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On the green transformation of the iron and steel industry: Market and competition aspects of hydrogen and biomass options

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ABSTRACT

The iron and steel industry is a major emitter of carbon dioxide globally. To reduce their carbon footprint, the iron and steel industry pursue different decarbonization strategies, including deploying bio-based materials and energy carriers for reduction, carburisation and/or energy purposes along their value-chains. In this study two potential roles for biomass were analysed: (a) substituting for fossil fuels in iron-ore pellets induration and (b) carburisation of DRI (direct reduced iron) produced via fully hydrogen-based reduction. The purpose of the study was to analyse the regional demand-driven price and allocative effects of biomass assortments under different biomass demand scenarios for the Swedish iron and steel industry. Economic modelling was used in combination with spatial biomass supply assessments to predict the changes on relevant biomass markets. The results showed that the estimated demand increases for forest biomass will have significant regional price effects. Depending on scenario, the biomass demand will increase up to 25 percent, causing regional prices to more than doubling. In general, the magnitude of the price effects was driven by the volumes and types of biomasses needed in the different scenarios, with larger price effects for harvesting residues and industrial by-products compared to those of roundwood. A small price effect of roundwood means that the incentives for forest-owners to increase their harvests, and thus also the availability of harvest residues, are small. Flexibility in the feedstock sourcing (both regarding quality and geographic origin) will thus be important if forest biomass is to satisfy demands in iron and steel industry.

1. Introduction

Globally, the iron and steel industry accounts for 7.2 percent of the total greenhouse gas emissions [1], with the direct emissions from the use of fossil coal and coke in blast furnaces constituting the largest emission source [2]. The emissions from the iron and steel industry also currently grow faster than any other industrial sector [3]. To mitigate the sector's climate impact, incremental energy and material efficiency improvements and energy carrier switching have been among the primary strategies [2]. Deployment of biomass-based fuels and reductants as a partial substitute for fossil fuels and reductants, has also been identified as an effective CO_2 mitigation strategy for the sector in the short to medium term [4–6]. While a complete substitution of coal for biomass in the iron and steel industry's processes is not technically feasible [7], it is also limited by sustainable biomass supply [8,9].

While increased efficiency has during the last decades significantly reduced the energy demand per tonne of produced steel, it has not been sufficient to impact the total greenhouse gas emissions from the sector [10]. Also, substitution of fossil fuels and reductants for biomass-based counterparts would only reach partial emission mitigation [11]. To radically reduce the emissions from iron and steel making, a combination of measures is required, including the development and deployment of so-called breakthrough technologies (with very low or zero carbon emissions) [12,13]. This basically entails to either phase-out the blast furnace, or to retrofit it with carbon capture and storage (CCS) in combination with partial substitution of fossil fuels and reductants for bio-based counterparts [14,15]. In recent years, several major steel producers have indeed announced ambitions to pursue deep decarbonization [16]. The primary strategy announced is to abandon the currently dominating primary steelmaking production pathway (blast furnace followed by basic oxygen furnace) to instead transition to hydrogen-based iron ore reduction where DRI (direct reduced iron) or

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HBI (hot briquetted iron) is produced, for downstream steelmaking through the electric arc furnace (EAF) route [17]. Even with hydrogen-based reduction, some elemental carbon must be introduced into the DRI or HBI to reach desired properties for the EAF steelmaking process [18]. Typical carbon content in currently commercial DRI (mainly produced using fossil gas/methane as reducing agent) ranges between 0.8 and 2.5 percent [19], but that can be as low as 0.5 and as high as 4.5 percent, for special applications [20]. To have fully fossil-free steel, the carbon must be of biogenic origin. Bio-syngas generated from biomass gasification has been suggested as a suitable carburising media to replace fossil carbon-containing gases [18,21]. Similarly, bio-based fuels will likely be needed in processes that are difficult to electrify, such as certain furnaces and kilns, as well as in reduction processes not based on blast furnaces [7,12].

A significant demand for biomass from the iron and steel industry will thus likely still emerge, even with the hydrogen-based pathway as the main decarbonization strategy. However, previous studies that have analysed the economic feasibility of using biomass in the iron and steel industry have omitted the impacts of the increased competition for biomass [22–24]. Extensive introduction of biomass in iron- and steelmaking would inevitably have effects on biomass resource markets (e.g. Ref. [11]). Resulting increases in biomass prices may also affect the economic feasibility of the iron and steel sector to use biomass. In addition, other biomass-using sectors (existing and emerging) could be crowed-out, reducing their ability to reach their emission targets. Despite a large number of studies having studied techno-economic characteristics of substituting for biomass in the iron and steel industry (e.g., Ref. [22,25,26]), previous research with a focus on spatial effects has mostly been concerned with identifying least-cost supply chain options for the system under consideration (e.g., Ref. [24,27]). Regional market effects from introducing biomass in the iron and steel industry was previously investigated by Olofsson [28]. However, he did not analyse that impact of large-scale deployment of deep decarbonization technologies and had a more limited geographical scale. Nwachukwu et al. [29] explore combined spatial and market effects with a focus on bio-product technology selection and production plant localisation. This paper extends previous research by providing a novel approach to soft-link technical energy system models with economic forest sector models under different biomass demand scenarios using a spatially imbalanced biomass distribution. However, it did not explicitly address the specific technological requirements facing iron and steel industry in its green transition.

Therefore, based on the gaps in previous research, the purpose of this study is to estimate regional price and allocative effects of woody biomass under technologically specific biomass demand scenarios for the Swedish iron and steel industry. Specifically, biomass price effects are analysed under the scenario where biomass is a substitute for fossil fuels and carbon in (a) iron-ore pellets induration, and (b) carburisation of DRI produced through hydrogen-based reduction. In this context, Sweden is an interesting case study with a large endowment of forest resources, a large iron and steel industry currently transitioning towards the production of green steel, and supportive national policies [8].

2. Methods and materials

The analysis is based on a combination of methods. A spatial assessment of technical supply potentials of different forest biomass assortments is outlined together with different scenarios for biomass demand in the iron and steel industry. These then forms the basis for the empirical model.

2.1. Case study

The Swedish iron and steel industry is concentrated to the northern parts of the country (see Appendix for map). Typically, biomass feedstocks are sourced regionally due to its bulkiness and low price-weight ratio. Consequently, it is expected that the effect on the biomass prices will be largest in that region due to increasing transportation costs from other regions. In the northern region the standing volume is approximately 1.2 billion cubic meters with an annual growth of 42.4 million cubic meters, of which 28.9 million cubic meters of roundwood is harvested annually. As illustrated in Fig. 1, the forest industries (sawmilling and pulping) use approximately 21.1 million solid cubic meters under bark of industrial roundwood, roughly equally shared between the two sectors. Harvesting residues from the harvesting operations, bark from the debarking process of industrial roundwood and the by-products from the sawmill sector (e.g., woodchips and sawdust) are important biofuels and feedstocks. For instance, of the 4 million cubic meters of by-products from the sawmill sector, some 2.7 million are used by the pulp and paper industry, roughly 0.1 million have other uses, and 1.2 million are used as biofuels. Bark is currently used as internal woodfuel by the forest industries. However untapped potentials are available should a demand develop. In addition, there are roughly 1.5 million cubic meters of harvesting residues ready to be used. Given technical choices to be made, this volume might facilitate a rapid transformation of the regional steel and mining sector. From a technical point-of-view, forest residues are also well-suited to be used in the production of biofuels for iron pellet kilns [30] and as gasification feedstock in the production of carburisation gas [31].

2.2. Potential biomass feedstock

Forest feedstocks from both final felling and commercial thinning are included in the assessment. The technical supply potential is estimated based on Swedish Forest Agency's Forest Impact Assessments ("today's forestry" scenario) [34]. To available supply of harvesting residues is limited by a set of technical and ecological restrictions, as described by Ref. [35]. The forest biomass potentials are complemented with historic data of harvests and growth, based on publicly available statistics [33, 36].

Fig. 2 presents the annual gross fellings in Norrbotten county between 1996 and 2020 together with the total annual growth in standing volume and the estimated biologically available volume of harvesting residues. The gross fellings are connected to the economic cycle, not least from an international trade perspective since the largest industrial users of roundwood (the forest industries) are exporting most of their production. The difference between annual gross fellings and annual growth is an indicator of long-term sustainability in the regional forest sector.

Harvesting residues are mainly extracted from final felling and in the form of tops and branches. There are no publicly available statistics on the actual extraction and utilization of harvesting residues. Thus, instead of presenting the actual extraction volumes of harvesting residues, the biological availability is used. The biological available volumes of harvesting residues are assumed to correspond to between 6 and 25 percent of the roundwood volume.[1] That is, harvesting 1,000 cubic meters of harvested roundwood would yield between 60 and 250 cubic meters of harvesting residues. However, the biological potential should not be confused with the more restrictive technical and economic potentials. In northern Sweden, the extraction of harvesting residue occurs on less than 20 percent of the harvested area. Consequently, the potential for increasing the extraction of harvesting residues is substantial.

2.3. Scenarios and assumptions

Technical scenarios are constructed for (a) iron ore pelletisation fuel and (b) bio-carbon based carburisation of DRI. The scenarios are analytically compared to a baseline scenario with no biomass demand

[1] For scenario-based costs and availabilities of harvesting residues see e.g., Agar et al. [57].

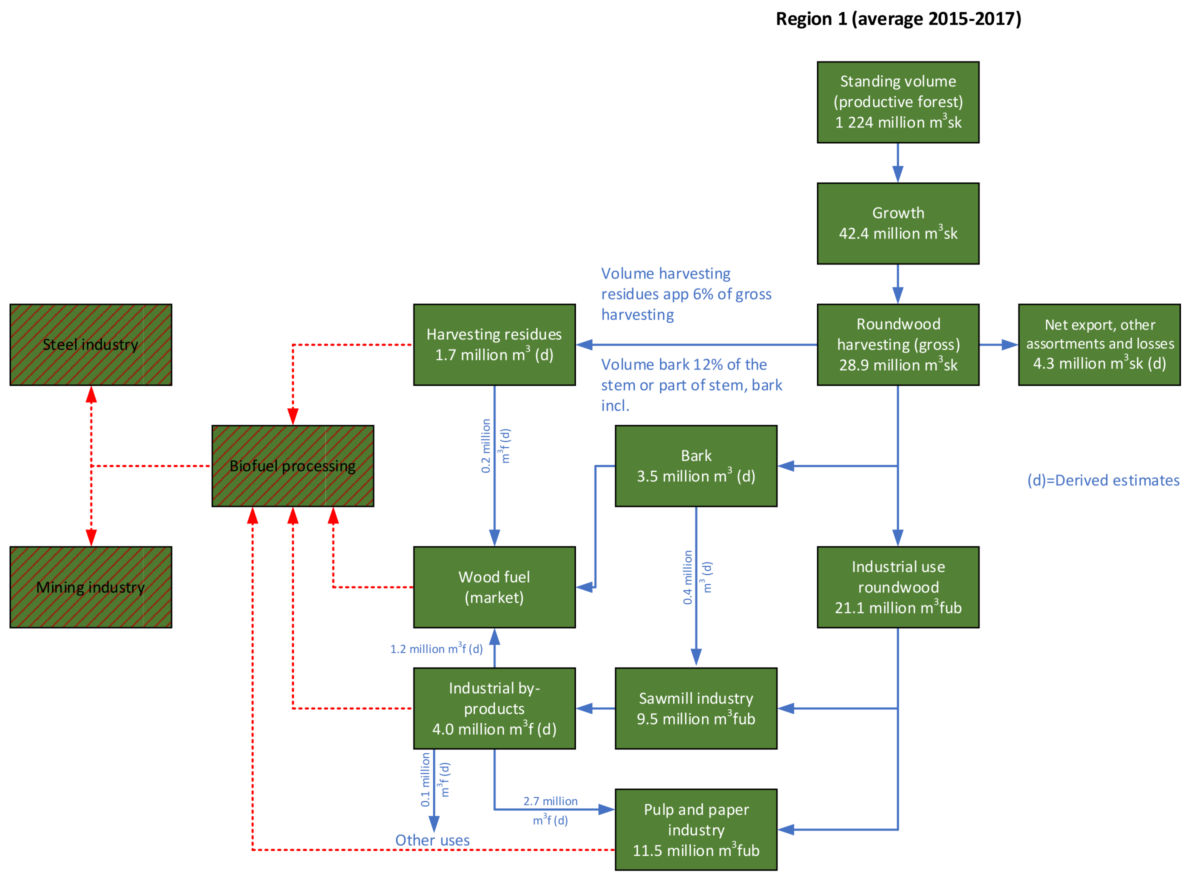

Fig. 1. Forest feedstock flow chart for counties of Norrbotten, Västerbotten, Västernorrland and Jämtland (excluding Härjedalens municipality) in Sweden (annual average 2015–2017) red flow lines indicate potential new demand by the iron and steel industry. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Source: Biometria [32]; Swedish Forest Agency [33] and own calculations.

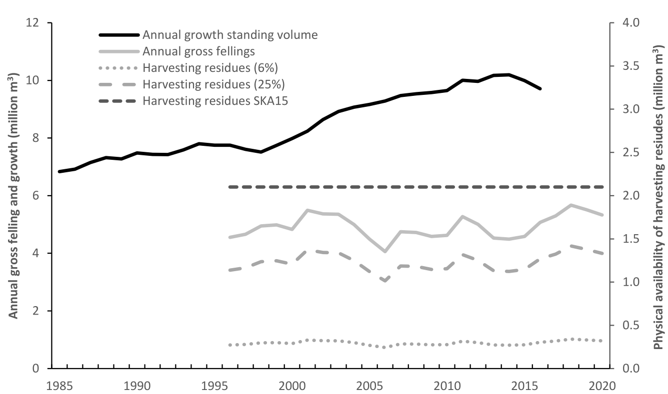

Fig. 2. Annual gross fellings (3-year average values) and growth (5-year average values) in Norrbotten and biological availability of harvesting residues based on estimations of 6 % and 25 % proportion of harvesting residues to roundwood volume (million m^3), respectively.
Source: Riksskogstaxeringen [36]; Swedish Forest Agency [33].

from the iron and steel sector. The implemented scenarios are summarised in Table 1.

The scenarios for carburisation of DRI are based on either a one or two percent carbon content in the produced DRI. Thermochemical gasification of biomass feedstocks using a steam/oxygen blown CFB (circulating fluidised bed) gasifier is the assumed gasification technology. The biomass feedstocks that can be used are harvesting residues and industrial by-products. A carbon conversion efficiency of 38 percent from elemental carbon in the feedstock to carbon in the DRI is used [37].

Table 1
Summary of analysed scenarios regarding fuel for iron ore pelletisation and DRI carburisation.

Scenario name	Iron ore pelletisation		Carburisation of DRI	
	Straight-grate	Grate-kiln	% C in DRI	DRI production option
DRI1-1 %			1	Option 1
DRI1-2 %			2	Option 1
DRI2-1 %			1	Option 2
DRI2-2 %			2	Option 2
PEL-DRI1-1 %	Pyrolysis oil	Charcoal	1	Option 1
PEL-DRI1-2 %	Pyrolysis oil	Charcoal	2	Option 1
PEL-DRI2-1 %	Pyrolysis oil	Charcoal	1	Option 2
PEL-DRI2-2 %	Pyrolysis oil	Charcoal	2	Option 2

In addition, two geographically different DRI production options are implemented (DRI1 and DRI2). The exact modelled DRI production levels are based on internal reports and presentations developed within the HYBRIT RP1 project (2016–2021). Comparable levels can, however, be derived by interpreting public information from the major iron and steel producing companies in Sweden. Recent scientific work applies similar estimates for the development of the Swedish DRI production [38]. The first option assumes a total DRI production of 3.2 million tonnes per year spatially distributed between Norrbotten county (2.3 million tonnes) and Södermanland county (0.9 million tonnes). The assumed DRI production level is comparable to the current steel production in those counties. The second option assumes a significantly increased DRI production of 16 million tonnes per year concentrated to Norrbotten county, based on announcements from the major iron ore producer in Sweden to transition from blast furnace pellets to DRI, and to in the longer term increase the total production of iron products.

Iron ore pelletisation scenarios are not implemented separately, instead they are implemented together in combinations with the carburisation scenarios. The iron ore production is assumed to use straight-grate (SG) and grate-kiln (GK) technologies with the entire production located in Norrbotten county. With the SG technology, the induration occurs in the preheating and firing zones of a traveling grate with a fuel demand of 55 kWh per tonne and with an annual pellet production of ca 7 million tonnes per year [39]. A series of oil-fired burners installed through the side walls of the preheating and firing zones provide the heat, and since the hot gas flows through the pellet bed, convection constitutes the dominating heat transfer mechanism. Various types of bio-oils, hydrogen or methane (natural gas or biogas) can replace the fossil oil in the SG technology relatively unproblematic [30]. Fast pyrolysis is assumed a suitable conversion technology for the SG technology using pyrolysis oil as biofuel, which can be produced using harvesting residues, all industrial by-products and pulpwood as biomass feedstock [30,40]. Data on the production of pyrolysis oil via fast pyrolysis is based on Wei et al. [41].

In the GK technology, the induration (or sintering) of the pellets occurs in a rotary kiln with a fuel demand of 77 kWh per tonne and with an annual pellet production of ca 17 million tonnes per year [39]. The technology uses a coal-fired burner located at the discharge end of the kiln. Radiation from the hot flame to the tumbling iron ore pellet bed constitutes the dominating heat transfer mechanism. Substituting the fossil coal used in the GK technology with biomass will probably be challenging due to different temperature profiles and risk for increased ash-related operational problems [30]. Slow pyrolysis is assumed a suitable conversion technology for the GK technology using charcoal as biofuel, produced using combinations of pulpwood, wood pellets and woodchips [30,40]. Data on the production of charcoal is based on Leme et al. [42] and Roberts et al. [43]. Charcoal for metallurgical applications requires a high fixed carbon content [44].

2.4. Swedish county forest sector model

Following Olofsson [28,45] a static partial equilibrium (PE) model is applied with the objective to maximise the economic wellbeing (i.e., economic welfare) for all agents, in all regions, given some constraints.,[23] Specifically, the sum of the consumer and producer surpluses, net of the total cost of inter-regional trade, are maximised. The model utilises a system of fixed input-output production functions. However, some degree of production flexibility is introduced by allowing for many different input bundles that can be used to produce one unit of output. In total, five biomass feedstocks are included combined into 603 input bundles, in the production of 15 output goods and four intermediate goods. Spatially, the model covers the 21 counties of Sweden (NUTS 3 level) and one aggregated region for the Rest of the World (ROW). Fig. 3 illustrates the model structure and main material flows. Modelling details can be found in the Appendix.

The industry sectors optimise the use of inputs to satisfy the exogenous demand for their outputs. Included industry sectors competing for biomass feedstocks are: (1) the sawmill industry, (2) pulp and paper industry (sulphate, sulphite, and mechanical pulp, in total nine different types), (3) district heating (DH) and combined heat and power (CHP), and (4) the wood pellet industry. The sawmill industry can only use sawlogs as biomass feedstock and supplies by-products in the form of woodchips and low-grade by-products (e.g., dry chips, sawdust and bark). The wood pellet industry is assumed to use by-products from the sawmill sector as biomass feedstock. The pulp and paper industry can use combinations of sawlogs, pulpwood and woodchips as biomass inputs. Potential biomass input for the district heating (DH) and CHP sector are pulpwood, harvesting residues, industrial by-products and wood pellets. Co-firing between any two feedstocks is allowed and modelled by dividing each feedstock into sets of feedstock bundles that change in 10-percent increments. The outputs are sawn wood from the sawmill industry, bleached and unbleached pulp from the pulp and paper industry, heat from the district heating and CHP, wood pellets from the pellet industry, and iron ore pellets and carburised direct reduction iron (DRI) from the mining industry. Liquefied bio-methane (LBG), charcoal, torrefied wood and pyrolysis oil from the bio-production sector are treated as intermediate products.

When solving the objective function, the model seeks to satisfy the demand for the outputs goods, which is based on current production levels for the existing industries and on scenario predictions for the undeveloped industries (i.e., the iron-ore pellets induration, and carburisation of DRI). The model continues to allocate biomass inputs to an industry if it is available, and if it is economically to do so. The supply of forest biomass is determined endogenously with an upper availability limit. Furthermore, feedstock balance constraints are imposed, ensuring that the use of the biomass does not exceed its availability. The marginal solutions to the balance constraints are interpreted as the shadow price of the biomass [46]. Technically, the shadow price is the value of the Lagrange multiplier at the optimal solution, which means that it is the infinitesimal change in the objective function arising from an infinitesimal change in the constraint.

2.5. Data

To avoid price effects based on the global Covid pandemic, the war in Ukraine, and recession effects, the year 2016 is chosen as based year. The price effects are presented as percentage changes partly for that reason, i.e., it is not the price levels that are of interest but rather their change in relation to the base year. Detailed data tables are presented in the Appendix. Biomass input prices on sawlogs and pulpwood are average 2016-prices of delivered logs for Northern, Middle, and Southern Sweden [33]. The reservation price of the biomass feedstocks represents the price below which forest-owners stop supplying the feedstock. Empirically, the reservation price is based on logging costs of all large-scale harvesting operations in the base year (2016) in Sweden [33]. It is assumed that roundwood and harvesting residues have the same reservation cost since reliable estimates for harvesting residues are unavailable.

The output prices (the price of the final products) are based on average monthly 2016 prices. The price of harvesting residues is the average 2016 price on forest chips used by the district heating industry [47]. The price of sawn wood is SEK 1,892 per cubic meter [48]. The price of different sulphate pulp assortments (BSKP, BHKP, USKP, CTMP and SEC) is assumed to be SEK 7,482 per air-dry-tonne (adt) [49]. The price of different sulphite pulps (BSSP, BHSP and USSP) and mechanical pulps (TMP and ground wood pulp) are estimated as a proportion of the sulphate pulp price since they lack readily available price data. The proportions are estimated using annual price data from the Swedish Forestry Agency (2013) between 1975 and 2013. The sulphite pulp price averaged 94 percent and mechanical pulp 71 percent of the sulphate price. Thus, the price of sulphite pulp is assumed to be SEK 7,048 per adt and the price of mechanical pulp SEK 5,570 per adt.

Regional heating prices are collected from Swedenergy (2017) based on the average municipal prices for single household houses in 2016. The price of wood pellets is based on the price of densified wood fuels used by the district heating sector (Swedish Energy Agency and Statistics

[2] There is a large literature on forest sector models and how they have been applied to analyse market effects. For further reading please see e.g., Jåstad et al. [58]; Mustapha et la. [59]; Jåstad et al. [60]; Hurmekoski and Sjølie [61].

[3] Since the market effects are expected to occur instantaneously when the capital investments are in place, a static model was preferred compared to a dynamic model.

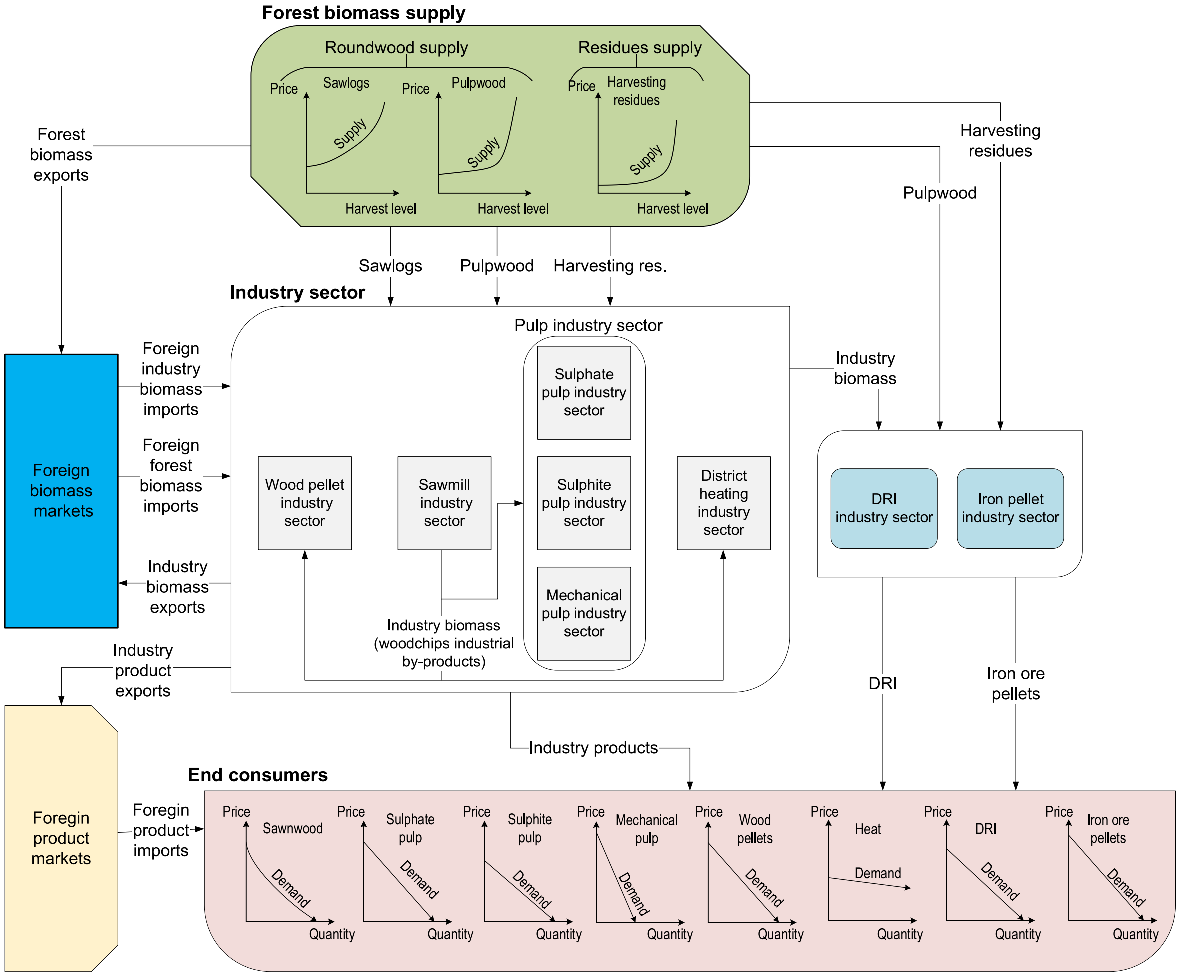

Fig. 3. Schematic overview of the applied Swedish county forest sector model (SCFSM).

Sweden, 2018). In 2016, the price of densified wood fuels was SEK 273 per MWh. This suggest that, with an estimated energy content of 4.5 MWh per tonne, the output price for wood pellets is set to SEK 1,228 per tonne.

The roundwood supply elasticity is 0.28 for sawlogs and 0.14 for pulpwood for all counties [50]. The harvesting residues supply elasticity is collected from Carlsson [51] and is equal to 1.26 for all counties. For the sawn wood (output) the own-price elasticity is −0.16 (Buongiorno et al., 2003). It is assumed that all pulp types have the same own-price elasticity of −0.18 (Chas-Amil and Buongiorno, 2000). The own-price elasticity of heat is set to −0.25 (Hellmer, 2013) and to −0.62 for wood pellets (Buongiorno et al., 2003). Finally, the own-price elasticity for iron ore pellets and carburised DRI was assumed to be −0.25 (Barnett and Crandall, 1993).

The production capacity for the industry sectors is based on site-specific data, from the techno-economic localisation model BeWhere Sweden, aggregated to county level to synchronise with the geographic representation [24,52]. The production capacity for each regional industry sector is set to 25 percent above the current industrial production levels to allow surplus biomass production and trade between counties. Counties with a surplus of biomass feedstocks can trade with other counties with deficits if it is economically to do so.

A transport cost is determined for each biomass feedstock based on Nwachukwu et al. [24]. Inputs can be transported by sea, rail, or road (or in combinations of these modes). The distance between two specific counties is determined by the distance between the largest biomass feedstock using facility and the area with the largest available biomass feedstock. International trade in industrial by-products, i.e., woodchips and harvesting residues, is restricted to 0.1 million cubic meters per feedstock and county.

3. Results

The forest sector model is implemented in General Algebraic Model System (GAMS) and solved using the CONOPT solver. Not all scenario results are presented below but are available from the authors upon request. Furthermore, results on interregional trade, other biomass using sectors and harvesting levels are also available upon request.

3.1. Biomass consumption changes

The low and high estimates of the total consumption of biomass for the scenarios are presented in Table 2. The consumption is calculated based on the scenarios' conversion technology and on the properties of the various biomass assortments. No synergy effects are considered when combining the iron ore pelletisation and DRI carburisation scenarios. Therefore, the annual total biomass consumption for the combined scenarios is the sum of the consumption from the two individual scenarios.

Fig. 4 presents the percentage change in aggregate consumption for harvesting residues and roundwood compared to the baseline scenario. The results suggest that the consumption of roundwood will increase by less than five percent in all scenarios. However, the consumption changes for harvesting residues are higher. In the DRI carburisation scenarios the consumption changes depend on both the DRI production level (DRI1 or DRI2) and carburisation degree (1 % or 2 %). For

Table 2
Total biomass consumption for the different scenarios.

Iron ore pelletisation	Annual total biomass consumption (1,000 m^3 y^{-1})[a]		Annual total biomass consumption (TWh y^{-1})[b]	
	Low	*High*	*Low*	*High*
PEL	2,450	3,150	4.7	6.0
DRI carburisation				
DRI1-1 %	374	470	0.7	0.9
DRI1-2 %	748	939	1.4	1.8
DRI2-1 %	1,900	2,390	3.6	4.6
DRI2-2 %	3,800	4,770	7.3	9.1
Technology combination [c]				
PEL-DRI1-1 %	2,824	3,620	5.4	6.9
PEL-DRI1-2 %	3,198	4,089	6.1	7.8
PEL-DRI2-1 %	4,350	5,540	8.3	10.6
PEL-DRI2-2 %	6,250	7,920	12.0	15.1

[a] The ranges are due to different properties of different biomass assortments.
[b] The conversion from cubic meter solid under bark to MWh is based on the conversion factors for pulpwood listed in the appendix (Table A-4).
[c] Adding the biomass consumption for iron ore pelletisation to that of DRI carburisation.

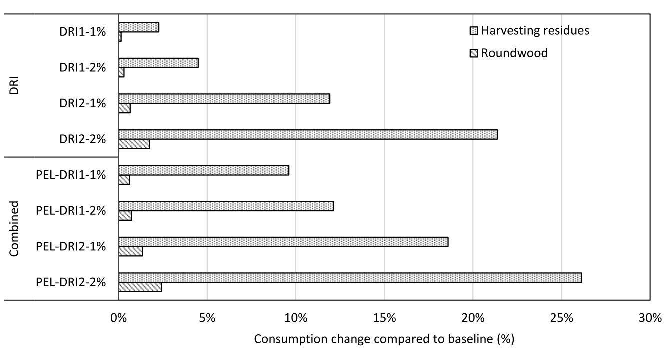

Fig. 4. Changes in national consumption of harvesting residues and roundwood (sawlogs and pulpwood) caused by the scenarios compared to the baseline with no biomass consumption from the iron and steel sector.

instance, if the high DRI production is combined with a two percent carburisation (DRI2-2 %), the consumption for harvesting residues will increase by more than 21 percent. In contrast, if the low DRI production is combined with a one percent carburisation (DRI1-1 %), the consumption for harvesting residues will increase by just over two percent. Not surprising, the highest consumption changes occur when iron ore pelletisation is combined with DRI carburisation (combined scenarios). The results suggest that the consumption for harvesting residues will increase by more than 26 percent with a high DRI production, a two percent carburisation and with iron ore pelletisation (PEL-DRI2-2 %).

3.2. *Price effects*

Not surprisingly, the highest price effects[4] can, in general, be observed in Norrbotten county since it is there the iron and steel industry are mainly located. Fig. 5 visualises the spatial price effects, in relation to baseline prices, from DRI carburisation using a carburisation level of one percent and for both DRI production options. With a carburisation level of one percent, and with the lower DRI production option (DRI1), the price effects on roundwood will be marginal (<5 percent). In addition, the price effects on roundwood are uniformly distributed across the counties. Harvesting residues and industrial by-products have moderate price effect for most counties (<5 percent) except for Norrbotten where the price effects is between 5 and 25 percent. With the higher DRI production option (DRI2), the demand for biomass will increase. Consequently, the price effects will be higher. For roundwood, the highest price effect can be observed in counties in the mid- and south of Sweden (5–25 percent), while the remaining counties will have smaller price effects (<5 percent). For harvesting residues and industrial by-products, the price effects are more pronounced. For instance, the price effect for both assortments in Norrbotten, where the DRI production is located, will be substantial (>100 percent). The other counties have diminishing price effects the further away they located from Norrbotten.

Fig. 6 illustrates the price effects with a carburisation level of two percent. Similar spatial patterns as for one percent carburisation level are observed, albeit with overall larger price effects. In this case, the biomass demand increases from 0.7 to 0.9 to 1.4–1.8 TWh per year for the low DRI production option (DRI1), and from 1.4 to 1.8 to 7.3–9.1 TWh per year for the high DRI production option (DRI2). Specifically, with the low DRI production option (DRI1), the price effects for harvesting residues and industrial by-products are between 50 and 100 percent, while roundwood remains relatively unaffected (<5 percent). With the high DRI production option (DRI2), the price effects will be larger and affect all counties. For instance, in the most northern counties the price effect of harvesting residues and industrial by-products will exceed 100 percent. Furthermore, the price effects on roundwood will also be more pronounced compared to the other scenarios with price effect between 25 and 50 percent in certain counties.

Finally, the spatial price effects from combining the biomass demand from DRI carburisation with the biomass demand from iron ore pelletisation are depicted in Fig. 7. The discussion focuses on DRI carburisation of one percent carbon content but with both DRI production options (DRI1 and DRI2). In this case, an additional 4.7–6.0 TWh per year of biomass are demanded by the iron ore pelletisation. For the low DRI production option (DRI1), the spatial price effects for roundwood are roughly split between <5 percent and 5–25 percent. However, the price effects for harvesting residues and industrial by-products are more pronounced. Since the both the DRI and pellet production are in the most northern counties, they also exhibit the largest price effect. For instance, in Norrbotten the price effect is above 100 percent for both harvesting residues and industrial by-products, while Västerbotten would experience price effects between 50 and 100 percent. For the other counties, the price effects are lower and more uniformly distributed. For the high DRI production (DRI2) even more biomass is demanded, resulting in larger price effects. The price effects on roundwood are between 5 and 25 percent in most counties. For harvesting residues and industrial by-products, the price effects are still most severe in the most northern counties. However, the larger price effects are also observed further south but with a diminishing rate.

4. Discussion

The results indicate economically significant price effects from an increase in forest biomass consumption by the iron and steel industry. Generally, the price effects for harvesting residues and industrial by-products are higher compared to those of roundwood. This finding is similar to Olofsson [28] but higher compared to Nwachukwu et al. [29] who find that biomass prices will increase by up 62 percent. In this study, the different price effects between the biomass categories can partly be explained by the initial higher price of roundwood (baseline prices). Thus, even with significant price effects on harvesting residues and industrial by-products, the effects are not large enough to offset the initial high price of roundwood.

[4] The estimated price effects should not be interpreted as price forecasts. Instead, they signal how the biomass prices will be affected given an increased consumption from the iron and steel industry, while all other price affecting factors remain the same.

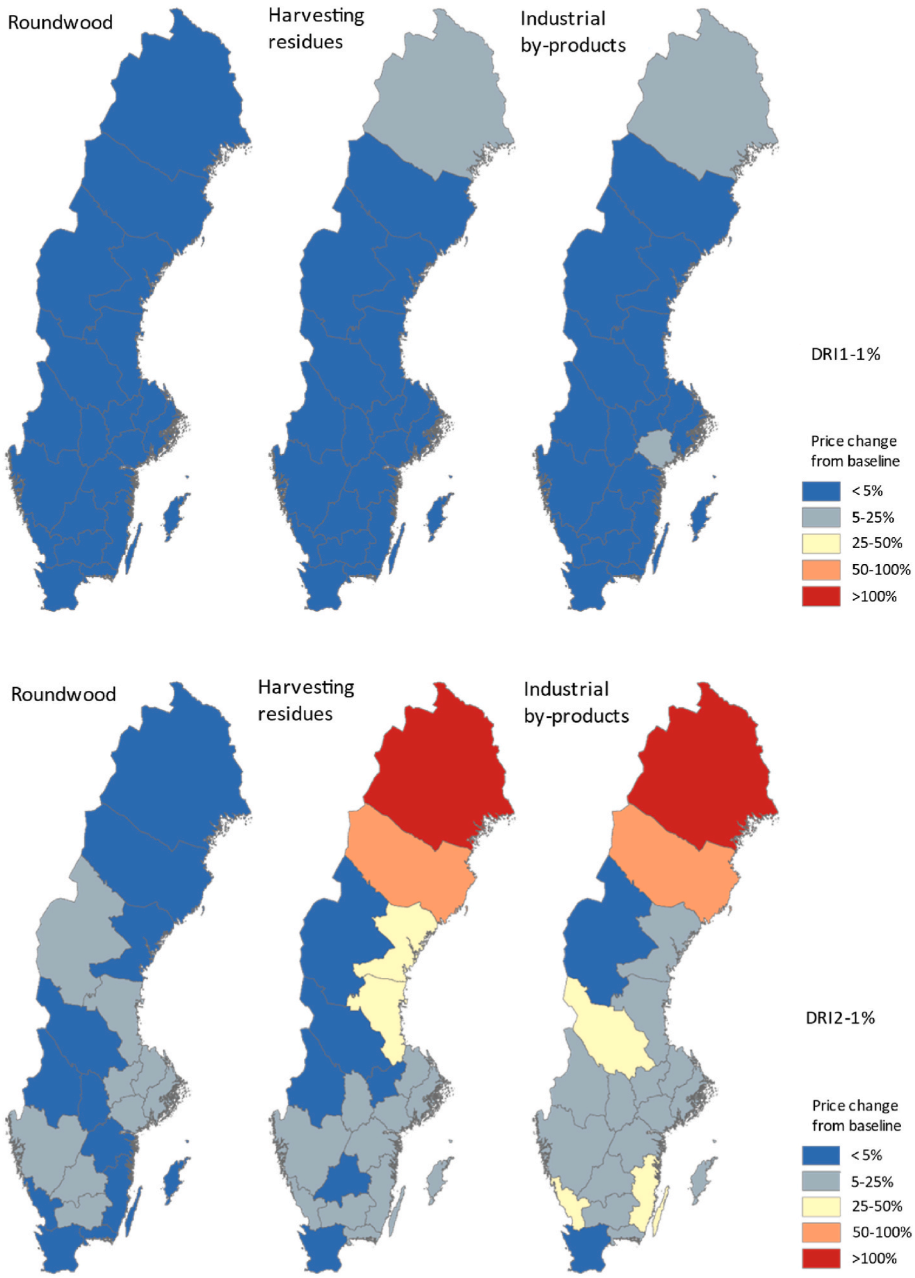

Fig. 5. Price effects on the forest biomass assortments in relation to baseline prices for DRI carburisation scenarios: 1 % C in the DRI, DRI production option 1 (top) and option 2 (bottom).

The spatial distributional pattern of the price effects can be explained by the mechanism of the model [28,45]. The price effects are mainly demand driven, i.e., by the additional volumes of forest biomass needed by the iron and steel industry, but restrictions in technical feasible biomass feedstocks are also an important driver. With a large increase in biomass demand, the local biomass availability is quickly depleted, pushing the local price upwards. Eventually the local price will exceed the price in adjacent counties, including the transportation costs to bring the biomass to its demand node. At that point, it is more economical to start trading biomass between counties. With a large increase in biomass consumption, counties farther and farther away from the demand node will see their biomass availability decrease and price increase. Transportation costs for harvesting residues and industrial by-products constitute a significant part of the value of the feedstock compared to roundwood (sawlogs and pulpwood). This suggests that it is not economical to start importing these assortments from other counties before the local price has increased significantly. The results also support the importance of inter-regional trade for an optimal allocation of biomass. This result is further supported by Olofsson [28] and Carlsson [51]. Regional trade obstructions, such as additional taxes on heavy trucks, will reduce the efficiency and increase the cost for the biomass using sectors, including the iron and steel industry. On the other hand, investments in transportation infrastructure and improved transnational cooperation will reduce the cost.

The estimated price effects are not price forecasts. Rather, they are indicating the singular effect of increasing biomass demand by the iron and steel industry on the biomass prices, keeping all other factors constant. There are other market forces, not considered in this study, that can further affect the biomass prices. For instance, changes in the supply of forest resources, e.g., forest-owners' behavioural changes to price incentives which could have a price mitigating effect [53]. Also, exogenous changes in biomass demand by sectors other than the iron and

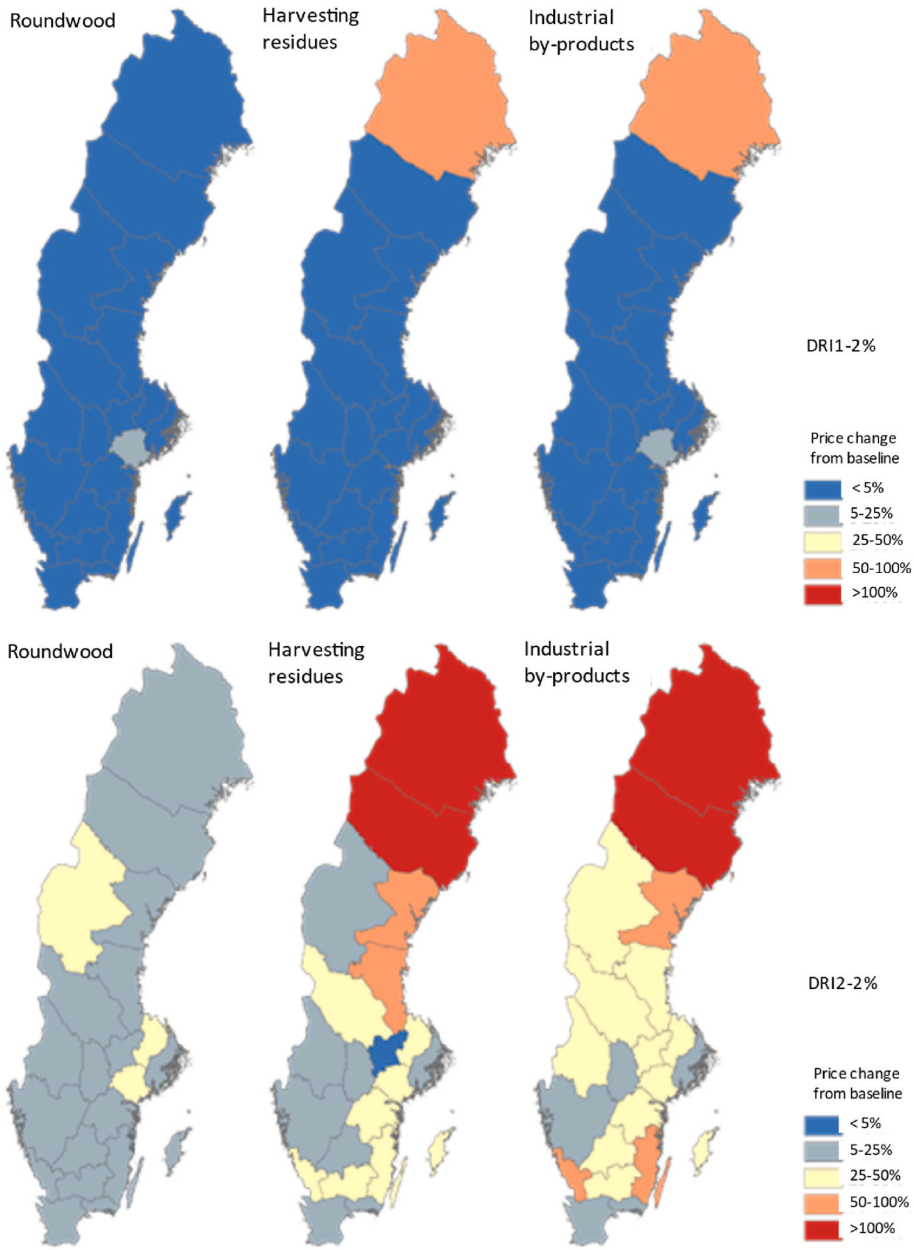

Fig. 6. Price effect on the forest biomass assortments in relation to baseline prices in DRI carburisation scenarios: 2 % C in the DRI, DRI production option 1 (top) and option 2 (bottom).

steel industry will affect the prices. This price effects could be either price mitigating or price increasing depending on if the other sectors increase or decrease their demand. Finally, policy design and implementation can affect the price of biomass (Singh et al., 2014), e.g., policy options reducing the transportation costs or tax burden of harvesting residues and industrial by-products.

5. Conclusions

The transition towards a green, or fossil-free, iron and steel industry will require significant amounts of biomass or hydrogen, depending on production technology choices. Subsequently, the demand increase is expected to affect the biomass prices, changing the market conditions in which the initial investment decisions are made. This study estimates regional price effects from an increasing demand of forest biomass by the iron and steel industry in Sweden. The choice of production technology is to use biomass in the iron-ore pellets induration process, and in the carburisation of DRI produced by hydrogen-based reduction, which are the technological options currently in focus in Sweden. The general conclusion is that the expected biomass demand increase will have an economically significant impact on the forest biomass prices. The spatial distribution of the price effect indicates that the most significant price effect occurs in the region where the iron and steel industry is located, with a diminishing effect in regions further away due to transportation costs.

The competition for roundwood and industrial by-products are currently intense. Since the biomass supply is rigid and the expected demand increase is large, it is feasible to observe large price effects for roundwood and industrial by-products. Harvesting residues are currently not used that much in affected regions, suggesting that there might be a surplus supply available. However, the extraction costs are relatively high in the affected regions due to low population density and missing transportation infrastructure. Consequently, an increase in the supply of harvesting residues can only occur if their price covers the

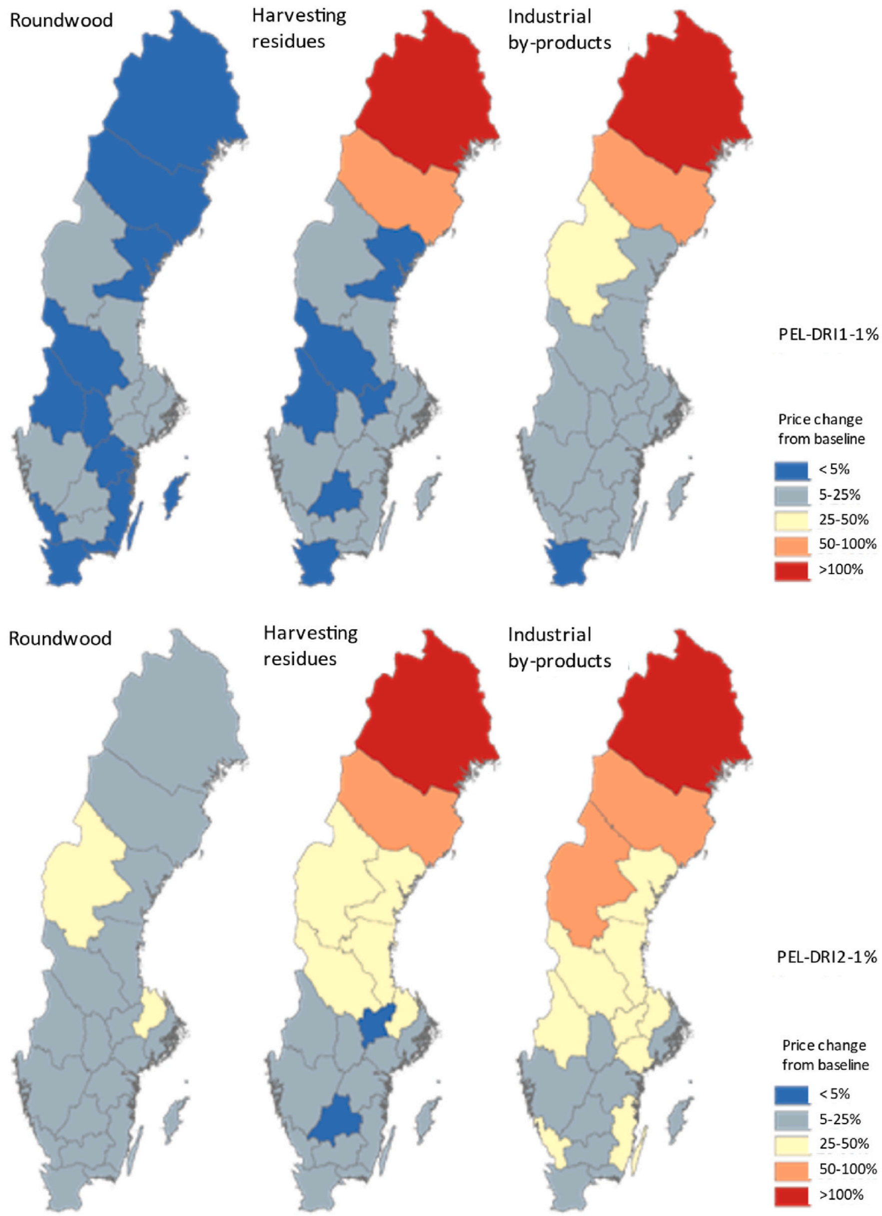

Fig. 7. Price effects on the forest biomass assortments in relation to baseline prices in scenarios combining biomass demand from iron ore pelletisation and DRI carburisation: 1 % C in the DRI, DRI production option 1 (top) and option 2 (bottom).

extraction and transportation costs. From that perspective, the relatively large price effects for harvesting residues are feasible.

In particular, the estimated price effect will have several consequences. Firstly, the allocation of forest biomass between using sectors will adjust to the new equilibrium. Sectors with an ability to pay the higher biomass prices will secure their feedstock needs, while other sectors will be forced to either find suitable substitutes or to reduce their production (and thereby their feedstock needs). Individual firms might be forced to relocate, or even leave the market entirely. Specifically, the pulp and paper industry, which is a major regional competitor for roundwood and industrial by-products, will be forced to accept higher biomass price. However, the price effect on roundwood is more moderate compared to industrial by-products, suggesting that they are likely to be able to adjust. The district heating sector uses harvesting residues but is generally relying on industrial waste heat, especially in the regions mostly affected by increased prices. To the extent that the price increase of harvesting residues is affecting the district heating sector, they are likely to pass the cost increase over to their consumers since they are regional regulated monopolies.

Secondly, the biomass price increases are expected to only moderately affect the domestical supply of biomass. In the short-term, the harvested volumes are already close to what is sustainable, but the economics of harvesting biomass from e.g., high-cost sites, improve. However, harvesting residues and industrial by-products are by-products in an economic sense, suggesting that their supply is not affected by changes in their own-price. For example, the volume of harvesting residues depends on the volume of harvested roundwood, which is affected by the price of roundwood, not the price of harvesting residues. Since the price effect is relatively low for roundwood, the incentives for forest-owners to increase their harvest of roundwood, where sustainably possible, is low. Consequently, the supply of harvesting residues will not increase enough to mitigate the price effect from an increased demand by the iron and steel industry. In the long-term, land-use changes are not feasible since the regional opportunity cost for land-use change is likely to be too high. However, the price increases will make biomass import more profitable, somewhat compensating the lack of domestic supply.

Thirdly, the iron and steel industry face a trade-off between the expected increase in biomass prices and the expected return of the investments (e.g., a price premium for green steel). The premises of this trade-off need to be understood by the industry before large-scale investments are made. For example, higher biomass prices might be acceptable if they can be offset by either a higher production of steel or if a price premium can be charged on the green steel. Moreover, the analysed production technologies are close to commercialisation, but still have adjustment possibilities to affect the use of biomass. This imply that there might be mitigating actions for the iron and steel industry to take (e.g., increasing the conversion efficiency from feedstock carbon to DRI carbon, and set up price-fixed, long-term biomass procurement contacts including imports).

Finally, in a policy context, the transition to a production of green steel will reduce, or eliminate, the need to hold emission permits, i.e., the iron and steel industry is included in the EU ETS. This will either generate additional revenues, if the permits are grand-fathered, or reduce the production cost, if they are acquired on the permit market. This effect is transitory since the emission cap in EU ETS will gradually approach zero over the next decade. However, since the number of permits is fixed at any time-point, the total emission in EU will not change as consequence of the production of green steel. Current domestic policies, such as the Swedish carbon tax, are not affecting the production process of the iron and steel industry (since they are part of the EU ETS). However, future policy revisions might be implemented to capture other potential externalities, such as damage to forest ecosystem services or reduced biodiversity from an increasing extraction of harvesting residues.

CRediT authorship contribution statement

Robert Lundmark: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Elisabeth Wetterlund:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. **Elias Olofsson:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing.

Data availability

Data will be made available on request.

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Appendix

Mathematical model formulation

The objective function maximises the total economic welfare by satisfy regional exogenous demand (i.e., production targets), which is based on current production levels for the existing forest industry and estimated scenario targets for the iron and steel industry. The model continues to allocate biomass to an industry if the feedstock is available, and/or if it is cheaper than other feedstocks that can be used in the production. The supply of biomass is determined by the model, but calibrated using technical estimates for biomass availability, thereby introducing an upper regional limit for biomass supply. The model is expressed as follows, with sets, variables and parameters presented in Table A-3:

$$Max\ Welfare = \sum_{i,o}\int_{l}^{Q}\left(p_{i,o}\left(\frac{Q_{i,o}}{q_{i,o}}\right)^{1/\xi_{i,o}}\right)dQ_{i,o} - \sum_{i,RW}\int_{0}^{H}\left(a_{i,RW}+\omega_{i,RW}H_{i,RW}^{e_{i,RW}}\right)dH_{i,RW} - \sum_{i,HR}\int_{0}^{R}\left(b_{i,HR}+\frac{\sum_{RW}h_{i,RW}}{\sum_{i,RW}H_{i,RW}}\rho_{i,HR}R_{i,HR}^{\mu_{i,HR}}\right)dR_{i,HR} - \sum_{IM,EX,T}\left(tc_{IM,EX,T}TR_{IM,EX,T}\right) \quad (1)$$

s.t.

$$Q_{i,o} - \sum_{AC}\left(\theta_{i,AC,o}X_{i,AC}\right) + \sum_{IM}TR_{i,IM,o} - \sum_{EX}TR_{i,EX,o} = 0 \quad (2)$$

$$-\sum_{AC}\left(\theta_{i,AC,RW}X_{i,AC}\right) - H_{i,RW} + \sum_{IM}TR_{i,IM,RW} - \sum_{EX}TR_{i,EX,RW} = 0 \quad (3)$$

$$-\sum_{AC}\left(\theta_{i,AC,HR}X_{i,AC}\right) - R_{i,HR} + \sum_{IM}TR_{i,IM,HR} - \sum_{EX}TR_{i,EX,HR} = 0 \quad (4)$$

$$-\sum_{ByC}\left(\theta_{i,ByC}X_{i,ByC}\right) + \sum_{IM}TR_{i,IM,BP} - \sum_{EX}TR_{i,EX,BP} \geq \sum_{ByP}\left(\theta_{i,ByP,BP}X_{i,ByP}\right) \quad (5)$$

$$Q_{i,o} \leq q_{i,o}\ H_{i,RW} \leq h_{i,RW}\ R_{i,RW} \leq r_{i,RW}\ X_{i,AC} \leq k_{i,AC} \quad \text{(6a-d)}$$

Equation (1) is the objective function, where its first term denotes the sum of consumer surpluses from end-products and the second term expresses the sum of producer surpluses from all roundwood assortments (i.e., sawlogs, pulpwood and fuelwood). The third term is the sum of producer surpluses from harvesting residues, and the fourth term captures the reduction in welfare from the cost of inter-regional trade. Equations (2)–(6) are constrains. Equation (2) states that consumption in each county must equal production, net of trade. This constraint also ensure that all produced products will be consumed. Equation (3) states that roundwood demand is satisfied through county-specific roundwood harvest or trade. Equation (4) states the same but for harvesting residues. Equation (5) states that by-product demand is less or equal to its supply, thus allowing for a surplus in supply but not a surplus in demand.[5] Finally, Equations (6a-d) state that there exists an upper constraint for end-product demand, roundwood harvest, extraction of harvesting residues and an upper production capacity, respectively. Furthermore, from the balance constraints for roundwood (2), harvesting residues (3) and industrial residues (4) it is possible to obtain a regional shadow price for each feedstock [46].

Table A-3
Set, variable and parameter descriptions

Sets	Description
i	County
o	End-products
RW	Roundwood assortment
HR	Harvesting residues
BP	Industrial by-products
T	Tradable goods
IM	Importing county (subset of i)
EX	Exporting county (subset of i)
AC	Activity set
ByC	By-product consumer (subset of AC)
ByP	By-product producer (subset of AC)

Variables	**Description**
H	Roundwood harvesting rate
Q	Consumption quantity of end-product
R	Harvesting rate residues
TR	Tradable quantities
X	Utilization of woody input

Parameters	**Description**
a	Reservation price roundwood
b	Reservation price harvesting residues
h	Observed harvesting rate of roundwood
k	Capacity constraint for the forest industry
l	Lower integral value
p	Observed price
q	Observed end-product consumption
r	Observed extraction rate of harvesting residues
tc	Unit transport cost
ε	Inverse elasticity of roundwood supply
Θ	Leontief production function (industry specific input-output coefficients)
μ	Inverse elasticity of harvesting residue supply
Ξ	Own-price elasticity of end-products
Φ	Shift parameter harvesting residues
Ω	Shift parameter roundwood
H	Roundwood supply elasticity
N	Harvesting residues supply elasticity

Data tables

Table A-4
Unit conversions, energy content and density of biomass assortments

Biomass type	Moisture content (%)	Heating value (LHV), wet (MWh/tonne)	Density[a]
Roundwood (pulpwood, sawlogs)	50	2.3	0.83 tonne/m^3f
Woodchips	54	2.5	0.78 tonne/m^3f
Sawmill residues	50	1.9	0.81 tonne/m^3f
Harvesting residues	45	2.5	0.85 tonne/m^3f
Pellets	8	4.5	0.70 tonne/m^3s

[a] m^3s = m^3 loose, m^3f = m^3 solid (average bulk densities are used).
Source: Ringman (1995) and Swedish Forest Agency [33].

Table A-5
Availability and prices of biomass feedstock by county and assortment (in 1,000 m^3fub)

County	Availability[1]	Reservation price[2]	Feedstock prices[2]

(continued on next page)

[5] International trade in industrial by-products is restricted to 100,000 m^3fub per county. This constraint reflects that international trade in by-products is currently limited (SFA, 2014).

Table A-5 (*continued*)

County	Availability[1]			Reservation price[2]	Feedstock prices[2]		
	Sawlog	Pulpwood	Harvesting residues	*Sawlog/Pulpwood/Harvesting residues*	Sawlog	Pulpwood	Harvesting residues
	Sawlog	Pulpwood	Harvesting residues	*Sawlog/Pulpwood/Harvesting residues*	Sawlog	Pulpwood	Harvesting residues
Blekinge	1,040	794	513	131	557	300	381
Dalarna	3,711	3,014	2,081	131	460	254	381
Gävleborg	3,165	2,600	1,785	119	429	274	381
Gotland	169	148	95	131	460	254	381
Halland	1,168	866	604	131	557	300	381
Jämtland	4,908	3,375	2,882	119	429	274	381
Jönköping	2,574	2,022	1,239	131	557	300	381
Kalmar	2,119	1,688	1,161	131	557	300	381
Kronoberg	1,718	1,257	836	131	557	300	381
Norrbotten	3,417	2,490	2,027	119	429	274	381
Örebro	797	640	398	131	460	254	381
Östergötland	2,281	1,720	1,118	131	460	254	381
Skåne	1,632	1,300	695	131	557	300	381
Södermanland	911	665	453	131	460	254	381
Stockholm	439	411	206	131	460	254	381
Uppsala	919	754	410	131	460	254	381
Värmland	3,157	2,356	1,714	131	460	254	381
Västerbotten	4,648	3,491	2,738	119	429	274	381
Västernorrland	3,415	2,515	1,885	119	460	254	381
Västmanland	1,037	803	463	131	429	274	381
Västra Götaland	3,303	2,695	1,526	131	460	254	381
ROW[3]	4,653	3,560	0	128	480	272	381

[1] 1,000 m^3 solid excluding bark.
[2] SEK per m^3 solid excluding bark. ROW prices assumed as average of domestic Swedish prices.
[3] Estimates is 10 percent of Swedish supply of roundwood, ROW supply of harvesting residues is assumed to zero.
Source: Swedish Forest Agency [33]; Swedish Energy Agency [47].

Table A-6
Output prices

Good	Output price	Unit	Comments
Sawn wood	1,892	SEK per m^3	Average of monthly 2016-prices [48]
Sulphate pulps (BSKP, BHKP, USKP, CTMP, SEC)	7,482	SEK ADt^{-1}	Average of monthly 2016-prices for sulphate softwood pulp, assumed to be valid for all sulphate pulps [49]
Sulphite pulps (BSSP, BHSP, USSP)	7,048	SEK ADt^{-1}	Estimated as proportion of sulphate pulp price (average of 94 %), using prices statistics from 1975 to 2013 [33].
Mechanical pulps (TMP, GWP)	5,570	SEK ADt^{-1}	Estimated as proportion of sulphate pulp price (average of 71 %), using prices statistics from 1975 to 2013 [33].
Wood pellets	1,228	SEK $tonne^{-1}$	Estimated from the price of densified wood fuels used by the DH sector [47].
DRI	2,000	SEK $tonne^{-1}$	Based on estimate by [28]
Iron ore pellets	2,000	SEK $tonne^{-1}$	

Table A-7
District heating prices (DH) and output quantities for heat, sawn wood and wood pellets

County	Price DH[1] (SEK MWh^{-1})	Heat (TWh)	Sawn wood (1,000 m^3)	Wood pellets (1,000 tonnes)
Blekinge	875	0.408	9	0
Dalarna	901	0.778	1,699	137
Gävleborg	891	0.814	1,044	179
Gotland	974	0.177	33	4
Halland	840	0.608	1,095	118
Jämtland	876	0.599	716	87
Jönköping	862	1.380	1,009	240
Kalmar	895	0.418	1,383	121
Kronoberg	819	1.114	1,368	1
Norrbotten	839	0.862	1,193	126
Örebro	940	1.211	632	69
Östergötland	918	3.031	656	65
Skåne	894	5.236	237	0
Södermanland	915	0.813	195	52
Stockholm	924	17.28	0	0
Uppsala	924	1.870	361	1
Värmland	956	0.729	1,135	130

(continued on next page)

Table A-7 (*continued*)

County	Price DH[1] (SEK MWh^{-1})	Heat (TWh)	Sawn wood (1,000 m^3)	Wood pellets (1,000 tonnes)
Västerbotten	836	1.293	1,803	73
Västernorrland	877	1.158	1,530	99
Västmanland	876	1.790	538	175
Västra Götaland	852	5.941	563	126
ROW[2]	890	0.000	1,720	180

[1] Average of municipal prices for single households.
[2] ROW production is estimated to 10 percent of domestic Swedish production for sawn wood and wood pellets.
Source: Statistics Sweden (2019); Swedenergy [54].

Table A-8
Pulp output quantities (in 1,000 air dried tonnes)

County	BSKP	BHKP	USKP	CTMP	SEC	BSSP	BHSP	USSP	TMP	GWP
Blekinge	169	55	0	0	0	0	0	0	0	30
Dalarna	775	446	375	0	0	0	0	0	584	78
Gävleborg	0	0	0	0	0	0	0	0	0	0
Gotland	0	0	0	0	0	0	0	0	0	0
Halland	706	0	0	0	0	0	0	0	259	154
Jämtland	0	0	0	0	0	0	0	0	0	0
Jönköping	0	0	0	0	0	0	0	0	0	0
Kalmar	491	155	0	0	0	0	0	0	0	0
Kronoberg	0	0	0	0	0	14	3	17	0	0
Norrbotten	428	0	523	0	0	0	0	0	447	0
Örebro	65	133	193	0	0	0	0	0	0	0
Östergötland	112	51	150	0	58	0	0	0	0	0
Skåne	0	0	0	0	0	0	0	305	0	0
Södermanland	0	0	0	0	0	0	0	0	0	0
Stockholm	0	0	0	0	0	0	0	0	466	68
Uppsala	0	0	0	0	0	0	0	0	0	0
Värmland	396	87	332	206	211	21	4	25	0	74
Västerbotten	0	0	230	0	0	0	0	0	680	0
Västernorrland	718	284	225	83	0	105	22	127	0	0
Västmanland	0	0	0	0	0	0	0	0	0	0
Västra Götaland	0	0	59	0	0	0	0	0	0	0
ROW[1]	275	84	124	0	6	14	3	47	244	40

[1] ROW production is estimated to 10 percent of domestic Swedish production.

Table 9
Output quantities for bio-products (in million tonnes)

County	Charcoal	Pyrolysis oil	DRI (DRI1)	DRI (DRI2)	Iron ore pellets (GK)	Iron ore pellets (SG)
Blekinge	0.00	0.50	0	0	0	0
Dalarna	1.21	0.50	0	0	0	0
Gävleborg	0.38	0.50	0	0	0	0
Gotland	0.00	0.50	0	0	0	0
Halland	3.38	0.50	0	0	0	0
Jämtland	0.41	0.50	0	0	0	0
Jönköping	0.86	0.50	0	0	0	0
Kalmar	0.88	0.50	0	0	0	0
Kronoberg	1.18	0.50	0	0	0	0
Norrbotten	5.25	0.50	2.35	16.5	17.9	9.00
Örebro	0.04	0.50	0	0	0	0
Östergötland	0.04	0.50	0	0	0	0
Skåne	0.52	0.50	0	0	0	0
Södermanland	1.14	0.50	0.90	0	0	0
Stockholm	0.00	0.50	0	0	0	0
Uppsala	0.33	0.50	0	0	0	0
Värmland	0.41	0.50	0	0	0	0
Västerbotten	2.00	0.50	0	0	0	0
Västernorrland	0.65	0.50	0	0	0	0
Västmanland	0.38	0.50	0	0	0	0
Västra Götaland	0.89	0.50	0	0	0	0

Table A-10
Input-output coefficients for the different industrial operations

Industry operation[1]	Feedstocks	Input	Output	Output secondary products
Sawmill	Sawlogs	2.13 m^3fub	1 m^3	0.573 m^3fub woodchips 0.573 m^3fub by-products[2]
BSKP	Pulpwood, sawlogs, woodchips	5.10 m^3fub	1 Adt	No secondary output
BHKP	Pulpwood, sawlogs, woodchips	4.10 m^3fub	1 Adt	No secondary output
USKP	Pulpwood, sawlogs, woodchips	4.60 m^3fub	1 Adt	No secondary output
CTMP	Pulpwood, sawlogs, woodchips	2.55 m^3fub	1 Adt	No secondary output
SEC	Pulpwood, sawlogs, woodchips	2.30 m^3fub	1 Adt	No secondary output
TMP	Pulpwood, sawlogs, woodchips	2.50 m^3fub	1 Adt	No secondary output
GWP	Pulpwood, sawlogs, woodchips	2.40 m^3fub	1 Adt	No secondary output
BSSP	Pulpwood, sawlogs, woodchips	4.80 m^3fub	1 Adt	No secondary output
BHSP	Pulpwood, sawlogs, woodchips	4.20 m^3fub	1 Adt	No secondary output
USSP	Pulpwood, sawlogs, woodchips	4.40 m^3fub	1 Adt	No secondary output
DH and CHP	Pulpwood	0.52 m^3fub	1 MWh	No secondary output
	Harvesting residues	0.47 m^3fub	1 MWh	No secondary output
	Woodchips	0.65 m^3fub	1 MWh	No secondary output
	Industrial by-products	0.59 m^3fub	1 MWh	No secondary output
	Wood pellets	0.22 tonnes	1 MWh	No secondary output
Wood pellets	Industrial by-products	2.22 m^3fub	1 tonne	No secondary output
Charcoal	Pulpwood	0.94 m^3fub	1 MWh	No secondary output
	Woodchips	1.18 m^3fub	1 MWh	No secondary output
	Industrial by-products	0.93 m^3fub	1 MWh	No secondary output
	Wood pellets	0.40 tonnes	1 MWh	No secondary output
LBG	Pulpwood	0.75 m^3fub	1 MWh	No secondary output
	Harvesting residues	0.74 m^3fub	1 MWh	No secondary output
	Woodchips	0.94 m^3fub	1 MWh	No secondary output
	Industrial by-products	0.68 m^3fub	1 MWh	No secondary output
Torrefied wood	Pulpwood	0.50 m^3fub	1 MWh	No secondary output
	Harvesting residues	0.45 m^3fub	1 MWh	No secondary output
	Woodchips	0.56 m^3fub	1 MWh	No secondary output
	Industrial by-products	0.54 m^3fub	1 MWh	No secondary output
Pyrolysis oil	Pulpwood	0.75 m^3fub	1 MWh	0.30 MWh
	Harvesting residues	0.67 m^3fub	1 MWh	0.30 MWh
	Woodchips	0.84 m^3fub	1 MWh	0.30 MWh
	Industrial by-products	0.81 m^3fub	1 MWh	0.30 MWh
Carburised DRI	Pulpwood			
	Harvesting residues			
	Industrial by-products			

[1] BSKP = bleached softwood kraft paper, BHKP = bleached hardwood kraft paper, USKP = unbleached softwood kraft paper, SEC = semi-chemical pulp, CTMP = and chemo-thermo mechanical pulp, TMP = thermo-mechanical pulp, GWP = groundwood pulp, BSSP = bleached softwood sulphite pulp, BHSP = bleached hardwood sulphite pulp, USSP = unbleached softwood sulphite pulp, DH = district heating, CHP = combined heat and power.
[2] Bark, sawdust and other falling by-products.
Source: Data for competing industries from Ref. [33,54]. Data for bio-products [37,41–43,55,56].

Maps

Fig. ure A-8. County map of Sweden

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