary logging can be reduced to balance out short-term supply peaks. This mitigates the price-

				reducing effect of supply shocks (indicated by salvage logging).
	-	Salvage logging, 10^6 PU * Mills input, Export Quantity, 10^6 PU	Interaction between salvage logging and roundwood exports	If sufficiently high, exports can be increased to balance out short-term supply peaks. This mitigates the price-reducing effect of supply shocks (indicated by salvage logging).
	-	Salvage logging, 10^6 PU * Assortment share (saw mills)	Interaction between salvage logging and the sawlogs share	With high salvage logging, the (sawlog) assortment share is lower than otherwise, as damaged logs are used for pulping. This mitigates the negative effect of salvage logging on the domestic roundwood (sawlog) prices.
	+	Salvage logging, 10^6 PU * Assortment share (pulp mills)	Interaction between salvage logging and the pulpwood share	With high salvage logging, the (pulpwood) assortment share is higher than otherwise, as damaged logs are used for pulping. This further increases the negative effect of salvage logging on the domestic roundwood (pulpwood) prices.

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

3. Results

3.1 The historical development of the forest-based sector in Europe

3.1.1 Austria 1994-2019

In 1994, the Austrian economy developed favourably which led to increased levels of production in the forestry sector. However, as the wood price was low, many forestry operations faced difficulties bearing the high harvesting costs that typically dominate in alpine locations (Enache et al., 2016). In 1998, the general economic situation, paired with the upward trend of the US dollar and the reduced tensions in the European currency system, positively impacted the sawmilling industry. In addition, the flourishing construction sector improved the export situation to Italy and Switzerland. Exports to the rest of Europe stayed

the same as a result of strong Scandinavian competition (Federal Ministry of Agriculture and Forestry, 1999).

In December 1999, the largest Central-European windthrow of the century ('Lothar') hit the Austrian forests. As a result, the sawmill industry produced record numbers of sawnwood in the year 2000, before dropping by 2% (1.8 billion Euros) in 2001. In 2001, removals from the forest were still 1.4% higher than the year before, but the sawnwood price stabilized due to strong demand. As a result, the quantities of sawnwood stored in Austria were reduced. By the end of 2001, the average cost for Austrian processors increased as the cheap roundwood affected by the windthrow was depleted. During the first quarter of 2002 prices remained stable and high-quality wood was marketed without price reductions. (Federal Ministry of Agriculture, Forestry, Environment and Water Management, 2005).

Similar to the sawmilling industry, the pulp and paper industry declined over the course of 2000-2003 as a result of falling consumption. Part of this downwards trend can be ascribed to the growing substitution of pulp from recovered paper. (Federal Ministry of Agriculture, Forestry, Environment and Water Management, 2002). In 2004, a record quantity of 4.85 million tonnes of paper, cardboard and paperboard was produced in Austria and the export rose to 85.1%, but due to decreasing prices (amplified by the low standing of the dollar) the turnover rose by only 1.9%. In 2005 the unfavourably low prices remained stable (Federal Ministry of Agriculture, Forestry, Environment and Water Management, 2005).

In January 2007, Austria was again hit by a big storm ('Kyrill') which led to record harvest levels. Simultaneously, due to the upcoming financial crisis, the demand for wood slackened and the exports decreased. As a result, the European market for sawnwood became saturated over the course of 2007. Early 2008, the storm events 'Paula' and 'Emma' led to further price decreases until the market stabilized at a low level in the summer of 2008. To cope with the situation, large forest enterprises, such as the Austrian Federal forests, used wet-storage after storms to reduce market fluctuations and maintain wood quality. In addition, only the most urgent harvesting activities were carried out and the sawmill production was curbed. Similar trends can be observed in the pulp and paper industry: Due to the windfalls in early 2007 and early 2008, the production and distribution costs dramatically increased and several pulp and paper mills had to stop production temporarily. The market was saturated and the overall demand dropped (despite rising in Eastern Europe and Asia) (Federal Ministry of Agriculture, Forestry, Environment and Water Management, 2008).

In 2010, the export market expanded rapidly again and the production loss suffered as a result of the economic crisis was back to pre-crisis levels in 2011. This can partly be ascribed to higher quantities of wood reserves being harvested in private forests and the favourable cost

structure that makes it easy for private forests to react flexibly to (high) timber prices. The remained stable at an attractive level in 2012 and 2013. Nevertheless, many companies could not keep up with the increasing costs for energy, wood and recovered paper (Federal Ministry of Agriculture, Forestry, Environment and Water Management, 2012).

In 2014, a severe winter with large amounts of ice, snow, floods and squalls caused significant forest damage in the South of Austria, Slovenia and Croatia. As a result, the percentage of damaged wood increased slightly, but the total volume was still rather low compared to the past ten years. Luckily, the wet winter led to limited bark beetle outbreaks in Summer. At the start of the felling season in October, a strong demand was observed and favourable weather conditions stimulated the harvesting activities. Furthermore, it was possible to reduce the volume of wood at storage locations. Over the course of the year, sawnwood exports decreased whereas the exports for pulpwood increased. Most prices increased slightly, but those of pulpwood decreased (Federal Ministry of Agriculture, Forestry, Environment and Water Management, 2014).

In 2015, the percentage of salvage logging increased further with 12.9% compared to 2014 but was still low compared to the last decade. The most important causes of damage were storms, bark beetles and snow and icing. (Federal Ministry of Agriculture, Forestry, Environment and Water Management, 2016).

In 2016 and 2017, the market continued to be oversupplied with damaged wood (both domestic and imported) which resulted in decreasing domestic prices. This was further fortified by extreme weather events and the most significant bark beetle outbreaks ever recorded in the Summer of 2018. Many trees that were already weakened by lower precipitation and higher temperatures could not withstand the outbreaks. As a result, the volume of wood removed exceeded the increment. In October 2018, the situation was intensified by cyclone Vaia and the domestic timber market further declined. Storage was only limited available and wood transportation was delayed by several weeks. Simultaneously, the exports to far foreign markets (E.g., China) which normally helped relieve the market were decreasing (Federal Ministry for Sustainability and Tourism, 2019).

3.1.2 Czechia 1998-2019

The Czech sawmills mostly process coniferous sawnwood (soft wood); non-coniferous sawn wood (hardwood) comprises only 10% of the production. In 1999, the production of sawn softwood grew by 4.9% compared to 1998. The domestic consumption dropped by 4.3%, but exports increased by 20.2% (mostly to Germany, Austria and Italy). The production, domestic consumption and exports of sawn hardwood grew slightly. Regarding the pulp and paper

industry, the exports of pulp grew by 5.2% and higher average unit prices were achieved(Timber Committee, European Forestry Commission, 2000).

Similar to the situation in Austria, storm Lothar (December 1999) caused damage to the Czech forests leading to considerably increased removals in the following two years. As a result of the large inflow of wood, the exports grew, but the prices decreased, adding up to a downwards trend on the sawmilling market. In contrast, the production of wood pulp recorded an upward trend. In 2002, imports and exports of sawnwood rose slightly, whereas imports and exports of pulpwood dropped slightly (Timber Committee, European Forestry Commission, 2002).

The longer trend of exporting large volumes of timber compared to the national removal volumes continued in the following years. As a result, the domestic raw material is not processed by the national wood processing industry into products with a higher value (Timber Committee, 2012). At the time, the government also did not regulate exports nor imports of roundwood (Vancura & Trejbalova, 2004). As a result, the economic crisis in 2007/2008 hit hard in the Czech forest sector (Timber Committee, 2012).

In January 2007, storm Kyrill caused significant damage in the Czech forest and harvests reached the highest values since the establishment of the Czech Republic. Despite the storm events Paula and Emma in early 2008, the harvest recorded an unusual drop (12.5%) which continued in 2009. The European markets became saturated as a result of the large removals. Simultaneously, the exchange rate of the Czech Koruna towards Euro and US Dollar grew. As a result, the domestic consumption and exports significantly dropped. As a result, many forestry and processing enterprises had to reduce their production significantly or went out of business (Timber Committee, 2009).

The total demand of wood and therefore the production and turn-over in the entire processing industry continued to decrease until 2012. Especially the demand from the construction industry dropped significantly (30%) between 2008 and 2012. Similarly, the exports of sawnwood decreased (although still 74.3% of all the produced sawnwood was exported from Czechia in 2011). In the period 2010-2012, the share of hardwood in the logging mix increased to 13.4% due to the increased availability in mature stands. Simultaneously, the demand for hardwood increased (mainly outside of Czechia). Regarding the pulp and paper industry, both imports and exports fell in 2011 and further in 2012(Timber Committee, 2012).

In 2014, Moravia and Silesia were hit by windfalls leading to the planned forest management to be replaced by salvage logging. The export volumes of Czechia remained high. However, due to an increase in internal demand, commodities had to be imported from Germany, Slovakia and Poland to compensate for high exports. The market of pulpwood grew sharp

over the last years (1.9% in 2013 and 7% in 2014) (Committee on Forests and the Forest Industry, 2015).

In 2015 and 2016, salvage logging further increased as a result of the obligation to reduce bark beetle damage (which was fortified by continuous drought and warm weather). As a result, the prices of all coniferous assortments dropped gradually over 2015 and 2016. The increased removals were used to further boost both the domestic wood-processing industry and the exports to Austria and Germany. Unfortunately, sawmills in Germany and Austria report higher prices as sawmills in Northern and Eastern Europe. (Committee on Forests and the Forest Industry, 2017).

In the years following 2016, high numbers of salvage logging were reported and the prices dropped even further. Exports and domestic consumption of roundwood continued to increase due to the revival of the construction industry and the growing numbers of wooden family houses. The increase in demand did not prevent large amounts of coniferous roundwood to be stored in Czech sawmills over the course of both 2018 and 2019. Regarding the pulp and paper industry, investments have allowed for higher quality processing to better meet the domestic demands. As a result, the large amounts of damaged wood available boosted the sector to meet the domestic consumption. In addition, the imports of pulpwood dropped massively (66.7%) and the overall exports of pulpwood grew by 26.8% (Committee on Forests and the Forest Industry, 2019).

In 2019, the high numbers of salvaged wood saturated the market and the surplus of harvested roundwood was exported as no other solution was possible. Especially, as the domestic demand dropped with 9.4% over the course of 2019. (Committee on Forests and the Forest Industry, 2020).

3.1.3 Finland 1999-2019

At the beginning of research period, the demand for forest industry products in Finland developed favourably. The material consumption of the Finnish forest industry reached a record level, leading to high prices for spruce sawlogs. However, the prices for pine, birch and redwood were slightly falling due to oversupply on the market. Similar to the situation for sawmills, the pulp and paper industry grew by average of 2% in 1998 compared to the previous year (Finnish Forest Industry Federation, 1999).

At the turn of the century, the Finnish economy grew strongly, the raw material consumption grew, the trade balance developed favourably and so did the export price for all commodities. The domestic consumption of sawnwood was exceeded the exports of sawnwood. Exports to

countries outside of Europe increased (with Japan reaching an all-time high) and exports inside Europe decreased (partly due to oversupply caused by storm Lothar). In 2001, the results were opposite; the domestic consumption decreased and the trade balance became negative. Furthermore, the raw material prices increased and the sawn timber prices decreased. Due to this unstable market situation, the sawmills had to significantly reduce production. In 2001, the demand for pulpwood developed unfavourably due to the economic situation and production slowed down (Finnish Forest Industry Federation, 2001).

Finland was hit by unusual storms in the late 2001 and summer 2002. However, the roundwood markets were not negatively impacted and the damaged wood was harvested rather quickly. As a result of new investments in the processing industry, capacities increased and the harvested wood could be processed further. In the pulp and paper industry, the weakened demand for pulp and paper continued in the year 2002 and downtime in production had to be taken in the first half of the year. Analogous, the prices slowly decreased further (Finnish Forest Industry Federation, 2002).

In 2003, the situation on the market and in the Finnish forestry industry allowed for higher production and higher prices. Simultaneously, the European demand for forest industry products went up, especially from the construction sector (Vantaa Research Centre, 2004) (Finland Sources, 2007). The growth continued and the Finnish forest industries thrived. As an indication, in 2006 a 14% growth was obtained compared to 2005. This can be ascribed to a high demand for forest products in the sawmilling industry. However, sawmills were limited by the availability and price of domestic wood. In addition, the cost competitiveness was difficult to maintain due to rising energy prices and high transport costs. Similarly, the pulp and paper industry continued to grow. The demand for Finnish paper products increased outside of Europe, especially in China. However, the prices for pulp and paper end products decreased (Finland Sources, 2007).

In 2007, the Finnish forest industry felt the first effects of the economic crisis. In 2008, the consumption of industrial roundwood decreased by 12%. Compared to 2008, Finish sawmills and pulp mills had to reduce their production by respectively one-third in 2009. However, the roundwood imports still increased as Russia planned to restrict its exports (approximately 60% of the Finnish exports originated from Russia. The growth in demand from the construction sector that has been observed in the last 15 years came to an end. To boost roundwood trade, in 2008 the Finnish government decided upon tax exemptions that would extend for two years. The measures only minorly stimulated the sawmilling and pulp industry (Finnish Forest Industry Federation, 2009).

In 2010, the Finnish roundwood market experienced a slight revival as the prices for softwood increased. Nevertheless, the market situation was still unfavourable. In 2011 the domestic consumption and traded volumes fell down again as a result of overcapacity on the European market markets and the uncertain standing of the Euro. In addition, Finland shifted its exports to developing markets in North Africa and Asia where the competition was less tight compared to Europe. In 2012, the Finnish imports reduced by 10% (partly due to Russia cutting its exports). Regarding the Finnish pulp and paper industry, the market seemed to recover from the financial crisis in 2010. However, in 2011, the uncertainty in Europe increased, the demand slackened and the production and export turned downwards (Finnish Forest Industry Federation, 2012).

The situation improved at the end of 2012 and production, prices and exports increased. As a result, forest removals increased by 11% in 2014 and reached an all-time high. Most of the removals originated from private, non-industrial forests rather than company and state forests. The sawnwood prices increased by 3-5% and the prices of pulpwood increased by 1-2%. Finland continued to strengthen its exports to Africa and Asia, still facing strong competition in Europe(Finnish Forest Industry Federation, 2014).

In 2015, the steady growth stopped and the production of coniferous sawnwood declined by 3%. Simultaneously, the domestic sawnwood consumption hit an all-time low. Although exports volumes were still growing, the export prices decreased (5% in 2014) as a result of the unstable political situation in the important Finnish export markets in North Africa and the Middle East. The situation in the pulp and paper industry approximately stayed the same; the demand for paper on the export market decreased whereas the demand for pulp and paper board increased (Finnish Forest Industry Federation, 2016).

In 2017, the export volumes and prices of sawnwood increased again due to high demands. As a result, the total removals increased by 9%. The year 2017 marked an all-time high in exports of sawnwood. The decreased demand on the North African and Middle Eastern markets was compensated by a rapidly increasing demand on the Chinese market. In addition, the domestic demand and European increased as a result of growing construction activities. At the end of 2017, the sawnwood production was constrained by poor harvesting conditions. The situation was more strenuous in the pulp and paper industry as a result of declining demand. Several paper mills were closed down (Finnish Forest Industry Federation, 2018).

The year 2018 marked a peak in the Finnish sawmill industry, with good export rates and high prices. As a result, investments were made to improve the production bottlenecks. However, from November 2018 the prices for sawnwood decreased steadily and harvesting operations of sawnwood decreased. The year 2018 marked a cyclical turning point for the pulp and paper

industry with 1 % annual increase. However, the positive development stabilized again in 2019 (Finnish Forest Industry Federation, 2019).

3.1.4 Germany 1995-2019

Similar to the other case study countries, the late nineties marked a period of growth for the German forest sector. Regarding the market for sawnwood, there was ample of domestic demand (especially from the woodworking and furniture industry) and the prices remained stable at a high level. As a result, the production of coniferous sawnwood (softwood) increased by around 1% in 1998 and the production of non-coniferous sawnwood (hardwood) increased by around 11%. Similarly, the pulp and paper industry experienced high demands and a new sulphate mill was opened in Eastern Germany. Domestic sales increased by 2%, whereas exports declined by 3% due to economic crises in South-East Asia, South America and Russia. Similar to other countries, recycling rates went up in the end of the nineties (Federal Ministry of Food, Agriculture and Forestry, 1999).

In December 1999, Germany was hit by storm Lothar resulting in large windfall events increasing salvage logging by 31% to 49.1 million m3. Regular felling was limited as far as possible by adopting 'the Compensation for Forest Damage Act'. A small part of the damaged wood (100.000 m^3) was withdrawn from the market and stored dry or on plastic. In the summer 2000, salvage logging increased further as a result of bark beetle infestation (Federal Ministry of Consumer Protection, Food, Agriculture, 2001).

The sawn softwood market lost momentum over the course of 2000 as a result of the large oversupply on the European market. In addition, the storm damage resulted in a production gap between North and South Germany. Another downfall was the weakened demand from the construction sector. It was not possible to reduce these pressures on the domestic market with foreign trade. In contrast, regarding pulp and paper, the production increased by 9% and the annual sales increased by 22% in 2000 compared to 1999. The demand was high and the capacities had improved due to prior investments. In 2001, the pulp industry slackened (Federal Ministry of Consumer Protection, Food, Agriculture, 2001).

In the period 2001 to 2006, logging of wood increased by 58% as a result of the storms Lothar and Kyrill and bark beetle infestations. The turnover in the sawmills and pulp mills industry tended to benefit from the increased wood supply and lower prices. The revenue development in the sawmill industry (+36 %) and the wood and pulp producers (+73 %) was significant over the period 2001 to 2007. The significantly increased wood supply and the increased production are not sufficiently reflected in the development of German domestic consumption which only

increased by 4% overall. Germanys net import surplus of wood and wood-based products in 2001 reversed to a net export surplus by 2007 (Seintsch, 2010).

This long period of growth came to an end in 2008 due to the financial crisis. Fortunately, the numerous investments in processing facilities in the first years of the century lead to production to quickly recover by 2010. One other driver was the construction sector, which domestically takes on 2/3th of all forest removals. An important development driving this demand was the awareness of improving the energy efficiency (set in motion by the first Thermal Insulation Ordinance and now substantiated by the Renewable Energies Heat Act and Green Building Certificates). In the pulp and paper industry the turnover increased by 17% and also exports increased significantly by approximately 19% (Federal Ministry of Consumer Protection, Food, Agriculture, 2011).

The German trade in sawnwood and pulpwood was characterized by a net export surplus since 2004. Between 2010 and 2015, this situation reversed in terms of volumes. However, exports still exceeded imports in monetary terms. This does not apply to the market of soft sawnwood, which was still dominated by an export surplus (Federal Ministry for Food and Agriculture, 2015; Federal Ministry of Consumer Protection, Food, Agriculture, 2013).

In 2015, the export surplus of softwood and the import surplus of hardwood. on the one hand and limited hardwood processing potentials in Germany on the other hand became a challenge for the German forest sector. The German market is dominated by softwood processing which accounts for 90% of the roundwood utilisation. As a result, strategies are developed to find additional import opportunities for softwood, to develop processing capacities for hardwood products or to improve raw material efficiency and intensified ‘cascading’ use of wood (Federal Ministry for Food and Agriculture, 2017).

In 2017 and 2018, roundwood production in Germany was hit hard by windthrow and pests; in Spring heavy storms led to significant forest damaged and the following drought period in summer and autumn caused severe bark beetle infestations. The latter hit caused 30 million m^3 of spruce wood to be salvaged. In 2019 the damage increased up to another 70 million m^3. As a result, the damaged wood accumulated leading to overfull storage, oversupply, market pressure and rapidly dropping prices. As a result, the existence of many forest holdings was threatened. In 2018, tax reductions were offered for those forest enterprises hit hard by the storm events. In 2019, the Federal government decided to dedicate 25 million Euros of the “German Joint Task for the Improvement of Agricultural Structures and Coastal Protection (GAK)” budget to tackle the deterioration of German forests and forestry. Furthermore, the Landwirtschaftliche Rentenbank (A development Agency for Agribusiness and Rural areas)

offered beneficial financing conditions for reforestation efforts (Federal Ministry for Food and Agriculture, 2019).

3.1.5 Sweden 1995-2019

In contrast to the other case study countries, the situation on the Swedish forest product market and forest-based industry in 1998 and 1999 was less bright. Compared to the record production of sawn softwood achieved in 1997, in the last two years of the century decreasing pulpwood and sawnwood prices resulted in low profitability in both the sawmilling and pulp industry. As a result, several sawmills had to close down, whereas others have tried to invest in growing capacities. In contrast, the pulp industry imported large numbers of coniferous roundwood. At the turn of the century, the domestic and foreign demand increased and the prices of sawnwood and spruce were going up (National Institution of Economic Research, 1999).

Things changes in December 1999 as severe windstorms hit the spruce stands in the South of Sweden, leading to increased harvests. Simultaneously, the prices for roundwood, pulpwood and sawnwood and the demand increased (especially in the construction sector). At this point in time, it was expected that the shortage of good quality sawn hardwood and the increasing demand for it would become a problem.

In the Summer 2000 heavy rainfall caused problems for forest logistics. As a result, production and prices of sawnwood and pulpwood fell over the course of 2001 (National Institution of Economic Research, 2000). During 2001, large areas of forest were damaged by the *Gremmeniella abietina* fungus and several stands had to be felled prematurely. As a result, an increased volume of pine pulpwood and pine sawnwood entered the market. Furthermore, several storms caused damage during the winter. As a result, the production of sawnwood and pulpwood increased in 2002 which satisfied the high demand (National Institution of Economic Research, 2002).

Over the period 2001 to 2006, the forest removals of Sweden have increased steadily (with the exception of a minor decline in 2003 as a result of the high removals in the previous years). A similar picture can be sketched for the exports. In 2007, Sweden was the world's third largest exporter of (mostly coniferous) sawnwood after the Russian Federation and Canada. The most important export market was Europe. In contrast, Swedish imports have largely declined as the domestic market increased its production and subsequently its importance. The Swedish pulp and paper industry has been expanding too in the period 2000 to 2006, although the growth has slowed down somewhat as a result of digitalization and lesser demand for paper products (Jonsson et al., 2011).

The recession ended this growth in 2008 and 2009, but by the end of 2009 the forest sector started to recover. In 2010 the recovery accelerated as a result higher demand in the construction sector, the increased awareness of wood as a renewable solution and the new energy efficiency requirements for wood in buildings. As a result, demand increased in Europe and abroad. As the Swedish forest sector is export-oriented, the sawmills and pulp mills could easily capitalize on this demand (National Institution of Economic Research, 2011).

From 2011 to 2012, the sawnwood prices fell by 10% as a result of a decline in new housing projects and the resulting reduced demand. As a result, less wood was removed in 2013. Luckily, the export of sawnwood increased by 2%, slightly compensating the lack of domestic demand. Regarding the situation in the pulp and paper industry. (National Institution of Economic Research, 2013). In 2014, the demand in the construction sector revived. and forest removals increased again (14% more sawnwood removals compared to 2013).

In contrast to the sawmilling industry, over the period 2014-2017, the pulp and paper industry faced oversupply on the European markets as a result of unfavourable weather conditions, windthrows and bark beetle outbreaks. As a result, price fluctuations were frequent, but overall the prices seems to increase slightly (National Institution of Economic Research, 2015). Furthermore, as a result of the structural changes and shutdowns in the Norwegian forest industry, Sweden imports large amounts of pulpwood from Norway. To improve the capacity and increase the prices, large investments in the pulp and paperboard industry were done (National Institution of Economic Research, 2017).

In 2018, large bark beetle infestations led to high harvests, especially in Southern Sweden. As a result of oversupply on the European market, the prices of sawnwood are decreasing. The bark beetle infestations also led to an increase of salvaged wood to the pulp industry. As a result, the pulpwood prices of spruce and birch decreased again and the slight increasing trend from 2015 onwards came to a halt (National Institution of Economic Research, 2019).

3.2 Descriptive statistics and econometrics analysis of demand and supply shocks

The next sections present the findings of the regression analysis for the value chains in the selected countries. The coefficients in Tables 3-9 can be interpreted as the annual change in the roundwood price of the given assortment in response to the unit change of a predictor. The model has a log-log functional form, i.e., the coefficients can be directly interpreted as elasticities (a 1% increase in x_1 increases the domestic roundwood price by about β_1%).

3.2.1 Austria

For the Austrian sawmill value chain, neither demand- nor supply-side interaction effects are evident (Table 5), i.e., with given data and sample size no direct moderation of disturbance-induced effects was identified. In view of the low roundwood export volumes, we expected that variations in exports would not be sufficient to fully balance out roundwood oversupply situations. A surprising fact was that the Austrian forestry sector does not achieve a stabilisation of the domestic roundwood prices via the control of voluntary logging, although voluntary logging and salvage logging are negatively correlated to some degree (Figure). If no interaction terms are included in the models, significant effects for product unit values and salvage logging on the domestic roundwood price are found. In accordance with the theory, both a demand-driven price transmission from wood products to roundwood and a price-reducing effect on roundwood prices due to supply-side disturbances can be empirically shown. The positive association of the assortment share with the domestic roundwood price does not correspond with the expectation that an increase in the share of sawlogs in the total logging is accompanied by a reduction in the price of this assortment. Together with the highly significant effect of product unit value, this could suggest that the change in assortment shares in Austria has been driven more by increased demand for logs than by increased supply through salvage logging. Overall, the results suggest that the Austrian saw mill value chain is indeed affected by demand and supply-side shocks, but not fully in accordance with expectations.

No results can be reported for the Austrian pulp mill value chain, as the explanatory power of the models both with and without interaction effects is too low.

Table 5: OLS estimates for the roundwood price of the Austrian saw mill value chain (log-log model). Significance levels include 1% (***), 5% (**), 10% (*).

Full/best model	Full model	Best model	Full model	Best model
Method	OLS	OLS	OLS	OLS
No. Observations	28	28	28	28
Prob (F-statistics)	0.0831	0.0153	0.0148	0.0017
Adj. R-squared	0.293	0.3545	0.3567	0.3941
AIC	-51.9709	-56.6011	-56.6972	-60.6366
Durbin-Watson	1.939	1.9228	1.9291	1.9123
Prob (Jarque-Bera)	0.2348	0.3993	0.2906	0.4449
Prob (Breusch-Pagan)	0.8718	0.9179	0.505	0.8231
Prob (Rainbow)	0.1257	0.2257	0.3447	0.2937
const	0.0099	0.0051	0.0046	0.0008
Product unit value (10^6 LCU†/10^6 PU††)	0.9002	0.4312	** 0.5283	*** 0.5165

Roundwood imports (10^6 PU)	1.429	-0.4383	-0.1483	
Roundwood exports (10^6 PU)	0.2614		-0.0232	
Voluntary logging (10^6 m^3)	-0.3035		0.013	
Salvage logging (10^6 m^3)	-0.5254	-0.0599	-0.0898	** -0.0815
Assortment share (10^6 m^3/10^6 m^3)†††	0.3255	0.7112	* 0.8213	* 0.5832
Product unit value * Roundwood imports	-0.3126	0.0541		
Salvage logging * Voluntary logging	0.2107			
Salvage logging * Roundwood exports	-0.2177			
Salvage logging * Assortment share	0.5348	0.0662		

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

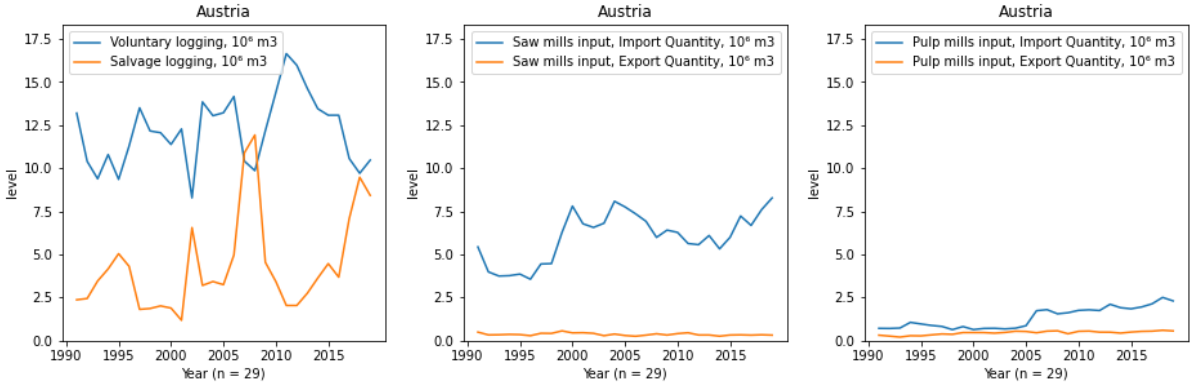
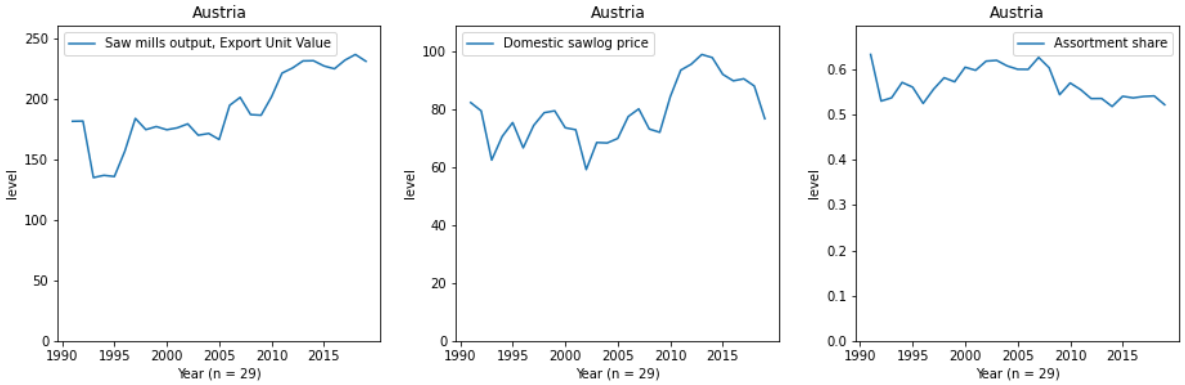


Figure 1. Austrian trade and logging quantities used for OLS estimation before log-transformation and differencing.



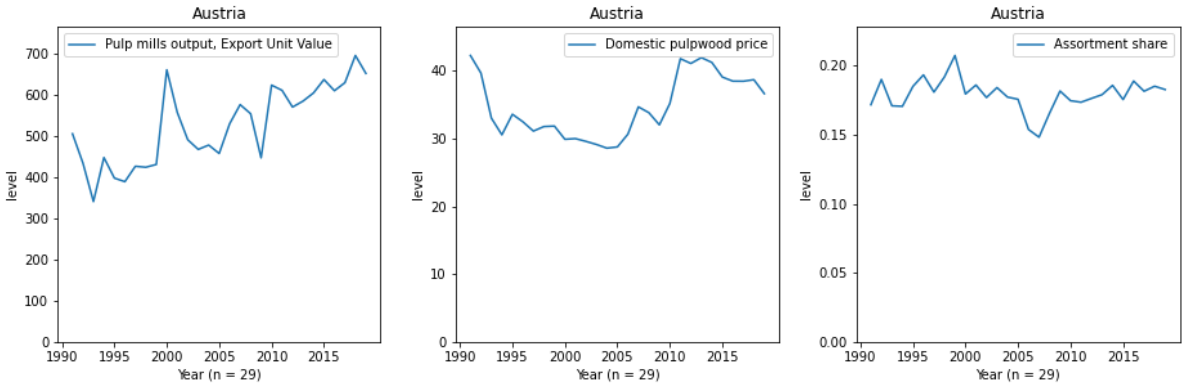


Figure 2. Austrian product export values, domestic roundwood prices, and assortment shares used for OLS estimation before log-transformation and differencing.

3.2.2 Czechia

As for the Czech saw mill industry, two interaction effects significant at the 10% level can be reported (Table 6). First, a negative interaction between salvage logging and roundwood exports indicates that the partial effect of salvage logging on roundwood price diminishes with increasing roundwood exports. Unexpectedly, we found a positive sign for salvage logging. A possible explanation is that windthrow events affected particularly high grades of sawlogs and thus triggered shortages in the sawmill industry. This effect is less pronounced when roundwood exports are high, presumably since better qualities are more likely to be exported and therefore domestic prices are less affected. Second, the effect of salvage logging on domestic sawlog prices increases with the proportion of sawlogs in the total harvest. Considering the "shortage effect" of salvage logs on high-grade sawlogs, this finding seems plausible. The assortment share thus represents a potential resilience predictor that can be used to moderate effects of disturbances on the Czech sawmill industry. The fact that no moderation of the effects of demand-side shocks can be seen may be explained by the comparatively low import volumes of roundwood, which are probably too low to balance out short-term demand peaks on the domestic market.

The models without interaction effects show a number of significant coefficients. As expected, the product unit value is positively related to the roundwood price, while voluntary logging is negatively associated. The signs of the coefficients for roundwood imports and roundwood exports deviate from the expectation. In contrast to Austria, the price reducing effect of exports would imply that roundwood price is driven more by supply shocks. However, the imported volumes have been clearly lower than the exported volumes. Like Austria, the Czech saw mill industry is affected by demand and supply side disturbances, but it has been able to absorb supply shocks to some extent by increased roundwood export volumes.

For the pulp industry in Czechia no statements can be made due to a very low explanatory value of the estimates.

Table 6: OLS estimates for the roundwood price of the Czech saw mill value chain (log-log model). Significance levels include 1% (***), 5% (**), 10% (*).

Full/best model	Full model	Best model	Full model	Best model
Method	OLS	OLS	OLS	OLS
No. Observations	20	20	20	20
Prob (F-statistics)	0.0455	0.0455	0.0165	0.0031
Adj. R-squared	0.5413	0.5413	0.4904	0.5357
AIC	-50.1209	-50.1209	-48.6618	-51.6627
Durbin-Watson	2.2573	2.2573	2.568	2.5845
Prob (Jarque-Bera)	0.7766	0.7766	0.8004	0.8172
Prob (Breusch-Pagan)	0.1852	0.1852	0.2367	0.391
Prob (Rainbow)	0.2964	0.2964	0.6835	0.5325
const	0.0221	0.0221	0.0182	0.0153
Product unit value (10^6 LCU†/10^6 PU††)	* 0.3144	* 0.3144	*** 0.3707	*** 0.3591
Roundwood imports (10^6 PU)	0.6213	0.6213	** 0.1357	*** 0.1530
Roundwood exports (10^6 PU)	-0.0014	-0.0014	** -0.1800	*** -0.1763
Voluntary logging (10^6 m^3)	0.1569	0.1569	* -0.2320	*** -0.2097
Salvage logging (10^6 m^3)	* 1.5624	* 1.5624	-0.0194	
Assortment share (10^6 m^3/10^6 m^3)†††	* -2.1722	* -2.1722	-0.2661	
Product unit value * Roundwood imports	-0.0613	-0.0613		
Salvage logging * Voluntary logging	-0.1996	-0.1996		
Salvage logging * Roundwood exports	* -0.1483	* -0.1483		
Salvage logging * Assortment share	* 1.6584	* 1.6584		

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

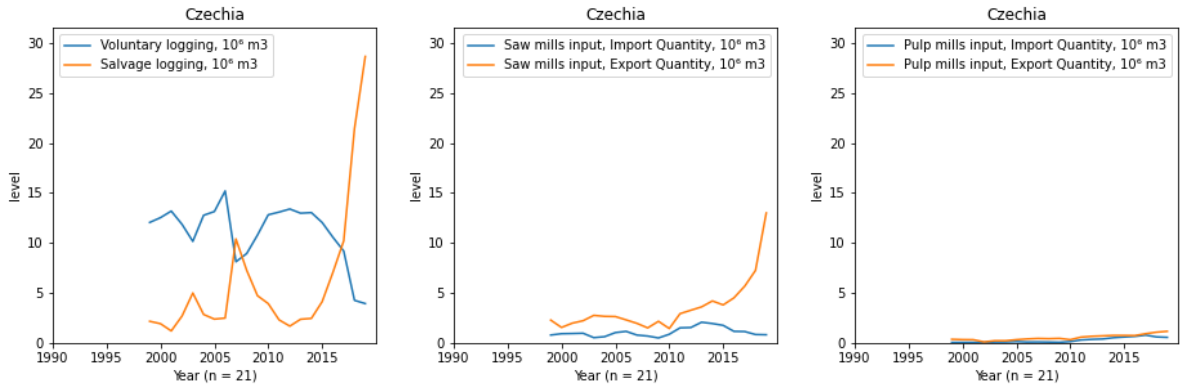


Figure 3: Czech trade and logging quantities used for OLS estimation before log-transformation and differencing.

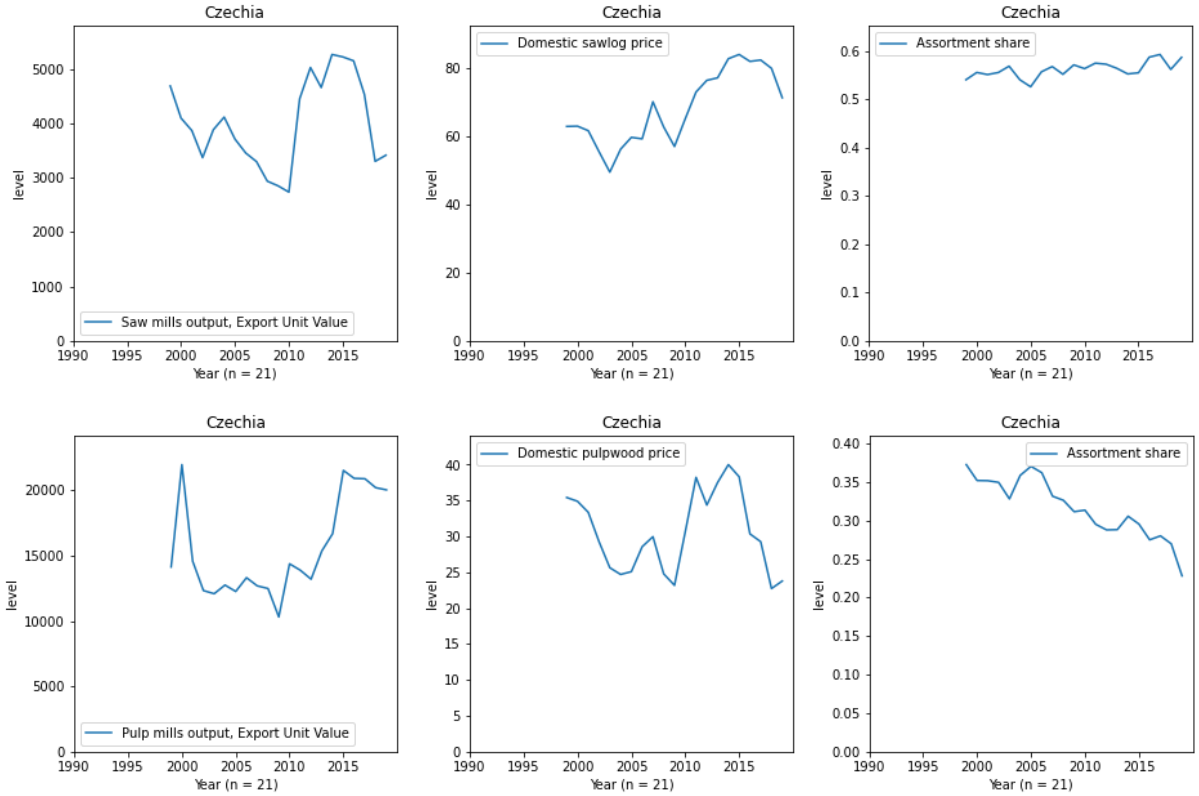


Figure 4. Czech product export values, domestic roundwood prices, and assortment shares used for OLS estimation before log-transformation and differencing.

3.2.3 Finland

In Finland, the increased demand for wood-based products affects the domestic sawlog price negatively when the interaction with roundwood imports considered. This effect intensifies with increasing roundwood imports (significant at the 10% level in the best model) (Table 7). The finding suggests that the Finnish saw mill value chain is able to overcompensate for the effects of demand shocks via alterations in roundwood imports. However, these results should be interpreted with caution, as the Durbin-Watson test results are at the upper acceptable limit. In line with other countries, the product unit value plays an important role in determining the roundwood price in the models without interaction effects. Furthermore, a positive effect of voluntary (non-salvage) logging is found at the 10% significance level, which would suggest the voluntary logging was driven by market demand. This finding can be attributed to the limited scale of supply-side disturbances in Finland, which means that voluntary logging is likely to be more strongly driven by expected roundwood prices than in other countries presenting higher disturbance frequencies and magnitudes. Supply-side shocks played a marginal role in Finland in the past, for which reason no interaction effects to moderate supply shocks could be found.

Table 7: OLS estimates for the roundwood price of the Finnish saw mill value chain (log-log model). Significance levels include 1% (***), 5% (**), 10% (*).

Full/best model	Full model	Best model	Full model	Best model
Method	OLS	OLS	OLS	OLS
No. Observations	20	20	20	20
Prob (F-statistics)	0.0088	0.002	0.001	0
Adj. R-squared	0.7008	0.7213	0.6853	0.7174
AIC	-57.3256	-58.7286	-56.9592	-61.7457
Durbin-Watson	2.6323	2.784	2.2565	2.0335
Prob (Jarque-Bera)	0.8449	0.5892	0.1222	0.3501
Prob (Breusch-Pagan)	0.4103	0.2662	0.5278	0.5706
Prob (Rainbow)	0.8503	0.6053	0.5534	0.3899
const	-0.002	-0.0081	0.0058	0.0109
Product unit value (10^6 LCU†/10^6 PU††)	-1.4305	-1.2324	** 0.7927	*** 0.7646
Roundwood imports (10^6 PU)	-5.503	* -5.3679	0.0177	
Roundwood exports (10^6 PU)	-0.0457		-0.0171	
Voluntary logging (10^6 m^3)	* 0.8024	** 0.8204	0.4921	* 0.3427
Salvage logging (10^6 m^3)	0.8101	0.7277	0.0024	
Assortment share (10^6 m^3/10^6 m^3)†††	-0.9067	* -1.1390	-0.4014	
Product unit value * Roundwood imports	1.0256	* 0.9935		
Salvage logging * Voluntary logging	-0.1839	-0.1852		
Salvage logging * Roundwood exports	0.0086			
Salvage logging * Assortment share	0.0685	-0.0246		

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

In contrast to Austria and Czechia, estimation was possible for the Finnish pulp value chain, although these results should be interpreted with caution due to Durbin-Watson test results being at the lower limit (Table 8). First, there is a negative effect of the interaction between salvage logging and the assortment share, which, however, should only be attributed having minor importance given the low level of salvage logging. At the same time, a positive coefficient for voluntary logging can be reported, which – as already found in the Finnish saw mill industry – is probably due to the fact that voluntary logging is more strongly driven by demand and expected roundwood prices than in other countries. It is interesting to note that the price transmission from wood products to roundwood is not present in the Finnish pulp value chain, notwithstanding that there is no significant moderation of the effects of demand shocks. The fact that supply-side disturbances play a lesser role in Finland is also shown by the assortment share, which has a positive coefficient (significant at the 5% level in the models

without interaction effects). Apparently, the assortment composition here follows demand driven logic and the expectations with regards to domestic roundwood prices more closely than in countries where the assortment shares and consequently the (assortment-related) roundwood prices are more strongly influenced by climate change-induced disturbance events. In addition, the best model solution results in a positive coefficient for roundwood exports, which, however, should not be overinterpreted by virtue of very limited roundwood export volumes. The Finnish pulp industry is a special case in this analysis, as both supply- and demand-side disturbances explaining the roundwood price change seem to play a minor role.

Table 8: OLS estimates for the roundwood price of the Finnish pulp mill value chain (log-log model). Significance levels include 1% (***), 5% (**), 10% (*).

Full/best model	Full model	Best model	Full model	Best model
Method	OLS	OLS	OLS	OLS
No. Observations	20	20	20	20
Prob (F-statistics)	0.0637	0.0075	0.0307	0.0015
Adj. R-squared	0.4966	0.516	0.4303	0.5332
AIC	-51.2184	-53.1689	-49.3895	-55.2192
Durbin-Watson	1.0071	0.8985	1.3795	1.3601
Prob (Jarque-Bera)	0.0899	0.0853	0.8101	0.8134
Prob (Breusch-Pagan)	0.9548	0.4305	0.9871	0.9583
Prob (Rainbow)	0.747	0.2987	0.6751	0.6027
const	-0.0073	-0.0006	-0.0048	-0.005
Product unit value (10^6 LCU†/10^6 PU††)	-0.0529		0.0186	
Roundwood imports (10^6 PU)	0.3002		0.0049	
Roundwood exports (10^6 PU)	-0.1045		0.1095	** 0.1109
Voluntary logging (10^6 m^3)	0.621	*** 0.6993	** 0.6471	*** 0.6798
Salvage logging (10^6 m^3)	-1.3988	-0.6716	-0.0062	
Assortment share (10^6 m^3/10^6 m^3)†††	-1.5008	0.0118	** 1.1733	*** 1.1967
Product unit value * Roundwood imports	-0.0073			
Salvage logging * Voluntary logging	0.0751	-0.0173		
Salvage logging * Roundwood exports	-0.1476			
Salvage logging * Assortment share	* -1.3057	** -1.0558		

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

Figure 5: Finnish trade and logging quantities used for OLS estimation before log-transformation and differencing.

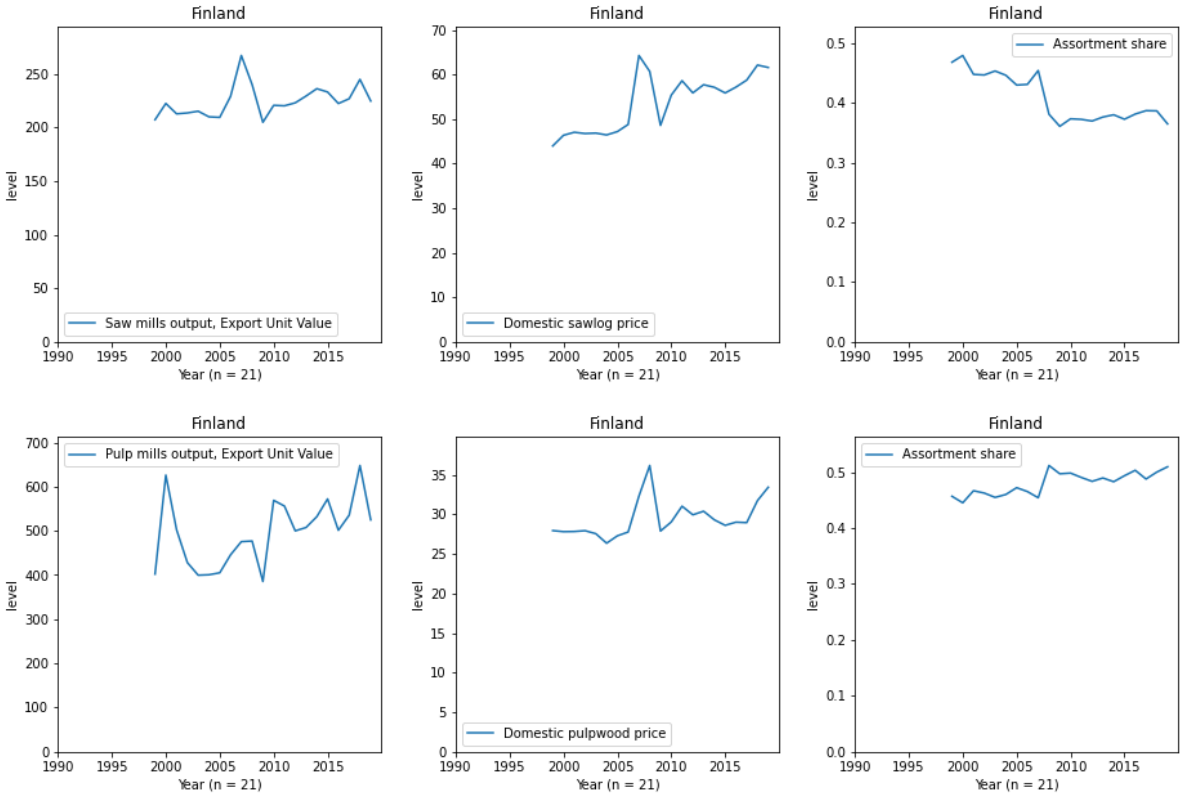


Figure 6. Finnish product export values, domestic roundwood prices, and assortment shares used for OLS estimation before log-transformation and differencing.

3.2.4 Germany

No significant interaction effects was identified for the German saw mill industry (Table 9). For the demand side, this can be explained by the fact that – unlike in the neighbouring saw mill value chains of Austria and Czechia – the models without interaction terms show no transmission of product prices on domestic roundwood prices. This largely suggests

independence of demand-side shocks that would require countermeasures on the part of the saw mill industry. Furthermore, it is questionable whether Germany, considering its comparatively low sawlog trade volumes, would be able to react on peaks in the domestic roundwood price by rapidly increasing imports. Although significant results at the 10% level are shown for roundwood import and export flows, these should not be interpreted further due to the low trade volumes. For salvage logging, the best model estimates show a significant positive coefficient. Similar to Czechia, this implies that forest disturbances may cause relative shortages of high-quality sawlogs; however, in Germany this effect is not mitigated by foreign trade or other resilience factors.

Table 9: OLS estimates for the roundwood price of the German saw mill value chain (log-log model). Significance levels include 1% (***), 5% (**), 10% (*).

Full/best model	Full model	Best model	Full model	Best model
Method	OLS	OLS	OLS	OLS
No. Observations	24	24	24	24
Prob (F-statistics)	0.0713	0.0237	0.0606	0.0311
Adj. R-squared	0.3771	0.4385	0.2871	0.3222
AIC	-61.0489	-64.1037	-59.3721	-61.2096
Durbin-Watson	1.2252	1.1719	1.4518	1.4708
Prob (Jarque-Bera)	0.4338	0.2841	0.2782	0.2691
Prob (Breusch-Pagan)	0.306	0.4245	0.5593	0.4308
Prob (Rainbow)	0.4618	0.5045	0.2693	0.3813
const	0.0113	0.012	0.0071	0.0073
Product unit value (10^6 LCU†/10^6 PU††)	-0.036	-0.0583	-0.1219	-0.1185
Roundwood imports (10^6 PU)	1.0882	0.901	* 0.1202	* 0.1118
Roundwood exports (10^6 PU)	-0.1233	-0.0918	-0.0876	* -0.0950
Voluntary logging (10^6 m^3)	0.1268		-0.0194	
Salvage logging (10^6 m^3)	0.1832	** 0.0890	0.0126	** 0.0162
Assortment share (10^6 m^3/10^6 m^3)†††	0.4449	0.3989	* 0.4025	* 0.4124
Product unit value * Roundwood imports	-0.1886	-0.1508		
Salvage logging * Voluntary logging	-0.0217			
Salvage logging * Roundwood exports	-0.0065	-0.0138		
Salvage logging * Assortment share	0.1343	0.1238		

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

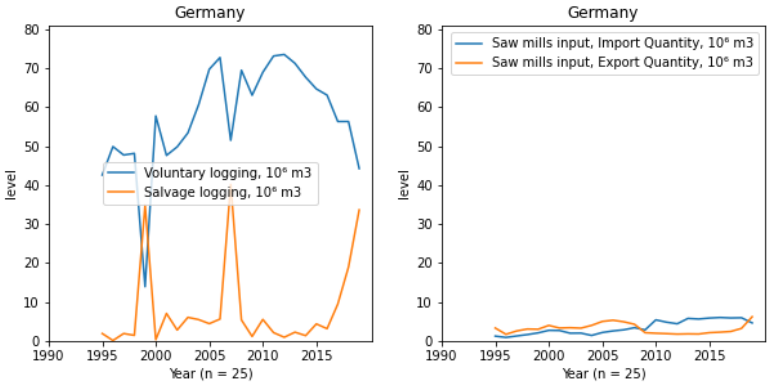


Figure 7: German trade and logging quantities used for OLS estimation before log-transformation and differencing.

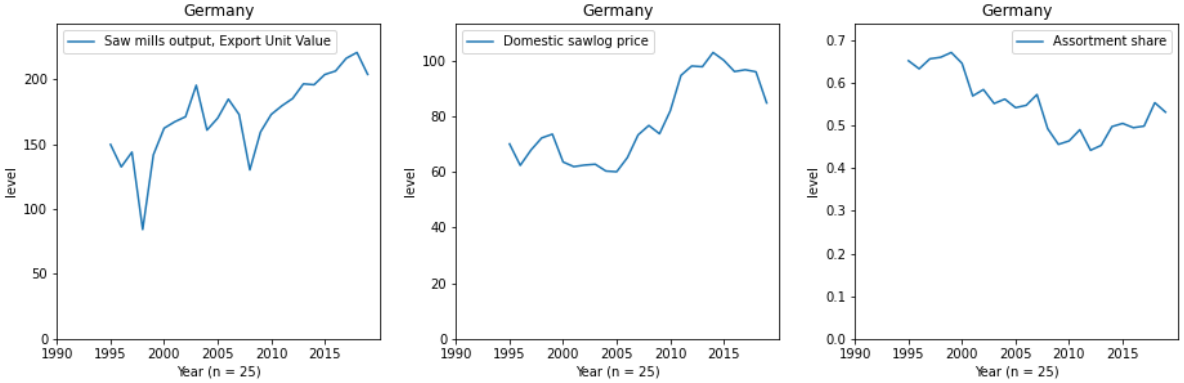


Figure 8: German product export values, domestic roundwood prices, and assortment shares used for OLS estimation before log-transformation and differencing.

3.2.5 Sweden

Two interaction effects can be reported for the Swedish saw mill industry (Table 10). On the one hand, there is a significant negative effect (10% significance level) for salvage logging and roundwood exports. This suggests that exports offset observed price-increasing effects of supply shocks (which presumably arise from short-term shortages of high-grade sawlogs due to windthrow). As in the case of Czechia, this might be explained by a tendency to export higher grades, causing domestic prices remain less affected at high export levels. However, it should be emphasised that the export volumes are not large enough for this effect to play a substantial role. On the other hand, the best model estimates show an interaction effect with a negative sign for salvage logging and voluntary logging. This indicates that the “shortage effect” of climate change-induced disturbances with regards to high-quality sawlogs diminishes with increasing voluntary logging. No price transmission from wood products to

roundwood is discernible, while a significant positive coefficient can be reported for voluntary logging (regardless of whether interaction effects are taken into account or not). Supply shocks do play a role in the domestic saw mill industry, but the demand side seems to have a stronger influence on harvesting decisions. Similar to Finland, alterations in voluntary logging appear more dependent on demand and expected future roundwood prices. Overall, the impact of demand and supply shocks on the Swedish saw mill value chain are of limited magnitude (with the exception of 2005) and together with Finland, Sweden constitutes a distinct group of northern European countries in the sample that has been less prone to forest disturbances in the study period.

Table 10: OLS estimates for the roundwood price of the Swedish saw mill value chain (log-log model). Significance levels include 1% (***), 5% (**), 10% (*).

Full/best model	Full model	Best model	Full model	Best model
Method	OLS	OLS	OLS	OLS
No. Observations	23	23	23	23
Prob (F-statistics)	0.0011	0	0.0001	0
Adj. R-squared	0.7382	0.8031	0.7145	0.7431
AIC	-61.4474	-69.9876	-60.8325	-65.3087
Durbin-Watson	1.1454	1.1712	1.6106	1.5015
Prob (Jarque-Bera)	0.6976	0.7301	0.9998	0.9955
Prob (Breusch-Pagan)	0.6631	0.6054	0.3945	0.1262
Prob (Rainbow)	0.5579	0.8762	0.9988	0.9996
const	-0.0014	-0.0013	0.0052	0.0065
Product unit value (10^6 LCU†/10^6 PU††)	0.4332		0.0157	
Roundwood imports (10^6 PU)	1.4018		0.0754	0.076
Roundwood exports (10^6 PU)	-0.0284	-0.0283	-0.0365	
Voluntary logging (10^6 m^3)	* 0.7450	*** 0.8317	*** 0.3692	*** 0.3784
Salvage logging (10^6 m^3)	0.4207	** 0.4863	* 0.0166	** 0.0179
Assortment share (10^6 m^3/10^6 m^3)†††	0.1144		0.0778	
Product unit value * Roundwood imports	-0.1889			
Salvage logging * Voluntary logging	-0.0932	** -0.1094		
Salvage logging * Roundwood exports	* -0.0237	* -0.0185		
Salvage logging * Assortment share	0.0087			

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

For the Swedish pulp industry, only partially estimated results can be reported (Table 11). Taking interaction effects into account, the best model reveals that an observed insignificant price-dampening effect of demand shocks is stronger at high levels of pulpwood imports, i.e., pulpwood imports are found to moderate the effect of demand shocks on domestic pulpwood prices to some degree. However, the level of pulpwood imports is primarily a consequence of management decisions by the pulp mill industry, which would – in the short term – benefit from decreasing rather than from stable pulpwood prices. This illustrates that the management of a resilience predictor is not always aimed at enhancing the value chain resilience, but is also subject to the vested interests of individual economic actors. Furthermore, there is a negative coefficient for the interaction of salvage logging and roundwood exports. Although such an outcome was expected, it should not be overestimated because of low trade flow levels. Omitting the interaction effects, only the assortment share shows a significant (positive) association with the domestic roundwood price. As in Austria and Czechia, the functional logic of the pulp mill value chain in Sweden is more difficult to capture than those of the saw mill industries. The reason for this may be found in the different characteristics of these value chains. Probably, pulp processing is inherently more resilient due to its broader raw material base, which makes supply-side shocks to play a lesser role.

Table 11: OLS estimates for the roundwood price of the Swedish pulp mill value chain (best model only) (log-log model). Significance levels include 1% (***), 5% (**), 10% (*).

Full/best model	Best model	Best model
Method	OLS	OLS
No. Observations	23	23
Prob (F-statistics)	0.054	0.0603
Adj. R-squared	0.3138	0.118
AIC	-43.0499	-41.0235
Durbin-Watson	1.9052	1.8384
Prob (Jarque-Bera)	0.0358	0.7507
Prob (Breusch-Pagan)	0.9946	0.6126
Prob (Rainbow)	0.4844	0.6454
const	0.0034	0.004
Product unit value (10^6 LCU†/10^6 PU††)	-0.1974	
Roundwood imports (10^6 PU)	** -7.4461	
Roundwood exports (10^6 PU)	0.0385	
Voluntary logging (10^6 m^3)		
Salvage logging (10^6 m^3)	** -0.0634	
Assortment share (10^6 m^3/10^6 m^3)†††		* 0.7761
Product unit value * Roundwood imports	** 0.8881	
Salvage logging * Voluntary logging		

Salvage logging * Roundwood exports	* -0.0574	
Salvage logging * Assortment share		

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

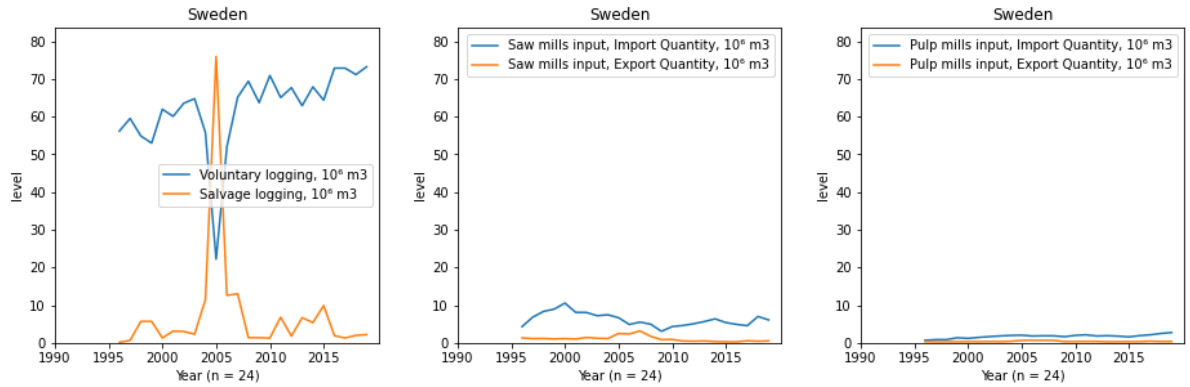


Figure 9: Swedish trade and logging quantities used for OLS estimation before log-transformation and differencing.

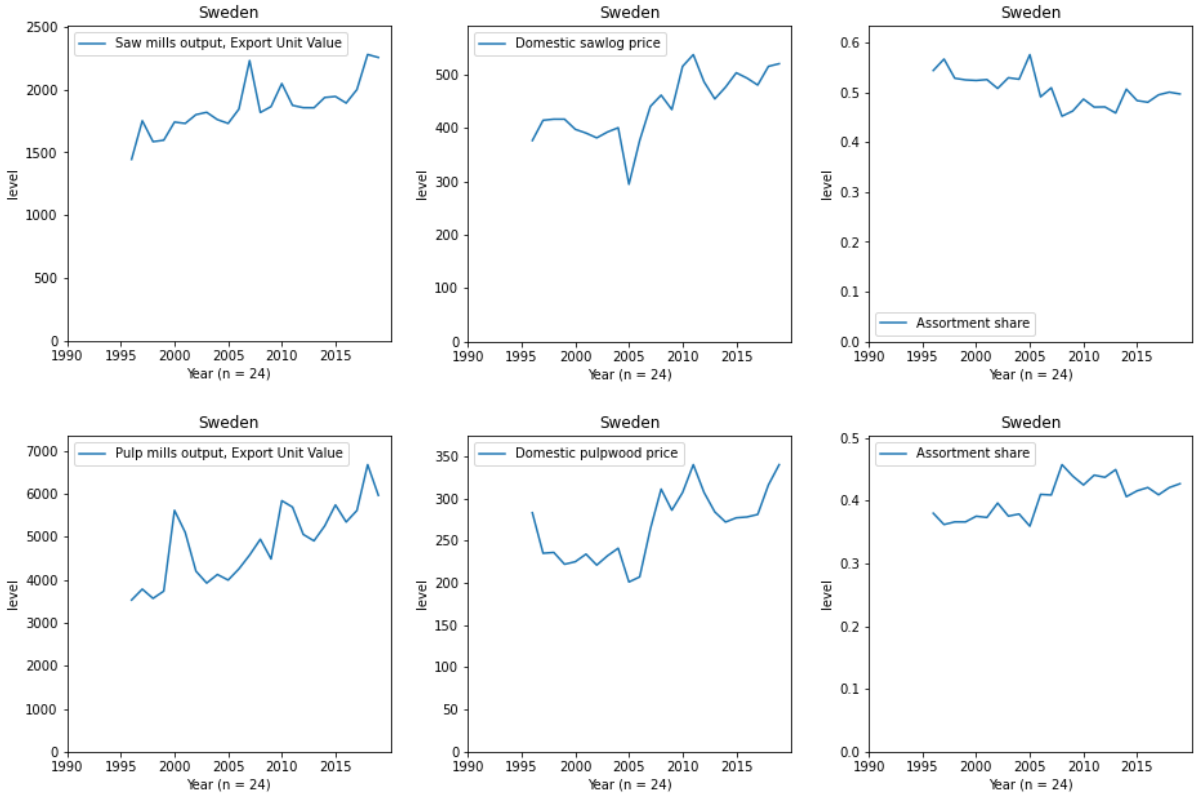


Figure 10. Swedish product export values, domestic roundwood prices, and assortment shares used for OLS estimation before log-transformation and differencing.

3.3 Estimation of Armington elasticities

Table 12 and Table 13 summarize the estimation results of Armington elasticities for the saw mill and pulp mill value chains under study. Positive and significant Armington elasticity estimates indicate substitutability between domestically harvested and imported roundwood the Czech and Finnish saw mill industries, for which reason sawlog trade may play a role as a resilience predictor in these countries. Austria and Sweden, on the contrary, exhibit a comparably low substitutability between domestic and foreign roundwood. With respect to pulp milling, positive and significant Armington elasticity estimates are found in Czechia, where pulpwood imports moderate the effect of supply shocks to some degree. The Swedish pulp mill industry presents a significant negative Armington elasticity estimate, suggesting that a high price for domestic or imported pulpwood has a positive effect on roundwood consumption from the respective origin (Lundmark & Shahrammehr, 2012). More plausible, however, seems the presence of measurement errors causing a negative sign. Austria and Finland show insignificant elasticities only.

Table 12: OLS estimates of the Armington elasticites for the saw mill value chains (log-log model). Significance levels include 1% (***), 5% (**), 10% (*).

Country	Austria	Czechia	Finland	Sweden
Method	OLS	OLS	OLS	OLS
No. Observations	29	21	21	24
Prob (F-statistics)	0.094	0.0059	0	0.0123
Adj. R-squared	0.1022	0.3718	0.8806	0.2796
Durbin-Watson	0.6906	0.6324	1.2722	0.968
Prob (Jarque-Bera)	0.3273	0.5922	0.6	0.7748
Prob (Breusch-Pagan)	0.1637	0.636	0.5938	0.7212
Prob (Rainbow)	0.9294	0.946	0.2099	0.0662
const	*** -0.6735	* 3.2803	*** -0.7020	*** -1.4965
Domestic roundwood price / roundwood import unit value	0.5523	*** 1.6413	*** 1.0211	0.3026
Time	** 0.0101	* 0.0287	*** -0.0666	** -0.0198

Table 13: OLS estimates of the Armington elasticites for the pulp mill value chains (log-log model). Significance levels include 1% (***), 5% (**), 10% (*).

Country	Austria	Czechia	Finland	Sweden
Method	OLS	OLS	OLS	OLS
No. Observations	29	21	21	24
Prob (F-statistics)	0	0	0.0594	0.001
Adj. R-squared	0.6798	0.8769	0.1881	0.4311
Durbin-Watson	0.7072	1.1276	0.4731	0.6516
Prob (Jarque-Bera)	0.4566	0.5279	0.5849	0.6609

Prob (Breusch-Pagan)	0.1246	0.6099	0.0025	0.1725
Prob (Rainbow)	0.3884	0.2365	0.1418	0.0026
const	*** -1.2621	-0.4939	*** -2.7615	*** -3.2394
Domestic roundwood price / roundwood import unit value	-0.0836	*** 1.3295	0.5526	** -0.2651
Time	** 0.0365	*** 0.1885	** 0.0266	*** 0.0215

4. Discussion and conclusions

4.1 Interpreting and generalising of the findings

Resilience of forest-based value chains to windthrow and bark beetle outbreaks based on an econometric analysis on roundwood price changes varied across forest-based value chains in Europe. Determining factors which statistically significantly moderate the adverse effects caused by windthrows and bark beetle outbreaks can help to enhance the resilience in forest value chains. This is expected to become even more important in the future as climate change will increase such disturbances and thereby adversely impact forest-based value chains. This deliverable provides a time series econometric model for five European countries (Austria, Czechia, Finland, Germany and Sweden) for which national roundwood market data was available. The selected countries have a large geographical spread and different forest types. Based on the findings, we made the first effort to outline priorities that potentially strengthen the stability in a forest value chain and help the forest-based sector take efficient and robust adaptation measures. The results of the analysis contribute to a body of literature dedicated to facilitating climate resilience in forest systems (Fuchs et al., 2022; Loeffler & Anderson, 2018; Schwarzbauer, 2007; Seidl et al., 2017; Zhai & Kuusela, 2020).

The results can be compared on two levels: First, based on descriptive statistics of salvage logging, production and domestic demand, we can identify factors influencing value chain resilience within countries; Second, based on the descriptive statistics of the import and export of roundwood, we can identify moderating effects of international trade affecting the resilience on the domestic market.

Regarding resilience within countries, the econometric models were more successful in case of sawnwood than for pulpwood. Regarding the latter, only models for Finland and Sweden reported any statistically significant effects. The share of assortments of the total production following a disturbance was used as a proxy to measure the quality deterioration. Hence, after a bark beetle outbreak or windthrow event, we expected to find a higher assortment share for

lower-quality assortments (pulpwood and energy wood). However, the effect of disturbances on quality change was found to be more complex. Future work should consider that quality deterioration may also take place within assortments.

Regarding the effect of international trade on value chain resilience, our results show observable differences whether demand or supply side effects act as primary driving forces on the market (to aid cross-country comparison, main results are summarized in Table 14). In Sweden and particularly in Finland, logging appear to be affected more by demand-side factors than by supply-side factors. Hence, the impacts caused by disturbances on the value chains in the past are often mediated by respective demand for wood-based products. As a result, the impacts, and in particular costs of disturbances on national forest-based value chains may be hidden or underestimated due to disturbances being more local than national. For Czechia and Germany, our findings indicate that factors on the supply-side of the value chain are the primary driving factor. Along these lines, the effects of management directed at optimising the extent of salvage logging and voluntary logging potentially enhances market stability. Lastly, for Austria it was not clear based on estimation results whether demand or supply-side factors are more prominent. As emphasized by Lundmark & Shahrammehr (2012), opportunities to increase substitutability between imported and domestic roundwood lie in increasing technical flexibility in the pulp industry, expanding the use of wood for energy, and removing trade barriers.

In line with the above, we can only draw tentative conclusions and theorise on what role the identified effects on value chain resilience. A first remark is that market behaviour on the national level, as measured by the changes in the price of wood assortments, has not been heavily affected by disturbance shocks in the last two decades. This can be ascribed to the fact that disturbance shocks may have local effects that are outbalanced on the domestic market, especially in larger countries such as Germany and Sweden. In addition, the partial absence of supply-side effects can be ascribed to a low magnitude of disturbances. Looking at the historical data, this seems to be the case for Finland compared to Central-Europe and Sweden. Therefore, our second remark is: The impact of increasing disturbances in the future may create different patterns. As climate change intensifies, the increasing frequency of disturbances will reduce the likelihood that oversupply is mediated by demand-side effects and international trade. Furthermore, if magnitude of disturbances increases, we might observe a shift from short-term oversupply to longer term undersupply, which would drive roundwood prices upwards.

Table 14: Cross-country comparison of roundwood logging, processing and trade quantities (mean and standard deviation [sd] of level data, i.e., non-log-transformed, non-differenced), and significant

(1% [***], 5% [**], 10% [*]) OLS estimates of Armington elasticities and effects on roundwood prices (considering interaction effects, best log-log model estimates).

	Austria		Czechia		Finland		Germany		Sweden	
	1990-2019		1998-2019		1998-2019		1994-2019		1995-2019	
Logging	mean	sd								
Salvage logging (10^6 m^3)	12.17	2.01	11.14	2.83	54.11	5.76	57.46	13.16	62.95	10.42
Voluntary logging (10^6 m^3)	4.36	2.74	6.05	6.77	1.24	1.54	7.99	11.12	6.57	14.77
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
Saw mills significant OLS estimates										
Armington elasticity			*** 1.6413		*** 1.0211					
Product unit value (10^6 LCU†/10^6 PU††)			* 0.3144							
Roundwood imports (10^6 PU)					* -5.3679					
Roundwood exports (10^6 PU)										
Voluntary logging (10^6 m^3)					** 0.8204				*** 0.8317	
Salvage logging (10^6 m^3)			* 1.5624				** 0.0890		** 0.4863	
Assortment share (10^6 m^3/10^6 m^3)†††			* -2.1722		* -1.1390					
Product unit value * Roundwood imports					* 0.9935					
Salvage logging * Voluntary logging									** -0.1094	
Salvage logging * Roundwood exports			* -0.1483						* -0.0185	
Salvage logging * Assortment share			* 1.6584							
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										
Armington elasticity			*** 1.3295				** -0.2651			
Product unit value (10^6 LCU†/10^6 PU††)										
Roundwood imports (10^6 PU)									** -7.4461	
Roundwood exports (10^6 PU)										
Voluntary logging (10^6 m^3)					*** 0.6993					
Salvage logging (10^6 m^3)									** -0.0634	

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			** -1.0558		
† LCU = Local Currency Unit †† PU = Physical Unit ††† The share of the harvest of the respective assortment (e.g., sawn roundwood for the sawmill value chain) compared to the total harvest.					

4.2 Validity and reliability of our analysis

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 indicated 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 logging, due to differing (user supplied) definitions between countries. Similarly, the “quality effect” of disturbances on roundwood prices can be only captured by the assortment share variable, which only captures very drastic reduction in the quality of logs when they have to be used as pulpwood or for wood energy generation. A more direct predictor could have captured the different rates of damage, which makes capturing the reduction in quality within the roundwood assortments possible. At least in Austria, the disturbances may not have actually affected the roundwood shares, but rather the quality within the assortment. Also, the model could have further included the energy wood share from total roundwood supply, 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, we are considering aggregate pulpwood and sawlog markets in the analysis, and hence, possible differences across wood species (spruce, pine, hardwoods) could be additional factors in place, but this breakdown could not be incorporated in the core variables dealing e.g., with salvage loggings.

4.3 Embedding our findings in RESONATE and avenues for future work

The results of the analysis manifest diverging results from five countries that traditionally have a strong forestry and forest-based value chains. Consequently, generalising the findings across EU with different market structures, diverse value chains and disturbance regimes needs to be done with even greater caution. Nevertheless, a few ideas for future work on forest resilience are brought forward.

As aforementioned, in some cases demand-side effects (Finland and Sweden) are found to drive value chain resilience, while in some cases supply-side related effects (Germany and Czechia) drive value chain resilience. Hence, in line with Biggs et al. (2012) resilience in forest-based value chains works in two directions. Future work should focus on determining the nature and importance of such effects over time and look towards future. In addition, further research should focus on how to manage risk related to unexpected disturbances to enhance value chain resilience across EU and beyond.

Our results related to value chain resilience allow us to point out a few potential areas of inquiry. One such effect could be industry structure. For example, Czechia has a relatively small processing industry and depends on exporting wood to other countries. In contrast, Finland processes most of its domestic roundwood and Finnish companies are leaders concerning wood innovations. We could further speculate that the volume of storage capacity in combination with management focused on differentiating the ratio between salvage logging and voluntary logging influences resilience. This suggests that having access to roundwood storage data would be useful.

Other effects can be found by inspecting domestic forest policies. For example, Finland offered tax reductions to boost roundwood trade during the economic crisis in 2008 (Finnish Forest Industry Federation, 2009) and the German Federal Ministry for Food and Agriculture offered tax reductions to forest enterprises hit by the storms in 2018 and 2019. Similarly, the Landwirtschaftliche Rentenbank (A development Agency for Agribusiness and Rural areas) processed beneficial financing conditions for reforestation efforts (Federal Ministry for Food and Agriculture, 2019). Furthermore, regulations on salvage logging (Vancura & Trejbalova, 2004) may occur or there could be welfare effects due to restrictions on wood imports and exports (Solberg et al., 2010).

Another effect that influences dominance of demand- or supply-side effects could be the fluctuations in the exchange rate between the Euro and the Swedish or Czech Krona (e.g., Hietala et al., 2013). In this rationale, we could speculate that import and export restrictions assert some influence on value chain resilience.

There is also the question of system boundaries and disturbance regimes on a spatial and temporal scale. The scale of bark beetle outbreaks or windthrow events might not compare to the scale of disturbances caused by forest fires, droughts or floods. For example, the scale of a bark beetle outbreak is often larger than the scale of a forest fire (Senf & Seidl, 2022). Furthermore, the intensity of past windthrow events and bark beetle infestations over the analysed period might not compare to the intensity of such events in the future. In the case of Czechia, the number and extent of bark beetle outbreaks is rising strongly. Furthermore, in this study, merely annual short-term impacts were captured (i.e., a new equilibrium was assumed to be reached with a one-year time lag). However, Fuchs et al., (2022) find that full market adjustment after a major disturbance typically take two years to phase out, for example, due to already signed wood supply contracts.

Lastly, it may depend on the perspective, whether it is price fluctuations or price stability that measures value chain resilience. Literature offers inconclusive evidence on the matter. On the one hand, price reductions allow the market to absorb increased amounts of roundwood in the absence of parallel demand shocks (Loeffler & 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 deliverable, we emphasise the power of moderating factors in stabilizing prices, such as increased trade, reduced voluntary logging and shifts in roundwood assortment shares. Such moderating factors help to alleviate the price volatility in case of major oversupply or undersupply caused by disturbances. Thus, price stability can also be considered as a measure for resilience in the roundwood market.

A few suggestions for future research came forward from our analysis. First, future work should consider that quality deterioration may also take place within assortments (e.g., high quality sawn wood to low quality sawn wood). Second, our results suggest that supply-side predictors are more dominant in the Scandinavian case studies and demand-side predictors are more dominant in the Central-European case studies. Therefore, future work should focus on the management effects responsible for such differences (as will be already partly dealt with in RESONATEs D3.3 in WP3). Third, forest disturbances have always been part of forest management, but they will increase in intensity and frequency due to climate change. Hence, the possibilities to empirically investigate whether the current resilience of forest-based value chains is sufficient to adequately moderate future disturbance events are limited. A way forward could be to in-depth analyse whether the impact on roundwood price stability also depends on the frequency and not only on the magnitude of the disturbance. Lastly, an important direction for future work expanding beyond RESONATE is to include simulation methods in forestry value chain research to estimate the future impact of disturbances (fortified

by climate change) and thresholds where the resilience of a forest is severely deteriorated (e.g., when salvage logging is exceeding the voluntary logging). In this way, it would be possible to see what demand-side or supply-side effects are most prominent and why. Furthermore, simulations allow us to test various scenarios and see how they enhance value chain resilience. In this regard, we could use the results of 4.1 (Future disturbance scenarios and biodiversity impact) as supply projections and the results of 4.2 (flexibility of societal demand under fast changing circumstances) as demand projections. This would allow us to analyse the potential of current resilience measures to cope with future more frequent and more severe disturbances.

5. References

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transactions on Automatic Control*, *19*(6), 716–723. https://doi.org/10.1109/TAC.1974.1100705

Biggs, R., Schlüter, M., Biggs, D., Bohensky, E. L., BurnSilver, S., Cundill, G., Dakos, V., Daw, T. M., Evans, L. S., Kotschy, K., Leitch, A. M., Meek, C., Quinlan, A., Raudsepp-Hearne, C., Robards, M. D., Schoon, M. L., Schultz, L., & West, P. C. (2012). Toward Principles for Enhancing the Resilience of Ecosystem Services. *Annual Review of Environment and Resources*, *37*(1), 421–448. https://doi.org/10.1146/annurev-environ-051211-123836

Committee on Forests and the Forest Industry. (2015). *Market Statement of the Czech Republic 2015*. UN Economic Commission for Europe.

Committee on Forests and the Forest Industry. (2017). *Market Statement of the Czech Republic 2017*. UN Economic Commission for Europe Seventy-fifth session.

Committee on Forests and the Forest Industry. (2019). *Market Statement of the Czech Republic 2019*. UN Economic Commission for Europe.

Committee on Forests and the Forest Industry. (2020). *Market Statement of the Czech Republic 2020*. UN Economic Commission for Europe Seventy-eight session.

Enache, A., Kühmaier, M., Visser, R., & Stampfer, K. (2016). Forestry operations in the European mountains: A study of current practices and efficiency gaps. *Scandinavian Journal of Forest Research*, *31*(4), 412–427. https://doi.org/10.1080/02827581.2015.1130849

European Commission. (2021). *New EU Forest Strategy for 2030*. European Union.

FAOSTAT. (2021, December 9). *Forestry Production and Trade. Food and Agriculture Organization of the United Nations.* http://www.fao.org/faostat/en/#data/FO

Federal Ministry for Food and Agriculture. (2015). *STATEMENT Germany 2015*. The 73rd session of the ECE Timber Committee Geneva,.

Federal Ministry for Food and Agriculture. (2017). *STATEMENT Germany 2017*. The 75th session of the ECE Timber Committee Geneva,.

Federal Ministry for Food and Agriculture. (2019). *STATEMENT Germany 2019*. The 77th session of the ECE Timber Committee Geneva,.

Federal Ministry for Sustainability and Tourism. (2019). *Austrian Market Report 2019*. The 74th session of the UNECE Committee on Forests and the Forest Industry.

Federal Ministry of Agriculture and Forestry. (1999). *Austrian Market Report 1999*. 57. Session of the UN-ECE Timber Committee Geneva.

Federal Ministry of Agriculture, Forestry, Environment and Water Management. (2002). *Austrian Market Report 2002*. 60th Session of the UN-ECE Timber Committee Geneva,.

Federal Ministry of Agriculture, Forestry, Environment and Water Management. (2005). *Austrian Market Report 2005*. UN-ECE Timber Committee Sixty-third session Palais des Nations, Geneva.

Federal Ministry of Agriculture, Forestry, Environment and Water Management. (2008). *Austrian Market Report 2008*. UNECE Timber Committee (66th session) and the FAO European Forestry Commission (34th session).

Federal Ministry of Agriculture, Forestry, Environment and Water Management. (2012). *Austrian Market Report 2012*. The 70th Session of the UNECE Timber Committee Geneva.

Federal Ministry of Agriculture, Forestry, Environment and Water Management. (2014). *Austrian Market Report 2014*. The 72nd session of the UNECE Committee on Forests and the Forest Industry.

Federal Ministry of Agriculture, Forestry, Environment and Water Management. (2016). *Austrian Market Report 2016*. The 74th session of the UNECE Committee on Forests and the Forest Industry.

Federal Ministry of Consumer Protection, Food, Agriculture. (2001). *STATEMENT Germany 2001*. The fifty-ninth session of the ECE Timber Committee Geneva,.

Federal Ministry of Consumer Protection, Food, Agriculture. (2011). *STATEMENT Germany 2011*. The 69th session of the ECE Timber Committee Geneva,.

Federal Ministry of Consumer Protection, Food, Agriculture. (2013). *STATEMENT Germany 2013*. The 71st session of the ECE Timber Committee Geneva,.

Federal Ministry of Food, Agriculture and Forestry. (1999). *STATEMENT Germany 1999*. The fifty-seventh session of the ECE Timber Committee Geneva,.

Finland Sources. (2007). *Forest industry production 2007*. http://www.finlandsources.fi/industry/forest-industry-production/

Finnish Forest Industry Federation. (1999). *Market Review and Prospects Finland 1999*. Economic Commission for Europe, Timber committee, 57th session.

Finnish Forest Industry Federation. (2001). *Market Review and Prospects Finland 2001*. Economic Commission for Europe, Timber committee, 59th session.

Finnish Forest Industry Federation. (2002). *Market Review and Prospects Finland 2002*. Economic Commission for Europe, Timber committee, 60th session.

Finnish Forest Industry Federation. (2009). *Market Statement Finland 2009*. ECONOMIC COMMISSION FOR EUROPE Timber Committee.

Finnish Forest Industry Federation. (2012). *Market Statement Finland 2012*. ECONOMIC COMMISSION FOR EUROPE Timber Committee.

Finnish Forest Industry Federation. (2014). *Market Statement Finland 2014*. ECONOMIC COMMISSION FOR EUROPE Timber Committee.

Finnish Forest Industry Federation. (2016). *Market Statement Finland 2016*. ECONOMIC COMMISSION FOR EUROPE Timber Committee.

Finnish Forest Industry Federation. (2018). *Market Statement Finland 2018*. ECONOMIC COMMISSION FOR EUROPE Timber Committee.

Finnish Forest Industry Federation. (2019). *Market Statement Finland 2019*. ECONOMIC COMMISSION FOR EUROPE Timber Committee.

Fuchs, J. M., v. Bodelschwingh, H., Lange, A., Paul, C., & Husmann, K. (2022). Quantifying the consequences of disturbances on wood revenues with Impulse Response

Functions. *Forest Policy and Economics*, *140*, 102738. https://doi.org/10.1016/j.forpol.2022.102738

Hänninen, R., Toppinen, A., & Toivonen, R. (2006). Transmission of price changes in sawnwood and sawlog markets of the new and old EU member countries. *European Journal of Forest Research*, *126*(1), 111–120. https://doi.org/10.1007/s10342-006-0135-5

Hetemäki, L., & Hurmekoski, E. (2016). Forest Products Markets under Change: Review and Research Implications. *Current Forestry Reports*, *2*(3), 177–188. https://doi.org/10.1007/s40725-016-0042-z

Hietala, J., Hänninen, R. H., & Toppinen, A. (2013). Finnish and Swedish Sawnwood Exports to the UK Market in the European Monetary Union Regime. *Forest Science*, *59*(4), 379–389. https://doi.org/10.5849/forsci.10-122

Hurmekoski, E., Smyth, C. E., Stern, T., Verkerk, P. J., & Asada, R. (2021). Substitution impacts of wood use at the market level: A systematic review. *Environmental Research Letters*, *16*(12), 123004. https://doi.org/10.1088/1748-9326/ac386f

IPCC. (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]*. Cambridge University Press.

Jonsson, R., Egnell, G., & Baudin, A. (2011). *SWEDISH FOREST SECTOR OUTLOOK STUDY 2011*. United Nations Food and Agriculture Organization Economic Commission for Europe of the United Nations.

Loeffler, D., & Anderson, N. (2018). Impacts of the Mountain Pine Beetle on Sawmill Operations, Costs, and Product Values in Montana. *Forest Products Journal*, *68*(1), 15–24. https://doi.org/10.13073/FPJ-D-17-00041

Lundmark, R., & Shahrammehr, S. (2012). Armington Elasticities and Induced Industrial Roundwood Specialization in Europe. *Journal of Natural Resources Policy Research*, *4*(3), 161–170. https://doi.org/10.1080/19390459.2012.693789

National Institution of Economic Research. (1999). *Market Statement Sweden 1999*. Timber Committee, Fifty-seventh session.

National Institution of Economic Research. (2000). *Market Statement Sweden 2000*. Timber Committee, Fifty-eight session in Joint Session with the FAO European Forestry Commission, Thirtieth session.

National Institution of Economic Research. (2002). *Market Statement Sweden 2002*. ECE Timber Committee, Sixtieth session.

National Institution of Economic Research. (2011). *Market Statement Sweden 2011*. ECE Timber Committee.

National Institution of Economic Research. (2013). *Market Statement Sweden 2013*. ECE Timber Committee.

National Institution of Economic Research. (2015). *Market Statement Sweden 2015*. ECE Timber Committee.

National Institution of Economic Research. (2017). *Market Statement Sweden 2017*. ECE Timber Committee.

National Institution of Economic Research. (2019). *Market Statement Sweden 2019*. ECE Timber Committee.

Ning, Z., & Sun, C. (2014). Vertical price transmission in timber and lumber markets. *Journal of Forest Economics*, *20*(1), 17–32. https://doi.org/10.1016/j.jfe.2013.07.002

Patacca, M., Schelhaas, M. J., Zudin, S., & Lindner, M. (2021). *Technical description of the Database on Forest Disturbances in Europe (DFDE).* I-Maestro Technical paper.

Prestemon, J. P., & Holmes, T. P. (2000). Timber Price Dynamics Following a Natural Catastrophe. *American Journal of Agricultural Economics*, *82*(1), 145–160. https://doi.org/10.1111/0002-9092.00012

Schelhaas, M. J., Patacca, M., Lindner, M., & Zudin, S. (2020). *Database on Forest Disturbances in Europe (DFDE)*. European Forest Institute. https://dfde.efi.int/db/dfde_app.php.

Schelhaas, M.-J., Nabuurs, G.-J., & Schuck, A. (2003). Natural disturbances in the European forests in the 19th and 20th centuries: NATURAL DISTURBANCES IN THE EUROPEAN FORESTS. *Global Change Biology*, *9*(11), 1620–1633. https://doi.org/10.1046/j.1365-2486.2003.00684.x

Schwarzbauer, P. (2007). Einflüsse von schadholzmengen auf rohholzpreise. Eine quantitativ-statistische Analyse am Beispiel Österreichs. *Allgemeine Forst- Und Jagdzeitung*, *178*(1), 1–8.

Seabold, S., & Perktold, J. (2010). statsmodels: Econometric and statistical modeling with python.". *Proceedings of the 9th Python in Science Conference.*

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D., Petr, M., Honkaniemi, J., Lexer, M. J., Trotsiuk, V., Mairota, P., Svoboda, M., Fabrika, M., Nagel, T. A., & Reyer, C. P. O. (2017). Forest disturbances under climate change. *Nature Climate Change*, *7*(6), 395–402. https://doi.org/10.1038/nclimate3303

Seintsch, B. (2010). *Entwicklungen des Clusters Forst und Holz zwischen 2000 und 2007 - Ergebnisse und Tabellen für das Bundesgebiet und die Laender-, Johann Heinrich von Thünen-Institut.* https://policycommons.net/artifacts/2077868/entwicklungen-des-clusters-forst-und-holz-zwischen-2000-und-2007-ergebnisse-und-tabellen-fur-das-bundesgebiet-und-die-laender/2833166/ on 20 Sep 2022. CID: 20.500.12592/gfrgft.

Senf, C., & Seidl, R. (2022). Deliverable 2.2. Europe's forest disturbance regimes. *Horizon 2020 Project RESONATE, Project No. 101000574*, *Technical University of Munich.*

Skogsstyrelsen. (2017). *Annual average prices on sawlogs and pulpwood. Delivery logs by Region, Assortment and Year.* http://pxweb.skogsstyrelsen.se/pxweb/en/Skogsstyrelsens%20statistikdatabas/?rxid=03eb67a3-87d7-486d-acce-92fc8082735d

Solberg, B., Moiseyev, A., Kallio, A. M. I., & Toppinen, A. (2010). Forest sector market impacts of changed roundwood export tariffs and investment climate in Russia. *Forest Policy and Economics*, *12*(1), 17–23. https://doi.org/10.1016/j.forpol.2009.09.016

Sousa-Silva, R., Verbist, B., Lomba, Â., Valent, P., Suškevičs, M., Picard, O., Hoogstra-Klein, M. A., Cosofret, V.-C., Bouriaud, L., Ponette, Q., Verheyen, K., & Muys, B. (2018). Adapting forest management to climate change in Europe: Linking perceptions to adaptive responses. *Forest Policy and Economics*, *90*, 22–30. https://doi.org/10.1016/j.forpol.2018.01.004

Sun, C. (2016). Timber Market Recovery after a Hurricane. *Forest Science*, *62*(6), 600–612. https://doi.org/10.5849/forsci.15-123

Timber Committee. (2012). *Market Statement of the Czech Republic 2012*. UN Economic Commission for Europe.

Timber Committee, European Forestry Commission. (2000). *Market Statement of the Czech Republic 2000*. Economic Commission for Europe, Food and Agriculture Organization.

Timber Committee, European Forestry Commission. (2002). *Market Statement of the Czech Republic 2002*. Economic Commission for Europe.

Timber Committee, K. (2009). *2009 MATTERS ARISING FROM THE UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE SESSION Note by the secretariat*. Forestry Development Dept., Ministry of Agriculture.

Tomek, W. G., & Kaiser, H. M. (1999). On improving econometric analyses of generic advertising impacts. *Agribusiness*, *15*(4), 485–500. https://doi.org/10.1002/(SICI)1520-6297(199923)15:4<485::AID-AGR5>3.0.CO;2-8

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

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

Vancura, K., & Trejbalova, K. (2004). *Czech Republic Report 2004*. Forestry Development Dept., Ministry of Agriculture.

Vantaa Research Centre. (2004). *Forest Sector Economic Outlook 2003–2004*. Economic Commission for Europe, Timber committee, 60th session.

Zhai, J., & Kuusela, O.-P. (2020). Estimating Price Dynamics in the Aftermath of Forest Disturbances: The Biscuit Fire in Southwest Oregon. *Forest Science*, *66*(5), 556–567. https://doi.org/10.1093/forsci/fxaa004

Zhou, M., & Buongiorno, J. (2006). Space-time modeling of timber prices. *Journal of Agricultural and Resource Economics*, *31*(1), 40–56.

6. Supplementary materials

Supplementary materials 1 comprise a presentation of the data used for the econometric analysis, with all exogenous variables plotted against domestic roundwood (sawlog/pulpwood) prices (Figures S1-S9). Note that the data presented (blue dots) have been log-transformed and first-differenced. The plots further display a linear fit (orange line) and a coefficient of determination (r^2).

6.1 Austria

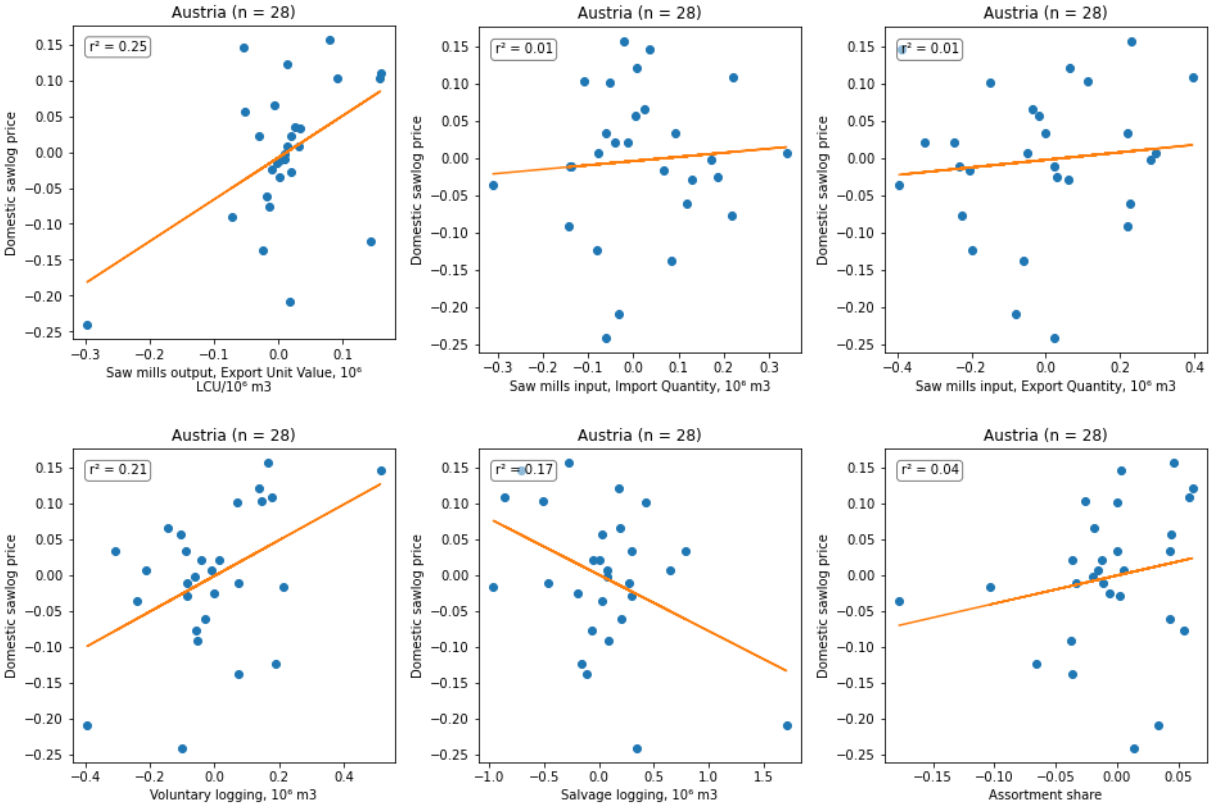


Figure S1: Correlation plots for domestic sawlog prices and predictors for Austria (log-transformed data, first differences).

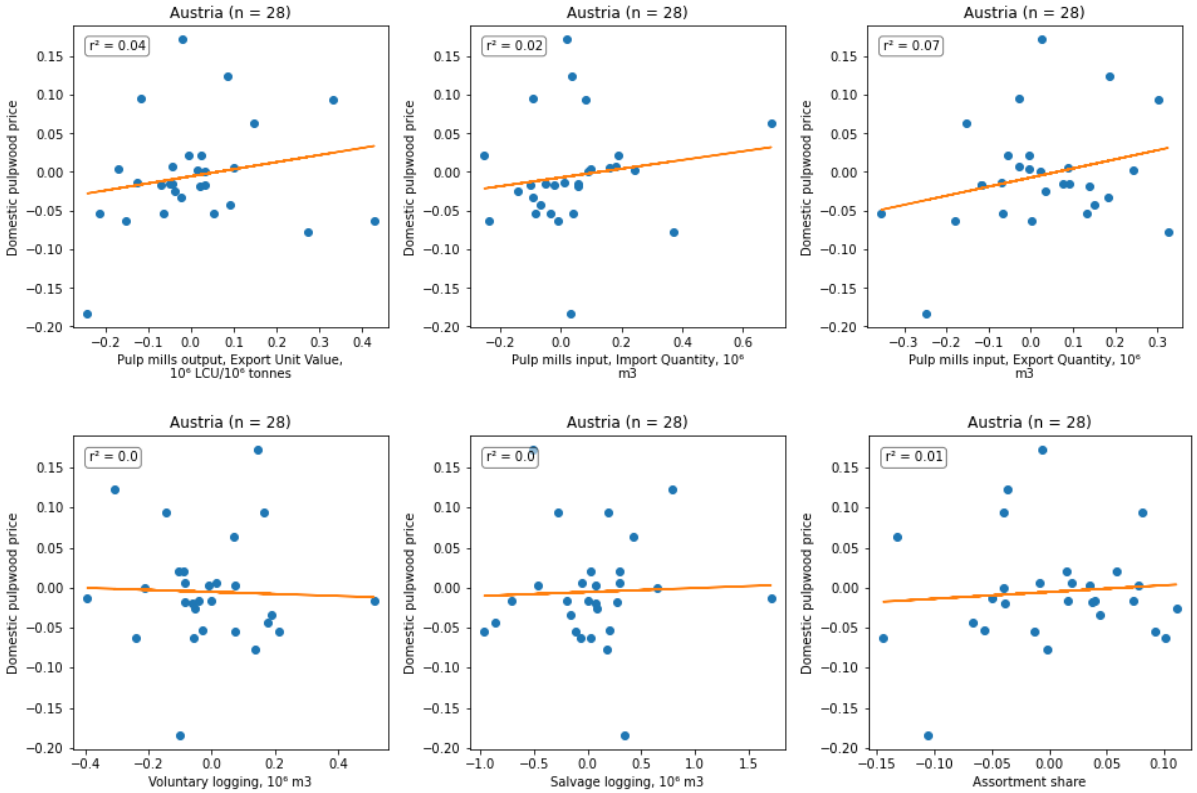


Figure S2: Correlation plots for domestic pulpwood prices and predictors for Austria (log-transformed data, first differences).

6.2 Czechia

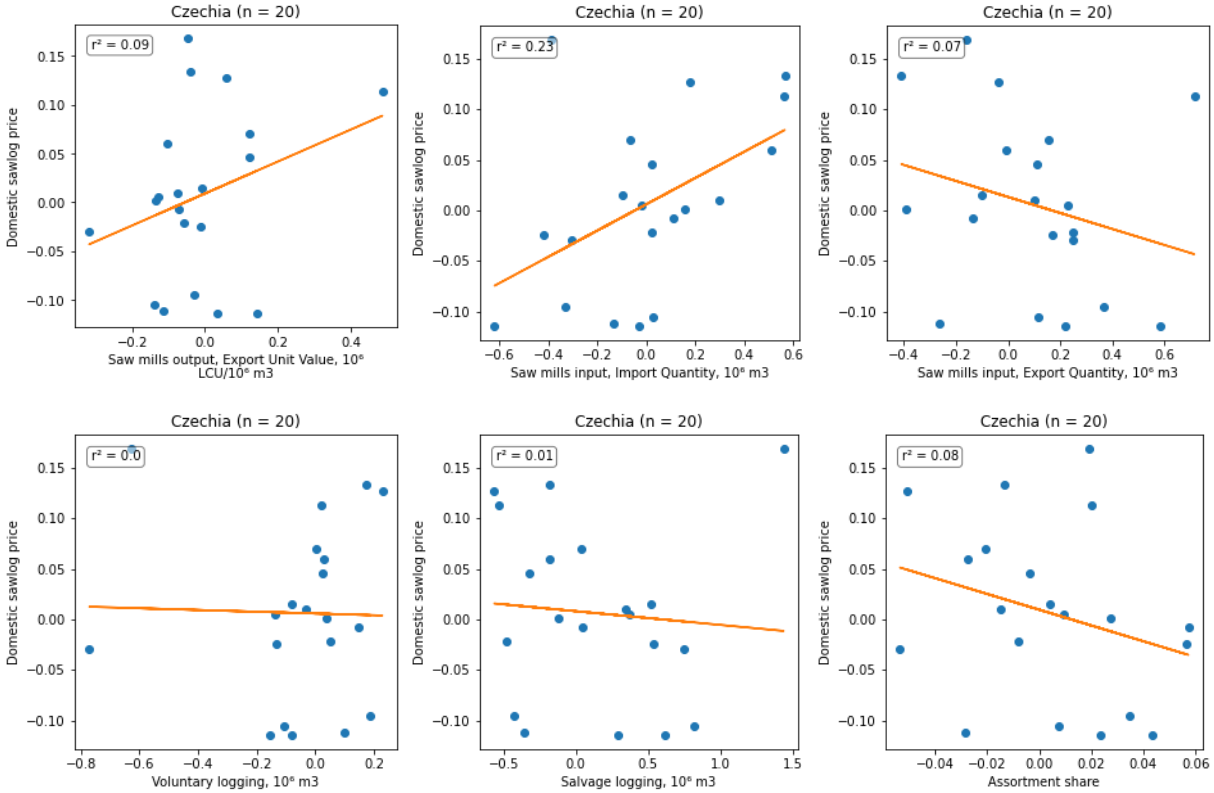


Figure S3: Correlation plots for domestic sawlog prices and predictors for Czechia (log-transformed data, first differences).

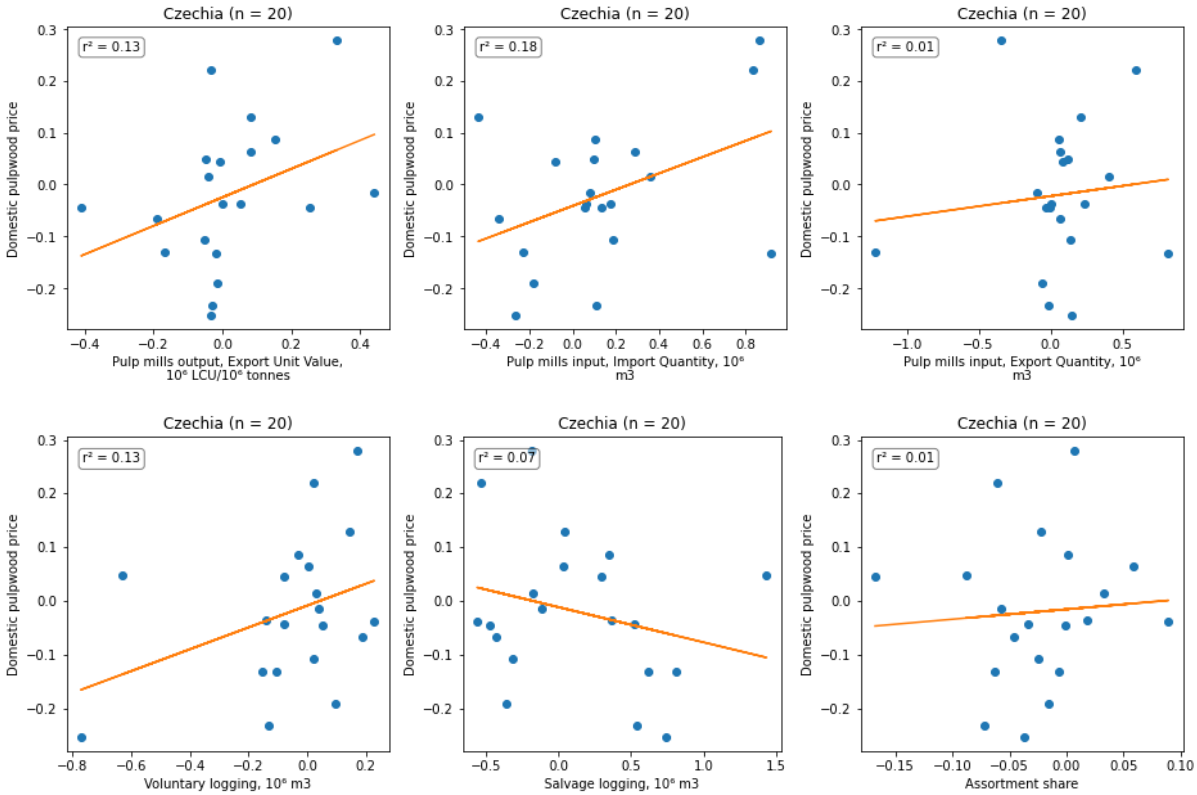


Figure S4: Correlation plots for domestic pulpwood prices and predictors for Czechia (log-transformed data, first differences).

6.3 Finland

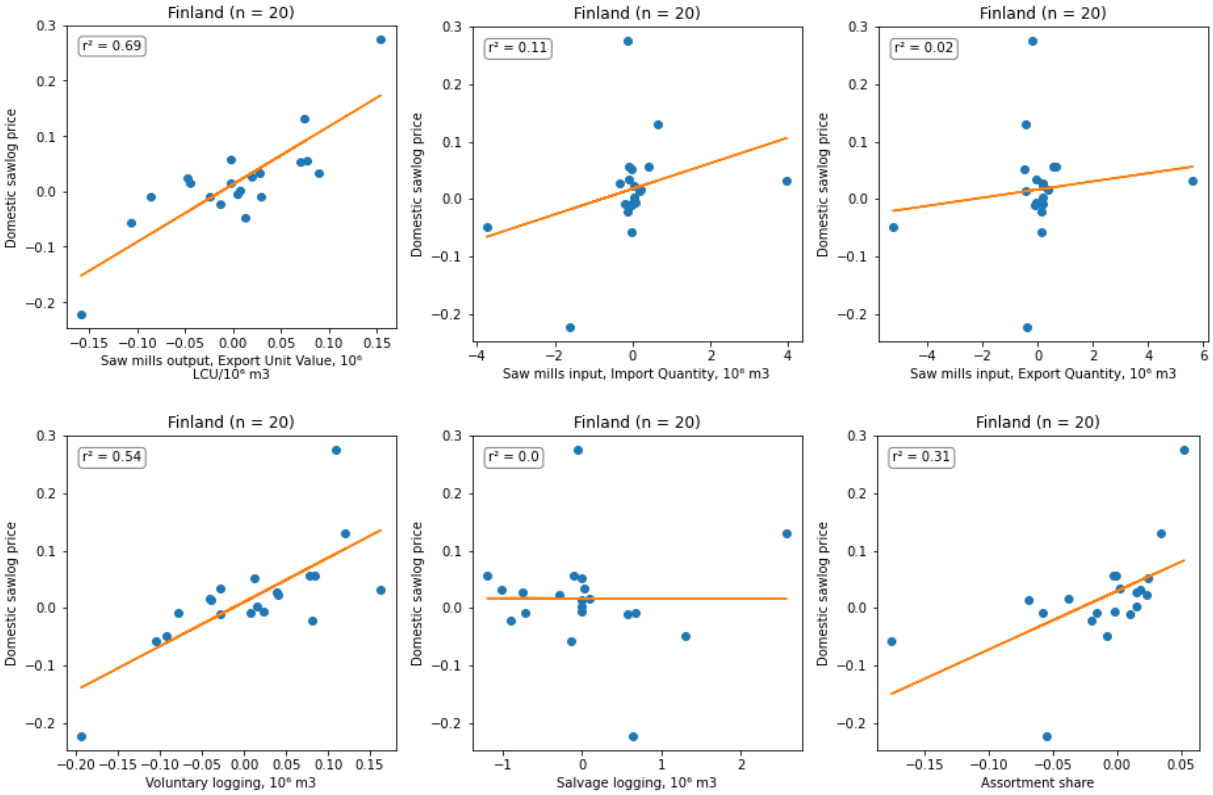


Figure S5: Correlation plots for domestic sawlog prices and predictors for Finland (log-transformed data, first differences).

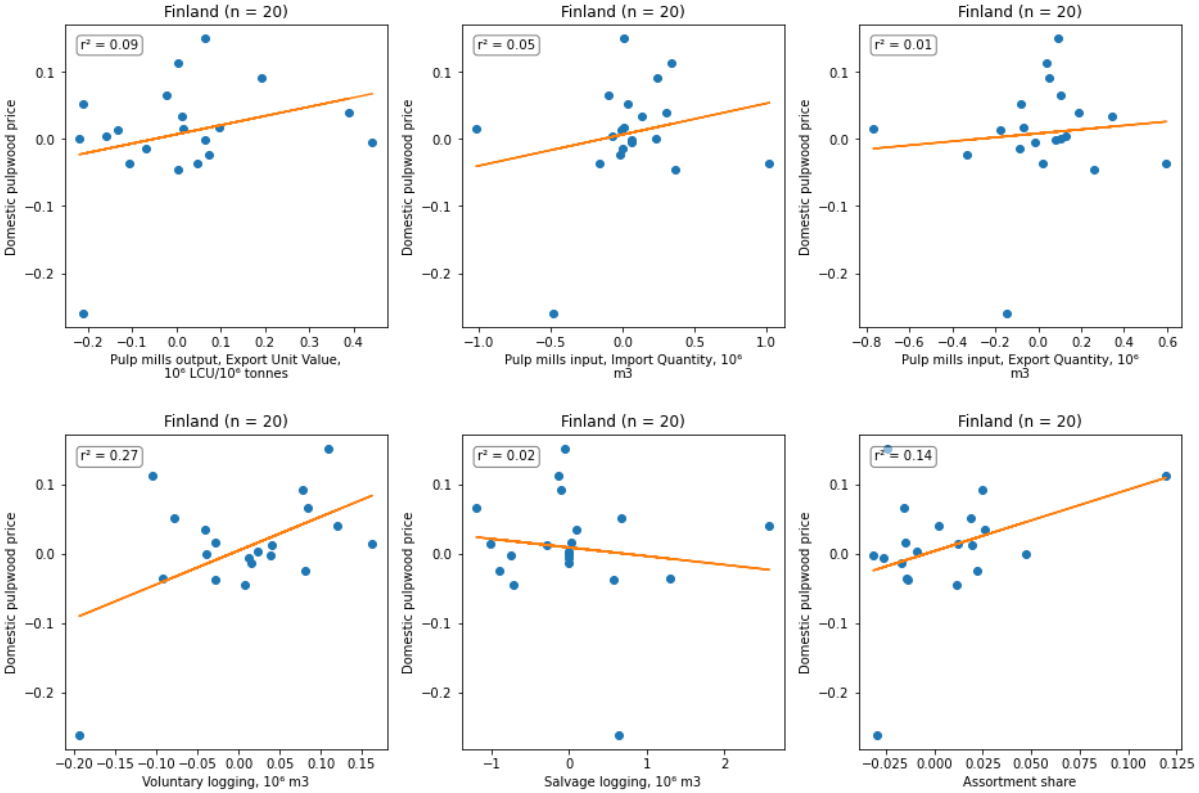


Figure S6: Correlation plots for domestic pulpwood prices and predictors for Finland (log-transformed data, first differences).

6.4 Germany

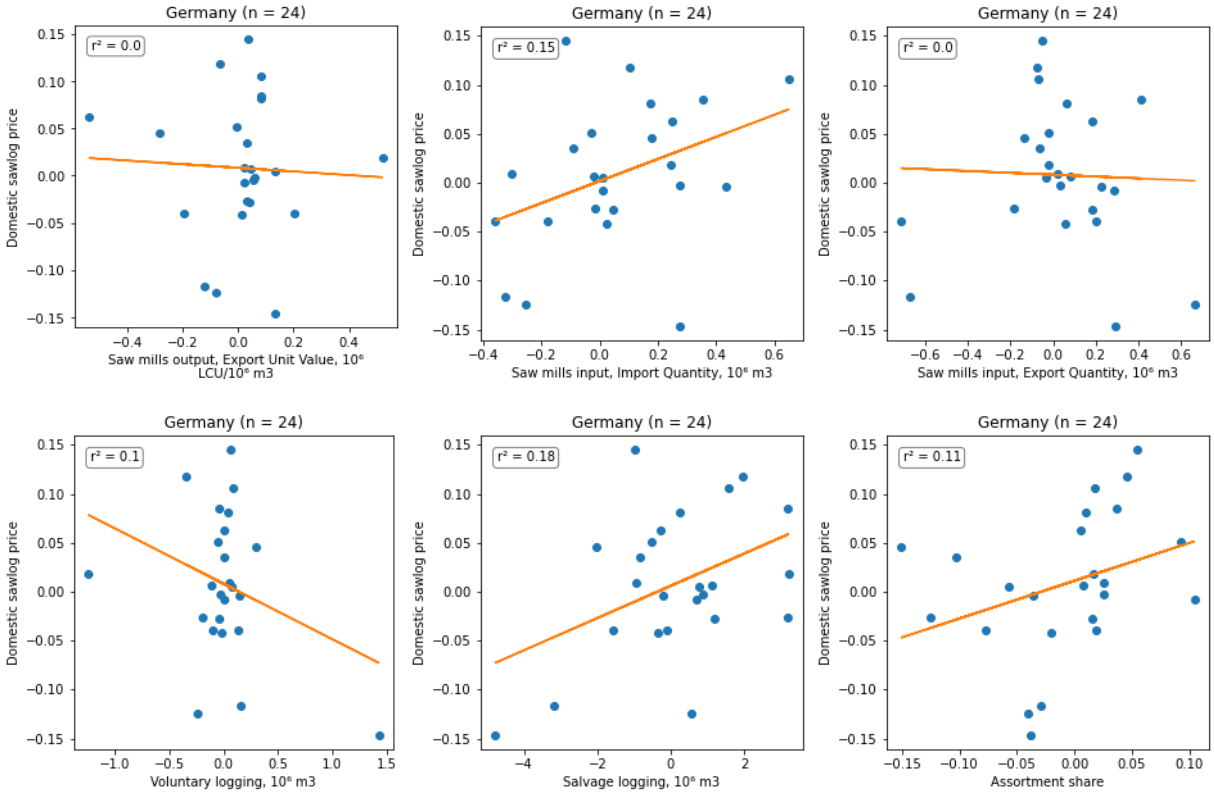


Figure S7: Correlation plots for domestic sawlog prices and predictors for Germany (log-transformed data, first differences).

6.5 Sweden

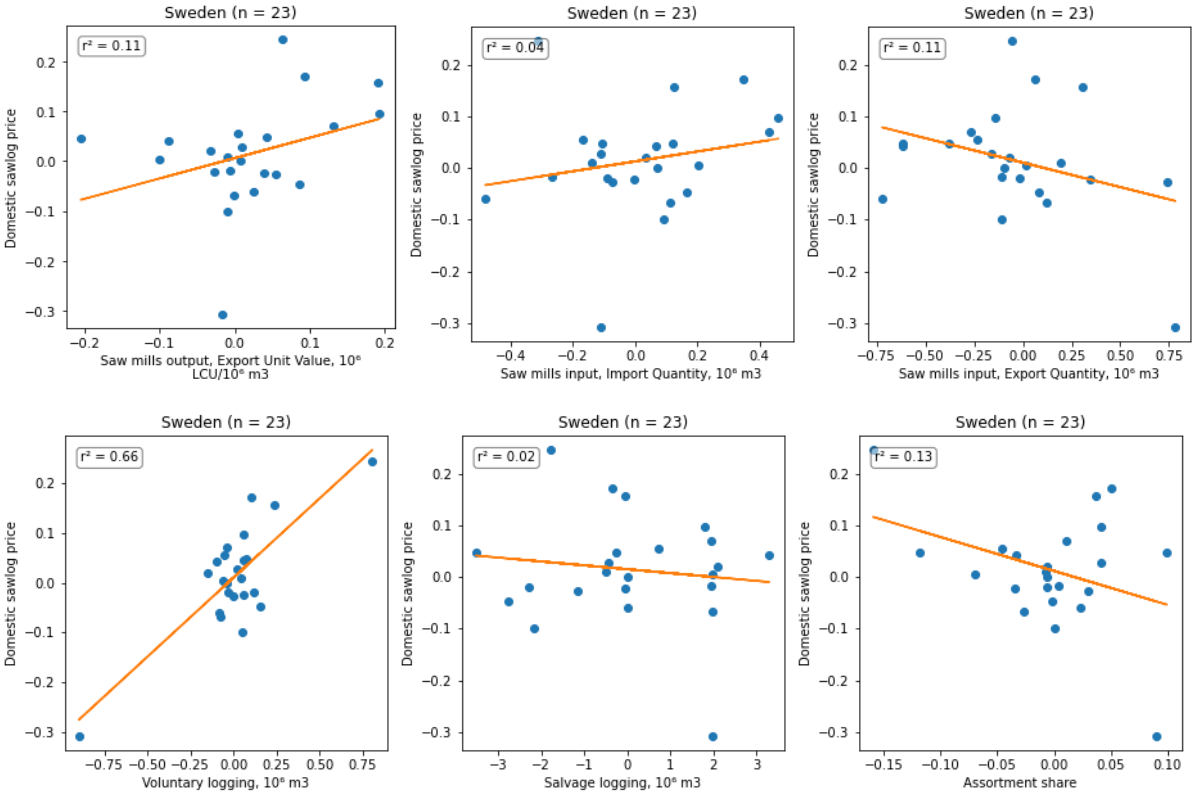


Figure S8: Correlation plots for domestic sawlog prices and predictors for Sweden (log-transformed data, first differences).

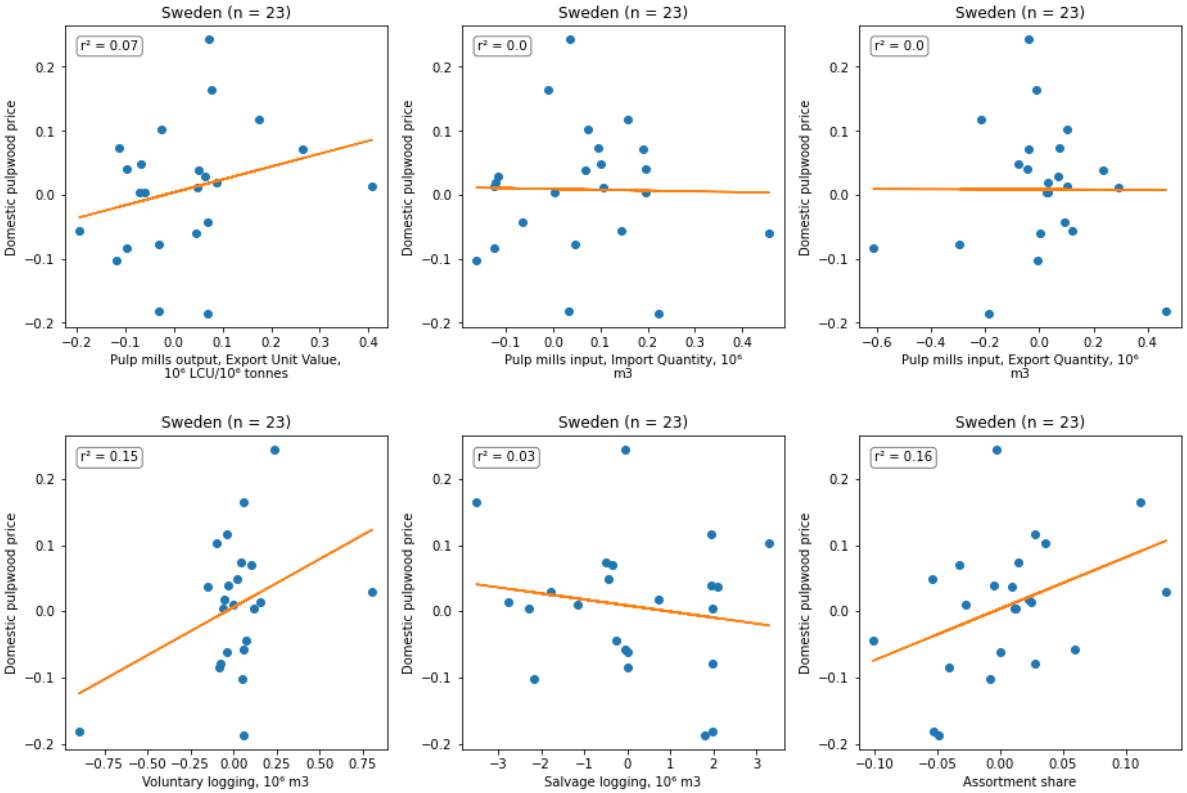


Figure S9: Correlation plots for domestic pulpwood prices and predictors for Sweden (log-transformed data, first differences).