# A Spatial-Explicit Price Impact Analysis of Increased Biofuel Production on Forest Feedstock Markets: A Scenario Analysis for Sweden

**Abstract:**

The present paper introduces an integrated spatially explicit framework for assessing price impact on forestry markets in Sweden. The framework is based on the "soft-link" of a price determination model, the SpPDM model with the BeWhere Sweden model. The aim is to analyse the impacts of increased forest-based biofuel production for transportation within the Swedish context by 2030. To that effect, we develop scenarios analyses based on the simulations of successive biofuel production targets, under different assumptions concerning the competition intensity for forest biomass and the use of industrial by-products. The results suggest marginal impacts on the prices of forest biomass. The average across spatial-explicit prices varies from 0% to 2.8% across feedstocks and scenario types. However, the distribution of the spatial-explicit price impacts displays large variation, with price impacts reaching as high as 8.5%. We find that the pattern of spatial distribution of price impacts follows relatively well the spatial distribution of demand pressure. However, locations with the highest price impacts show a tendency of mismatch with the locations of the highest demand pressure (e.g. sawlogs). This is a counterintuitive conclusion compared to results from non-spatial economic models. The spatial-explicit structure of the framework developed, and its refined scale allows such results to be reported. Hence, from a policy-making perspective, careful analysis should be devoted to the locational linkages for forestry markets of increased biofuel production in Sweden.

**Key words:** spatial analysis, biofuel, forest biomass, supply chain

## 1. Introduction

In recent decades, the transition from a fossil fuel-based economy to a biobased economy has gained much traction in policy circles and in the research community. This has been motivated by a number of interlinked issues such as reduction of greenhouse gas emissions, energy security and independence as well as renewable energy targets. In this transition, forest resources have an increasingly important role to play. The expected increase of the demand for forest resources will have a direct impact on the forestry sector and on its utilization of forest resources. For instance, it will affect market prices, profitability, rural employment, recreation and forest ecology. The transition will also create opportunities to develop, and invest in, new or improved value chains using forest resources, such as biorefineries [1]. Specifically, it is thus important to understand how the expected increase in the demand for forest product will affect its price level and competitive situation. Moreover, since forest resources typically are bulky and spatially distributed over large areas, their utilization are often associated with high transportation costs. This suggests that possible price and allocation effects from a demand increase are local (or regional) in its character. Thus, an appropriate analysis needs a spatial dimension. The purpose of this paper is to assess spatially the implications on the forest markets, in terms of changing prices and allocation patterns, from an introduction of large-scale production of transportation biofuel using forest biomass as feedstock.

An integrated model approach is developed and applied on Sweden. Sweden is a good case study since it is a pioneer in terms of early adoption of renewable energy, especially bioenergy, and is relatively well endowed with forest resources. For example, the share (level) of biomass of total energy supply has increased from 11 percent in 1983 (52 TWh) to 25 percent in 2015 (134 TWh) [2]. It has also been suggested that the annual bioenergy demand might increase by 40 TWh in 2030 and by over 60 TWh in 2050, taking into account demand for industrial use, heat and electricity generation, and as feedstock in the production of transport biofuels and chemicals [3–6]. However, large parts of the projected demand increase originates from new supply chains (fully or partly) that currently do not exist in Sweden.

In terms of industrial consumption of forest resources, the pulp and paper industry together with the sawmill industry account, on average, for almost the entire roundwood consumption (roughly equally divided between them). Only 8 percent of the harvested roundwood is used for other purposes [7]. Moreover, the net felling of roundwood in 2016 amounted to 74.8 million $m^3$ solid, of which 47 percent was sawlogs, 43 percent was pulpwood and approximately 10 percent was fuelwood [8]. Fig. 1 illustrates the spatial distribution of the net felling. As we can observe, net felling volumes availability is lower in the southern regions of Sweden, especially along the coastal lines; whereas in the northern regions, availability is high in volumes terms, especially in the mid-northern regions.

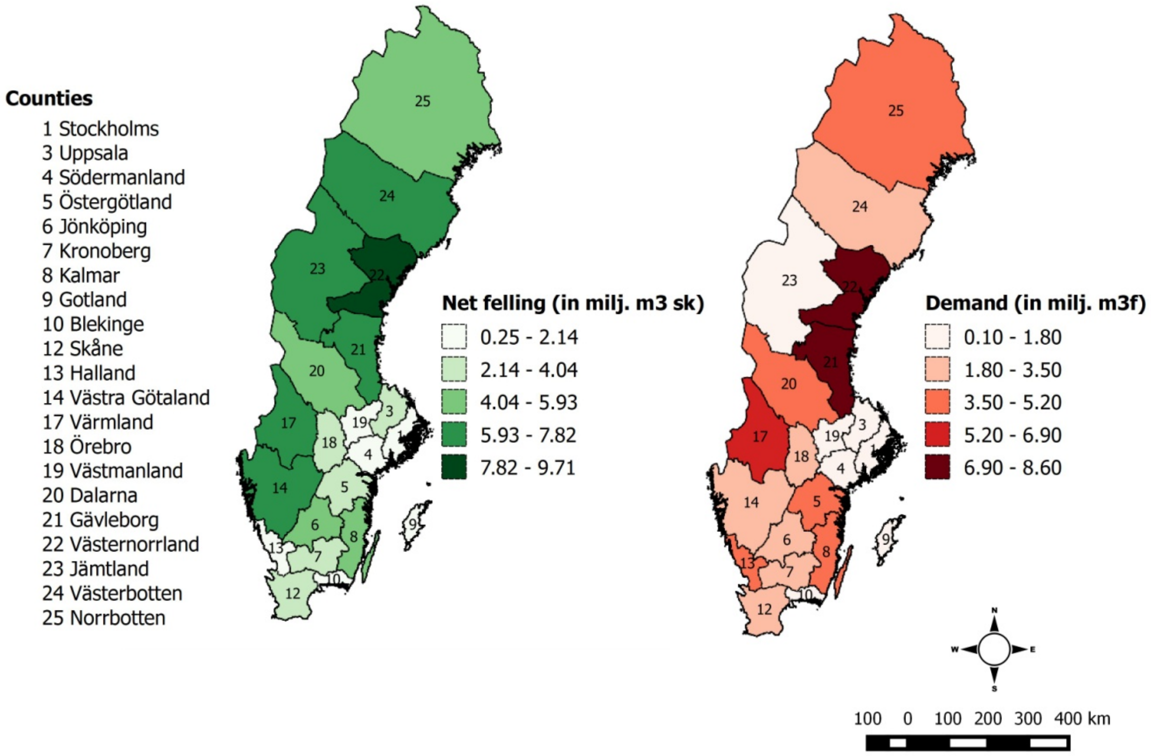


**Fig. 1.** County-level spatial distribution of 3-year average net felling (in million $m^3$ standing volume, $m^3$sk, for the period 2014-2016) and current demand[1] (in million $m^3$ solid, $m^3$f)
*Data source: https://www.skogsstyrelsen.se/statistik/statistikdatabas/ (Last accessed 1/18/2018)*

Recent empirical literature has focused primarily on model development characterized by system approaches to the analysis of value chains. The focus of such models spans a number of themes that covers issues related to procurement costs of forest feedstocks, transportation logistics, optimal localization of biorefineries, etc. [9–11]. Another development in the literature is the explicit treatment of the spatial dimension. To this effect, most modelling efforts used geographical information system (GIS)-based models that explicitly account for the spatial dimension [12–17], and/or a hybrid approach that uses a techno-economic routine of cost-minimization of the whole value-chain, all the while incorporating the spatial dimension explicitly [11,18–23]. In Sweden, a number of studies have been carried out, which focused primarily on a spatially-explicit harvest cost model and/or hybrid models as discussed

[1] The current demand is obtained from the BeWhere Sweden model for the business-as-usual (BAU) scenario, which represent current use of forest biomass across sectors (possible to add reference to this run?).

above [24–26]. However, most studies lack any feedback to forestry markets. Hence, the main objective of the paper is to introduce explicitly feedback-links to forestry markets in the context of highly disaggregated spatial models for forest value-chain optimization. We first test our modelling strategy within the Swedish context. The main contribution of our modelling framework lies in the ability to map out the distributions of price impacts at very refined spatial scales, which would provide valuable insights about their heterogeneous nature based on the scenarios adopted for supply availability, demand pressure, etc.

We organize the paper as follows. In Section 2, we discuss the scenarios adopted in the analysis, with a detailed description of key data inputs. In Section 3, we extend the discussion to the analytical framework adopted in the analysis by discussing model structure and integration. In Section 4, we present the results of the simulations and analyse the key factors driving them. We conclude in Section 5 with key findings and potential areas of further investigation.

## 2. Data and materials

Currently, bioenergy features prominently in Swedish energy and environmental policy-making and represents a cornerstone in the long-term strategy of decoupling the economy from fossil fuels and achieving greenhouse gas emissions reduction targets[27]. Forest-based biomass is the major source of feedstocks in the biofuel production in Sweden owing to its rich forest endowments.

For the spatial assessment the price impact and changing allocation patterns on forest feedstocks from an introduction of large-scale production of transportation biofuel, a set of plausible future scenarios need to be outlined. The scenarios included in the analysis represent the projected demand schedule for forest feedstocks in Sweden under incremental biofuel production targets by 2030. The scenarios are constructed based on a combination of different assumptions about biofuel production targets, demand from the forest industries and the use of by-products in the biofuel production process. Table 1 summarizes the set of selected scenarios for the analysis.

**Table 1**
Summary of scenarios characteristics

| Scenario driver | Scenario description |
|---|---|
| I) BAU | 1. 0 TWh of biofuel production for transportation |
| II) Biofuel demand | 1. 5 TWh of forest-based biofuel production for transportation<br>2. 10 TWh of forest-based biofuel production for transportation<br>3. 20 TWh of forest-based biofuel production for transportation<br>4. 30 TWh of forest-based biofuel production for transportation |
| III) Competition intensity | 1. Low (current demand from forest-based industries)<br>2. High (20% increase of demand from forest-based industries compared to Base scenario) |
| IV) Biomass supply | 1. Supply assessment for 2030, based on current forestry practices |
| V) Industrial by-product use | 1. No-Use (industrial by-products cannot be used for biofuel production)<br>2. Use (industrial by-products can be used for biofuel production) |

*Source: Authors' adaptation*

### *2.1. Business-as-usually (BAU)*

The business-as-usual (BAU) scenario refers to the current status-quo in terms of demand for the forest biomass, which includes the demand from all traditional users (e.g. forest industries, district heating, etc.). The base year for the BAU scenario is 2015. The analysis includes four variants of the BAU scenario, depending on the competition intensity for the forest biomass (“Low” and “High”) and the use of by-products (“Use” and “No-Use”) (Table 1).

### *2.2. Biofuel demand*

The biofuel demand scenarios capture the potential increase in demand for forest biomass stemming from increased production of transportation fuels. As such, the analysis includes four biofuel production-driven demand scenarios, with the objective to investigate the market price implications for increased biofuel production on forestry markets.

### *2.3. Competition intensity*

An increasing level of transportation biofuel production using forest feedstocks is in direct competition with traditional uses of forest feedstocks from the forest industries. Lately, the increasing interest in forest conservation and recreational usage has further intensified the competitive situation. Studies have pointed to the potential that exists in Sweden with respect to use forest feedstocks for bioenergy, in general, and for biofuels, in particular [25,28,29]. One study has shown that an increased bioenergy production will not cause a major disruption in the supply of forest feedstocks to the forest industries [30]. However, other studies have shown that increasing competition intensity for forest feedstocks will affect their allocation across different uses [26,31–33]. Many factors will affect the competition intensity for forest feedstocks. For instance, the demand for forest feedstocks is projected to increase, driven primarily by emerging and developing countries.

### *2.4. Biomass supply*

Sawlogs, pulpwood, harvesting residues[2] and stumps were considered from final felling and thinning. The supply potential for each assortment was estimated based on a modelled harvesting potential scenario from the Swedish Forest Agency's forest impacts assessment (SKA 15) [34] ("Today's forestry" scenario). Details can be found in the Supplementary Material.

### *2.5. Industrial by-product use*

Forest-based industrial by-products[3] in the form of wood waste from paper and pulp plants and sawmills represent a significant source of energy supply in Sweden. Overall, forest-based bioenergy represents approximately 18 percent of the total energy supply in Sweden [35]. The district heating sector (CHP) is a major user of industrial by-products in the generation of electricity and residential heating, where forest-based fuels constitute almost a third of the total fuel use [36]. In addition to this, sawmill chips constitute an important raw material source in the pulp and paper industry, where almost a quarter of the total feedstock volume consists of sawmill chips [7]. In recent years, the transportation sector has emerged as a potential new driver of demand for forest biomass (including forest by-products) due to increased usage of biofuels, which could lead to a changed allocation of by-products between sectors. To this effect, we include two scenarios related to the use/no-use of forest by-products in biofuel production. The case is thus assumed binary in that either the by-products are released to the market at a fixed price, or they are fully utilized internally, and thus not available for other users (in this case, biofuel production).

## 3. Method and model integration

[2] Harvesting residues refer to logging residues, typically leftover branches, stem tops, etc., from logging operations, i.e. thinning or final felling. They are mostly pre-treated with chipping and transferred to roadside stations for transportation via truck. Energy production is the largest consumer of logging residues.

[3] Forest-based industrial by-products refer to industrial chips, sawdust, shavings, trimmings and bark. They are supplied in fixed proportions from processes of production within the forest industries. They represent an important raw material in the forest industry value-chain, especially for the production of wood-based panels (i.e. medium-density fiberboard (MDF), high-density fiberboard (HDF), etc.) and wood pellet production. Increasingly, industrial by-products are being used an energy feedstock as well.

We develop an integrated-spatially explicit framework for the analysis of the impacts of increased biofuel production from forest biomass on feedstock prices in Sweden. The integrated modelling approach consists of two parts. In the first part, the optimal location and spatial forest feedstocks demand is determined under a set of exogenously given feedstock prices using the BeWhere-Sweden model. In the second part, the spatial-explicit feedstock demand changes are used in the spatial price determination model (SpPDM) in order to derive spatial price changes [37]. As such, the integrating framework relies on a “soft-link” between the SpPDM and the BeWhere Sweden models, which relies primarily on data exchange between the two models with respect to key variables of interest.

### *3.1. The BeWhere Sweden model*

The BeWhere Sweden model is an energy system model based on mixed-integer linear programming (MILP), with the aim to investigate forest-based value-chain design and localization of biorefineries. Model details and techno-economic model input data can be found in [38].

The model optimizes the total system cost for new biorefineries as well as competing industrial forest biomass demand. The system cost to be minimized is defined as the industrial feedstock procurement cost (i.e. feedstock and transport cost) and biofuel production costs, which includes feedstock cost, transport costs, and cost of conversion. The model is spatially explicit in a sense that it runs at the gridcell level. This is achieved through the division of Sweden into half degree gridcells (in total 334 gridcells), which is used to express the forest biomass supply, the harvest cost and demand. Competing industries as well as potential biofuel production facilities are modelled explicitly.

The biofuel production plants can either be localized as stand-alone plants, or integrated at existing industrial sites (host plants). Integration is considered regarding (1) potential utilization of industrial by-products as feedstock for biofuel production, and (2) heat integration, where surplus heat from the biofuel production process is utilized to meet heat demands in industrial processes or district heating systems. Competing industrial feedstock uses are considered, i.e., competing demand from the forest industry (sawmills, pulp and paper industry, pellets production) and the stationary energy sector (heat and electricity production). All available forest biomass assortments except sawlogs, as well as industrial by-products (in certain scenarios, see Section 2.5) are assumed technically possible to utilise as feedstocks for biofuel production.

Details on considered biofuel production technologies and the possible forest feedstocks assortments that can be used by the different technologies are presented in the Supplementary Material. Fig. 2 gives an overview of the main biomass flows in the BeWhere Sweden model.

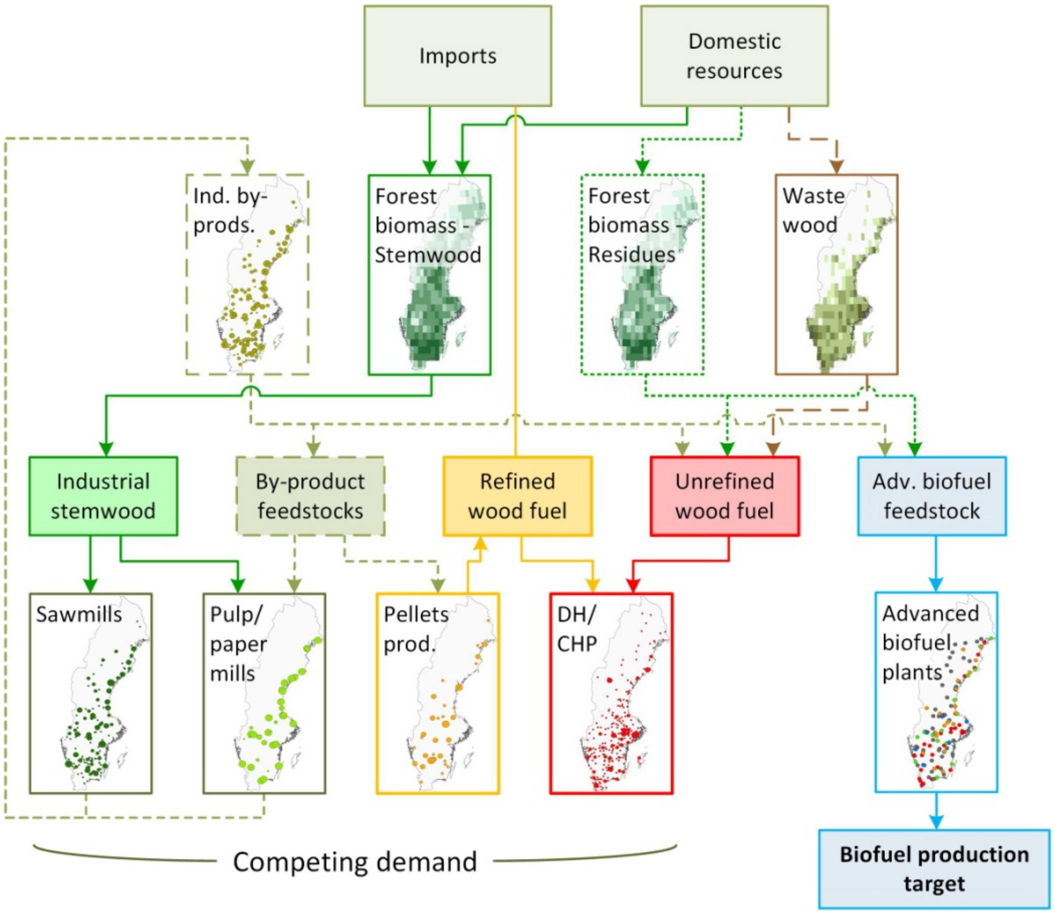


**Fig. 2.** Schematic overview of main biomass flows in BeWhere Sweden.
*Source: Wetterlund E et al. (2017)*[38]
Dashed lines represent residue flows, while solid lines represent virgin biomass flows. "Forest biomass - Stemwood" includes both sawlogs and pulpwood from thinning and final felling, "Forest biomass - Residues" includes harvesting residues from thinning and final felling and stumps from final felling.

### *3.2. The spatial price determination model (SpPDM)*

The price determination in the SpPDM model occurs through the interaction of demand and supply. However, the difference lies in the fact that the demand and supply are explicitly spatial, and markets are delineated by product and geographical location. The same half-degree gridcell representation of Sweden as in the BeWhere model is used. Fig. 3 conceptually outlines the framework adopted in the SpPDM model. A detailed discussion of the SpPDM model is provided, along with a detailed technical discussion of the distance-decay framework for estimating demand pressure in[37].

First, supply curves are constructed that characterize the supply potential associated with each market (i.e. gridcell) and resource (step 1) by the 2030 horizon. Second, using a merit-order framework, the cumulative supply is calculated from low to high cost based on spatial supply and harvest cost for the resources analysed (step 2). Third, the total demand associated with every market for each resource is determined using a distance-decay framework, which aims to evaluate the degree of spatial interaction across locations (step 3). Finally, the determination of equilibrium prices are made by juxtaposition of the supply curves and the estimates of the total demand at the gridcell level (step 4). Price impacts are derived as percentage changes from the BAU scenario for which a calibrated price vector is generated. This procedure is applied for every scenario included in the analysis.

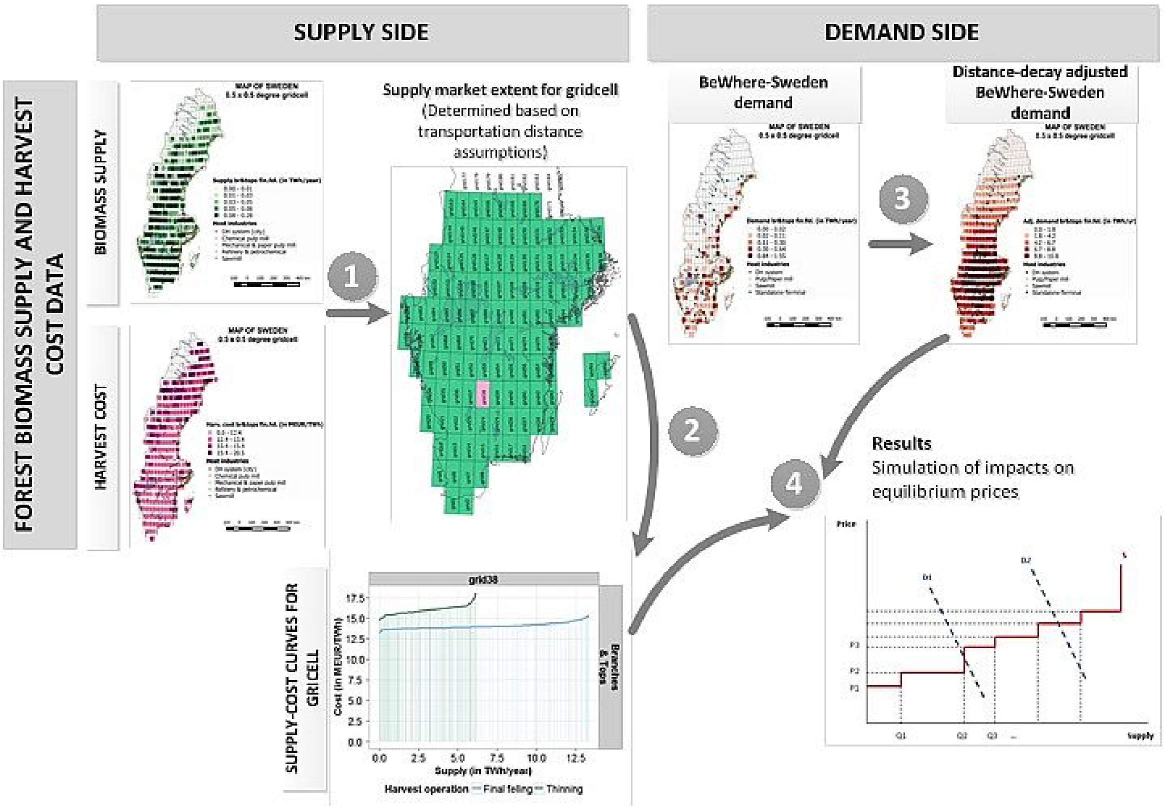


**Fig. 3.** Conceptual outline of the SpPDM model
*Source: Ouraich and Lundmark (2018)*[37]

### *3.3. Model linkage*

The model linkage occurs at multiple levels. The first level is represented by the spatial structure used in the models. Indeed, both models are run at similar spatial scales for the whole of Sweden. The second level is represented by the data exchange between the BeWhere Sweden and the SpPDM model. The same data for the availability estimates of forest biomass and procurement costs at the gridcell level are used in both models. However, within the context of the SpPDM model, the latter is used to build the gridcell-specific supply curves (Fig. 3). Additionally, we obtain estimates of demand from BeWhere Sweden at the gridcell level, and which serve as input data to estimate equilibrium prices for different scenarios. Hence, the SpPDM model uses the data from the BeWhere Sweden model as input data in the simulations conducted. The third level is the exchange of model results from the SpPDM model to the BeWhere Sweden model. As previously argued, the SpPDM model estimates price impacts at the gridcell level, which can be used to update the procurement cost data used in the BeWhere Sweden model. This feedback loop in terms of price impact estimates can be used to investigate the robustness of model results from the BeWhere Sweden model. However, in the current analysis, we stop at the first and second level of model linkages since we aim at analysing the impacts on forestry markets.

### *3.4. Input data description and calibration of forest feedstocks supply*

The data covers four types of harvested forest feedstocks: sawlogs, pulpwood, harvesting residues (i.e., branches & tops) and stumps. Moreover, the type of harvest operation, i.e. final felling and thinning, further identifies the data.

The estimates for the spatial feedstock availability and harvesting costs were obtained from Lundmark et al. (2015) [29] (cf. Section 2.4). Using biomass functions for tree growth, estimates for availability at the plot level were estimated using the input information from the SFI. The supply potential represents the economically feasible harvest level by 2030. Subsequently, the estimates were aggregated on the 0.5 x 0.5 degree spatial grid. The harvesting costs for the feedstocks were estimated based on a bottom-up approach using calibrated productivity functions for forest machinery (e.g. single-grip harvesters and forwarders) [38]. Fig. A1 and A2 (Appendix) summarize the spatial distribution of the availability and the cost of forest biomass respectively, with Table 2 summarizing the aggregated supply potential for each assortment.

**Table 2**

Aggregated modelled biomass supply and average modelled prices. Note that the prices are expressed as supply point prices (roadside, industries, import harbours, etc.), excluding transport costs.

| Biomass assortment | Supply potential [TWh/y] | Average price [EUR/MWh] |
|---|---|---|
| *Biomass from forestry operations* | | |
| Sawlogs | 89 | 23 |
| Pulpwood | 69 | 15 |
| Harvesting residues | 31 | 15 |
| Stumps | 16 | 22 |
| *Forest-based industrial byproducts* | | |
| Sawmill chips | 25 | 11 |
| Low-grade by-products | 23 | 10 |
| *Other woody biomasses* | | |
| Waste wood | 5.1 | 10 |
| Wood pellets | Unrestricted [a] | 30 |

[a]The modelled domestic production amounts to 8.1 TWh, and in addition to this, pellets can be imported with no restriction.

*Source: [11,24,25,39]*

An important assumption pertaining to the construction of regional supply curves is the transportation distance that defines the extent of the market supply for the $i^{th}$ gridcell. A distance matrix is used based on actual road and/or rail transport distance on inter-gridcells distance. Based on simulations from the BeWhere Sweden model, it has been determined that for each $i^{th}$ gridcell, supply of forest biomass can be acquired around a radius of 270 km. Fig. 4 summarizes the supply curves at the national level for Sweden, by type of forest biomass and by harvesting operation. Generally, the availability is higher under final felling compared with thinning; and with lower costs. The exception is for pulpwood where the availability is slightly larger under thinning, albeit with higher harvesting costs. These aggregate findings remain valid when investigating the regional supply curves at the gridcell level.

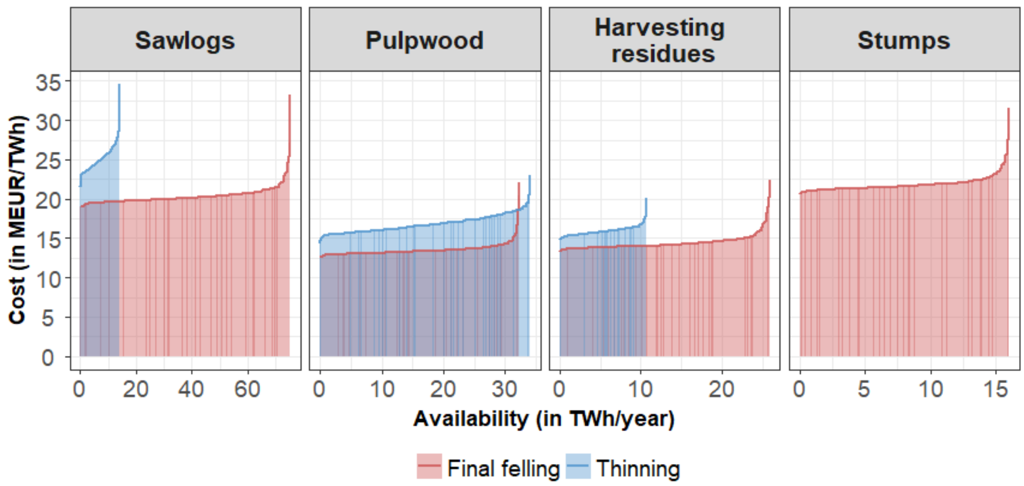


**Fig. 4.** National supply curves for forest feedstocks in Sweden by 2030

*Source: Authors' calculations*

## 4. Results and discussion

### *4.1. Demand impact*

Table 3 (or Fig. 5) summarizes the results for the aggregate demand for forest feedstocks under different assumptions concerning the biofuel production targets as simulated by the BeWhere Sweden model. The low/high rows refer to the competition intensity and the use/no-use rows refer to the ability to use industrial by-products in the biofuel production. The demand change for industrial by-products and wood chips from sawmills are not included in the results. In the scenario settings where they can be used in the production of biofuels (the 'Use by-products'' scenarios), the demanded quantity hits the upper boundary of what is available of the two feedstocks (24.9 and 23.5 TWh per year for chips and by-products, respectively) already in the lower biofuel production target levels and does not change across scenario settings.

As Table 3 (or Fig. 5) suggests, the demand of forest feedstocks, for obvious reasons, generally increases with a more stringent biofuel production target. Analysing the interaction between the level of competition and the stringency of the biofuel targets reveals interesting observations. Under the low competition scenario, pulpwood and harvest residues, especially from thinning operations, primarily meet the demand for forest biomass. For sawlogs and stumps, demand increases only marginally under the most stringent biofuel production targets, and especially for final felling operations. For instance, demand for pulpwood from thinning increases by 13.5 TWh (or by 67 percent) when use of by-products is allowed under the 30 TWh production target in comparison with the BAU. The increase is even larger under the no-use by-products scenario where demand increases by 16.5 TWh (or by 101 percent). Similarly for harvesting residues from thinning, demand increases by 6.4 TWh (or by 160 percent) when by-products use is allowed, and by 5 TWh (or by 92 percent) under the no-use by-products scenario for the 30 TWh scenario compared to the BAU.

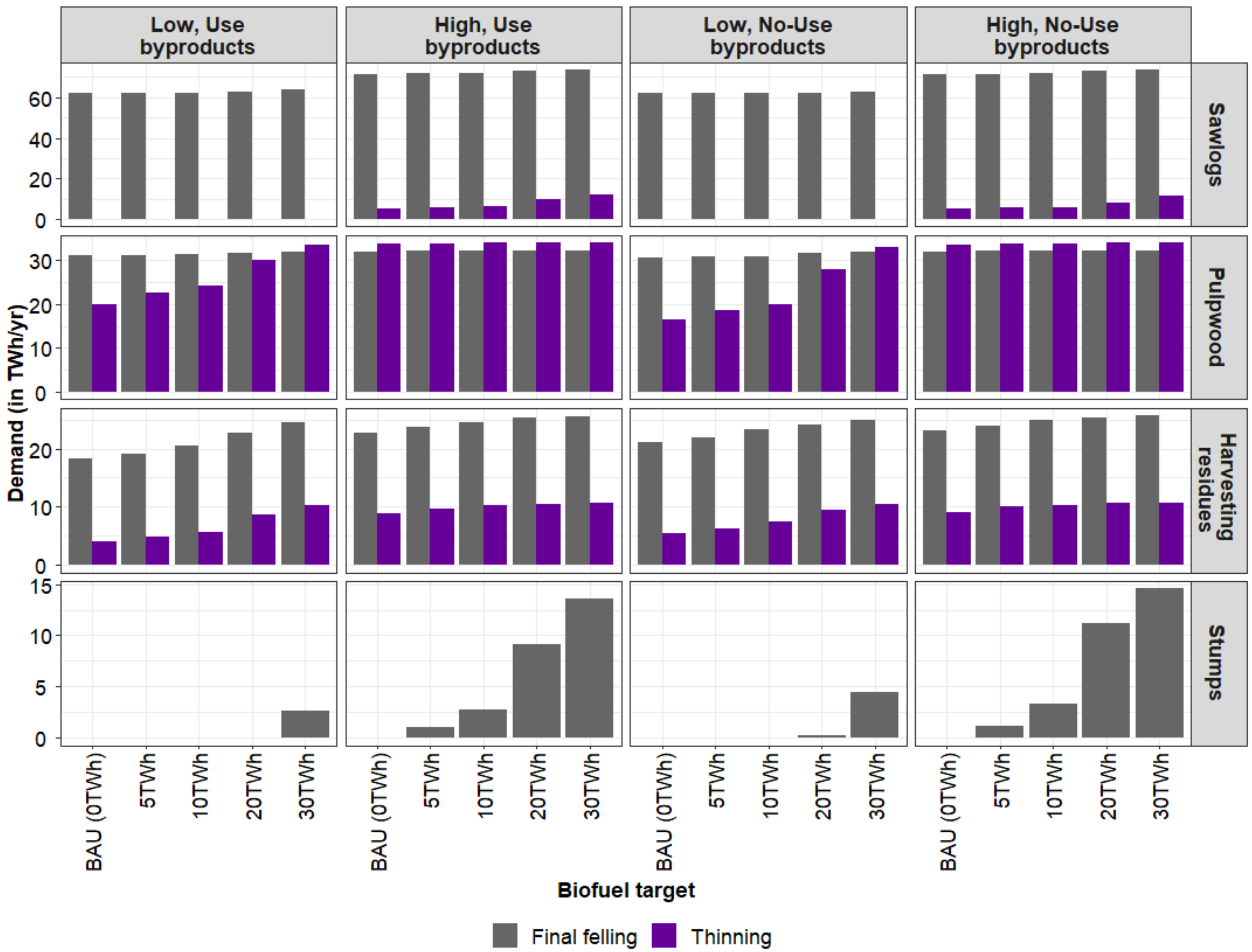


**Fig. 5.** Total forest feedstocks demand by biofuel production target and scenario type (in TWh $yr^{-1}$)
*Source: BeWhere Sweden simulations*

When comparing the structure of the demand between the low and high competition intensity scenarios, the results are in stark contrast. First, we observe that demand for sawlogs and stumps experience a substantial increase. For example, the demand of sawlogs would increase by 6.5 TWh (or 123 percent) for thinning and by 2.2 TWh (or 3.1 percent) for final felling when by-products use is allowed under the 30 TWh biofuel production target compared to the BAU. The results for stumps exhibit higher magnitudes, where demand increases by 13.5 TWh for the 30 TWh biofuel production target. The large percent change increase is driven by the low magnitude of the demand under the BAU scenario, and which does not exceed 0.05 TWh. For pulpwood, the demand increase is marginal; whereas for harvesting residues, the magnitude is much lower compared to the low competition scenario. The explanation of the dynamics can be found by comparing the structural change in demand when moving from low to high competition intensity, in light of the supply availability and structure for the harvest cost. Indeed, under the high competition scenario from the forest industries, a tightening in the market supply for pulpwood can be observed, driven by that demand hits the maximum availability. A similar trend is observed for harvesting residues. This argument is supported by the ratio of total demand to total availability for pulpwood from final felling that is tight, even under the low competition scenario, as suggested by demand-to-supply ratios above 0.9 (Table A1, Appendix). A similar trend is observed for pulpwood from thinning, albeit at lower magnitudes for low biofuel production targets, but which increase fast under the more stringent targets. Finally, comparing the incidence of the use or no-use by-products in the biofuel production, we observe that the demand is marginally larger under the no-use by-products. This can also be illustrated by the ratio of demand-to-supply (Table A1, Appendix). Moving from the use to no-use by-products scenarios, we observe that the ratios are relatively lower; which suggests that allowing by-products into the biofuel production mix alleviates some of the pressure on forest feedstocks markets.

Fig. 6-8 illustrates the spatial distribution of the forest feedstocks demand from final felling and thinning operations, respectively. It appears that the demand is concentrated primarily in the southern, and to a lesser extent, the middle regions of Sweden, for all the types of feedstocks. The distribution pattern is wide and covers a large span of the geographic area. In the northern regions, most of the demand is concentrated along the coastal line. Under increasing biofuel production targets, the spatial pattern does not change drastically. However, as the stringency of the biofuel target increases, we observe shifts in the locus of locations exhibiting the highest demand. In terms of the estimated demand pressure, similar conclusions apply with respect to the spatial distribution of demand (Fig. A4-A6, Appendix).

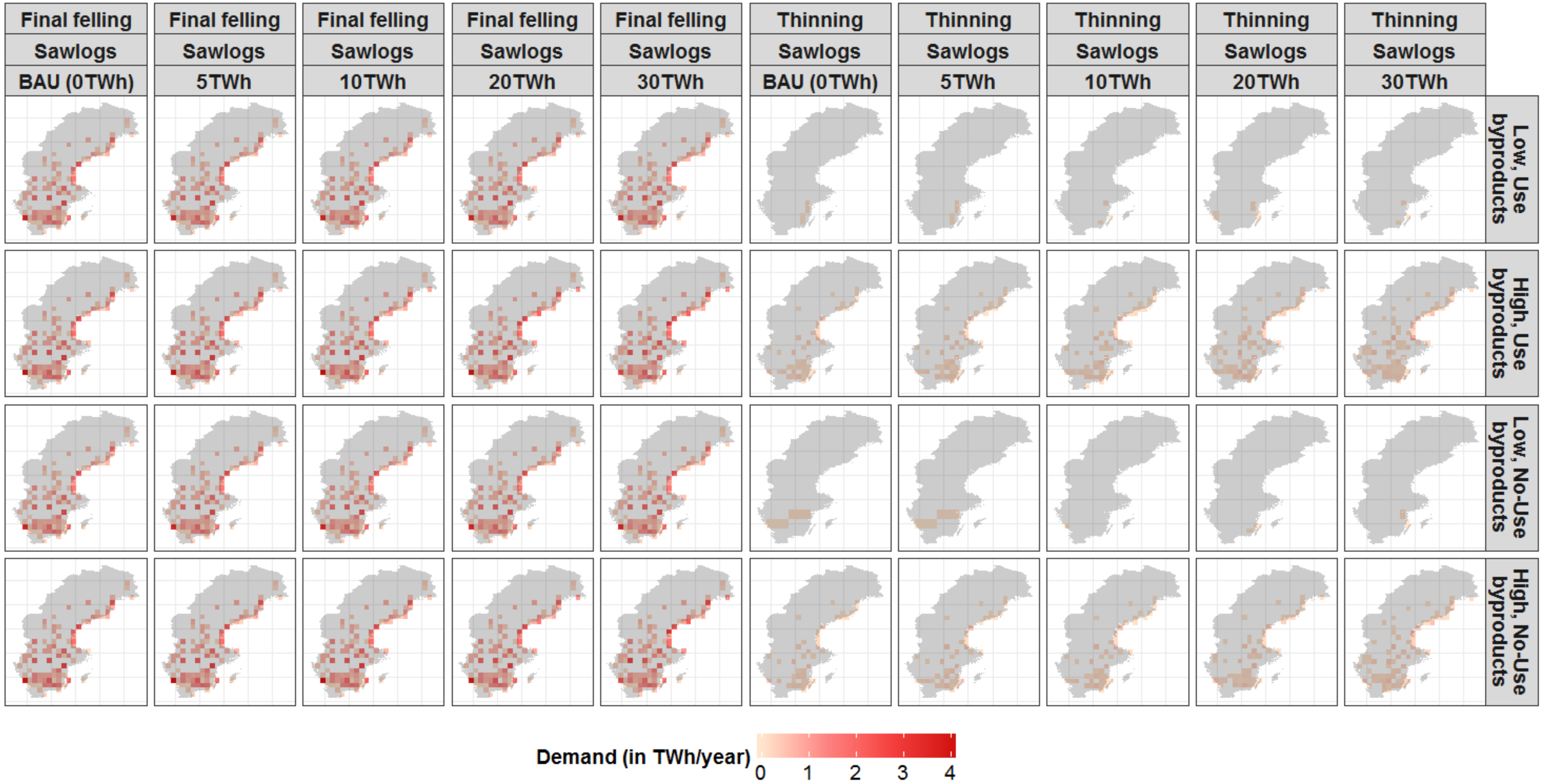


**Fig. 6.** Spatial distribution of demand for sawlogs from final felling and thinning (in TWh yr$^{-1}$)

*Source: BeWhere Sweden simulations*

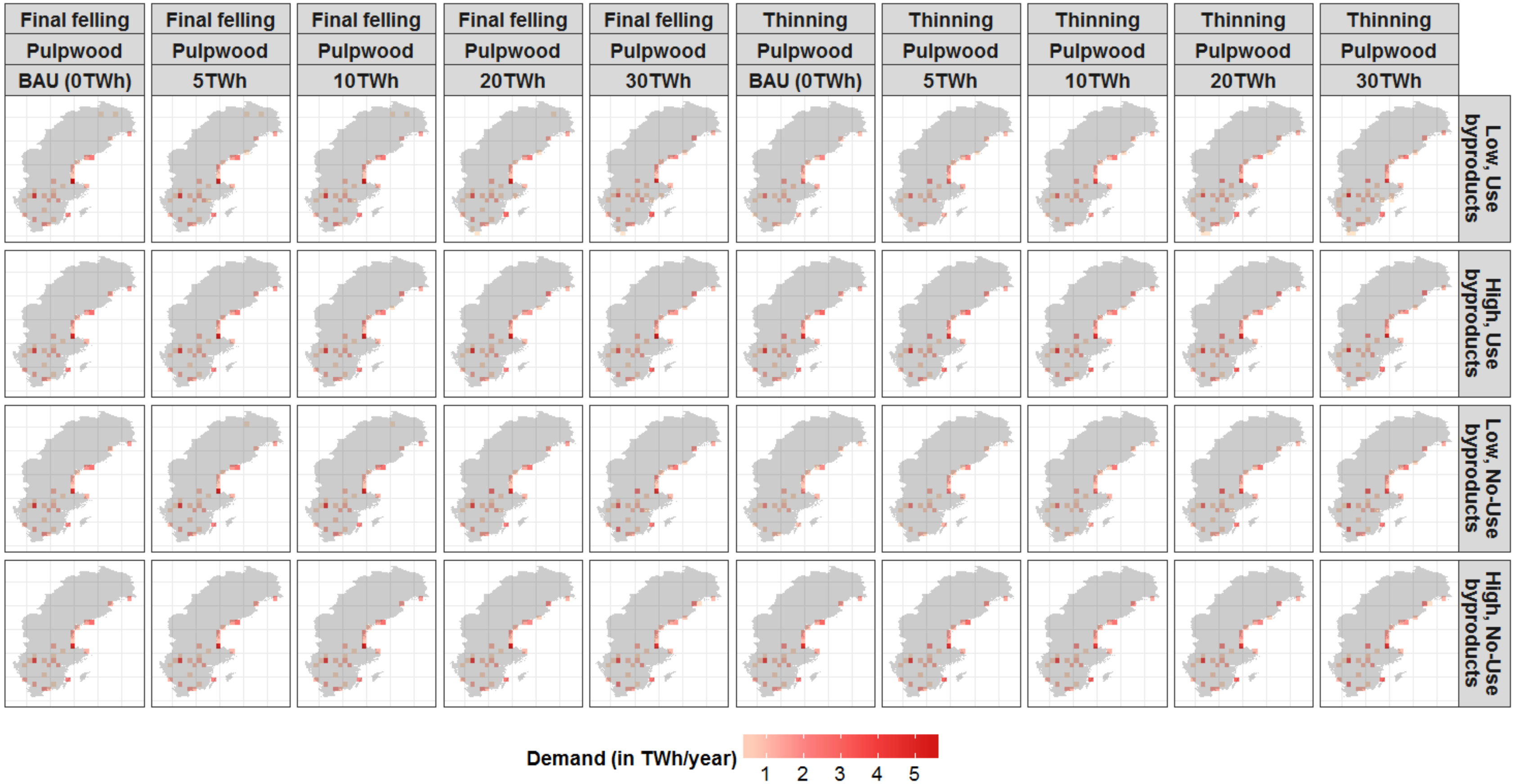


**Fig. 7.** Spatial distribution of demand for pulpwood from final felling and thinning (in TWh yr$^{-1}$)

*Source: BeWhere Sweden simulations*

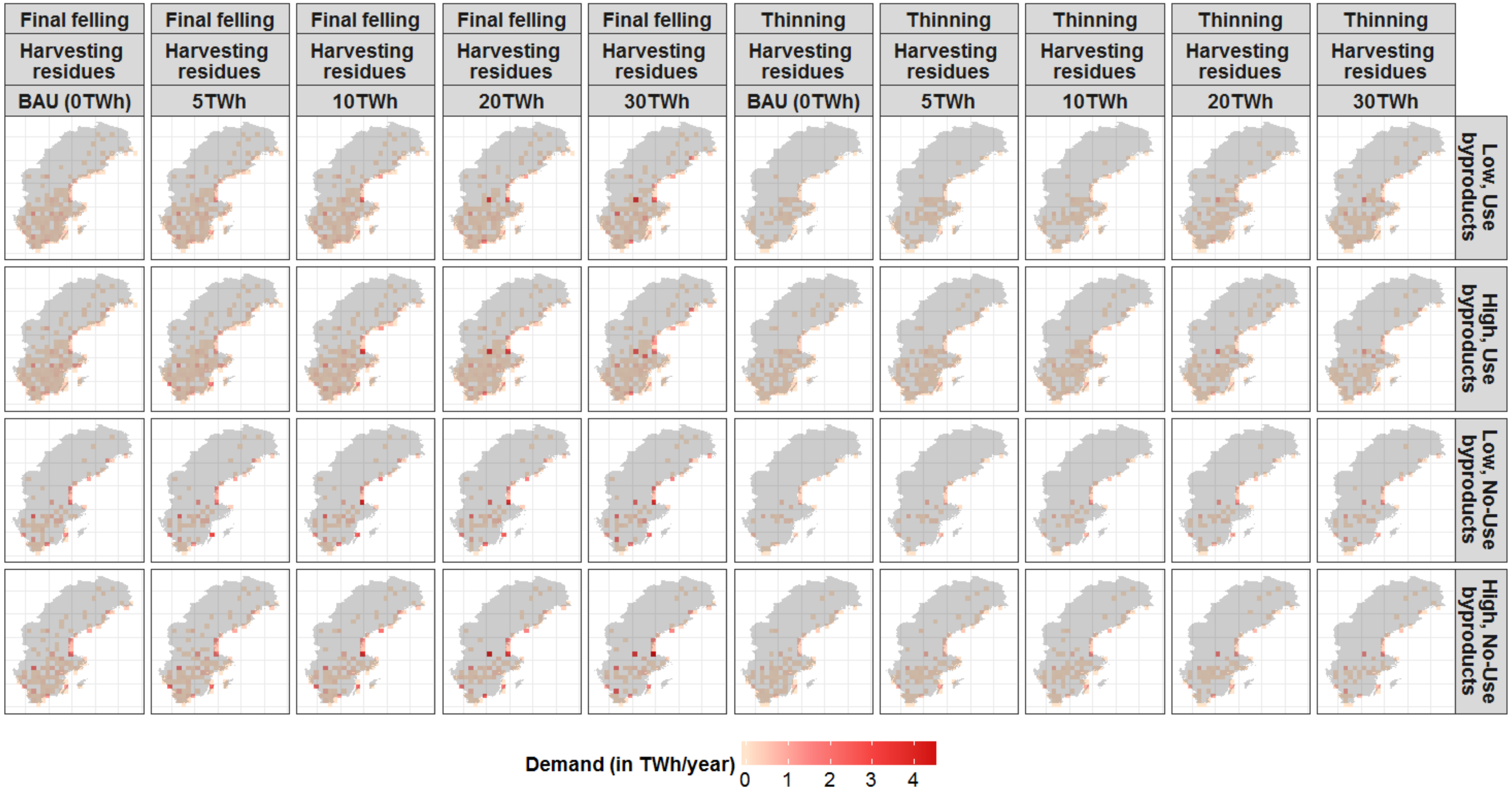


**Fig. 8.** Spatial distribution of demand for harvest residues from final felling and thinning (in TWh $yr^{-1}$)

*Source: BeWhere Sweden simulations*

### *4.2. Price impact*

The results of the estimation of the total demand pressure show that its spatial distribution does not differ from the BeWhere Sweden demand results as previously discussed. The spatial pattern shows that the highest level of demand pressure is located in the southern and middle-regions of Sweden, especially along the coastal line and/or around major urban areas (Fig. 6-8). Subsequently, the total demand pressure estimates at the gridcell level are juxtaposed with the gridcell-specific supply curve to derive market price equilibrium as previously discussed (cf. Sections 3.2 and 3.3).

Fig. 9 summarizes the average price impacts across gridcells, i.e. at the national level, for forest feedstocks under the different biofuel targets and scenario types. The results suggest that with increasing stringency in terms of biofuel production, prices will increase. However, we observe that the magnitude of the average price increase depends on the harvest operation, the competition intensity from the forest industries, and the use or no-use of by-products in the energy feedstock mix.

For pulpwood and harvesting residues, the results suggest relatively higher average price impacts, which are increasing with the biofuel production targets, especially under the low competition intensity scenario. In general, average price impacts are larger for thinning compared to final felling operations. This is not surprising as demand increases most for pulpwood and harvesting residues from thinning due to their relatively abundant supply and low cost structure (Fig. 9). However, for harvesting residues, we observe a reversal of dynamic for the high competition scenario. Indeed, we observe that price impacts are higher for thinning, which is driven by the higher demand levels (Fig. 9). Under the low biofuel production targets, the average price impacts on sawlogs and stumps are negligible. This is expected since that demand for sawlogs and stumps does not increase so much, especially under the low biofuel targets. However, when moving from the low to the high competition scenario, the average price impacts increase for both sawlogs and stumps with increasing biofuel target stringency. A number of factors drive these results. First, the low supply and high harvesting cost structure diminishes the economic viability of sawlogs and stumps. Second, the supply potential from pulpwood and harvesting residues is large enough to satisfy biomass demand requirements, especially under the low competition scenario. Thus, the results suggest that resource usage increases most for the cheapest feedstocks. As competition increases, demand for pulpwood and harvesting residues reaches the cap of potential availability, which in turn raises the economic viability of sawlogs and stumps as the biofuel target increases. This is clearly shown in the development of the demand increment for each feedstock (Fig. A3, Appendix).

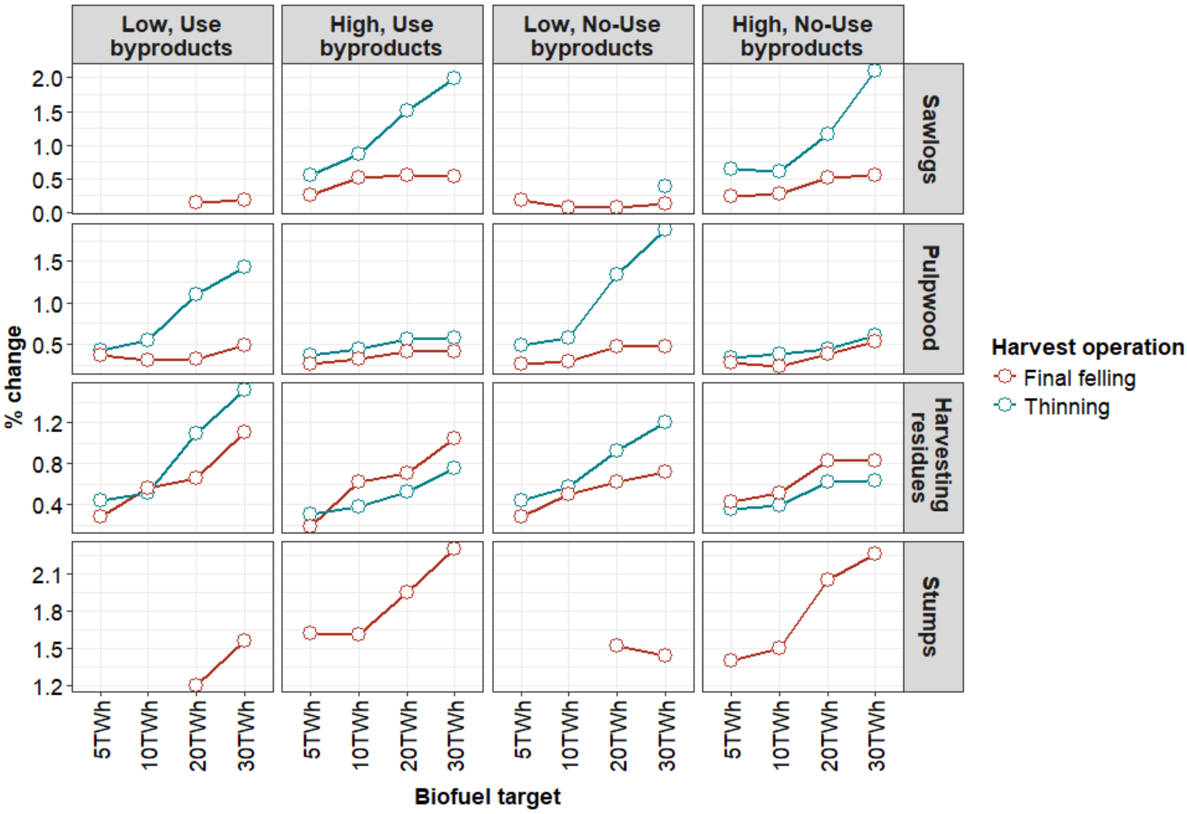


**Fig. 9.** Average price impacts by biofuel target, competition intensity and use/no-use of by-products (in % change from BAU)
*Source: Simulation results*

The spatial distribution of price impacts varies across feedstocks and scenarios. In general, the spatial distribution widens as the biofuel production targets increase. More specifically, for sawlogs and stumps, the spatial distribution of price impacts is relatively sparse under the low competition scenario, even when the biofuel target is at its highest point. This is a direct result of the relative low to no-demand under the low biofuel targets. This holds true for final felling operations, where harvesting cost is relatively higher. For pulpwood and harvesting residues, the results suggest that the price impacts are more spatially distributed compared with sawlogs and stumps. Additionally, for most feedstocks, the price impacts occur in locations where we observe increased demand pressure (Fig. 10-11). However, the highest price impacts do not always match the location of the highest demand pressure. For instance, for sawlogs from thinning, the highest price impacts are located inland in the northern regions of Sweden. However, the demand pressure is at its highest in the coastal areas. A potential explanation lies in the nature of the supply-curves. We notice that these regions are characterized by relatively low availability and high harvesting costs. Thus, the supply curves are more inelastic for gridcells in the inland areas.

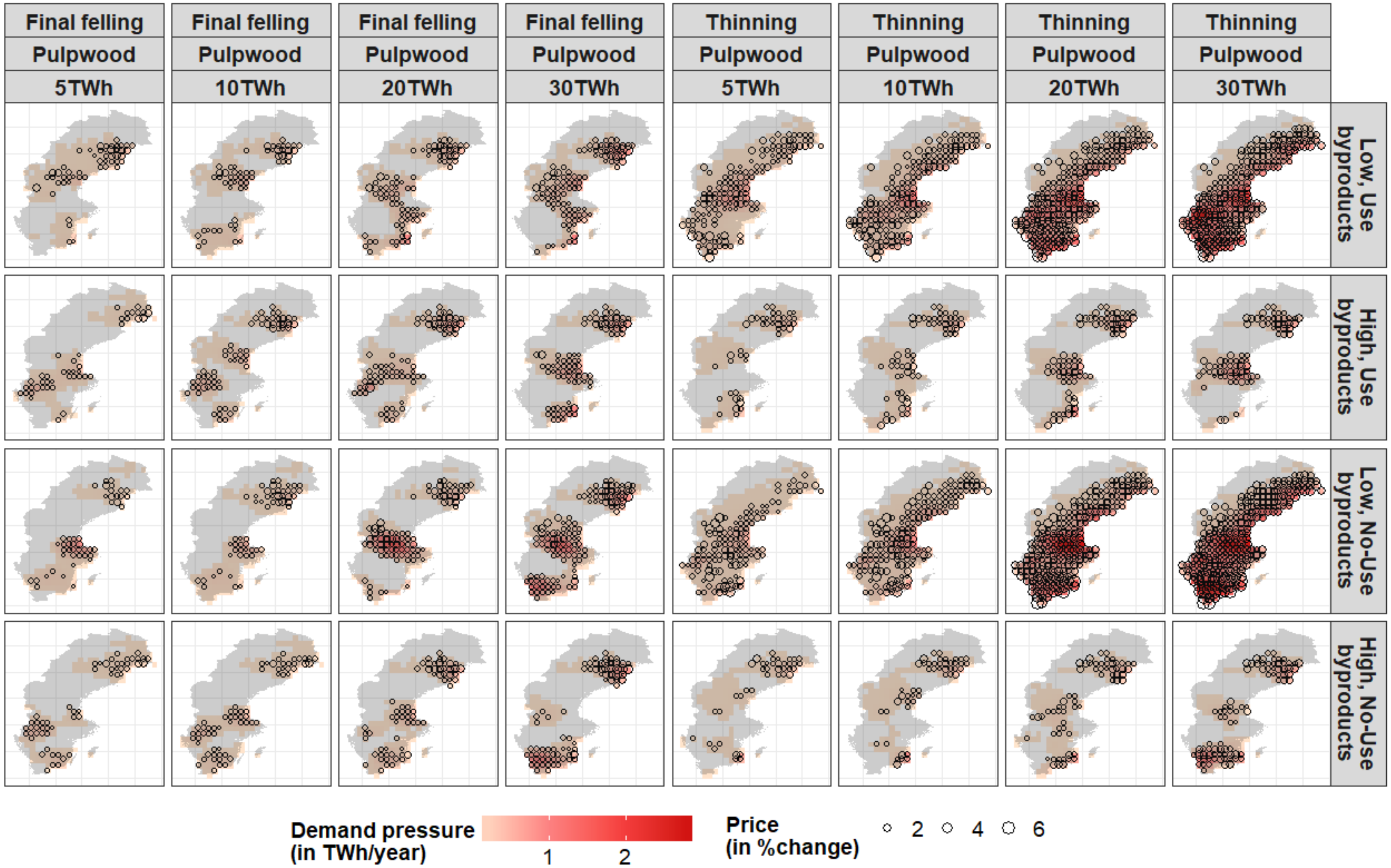


**Fig. 10.** Spatial distribution for pulpwood from final felling and thinning of demand pressure deviation from BAU (in TWh/year) and price impacts (in percent change from BAU)
*Source: Simulation results*

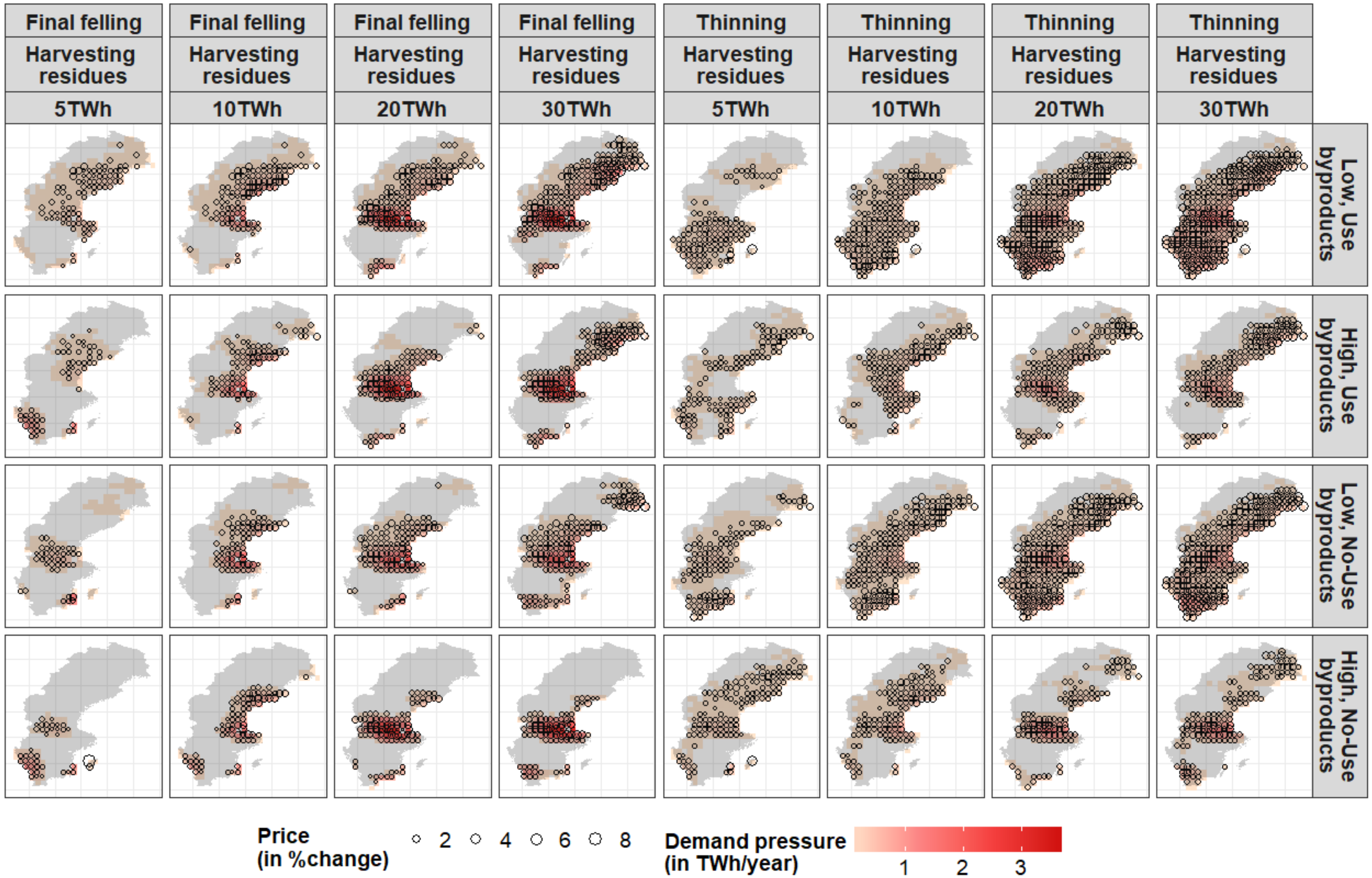


**Fig. 11.** Spatial distribution for harvesting residues from final felling and thinning of demand pressure deviation from BAU (in TWh/year) and price impacts (in percent change from BAU)

*Source: Simulation results*

### *4.3. Sensitivity analysis*

A sensitivity analysis is made with respect to the distance-decay parameters that govern the spatial interaction across location. More specifically, the impact on the aggregate demand pressure from changing the values of the parameter determining the intensity of the spatial interaction (gamma) [37]. Fig. 12 summarizes the results for the sensitivity analysis on the aggregate demand pressure for harvesting residues from final felling. We observe that as spatial interaction increases, the distribution of aggregate demand pressure diminishes. This result holds for all the feedstocks.

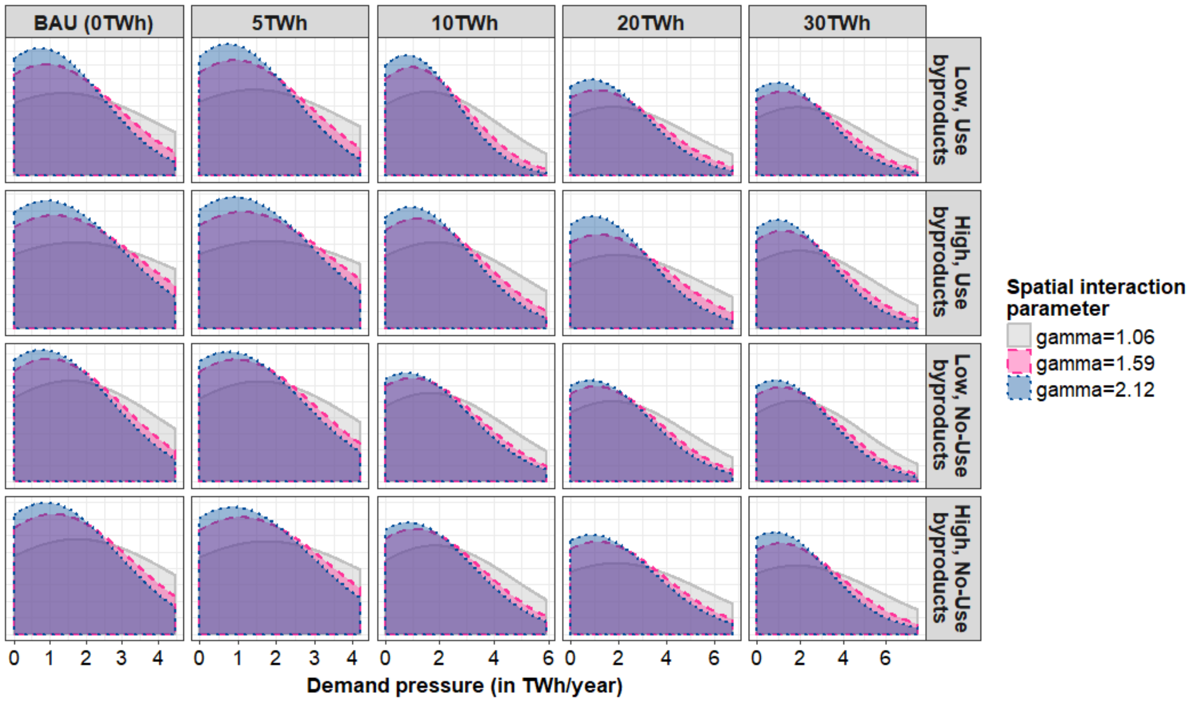


**Fig. 12.** Evolution of the aggregate demand pressure for harvesting residues from final felling under different assumptions on the level of spatial interaction (in TWh/year)
*Source: Authors' calculation*

However, when evaluating the deviation from the BAU scenario, we observe a reverse dynamic. Indeed, the distribution of the deviation tends to widen as the spatial interaction increases, especially under the high competition scenario (Fig. 13). As a result, the price impacts also tend to increase with increasing spatial interaction (Fig. 14).

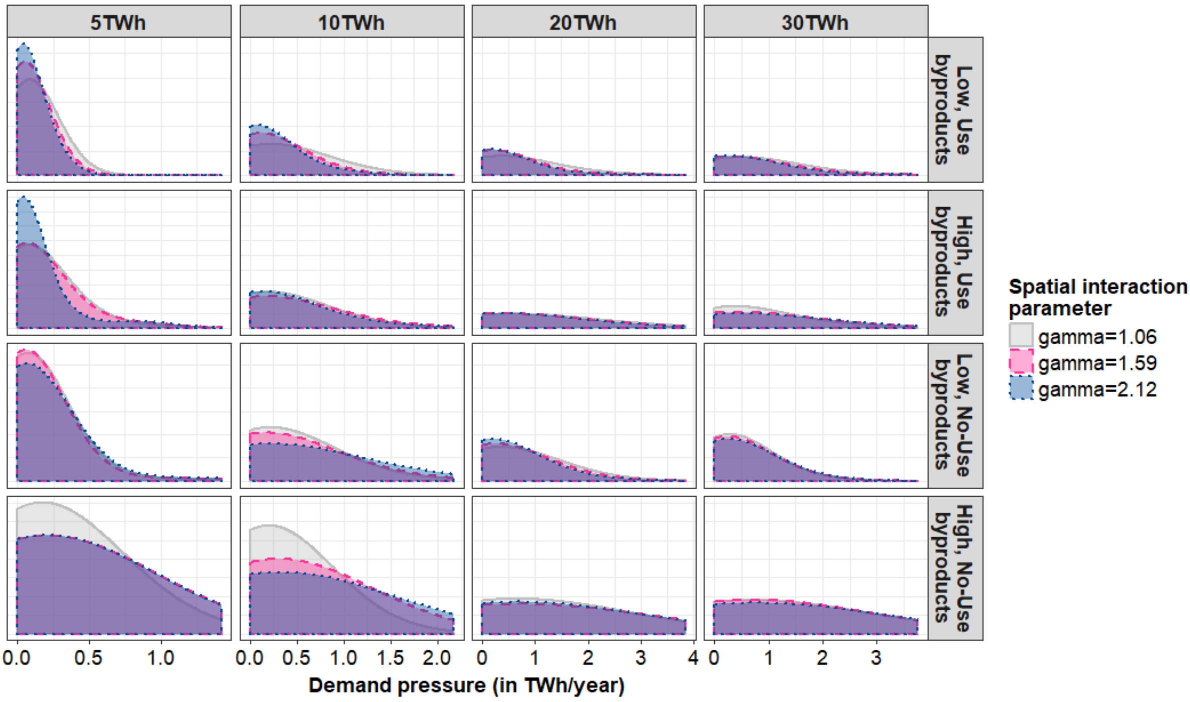


**Fig. 13.** Evolution of the deviation from the BAU of the aggregate demand pressure for harvesting residues from final felling under different assumptions on the level of spatial interaction (in TWh/year)

*Source: Authors' calculation*

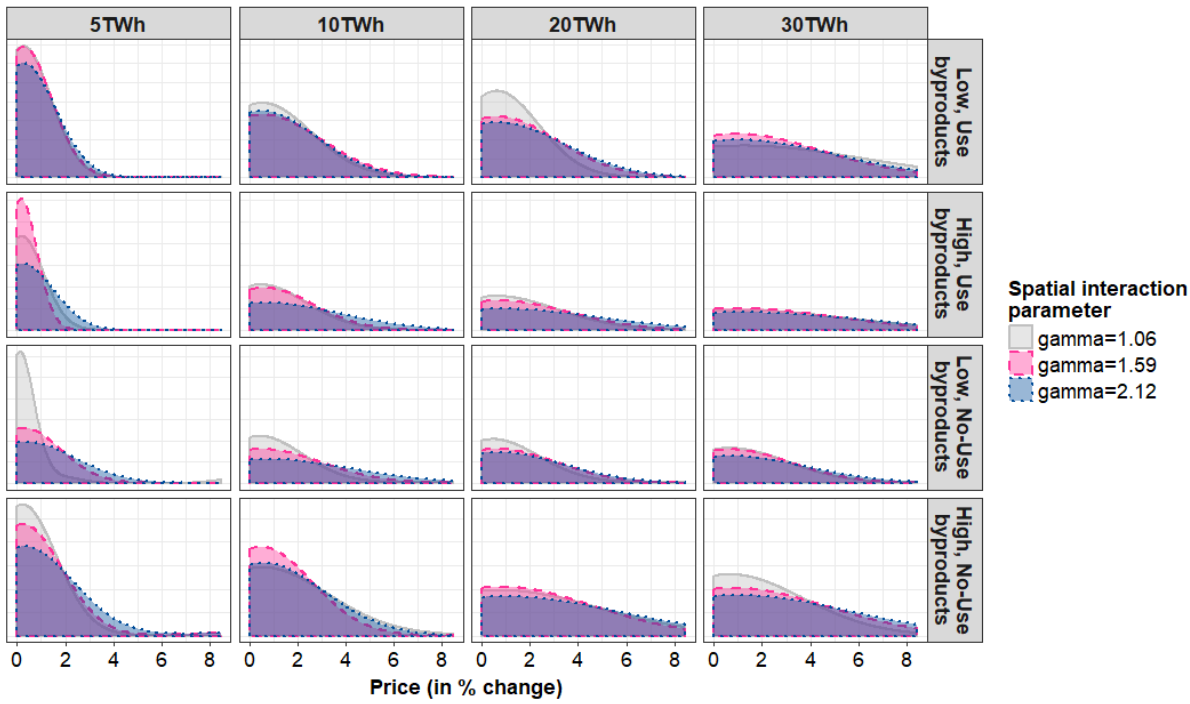


**Fig. 14.** Evolution of the price impacts for harvesting residues from final felling under different assumptions on the level of spatial interaction (in % change from BAU)

*Source: Authors' calculation*

## 5. Conclusions

The analysis and results presented in this paper have improved our understanding of the spatial price impact on forest markets from the introduction of a new high-volume user of forest biomass, such as large-scale production of forest-based transportation biofuels. The methodological approach is based in a novel spatially explicit approach for price determination based on changing demand patterns. The framework is applied to the Swedish forestry sector. The objective is to investigate the impacts of increased biofuel production by 2030 on market prices for forest feedstocks.

The results show that the feedstock prices will not in general increase that much from an increased biofuel production. On average, the price increase will not exceed three percent across the feedstocks in the highest biofuel production target (30 TWh). This implies that the production of considerable volumes of forest-based biofuel is possible, without significantly increasing the competition for the feedstock within the Swedish context. It also implies that the scarcity of the forest feedstocks is not as severe as otherwise might have been the case. Thus, from a policy perspective, there is no need for market intervention to secure woody feedstock availability for any particular use or to even-out the argued price effect on the feedstocks from implemented energy policies. Nonetheless, several studies point to the potential negative impacts of increased harvest intensity for logging residues and stumps on biodiversity preservation and forest growth [40–42].

Second, the results of the analysis suggest that policy-making should focus on the locational linkages of price impacts. Overall, the spatial distribution of price impacts matches well the spatial pattern of increased demand pressure. However, we observe also that the highest price impacts do not always match up with locations where demand pressure is highest. This implies that the severity of the competition effect will tend to be more localized, and is affected by local conditions in terms of availability of woody materials and costs. Thus, a special consideration must be given to the spatial character of the potential impacts of policy mandated production targets in the context of biofuel production from spatially heterogeneously distributed resources such as forest feedstocks.

Finally, there are potential routes in which the analysis could be extended further that merit mention. First, an important insight that emerges from the results relates to the impact of coarse spatial aggregation on model simulations. The current analysis uses a relatively coarse spatial aggregation based on 0.5 x 0.5 degree gridcells. Thus, the analysis could potentially be improved by utilizing a finer spatial scale, especially in what pertains to the characterization of availability of woody biomass. Second, the analysis focused solely on the demand-side dynamic of increased use for woody biomass from biofuel production. However, we could also consider the supply-side dynamics by taking into consideration different scenarios about availability of woody biomass, which is affected by climate change impacts, environmental policies of forest preservation, etc.

**Acknowledgement:** This work is supported by funding from the Swedish Research Council Formas dnr. 213-2014-184. Bio4Energy, a strategic research environment appointed by the Swedish government, is also gratefully acknowledged.

## References


[1] B. Solberg, L. Hetemäki, a M.I. Kallio, A. Moiseyev, H.K. Sjølie, Impacts of forest bioenergy and policies on the forest sector markets in Europe – what do we know ?, EFI Tech. Rep. 89 (2014) 86.

[2] Energimyndigheten, Energy in Sweden 2012, 2012.

[3] P. Börjesson, J. Hansson, G. Berndes, Future demand for forest-based biomass for energy purposes in Sweden, For. Ecol. Manage. 383 (2017) 17–26. doi:10.1016/j.foreco.2016.09.018.

[4] Skogsstyrelsen, Skogsstatistisk årsbok 2014, 2014.

[5] Naturvårdsverket, Sektorsunderlag industri: Underlag till Färdplan 2050, 2012. https://www.naturvardsverket.se.

[6] K. Duvemo, M. Fridh, S. Joshi, S. Karlsson, S.A. Svensson, S. Karlsson, S. Karlsson, Global framtida efterfrågan på och möjligt utbud av virkesråvara, Jönköping, 2015.

[7] SDC, Skogsindustrins virkesförbrukning samt produktion av skogsprodukter 2013-2017, Sundsvall, 2018. http://www.sdc.se/admin/Filer/Skogsindustrins virkesförbrukning och produktion 2017.pdf.

[8] Skogsstyrelsen, Grossfellings, (2018). https://www.skogsstyrelsen.se/en/statistics/subject-areas/grossfellings/.

[9] J. Kim, M.J. Realff, J.H. Lee, C. Whittaker, L. Furtner, Design of biomass processing network for biofuel production using an MILP model, Biomass and Bioenergy. 35 (2010) 853–871. doi:10.1016/j.biombioe.2010.11.008.

[10] S. Kim, B.E. Dale, Comparing alternative cellulosic biomass biorefining systems : Centralized versus distributed processing systems, Biomass and Bioenergy. 74 (2015) 135–147. doi:10.1016/j.biombioe.2015.01.018.

[11] K. Natarajan, S. Leduc, P. Pelkonen, E. Tomppo, E. Dotzauer, Optimal locations for second generation Fischer Tropsch biodiesel production in Finland, Renew. Energy. 62 (2014) 319–330. doi:10.1016/j.renene.2013.07.013.

[12] T. Ranta, Logging residues from regeneration fellings for biofuel production – a GIS-based availability analysis in Finland, 28 (2005) 171–182. doi:10.1016/j.biombioe.2004.08.010.

[13] M.T. Melo, S. Nickel, F. Saldanha-da-gama, Facility location and supply chain management – A review, Eur. J. Oper. Res. 196 (2009) 401–412. doi:10.1016/j.ejor.2008.05.007.

[14] T. Yoshioka, R. Sakurai, K. Aruga, H. Sakai, H. Kobayashi, K. Inoue, A GIS-based analysis on the relationship between the annual available amount and the procurement cost of forest biomass in a mountainous region in Japan, Biomass and Bioenergy. 35 (2011) 4530–4537. doi:10.1016/j.biombioe.2011.03.029.

[15] S. Gold, S. Seuring, Supply chain and logistics issues of bio-energy production, J. Clean. Prod. 19 (2011) 32–42. doi:10.1016/j.jclepro.2010.08.009.

[16] J. Höhn, E. Lehtonen, S. Rasi, J. Rintala, A Geographical Information System (GIS) based methodology for determination of potential biomasses and sites for biogas plants in southern Finland, Appl. Energy. 113 (2014) 1–10. doi:10.1016/j.apenergy.2013.07.005.

[17] F. Zhang, D. Johnson, M. Johnson, D. Watkins, R. Froese, J. Wang, Decision support system integrating GIS with simulation and optimisation for a biofuel supply chain, Renew. Energy. 85 (2016) 740–748. doi:10.1016/j.renene.2015.07.041.

[18] N. Parker, P. Tittmann, Q. Hart, R. Nelson, K. Skog, A. Schmidt, E. Gray, B. Jenkins, Development of a biorefinery optimized biofuel supply curve for the Western United States, Biomass and Bioenergy. 34 (2015) 1597–1607.

doi:10.1016/j.biombioe.2010.06.007.

[19] T.L. Jenkins, J.W. Sutherland, A cost model for forest-based biofuel production and its application to optimal facility size determination, For. Policy Econ. 38 (2014) 32–39. doi:10.1016/j.forpol.2013.08.004.

[20] J.E. Santibañez-Aguilar, J.B. Gonzalez-Campos, J.M. Ponce-ortega, M. Serna-gonzález, M.M. El-Halwagi, Optimal planning and site selection for distributed multiproduct biorefineries involving economic, environmental and social objectives, J. Clean. Prod. 65 (2014) 270–294. doi:10.1016/j.jclepro.2013.08.004.

[21] J.E. Santibañez-Aguilar, M. Rivera-toledo, A. Flores-tlacuahuac, J.M. Ponce-ortega, A mixed-integer dynamic optimization approach for the optimal planning of distributed biorefineries, 80 (2015) 37–62. doi:10.1016/j.compchemeng.2015.05.008.

[22] K. Natarajan, S. Leduc, P. Pelkonen, E. Tomppo, E. Dotzauer, Optimal Locations for Methanol and CHP Production in Eastern Finland, Bioenergy Res. 5 (2012) 412–423. doi:10.1007/s12155-011-9152-4.

[23] E. Wetterlund, S. Leduc, E. Dotzauer, G. Kindermann, Optimal use of forest residues in Europe under different policies—second generation biofuels versus combined heat and power, Biomass Convers. Biorefinery. 3 (2013) 3–16. https://link.springer.com/article/10.1007/s13399-012-0054-2.

[24] E. Wetterlund, Optimal Localisation of Next Generation Biofuel Production in Sweden – Part II, 2013.

[25] K. Pettersson, E. Wetterlund, D. Athanassiadis, R. Lundmark, C. Ehn, J. Lundgren, N. Berglin, Integration of next-generation biofuel production in the Swedish forest industry – A geographically explicit approach, Appl. Energy. 154 (2015) 317–332. doi:10.1016/j.apenergy.2015.04.041.

[26] S. de Jong, R. Hoefnagels, E. Wetterlund, K. Pettersson, A. Faaij, M. Junginger, Cost optimization of biofuel production – The impact of scale , integration , transport and supply chain configurations, Appl. Energy. 195 (2017) 1055–1070. doi:10.1016/j.apenergy.2017.03.109.

[27] K. Ericsson, S. Huttunen, L.J. Nilsson, P. Svenningson, Bioenergy policy and market development in Finland and Sweden? (vol 32, pg 1707, 2004), Energy Policy. 33 (2005) 129. <Go to ISI>://000223936000013.

[28] A. Olsson, R. Lundmark, Modelling the competition for forest resources : The case of Sweden, 3 (2014) 11–19. doi:10.11648/j.jenr.20140302.11.

[29] R. Lundmark, D. Athanassiadis, E. Wetterlund, Supply assessment of forest biomass - A bottom-up approach for Sweden, Biomass and Bioenergy. 75 (2015) 213–226. doi:10.1016/j.biombioe.2015.02.022.

[30] R. Lundmark, Cost structure of and competition for forest-based biomass, Scand. J. For. Res. 21 (2006) 272–280. doi:10.1080/02827580600688251.

[31] A. Olsson, Examining the Competition for Forest Resources in Sweden Using Factor Substitution Analysis and Partial Equilibrium Modelling, n.d.

[32] R. Lundmark, A. Olsson, Factor substitution and procurement competition for forest resources in Sweden, Int. J. Prod. Econ. 169 (2015) 99–109. doi:10.1016/j.ijpe.2015.07.029.

[33] A. Krook-Riekkola, E. Wetterlund, E. Sandberg, Biomassa, systemmodeller och målkonflikter, 2017.

[34] S. Claesson, K. Duvemo, A. Lundström, P.-E. Wikberg, Skogliga konsekvensanalyser 2015 – SKA 15, Rapport 10 2015, Skogsstyrelsen, Jönköping, 2015.

[35] Energimyndigheten, Energiläget, (2017). www.energimyndigheten.se.

[36] Energiföretagen, Tillförd energi, (2017). https://www.energiforetagen.se/statistik/fjarrvarmestatistik/tillford-energi/.

[37] I. Ouraich, R. Lundmark, A Spatial Price Determination Model for Multi-Market Heterogeneously Distributed Resources: An Application to Forestry Markets in Sweden, Geogr. Anal. (2018). doi:https://doi.org/10.1111/gean.12165.
[38] E. Wetterlund, M. Fallde, K. Pettersson, J. Olofsson, P. Börjesson, J. Lundgren, Bewhere - Stake-holder analysis of biofuel production in Sweden, 2017. www.f3centre.se.
[39] K.M. Holmgren, T.S. Berntsson, E. Andersson, T. Rydberg, Comparison of integration options for gasi fi cation-based biofuel production systems e Economic and greenhouse gas emission implications, Energy. 111 (2016) 272–294. doi:10.1016/j.energy.2016.05.059.
[40] J. de Jong, A. Dahlberg, Impact on species of conservation interest of forest harvesting for bioenergy purposes, For. Ecol. Manage. 383 (2017) 37–48. doi:10.1016/j.foreco.2016.09.016.
[41] J. de Jong, C. Akselsson, G. Egnell, S. Löfgren, B.A. Olsson, Realizing the energy potential of forest biomass in Sweden – How much is environmentally sustainable ?, For. Ecol. Manage. 383 (2017) 3–16. doi:10.1016/j.foreco.2016.06.028.
[42] G. Egnell, A review of Nordic trials studying effects of biomass harvest intensity on subsequent forest production, For. Ecol. Manage. 383 (2017) 27–36. doi:10.1016/j.foreco.2016.09.019.

# Appendix

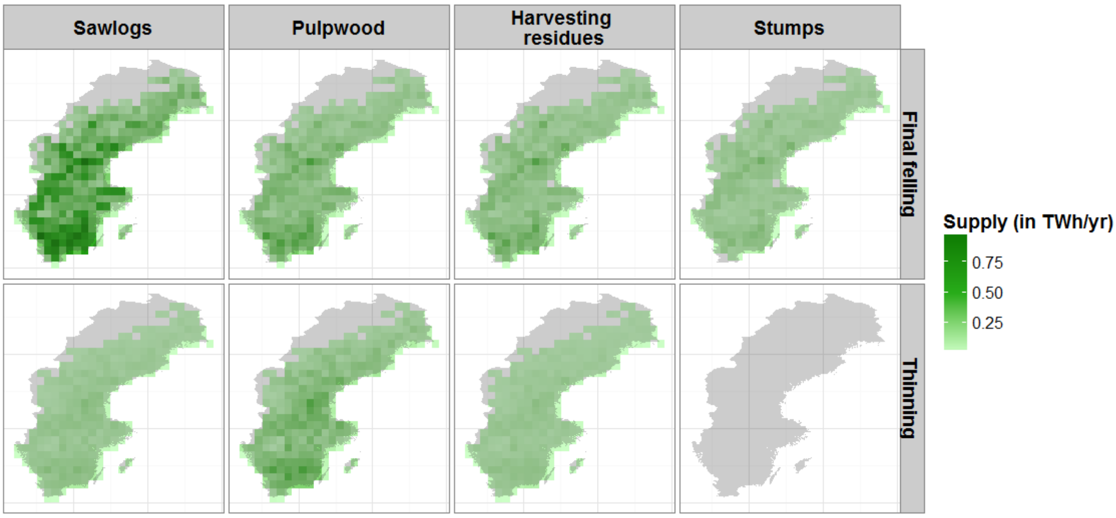


**Fig. A1.** Spatial availability of forest feedstocks by harvest operation (in TWh $yr^{-1}$)
*Source: Lundmark et al., (2015)*[29]

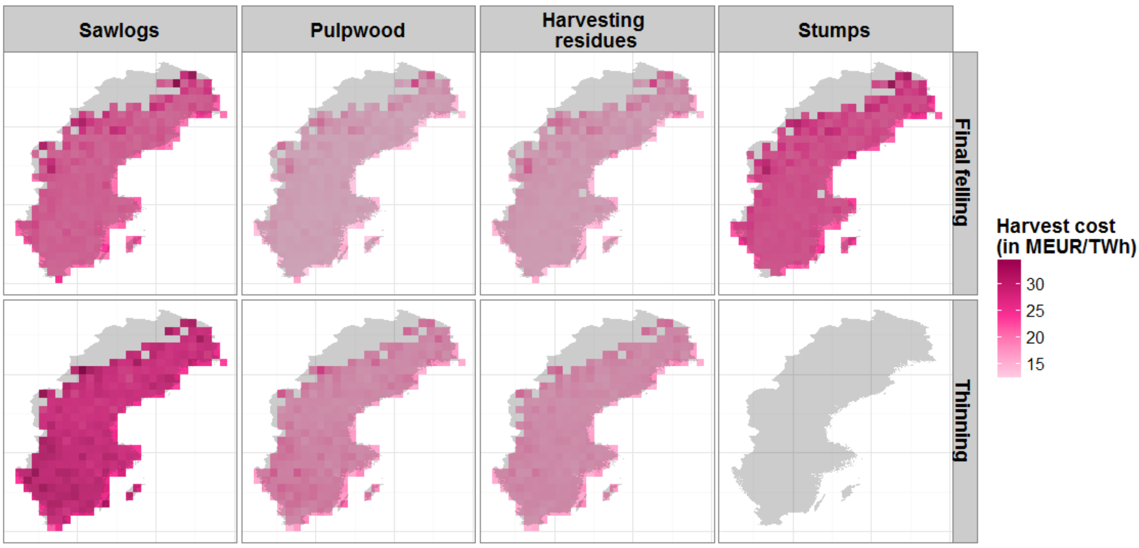


**Fig. A2.** Spatial harvest cost of forest feedstocks by harvest operation (in TWh $yr^{-1}$)
*Source: Lundmark et al., (2015)*[29]

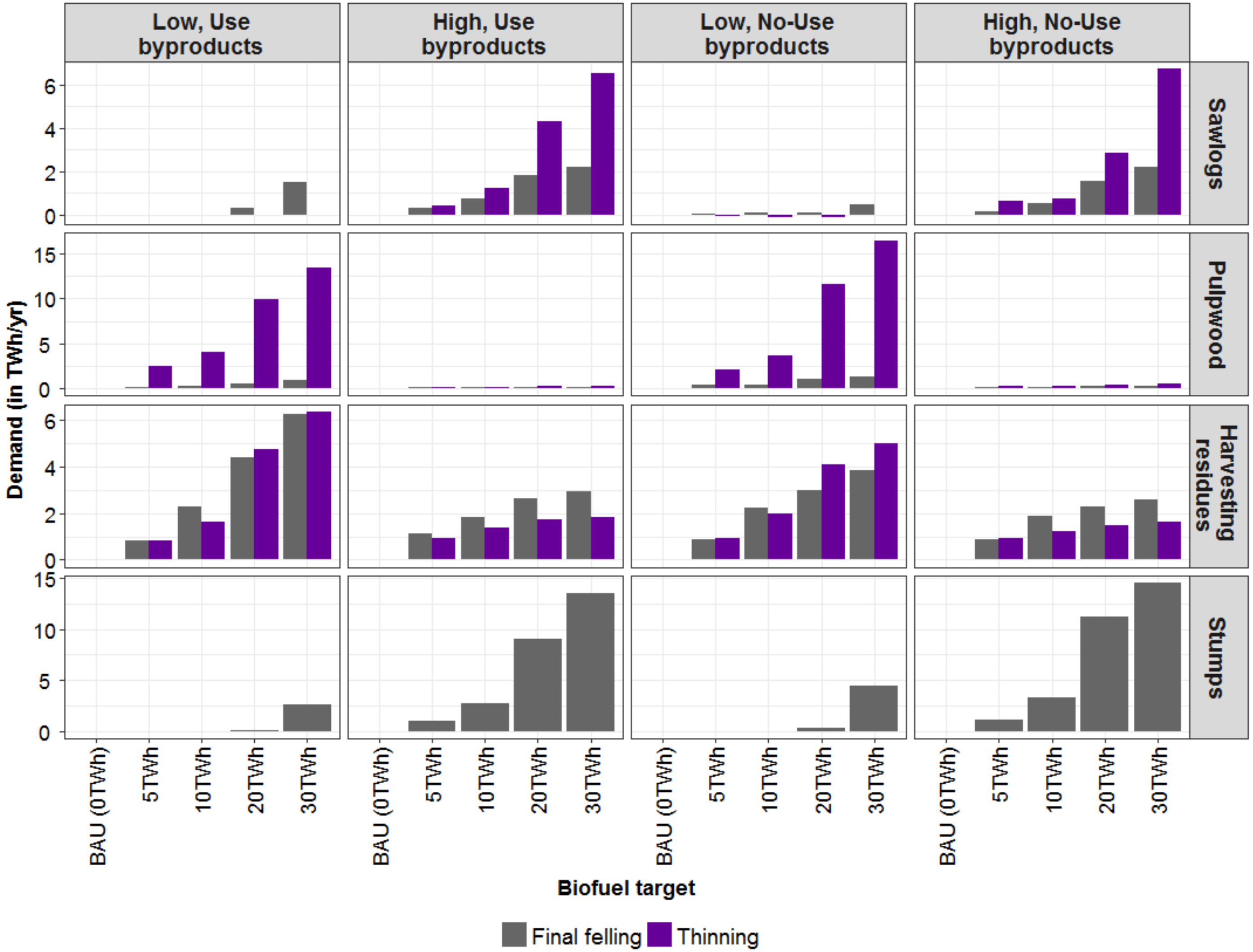


**Fig. A3.** Demand increments for forest biomass as deviation from the BAU scenario by competition intensity and by biofuel target (in TWh $yr^{-1}$)
*Source: Authors' calculation*

**Table A1**
Ratio of total supply to total demand for forest biomass by scenario type and biofuel production target

| | | Final felling (TWh) | | | | Thinning (TWh) | | |
|---|---|---|---|---|---|---|---|---|
| | Biofuel target | *Sawlogs* | *Pulpwood* | *Harvesting residues* | *Stumps* | *Sawlogs* | *Pulpwood* | *Harvesting residues* |
| **Low/Use by-products** | *BAU (0 TWh)* | 0.83 | 0.96 | 0.71 | 0.00 | 0.01 | 0.59 | 0.37 |
| | *5 TWh* | 0.83 | 0.97 | 0.74 | 0.00 | 0.01 | 0.66 | 0.45 |
| | *10 TWh* | 0.83 | 0.97 | 0.79 | 0.00 | 0.01 | 0.71 | 0.53 |
| | *20 TWh* | 0.83 | 0.98 | 0.88 | 0.00 | 0.01 | 0.88 | 0.81 |
| | *30 TWh* | 0.85 | 0.99 | 0.95 | 0.16 | 0.01 | 0.99 | 0.97 |
| **Low/No-Use by-products** | *BAU (0 TWh)* | 0.83 | 0.95 | 0.81 | 0.00 | 0.01 | 0.48 | 0.51 |
| | *5 TWh* | 0.83 | 0.96 | 0.85 | 0.00 | 0.00 | 0.54 | 0.59 |
| | *10 TWh* | 0.83 | 0.96 | 0.90 | 0.00 | 0.00 | 0.59 | 0.69 |
| | *20 TWh* | 0.83 | 0.98 | 0.93 | 0.02 | 0.00 | 0.82 | 0.89 |
| | *30 TWh* | 0.84 | 0.99 | 0.96 | 0.28 | 0.01 | 0.97 | 0.97 |
| **High/Use by-products** | *BAU (0 TWh)* | 0.95 | 0.99 | 0.88 | 0.00 | 0.38 | 0.99 | 0.82 |
| | *5 TWh* | 0.96 | 1.00 | 0.92 | 0.06 | 0.41 | 0.99 | 0.91 |
| | *10 TWh* | 0.96 | 1.00 | 0.95 | 0.17 | 0.46 | 1.00 | 0.95 |
| | *20 TWh* | 0.98 | 1.00 | 0.98 | 0.57 | 0.69 | 1.00 | 0.98 |
| | *30 TWh* | 0.98 | 1.00 | 0.99 | 0.85 | 0.84 | 1.00 | 0.99 |
| **High/No-Use by-products** | *BAU (0 TWh)* | 0.95 | 0.99 | 0.89 | 0.00 | 0.35 | 0.99 | 0.85 |
| | *5 TWh* | 0.95 | 1.00 | 0.93 | 0.08 | 0.40 | 0.99 | 0.93 |
| | *10 TWh* | 0.96 | 1.00 | 0.96 | 0.21 | 0.40 | 0.99 | 0.96 |
| | *20 TWh* | 0.97 | 1.00 | 0.98 | 0.70 | 0.55 | 1.00 | 0.99 |
| | *30 TWh* | 0.98 | 1.00 | 0.99 | 0.91 | 0.83 | 1.00 | 1.00 |

*Source: Authors' calculations*

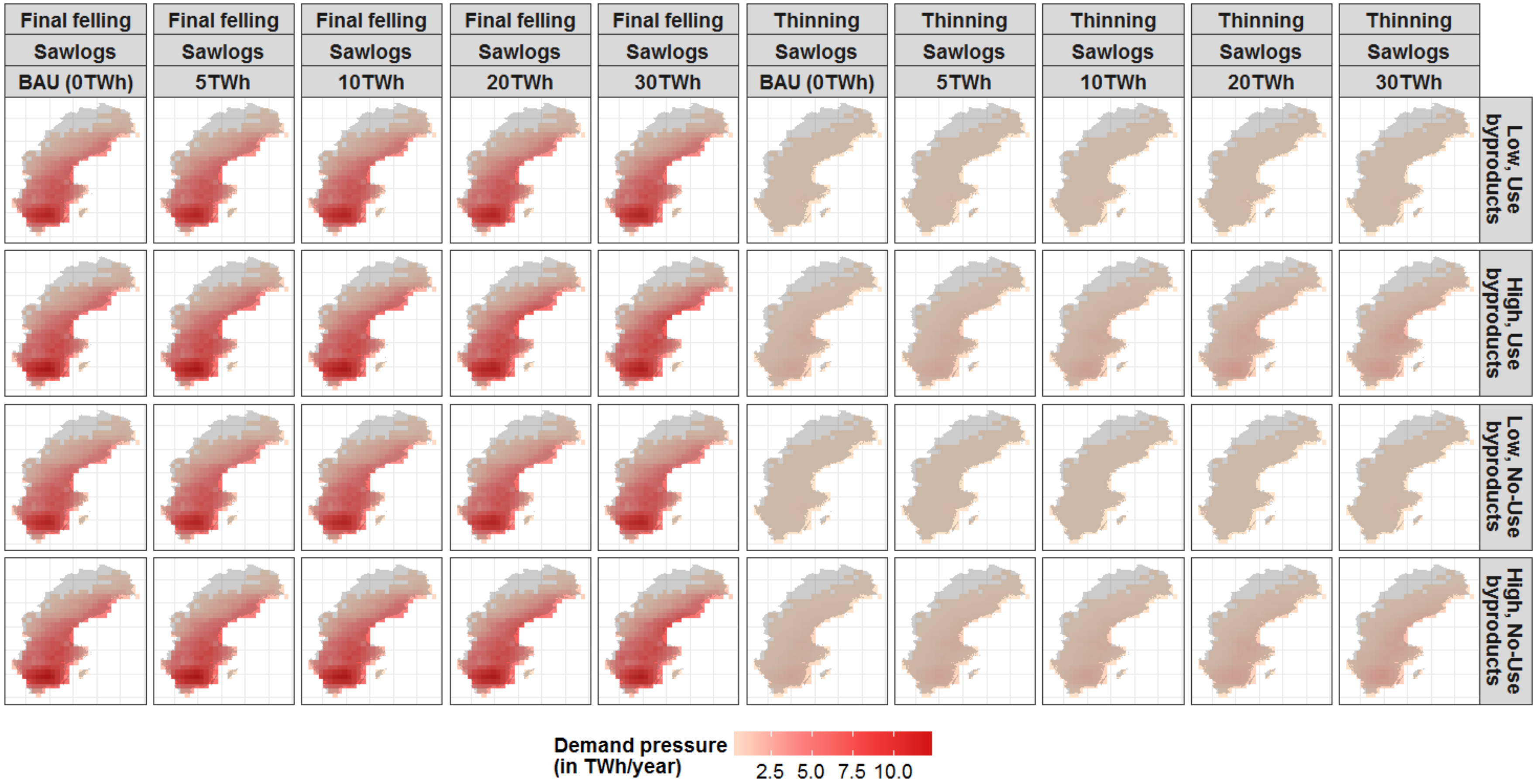


**Fig. A4.** Spatial distribution of demand pressure for sawlogs from final felling and thinning (in TWh $yr^{-1}$)
*Source: SpPDM model simulations*

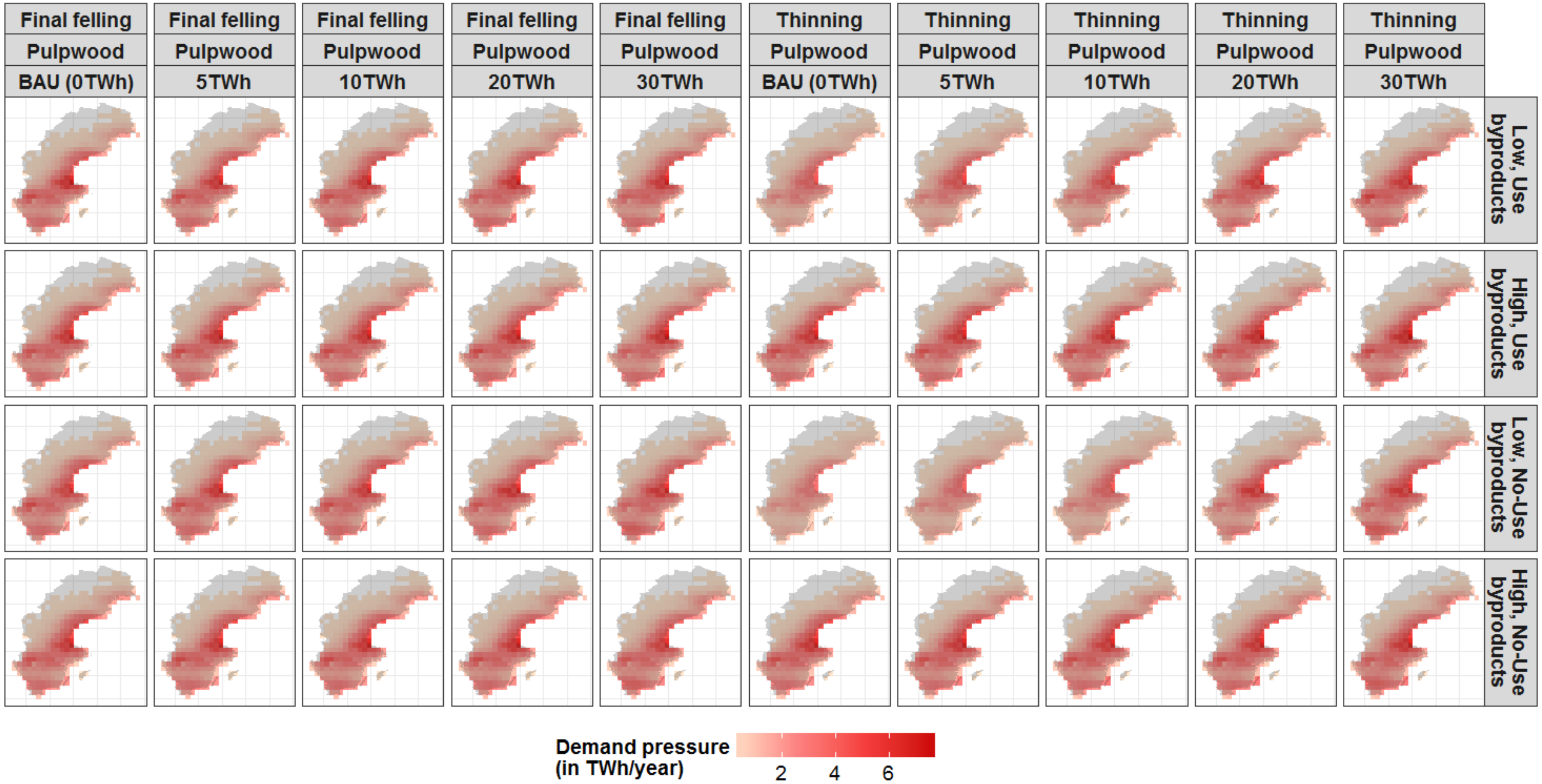


**Fig. A5.** Spatial distribution of demand pressure for pulpwood from final felling and thinning (in TWh $yr^{-1}$)
*Source: SpPDM model simulations*

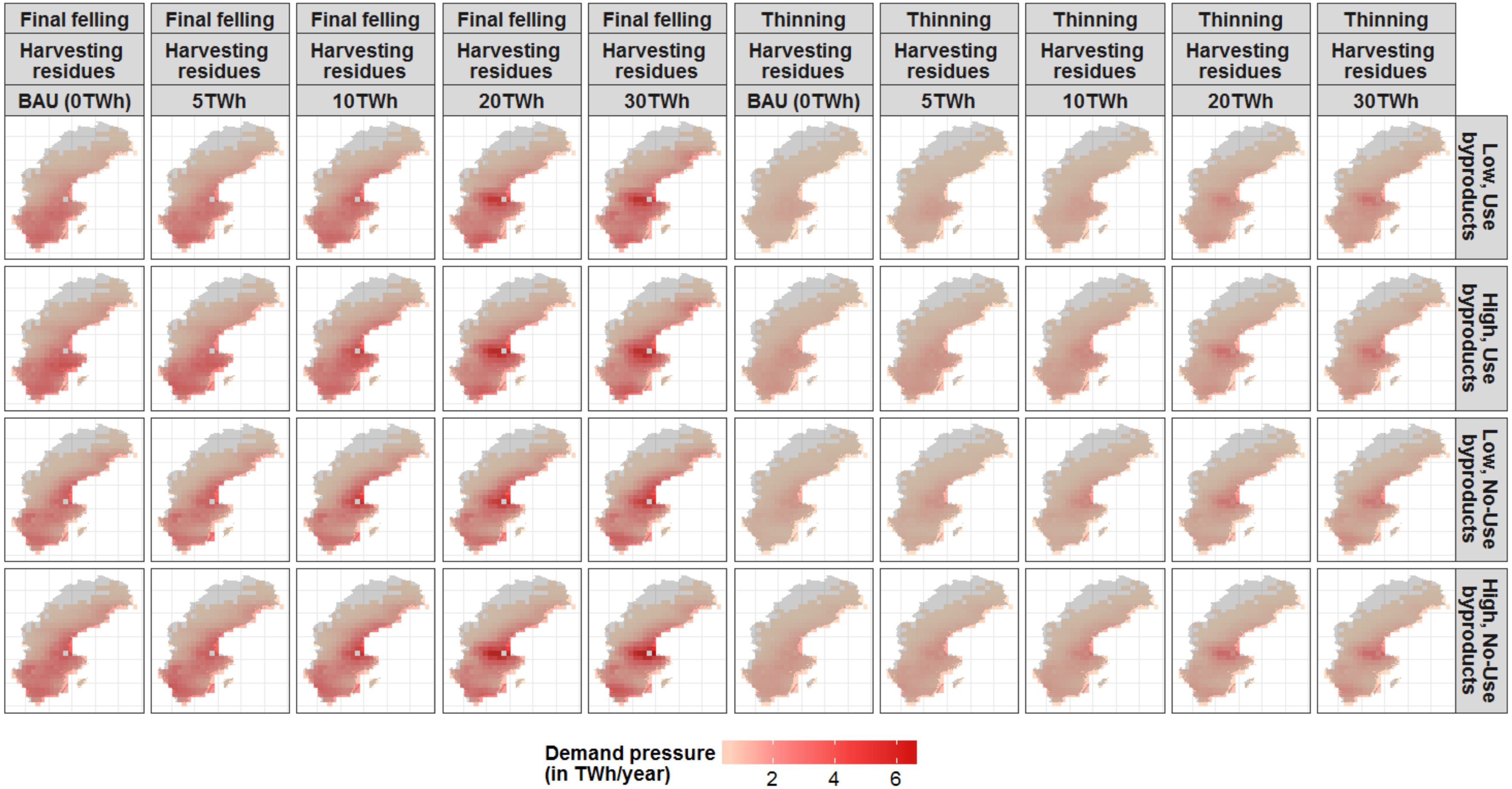


**Fig. A6.** Spatial distribution of demand pressure for harvesting residues from final felling and thinning (in TWh yr$^{-1}$)
*Source: SpPDM model simulations*

**Table A2**
Average price impacts for forest biomass in percent change from the BAU (0 TWh)

| | | Final felling | | | | | | | | Thinning | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *Sawlogs* | | *Pulpwood* | | *Harvesting residues* | | *Stumps* | | *Sawlogs* | | *Pulpwood* | | *Harvesting residues* | |
| | *Biofuel target* | *max* | *min* | *max* | *min* | *max* | *min* | *max* | *min* | *max* | *min* | *max* | *min* | *max* | *min* |
| **Low/Use by-products** | *5 TWh* | 0.00 | 0.00 | 1.37 | 0.00 | 1.12 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.61 | 0.00 | 4.87 | 0.00 |
| | *10 TWh* | 0.00 | 0.00 | 1.33 | 0.00 | 2.33 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 3.61 | 0.00 | 4.87 | 0.00 |
| | *20 TWh* | 0.58 | 0.01 | 1.66 | 0.00 | 2.22 | 0.01 | 1.20 | 1.20 | 6.90 | 4.82 | 6.56 | 0.00 | 4.87 | 0.02 |
| | *30 TWh* | 0.92 | 0.01 | 3.06 | 0.00 | 6.53 | 0.00 | 3.13 | 0.04 | 0.00 | 0.00 | 6.56 | 0.00 | 4.87 | 0.02 |
| **Low/No-Use by-products** | *5 TWh* | 0.18 | 0.18 | 0.93 | 0.00 | 1.33 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.61 | 0.00 | 2.16 | 0.00 |
| | *10 TWh* | 0.18 | 0.03 | 1.30 | 0.00 | 2.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.61 | 0.01 | 2.36 | 0.00 |
| | *20 TWh* | 0.18 | 0.03 | 1.54 | 0.00 | 2.35 | 0.00 | 2.05 | 0.30 | 0.00 | 0.00 | 6.56 | 0.01 | 2.51 | 0.00 |
| | *30 TWh* | 0.39 | 0.01 | 3.18 | 0.00 | 3.73 | 0.00 | 3.56 | 0.00 | 0.39 | 0.39 | 6.67 | 0.01 | 3.92 | 0.00 |
| **High/Use by-products** | *5 TWh* | 0.85 | 0.04 | 1.76 | 0.00 | 0.88 | 0.00 | 2.73 | 0.01 | 4.72 | 0.00 | 1.82 | 0.00 | 1.19 | 0.00 |
| | *10 TWh* | 1.63 | 0.00 | 1.51 | 0.00 | 2.26 | 0.00 | 3.56 | 0.00 | 5.45 | 0.00 | 2.40 | 0.00 | 1.35 | 0.00 |
| | *20 TWh* | 2.03 | 0.00 | 2.10 | 0.00 | 2.93 | 0.02 | 4.33 | 0.09 | 5.70 | 0.05 | 1.82 | 0.00 | 2.03 | 0.00 |
| | *30 TWh* | 2.03 | 0.00 | 2.01 | 0.00 | 4.86 | 0.00 | 11.30 | 0.09 | 6.37 | 0.05 | 2.69 | 0.00 | 3.16 | 0.00 |
| **High/No-Use by-products** | *5 TWh* | 0.77 | 0.00 | 1.76 | 0.00 | 8.45 | 0.00 | 2.48 | 0.04 | 5.45 | 0.02 | 1.82 | 0.03 | 4.87 | 0.00 |
| | *10 TWh* | 0.89 | 0.00 | 1.76 | 0.00 | 2.10 | 0.00 | 3.23 | 0.05 | 5.45 | 0.01 | 1.82 | 0.00 | 2.18 | 0.00 |
| | *20 TWh* | 2.03 | 0.00 | 1.95 | 0.01 | 3.18 | 0.00 | 4.87 | 0.09 | 6.06 | 0.02 | 1.82 | 0.00 | 2.18 | 0.01 |
| | *30 TWh* | 2.03 | 0.00 | 2.31 | 0.01 | 3.84 | 0.02 | 6.60 | 0.09 | 6.41 | 0.30 | 2.40 | 0.00 | 2.54 | 0.01 |

*Source: Authors' calculations*