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Downscaling of Long-Term Global Scenarios to Regions with a Forest Sector Model

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Abstract: *Research Highlights:* Long-term global scenarios give insights on how social and economic developments and international agreements may impact land use, trade, product markets, and carbon balances. They form a valuable basis for forming national forest policies. Many aspects related to long-term management of forests and consequences for biodiversity and ecosystem services can only be addressed at regional and landscape levels. In order to be attended to in the policy process, there is a need for a method that downscales national scenarios to these finer levels. *Background and Objectives:* Regional framework conditions depend on management activities in the country as a whole. The aim of this study is to evaluate the use of a forest sector model (FSM) as a method for downscaling national scenarios results to regional level. The national FSM takes the global scenario data (e.g., harvest level and market prices over time) and solves the national problem. The result for the region of interest is taken as framework conditions for the regional study. *Materials and Methods:* Two different specifications are tested. One lets product volumes and prices represent endogenous variables in the FSM model. The other takes volumes and prices from the global scenario as exogenous parameters. The first specification attains a maximum net social payoff whereas the second specification means that net present value is maximized under a harvest constraint. *Results:* The maximum net social payoff specification conforms better to economic factors than the maximum net present value specification but could give national harvest volume trajectories that deviates from what is derived from the global model. This means that regional harvest activity can deviate considerably from the national average, attesting to the benefit of the use of the FSM-based method

Keywords: scenario; global forest model forest sector; partial equilibrium model; forest region; green infrastructure

1. Introduction

The forest sector is facing major challenges because of the emerging modern bioeconomy and the implementation of international climate change mitigation agreements. National forest policies are currently developed in many countries. In the European Union (EU), member states form National Forest Programs under the EU Forest Strategy umbrella (EU 2013). Global scenarios of socioeconomic development have been pointed out as important when performing national-level analysis and discussing how policy-making may tackle trade-offs between conflicting objectives [1–4]. One set of global scenarios that is commonly used to perform such analysis is the global Shared Socioeconomic Pathways (SSP) and Representative Concentration Pathway (RCP) scenarios. While these global scenarios were originally developed to help produce the Intergovernmental Panel on Climate Change

(IPCC) Sixth Assessment Report, they form an intricate part of linking national decision to global developments as they provide insights on how social and economic developments and international climate agreements may impact land use, trade, product markets, and carbon balances. A range of studies provides the investigation frameworks as to how national forest policies could be formulated in view of potential developments on the global level [5–10].

National forest policies depend on finding a balance between a range of aspects under the three main pillars of sustainable forest management: ecological, economic and sociocultural. Analyses on a national level are typically based on projection systems that rely on national forest inventory (NFI) data [11]. NFI data is with few exceptions composed of measurements from an outline of plots. A number of aspects are satisfactorily analyzed by consolidating results from the plots. Examples include aspects such as harvest level [12], the ability to reduce GHG net emissions with the substitution of fossil-based by bio-based products [13], water brownification [14], volumes of dead wood [15], areas of old forest [1], the response of biodiversity to these changes [16], and recreational values [17].

No rigorous method has yet been presented to transfer global scenarios over the national level to the regional level. By a rigorous method is here meant that consistency is preserved as regards the market conditions behind the global scenario and the national scenario. Market conditions are what ultimately drive the distribution of resources in a global scenario. Thus, preserving those conditions when downscaling national scenarios would be essential for the region to form an integral part of the national level, and subsequently of the global system. One reason for the lack of tools is that the research area is still emerging; there are few examples where global scenarios have framed regional analyses. In a study by [18], climate change and prices from a global model are applied. However, the national wood demand scenarios are not included. For instance, several of the aforementioned global studies indicate increasing volume demands. How this challenge is approached and what consequences it has could be the very essence of the regional study. This is analyzed in [1]; however without letting the market conditions—except national harvest volumes—affect forest management.

One of few alternatives to reflect changes in demand at regional level is to assume that regional demand follows the national demand in relative terms. This is a reasonable approach if the region in question somehow resembles the national average. The obvious drawback is that different regions may have different histories with regards to forest management, industrial development, and impact of disturbances. For example, if the region has a relative shortage of forests mature for final felling compared to the rest of the country, the current harvests of the region would be smaller than the national average in the near future and probably larger than national average in later time periods. This is a pattern that can be identified for Sweden [12].

The aim of this study is to evaluate the use of a forest sector model (FSM) as a method for downscaling the global scenario results to the regional level, here represented by four counties. An FSM is defined by [19] as " … a model (numerical or strictly analytical) which takes into account both forestry and forest industries and the interaction between these two activities … ". The use of an FSM as a mechanism to translate high-level hierarchical data to regional level, to the best of our knowledge, has not been investigated before. The national FSM takes the global scenario data (e.g., harvest level and market prices over time) as exogenous parameters, solves the national problem, and derives demand for the region. The choice of an FSM is determined by the need to maintain the same basic principles for the national model as those operating in the global model. A range of global models are FSMs and driven by physical and economic conditions, like land use changes, GDP projections, costs structures, and final products demand. Among them are (European Forest Institute Global Trade Model (EFI-GTM) and Timber Supply Model (TSM) [20], European Forestry Dynamics Model (EFDM) [21], and GLOBIOM [22]. Thus, to couple a national model to any of these models, it would preferentially be an FSM. This precludes some models, e.g., Heureka/RegWise [23] and European Forest Information Scenario EFISCEN [24] model, both of which derive forest management as a function of the state of the forest. They are thus not designed to adapt economic factors or the interplay with the demand side through industrial processes.

The global FSM used in this study is GLOBIOM [22]. The demand scenarios for Sweden from GLOBIOM form the input to the national FSM, i.e., the Swedish Forest Sector Model (SweFor) model (detailed in Section 2.3). SweFor is applied assuming two specifications of demand. One specification stipulates that demand volumes according to GLOBIOM should be harvested, i.e., there is a volume target. The other version instead specifies demand functions based on volumes and prices from GLOBIOM. The second specification leaves the forest owners and other agents of the sector free to adjust harvest activities to the demand functions derived from the GLOBIOM national scenario. The criteria that evaluate the two national demand specifications are, firstly, to what extents the outcomes coincide with the current harvest level, and, secondly the extent of temporal variation in harvest volume. The outcomes of the application of the national FSM-based method are evaluated for four Swedish counties of different size and initial forest conditions.

2. Methods and Data

2.1. Forest Partial Equilibrium Models

Both GLOBIOM and SweFor are partial equilibrium models (PEM), a variant of FSMs. A PEM is partial in the sense that it factors prices that are established outside system boundaries and assumed prices to be unaffected by the forest sector. In contrast, prices and volumes of feedstocks and forest products are endogenous. It is an equilibrium model in the sense that all markets are cleared. PEMs are powerful tools for studying the interaction between industry branches and forest management within the forest sector [8,20]. PEMs have been used on a global as well as national level with different foci. A frequent theme for national-level studies is climate change where the effectiveness of mitigation efforts is investigated with due attention to industrial capacity, profitability and market saturation [25–28]. Another common area of study concerns the relation between the forest sector, policy interventions and biodiversity. Several of them are describing Nordic conditions [2,29,30]. These studies imply that PEMs can adequately reflect conditions of the sector, including aspects that depend on forest management.

A central concept for PEMs is a net social surplus, or net social payoff (NSP). It is defined as the integral under the demand function to the market-clearing volume, the consumer surplus, less the integral of the supply function for the same interval [31]. The first quantity represents the value to buyers and the second quantity represents the accumulated cost for producers to supply the market-clearing volume. Since the problems are multi-period, the net social surplus of different periods is discounted.

2.2. GLOBIOM

The global forest sector model used in this study is the Global Biosphere Management Model (GLOBIOM) [22,32], a PEM developed and maintained at IIASA. GLOBIOM is a global recursive dynamic partial equilibrium bottom-up model that covers the forestry, agricultural and bioenergy sectors and where economic optimization is based on the spatial equilibrium modeling approach [33]. The model is based on a bottom-up approach where the supply side of the model is built-up from the bottom (land cover, land use, management systems) to the top (production/markets). It is recursive in the sense that decisions are made period by period. Commodity demand is specified as a stepwise-linearized downward sloped function based on [34] with constant own-price elasticities parameterized using FAOSTAT data on prices and quantities [35], and price elasticities as reported in [36]. The model computes the global market equilibrium for forest and agricultural products by allocating land use amongst production activities to maximize the sum of producer and consumer surplus subject to resource, technological, demand and policy constraints. The level of production in a given area is determined by the forestry or agricultural productivity in that area (dependent on suitability and management), by market prices (reflecting the level of demand), and by the conditions and cost associated to the conversion of land, to the expansion of production and, when relevant, to international market access. Demand and international trade are represented at the level of 53 aggregated world regions (28 EU member countries, 25 regions outside EU).

The spatial resolution of the supply side relies on the concept of simulation units, which are in aggregates of 5 to 30 arcmin pixels belonging to the same altitude, slope, and soil class, and also the same country [37]. For crops, livestock, and forest products, Leontief production functions covering a comprehensive set of alternative production systems with different intensities are parameterized using biophysical models like EPIC [38], G4M [39,40], or RUMINANT [41]. In this study, we use a version of the GLOBIOM model that is similar to [9] and the scenarios considered are developed based on assumptions taken from the SSP-RCP scenario database [42]. As such, the scenarios are defined according to a combination of assumptions between the shared socioeconomic pathways (SSPs, [43]) and the representative concentration pathways (RCPs, [44,45]). The SSPs describe different pathways of population and economic growth, income distribution, trade and consumption patterns. The RCPs describe projections for the atmospheric concentration of greenhouse gases under different climate change mitigation policies. More information about the model and related publications can be found on the webpage www.globiom.org. From here on and if nothing else is stated, the term scenario refers to scenarios from GLOBIOM.

2.3. SweFor

In contrast to GLOBIOM, which is a recursive model, SweFor is an intertemporal model, meaning that all markets are cleared simultaneously in all periods. They share the same assumption in regards to agents' behavior, i.e., they are assumed to be profit maximizers. SweFor has a simple, though standard, demand side and a more elaborate supply side, especially the description of forest management and its linkage to further processing. The description of the state of the forest is given by a set of NFI plots. SweFor maintains the integrity and location of the individual NFI plot data and has, therefore, a rather high resolution. This makes SweFor well adapted to the analyses of long-term forest management and allows some flexibility to downscale to arbitrary definitions of regions through the mesh of plots covering Sweden. SweFor has the same structure as the Norwegian Forest Sector Model (NorFor) model [46] with differences as to how the forest is represented and the details of industrial processes.

The demand side of the sector is represented by four branches—sawn wood, mechanical pulp, chemical pulp and energy through district heating plants—each described by a demand function with constant elasticity. The constant elasticity approach is found in more aggregated models for analysis on a global or large regional level, for instance in GLOBIOM (see above) and EFDM [21], on a national level [47] or in models such as SRTS [48] which is designed for smaller regions.

Material flows are illustrated in Figure 1. The supply of logs and residues emanates from the NFI sample plots, each with a distinct location and representing a certain area of the Swedish forest. Harvested volumes from a plot are transported to facilities of different kinds that are within range. Here, a facility is a sawmill, pulp mill, or a heating plant, each with a specific capacity and location. Sawmills are divided into those accepting only pine, spruce or any species, respectively, and pulp mills are divided into those producing mechanical pulp, which only accepts spruce, and those producing chemical pulp and accept all tree species. Logging residues (e.g., branches and treetops) can only be transported to a heating plant, whereas logs can be used by any facility. There are flows of industrial by-products (i.e., sawdust, wood chips) between facilities such that the sawmill industry can deliver wood chips to pulp mills and sawdust to heating plants. Bark, in-line with current practices, is assumed to be used for heating purposes to support processes within each facility.

In the mathematical description of SweFor sets and parameters are in capital letters, while indices and variables are in small letters (Table 1).

In the equations of the mathematical model, an index is assumed to belong to the full set as it is defined above if nothing else is stated (Table 2). For clarity, the model is divided into four subsections; namely (a) transportation and production, (b) determination of capacity, (c) matching supply against demand, and (d) accounting for costs and surplus. The problem is to maximize net social surplus Equation (1) subject to constraints Equations (2)–(18).

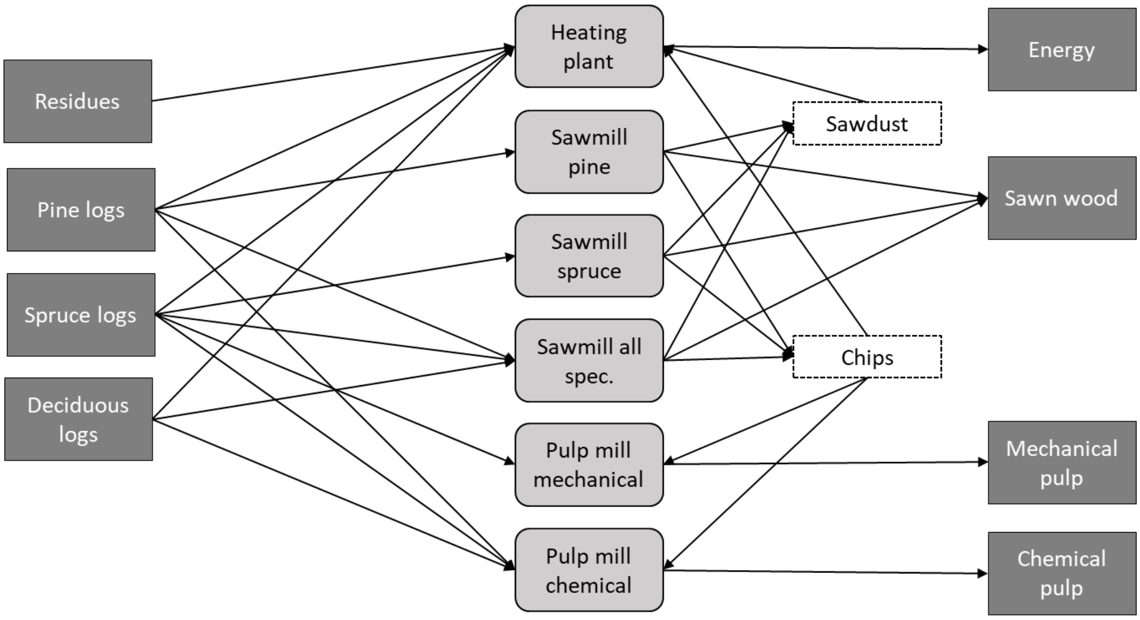

Figure 1. Types of biomass commodities that emanate from national forest inventory plots (boxes on the left), types of facilities that process feedstock (boxes in the center) thereby creating industrial by-products (i.e., sawdust and chips), and final marketed products (indicated on the right).

Table 1. Notation used for describing the SweFor model.

Sets and Indices	Explanation
S, s	Set of scenarios and set index
T, t	Set of time periods and set index
I, i	Set of NFI plots and t index
J, J_i, j	Set of management programs, the subset belonging to set I, and set index
F, f and f'	Set of factors and set index
C, c and c'	Set of facilities and t index
B, B_c, b	Set of facility types, the singleton set designating the facility type of facility c and set index
K, k	The set of elements constituting the stepwise demand functions, and set index
Variables	
x_{ij}	Share of the area of NFI plot i allocated to management program j
y_{fict}	Amount of factor f transported from NFI plot i to facility c in period t
$q_{fcc't}$	Amount of factor f transported from facility c to facility c' in period t
z_{fct}	Amount of factor f to be used as input at facility c in period t
o_{fct}	Amount of factor f produced at facility c in period t
r_{ct}	Capacity of facility c in period t
m_{ct}	Maintained capacity at facility c in period t
n_{ct}	Investment in new capacity at facility c in period t
v_{ft}	Total output of factor f in period t
u_{fkt}	Amount allocated to step k of factor f in period t
γ_t	Total cost in period t
θ_t	Total surplus in period t
π	Total net socl surplus
Parameters	
F_{fijt}	Available amount at roadside of factor f in period t represented by NFI plot i when allocated management program j
E_{ij}	Standing stock after harvest in period T represented by NFI plot i when allocated management program j
H_{ijt}	Cost due to forest management activities in period t represented by NFI plot i when allocated management program j
I_{ij}	The initial standing stock

Table 1. *Cont.*

Parameters	Explanation
$L_{bff'}$	Unit output of factor f' per unit input of factor f for facility of type b
R_c	Initial capacity of facility c
Q_{fkt}	Maximum amount to be allocated to step k of the demand function for factor f in period t
P_{fkt}	Price per unit at step k of the demand function for factor f in period t
T_f	Unit transport cost of factor f per distance unit
D_{ic}	Distance between NFI plot i and facility c
$D'_{cc'}$	Distance between facility c and facility c'
Λ_{bf}	Unit operating cost per input of factor f for a facility of type b
M_b	Maintenance cost per unit of capacity for a facility of type b
N_c	Cost of installing new capacity for a facility of type b
Ψ_c	Capital cost per unit of capacity for a facility of type b
Φ_t	Discount factor for period t

Table 2. Mathematical description of the SweFor model.

Maximize π subject to		(1)
Transport and production model		
$\sum_{j \in J_i} x_{ij} = 1$	$\forall\, i \in I$	(2)
$\sum_{j \in J_i} F_{ijt} \cdot x_{ij} \geq \sum_{c} y_{fict}$	$\forall\, i \in I, f \in F, t \in T$	(3)
$\sum_{i, j \in J_i} E_{ij} \cdot x_{ij} \geq I$		(4)
$z_{fct} = \sum_{i} y_{fict} + \sum_{c'} q_{fc'ct}$	$\forall\, f \in F, c \in C, t \in T$	(5)
$o_{fct} = \sum_{f'} L_{B_c f' f} \cdot z_{f'ct}$	$\forall\, f \in F, c \in C, t \in T$	(6)
$\sum_{c'} q_{fcc't} \leq o_{fct}$	$\forall\, f \in F, c \in C, t \in T$	(7)
$o_{fct} \leq r_{ct}$	$\forall\, f \in F, c \in C, t \in T$	(8)
Capacity model		
$r_{c1} = R_c$	$\forall\, c \in C$	(9)
$r_{ct} = m_{ct} + n_{ct}$	$\forall\, c \in C, t \in T \backslash \{1\}$	(10)
$m_{ct} \leq r_{c,t-1}$	$\forall\, c \in C, t \in T \backslash \{1\}$	(11)
Demand model		
$v_{ft} = \sum_{c} o_{fct}$	$\forall\, f \in F, t \in T$	(12)
$u_{fkt} \leq Q_{fkt}$	$\forall\, f \in F, k \in K, t \in T$	(13)
$v_{ft} \leq \sum_{k} u_{fkt}$	$\forall\, f \in F, t \in T$	(14)
Financial model		
$r_t = \sum_{i,j \in J_i} H_{ijt} \cdot x_{ij} + \sum_{fic} T_f \cdot D_{ic} \cdot y_{fict} + \sum_{fcc'} T_f \cdot D'_{cc'} \cdot q_{fcc't} + \sum_{fct} \Lambda B_{cf} \cdot z_{fct} + \sum_{c} M_{B_c} \cdot m_{ct} + \sum_{c} N_{B_c} \cdot n_{ct} + \sum_{c} \Psi_{Bc} \cdot r_{ct}$	$\forall\, t \in T$	(15)
$\theta_t = \sum_{fk} P_{fkt} \cdot u_{fkt}$	$\forall\, t \in T$	(16)
$\pi = \sum_{t} \Phi_t \cdot (\theta_t - r_t)$		(17)
and all variables ≥ 0 except π, γ_t and θ_t that are free and $x_{ij} \in (0, 1)$		(18)

The forest is modelled as a Model I [49], i.e., for each plot there is a number of management regimes, each covering the entire planning horizon and holding relevant information for each planning period. Equation (2) makes sure that the area represented by each plot i is allocated management programs. Equation (3) ensures that the deliveries to different facilities from each plot in each period do not exceed the amounts that are available. Equation (4) is a measure of sustainability, i.e., it secures that a volume equal to the initial standing volume is left at the end of the projection period. Equation (5) summarizes for each factor, facility, and period the amounts coming from plots or other facilities. Equation (6) gives the output of each factor for each facility c and period based on the Leontief production function B_c, i.e., the production function is defined for the kind of final forest product of the facility. Equation (7) puts an upper bound on the deliveries of each factor from each facility to other facilities; this only concerns by-products. Equation (8) limits production for each facility in each period to the available capacity; this only concerns the main factor output for the facility with the capacity for all other outputs set to infinity. Equation (9) sets the capacity to the existing capacity for each facility in the first period, whereas Equation (10) sets the capacity in further periods depending on how much is invested in new capacity and how much is maintained of the existing capacity from the previous period, the latter limited by Equion (11). Equation (12) summarizes the output of each factor for each period. Equations (13) and (14) ensure that for each factor in each period, output is distributed based on the stepwise demand function. Equations (12)–(14) is only effective for those outputs having a products market value. Equation (15) summarizes all costs in each period, i.e., costs of forest management including harvesting activities, transports of factors from plots to facilities, transports of factors between facilities, production costs at facilities, capacity maintenance and investment costs. Equation (16) assigns value to the volumes allocated to the steps of the demand function for each factor and period and Equation (17), finally, discounts gross surplus-value less costs to a total net social surplus value, which is maximized in Equation (1). It may seem superfluous to have Equation (12); it could easily be substituted into Equation (14). However, Equation (12) turned out to be indispensable in order to attain a solution in reasonable computing time.

The two different specifications of demand applied in SweFor can now be defined within the model frameworks. The specification where demand is represented with demand functions is termed MaxNSP since prices and supplied volumes are determined endogenously in the model by maximizing NSP. The MaxNSP problem is solved as stated in Equations (1)–(18). Market prices and volumes from the GLOBIOM scenarios are input for the demand functions that are implemented with parameters Q_{fkt} and P_{fkt} in the model. The other specification with fixed volumes solves the problem in relation to the constraint where supplied volumes should equal the amount of sawn wood, mechanical pulp, and chemical pulp as specified by the respective GLOBIOM scenario (energy is not constrained because the volumes assigned for energy production in GLOBIOM is a separate assortment whereas it is a combination of inputs in SweFor; cf. Figure 1). The ensuing problem will then be an ordinary NPV maximization problem with fixed volume requirements and termed MaxNPV. Technically, it means turning the variable v_{ft} in Equation (12) into a parameter with a fixed value for each period t and for each of the relevant factors f .

2.4. Data

The outcomes from GLOBIOM of the different scenarios at country level are presented in Appendix A. Three of the Swedish GLOBIOM scenarios are used in this study: RCP4p5.SSP3, RCP2p6.SSP4, and RCP2p6.SSP5. RCP4p5.SSP3 has the smallest total requirement on feedstock supply in the last period, scenario RCP2p6.SSP5 is the one most demanding in this respect, and RCP2p6.SSP4 has a supply requirement in between these two extremes.

The SweFor demand functions for the first period reflect the current situation as regards prices and volumes (see Appendix B for these items and other parameters of the SweFor model). Subsequent periods follow the relative change of prices and volumes of the GLOBIOM scenario where saw logs are associated with sawn wood and pulpwood is associated with chemical and mechanical pulp. The volume trend for the energy market is associated with the trend for harvest of non-industrial roundwood and the price trend with the trend from [50].

The SweFor model is set up with 41 sawmills, 35 pulp mills, and 63 heating plants. When implementing the model, transport options are limited in order to limit the size of the model.

Two conditions are satisfied for eligibility: (i) transport distance between a plot and facility or from a facility to another facility should not exceed 300 km Euclidian distance, and (ii) a plot can only be connected to a maximum of 10 (nearest) facilities of each type and by-products can only be transported to a maximum of 2 (nearest) facilities. Additional parameter settings are found in Appendix B.

Results from four Swedish counties with different characteristics are presented; Västerbotten (=N for Northern Sweden); Västmanland (=M for Mid Sweden); Kronoberg (=S for Southern Sweden); and Gotland (=I for an island county) (Figure 2 and Table 3). The N and S counties are the larger ones and are located in fairly well-developed forest industrial regions, while M has little own forest industry although located close to forest industrial regions, and I is an island. The main reason to choose counties instead of some other aerial unit is that they are easily identifiable with the NFI data.

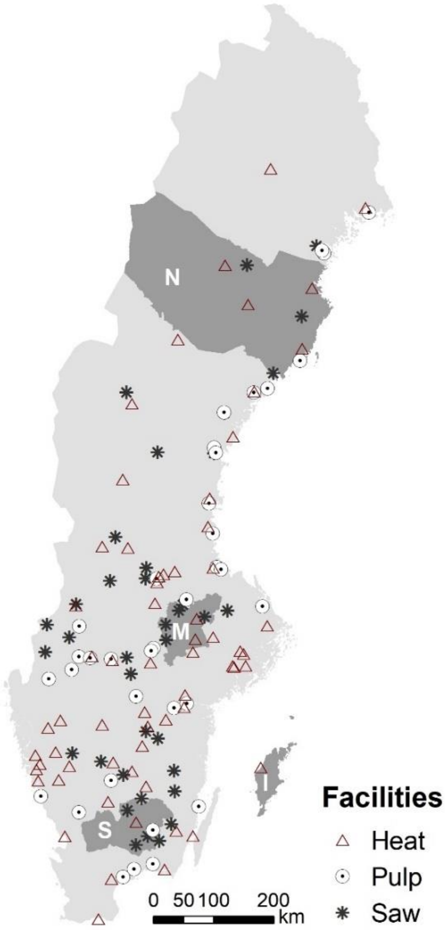

Figure 2. The location of study counties Västerbotten (N), Kronoberg (S), Västmanland (M), and Gotland (I) and the facilities heating plants, pulp mills, and sawmills.

Table 3. Size and number of national forest inventory plots of the four selected counties.

	County			
	N	**S**	**M**	**I**
Forest area (ha)	2,933,574	693,807	333,770	141,278
No. of plots	458	233	122	59
Mean volume (m^3 ha^{-1})	104	144	163	114
Average age (y)	68	43	50	75
Productivity (m^3 ha^{-1} y^{-1})	3.2	8.9	7.3	3.8
Conifers (% of volume)	81	80	77	76
Deciduous (% of volume)	19	18	23	24

A total of 5,553 NFI plots inventoried during 2012 [51] are used for the national scenario analysis. They represent 19.9 million ha of productive forest that supplies timber markets after subtracting 5% of the area assumed to be designated for private use (mainly firewood).

Several forest management programs are created for each NFI plot with the PlanWise application of the Heureka forest decision support system [23]. Scenario RCP4p5.SSP3 is in Heureka modelled with radiative forcing RCP4.5, whereas scenarios RCP2p6.SSP4 and RCP2p6.SSP5 are assumed to not have any climate change effect on growth. The system outputs used are available amounts at roadside of timber and slash, costs for silvicultural and harvesting operations, and standing volumes. About 130,000 forest management activities, corresponding to the x_{ij} variables of the model, were supplied by Heureka to SweFor. The time horizon is 100 years, distributed into 20 5-year periods. Present values are calculated with a real rate of 3% y^{-1}.

SweFor was formulated with the modelling tool AIMMS Developer version 4.20 [52] and solved with Gurobi version 7.5 [53] with LP method barrier. The problem size is typically about 0.6 million constraints and 10 million variables with CPU solution times of about 1 hour with Intel(R) i7-4770 at 3.4 GHz.

3. Results

3.1. National Level

The total harvest volume entering processing facilities over the next 100 years for the three scenarios according to methods MaxNSP and MaxNPV is shown in Figure 3 together with the national scenario figure for harvested wood going to sawmills and pulp mills. None of the demand specifications results in exactly the same numbers as the GLOBIOM scenario. MaxNPV deviates from the scenario for two reasons. Firstly, SweFor can assign wood for use in heating plants, whereas the scenario only covers what goes to sawmills and pulp mills. This is why MaxNPV is above scenario figures for almost all periods in scenarios RCP4p5.SSP3 and RCP2p6.SSP4. Secondly, the demand in scenario RCP2p6.SSP5 is so high that it cannot be fully met in the latter half of the projection period. This is due to the constraint on ending stocking, Equation (3), which is binding for all solutions and all scenarios and for MaxNSP as well as for MaxNPV. MaxNSP follows quite a different trajectory than the scenario. Harvest volumes, except for the last decades in RCP2p6.SSP5, are generally higher in the beginning and lower at the end of the planning horizon. The reason is that it is more profitable to harvest and process larger quantities in the beginning than later unless increased prices offset this effect. Contributing to this is the constraint on ending stocking. This constraint is also the likely cause for the slightly lower harvest during the first 70 years in scenario RCP2p6.SSP5 compared to the other two scenarios. Lower harvests in the beginning give room for a relative increase of the national harvest level at the end of the projection period when prices are relatively high. For instance, the price of sawn wood in the last period in scenario RCP2p6.SSP5 is almost double that of RCP2p6.SSP4, and almost four times that of RCP4p5.SSP3.

3.2. County Level

Figure 4 forms the basis for analyzing three issues: How patterns vary from period to period, to what extent initial harvests deviate from the current level, and the degree to which the FSM method makes a difference compared to the assumption that the relative contribution from a region stays the same over time. The study of the two latter questions relies on the data presented by [54] on current harvest volumes distributed on countries.

The MaxNSP specification of national volume demand relative to MaxNPV displays a smoother development over the periods for the larger regions N and S, while the smaller regions I and M have harvests that vary considerably from period to period for both MaxNPV and MaxNSP. There is a tendency for the harvest profile to express a larger variation over time with the MaxNPV formulation than with the MaxNSP formulation. This applies to both small and large regions.

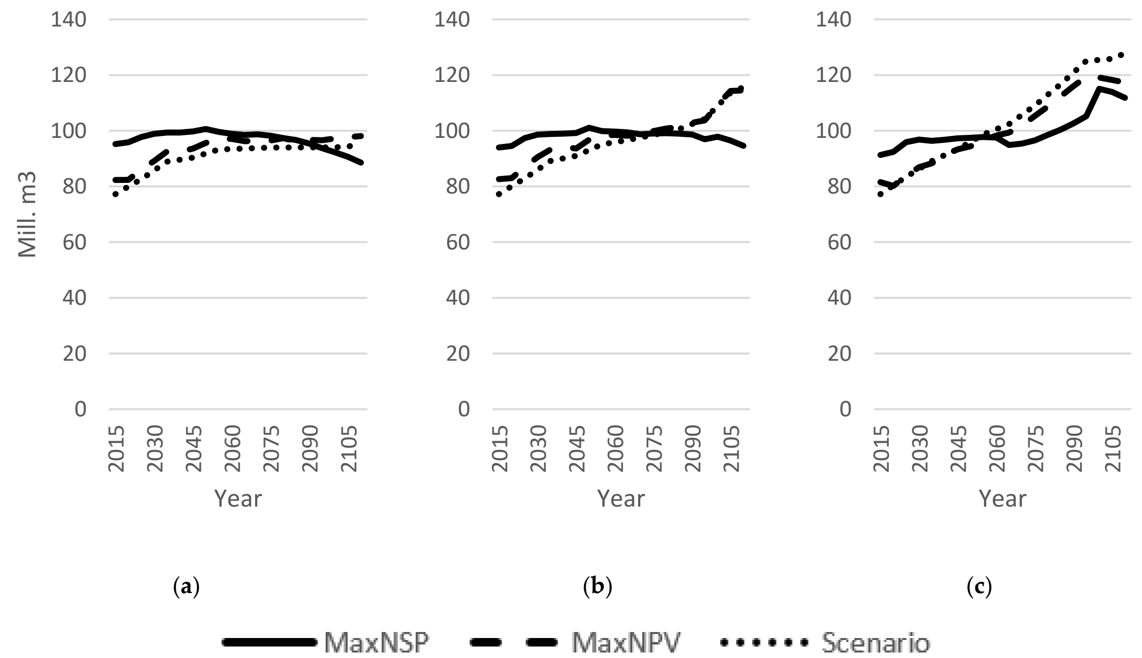

Figure 3. Total national harvest volume entering sawmills, pulp mills and heating plants for three scenarios computed with SweFor for demand specifications MaxNSP and MaxNPV (m^3 o.b. including treetops) and the harvest volume specified in the GLOBIOM national scenario destined for sawmills and pulp mills. (**a**) Scenario RCP4p5.SSP3; (**b**) scenario RCP2p6.SSP4; (**c**) scenario RCP2p6.SSP5.

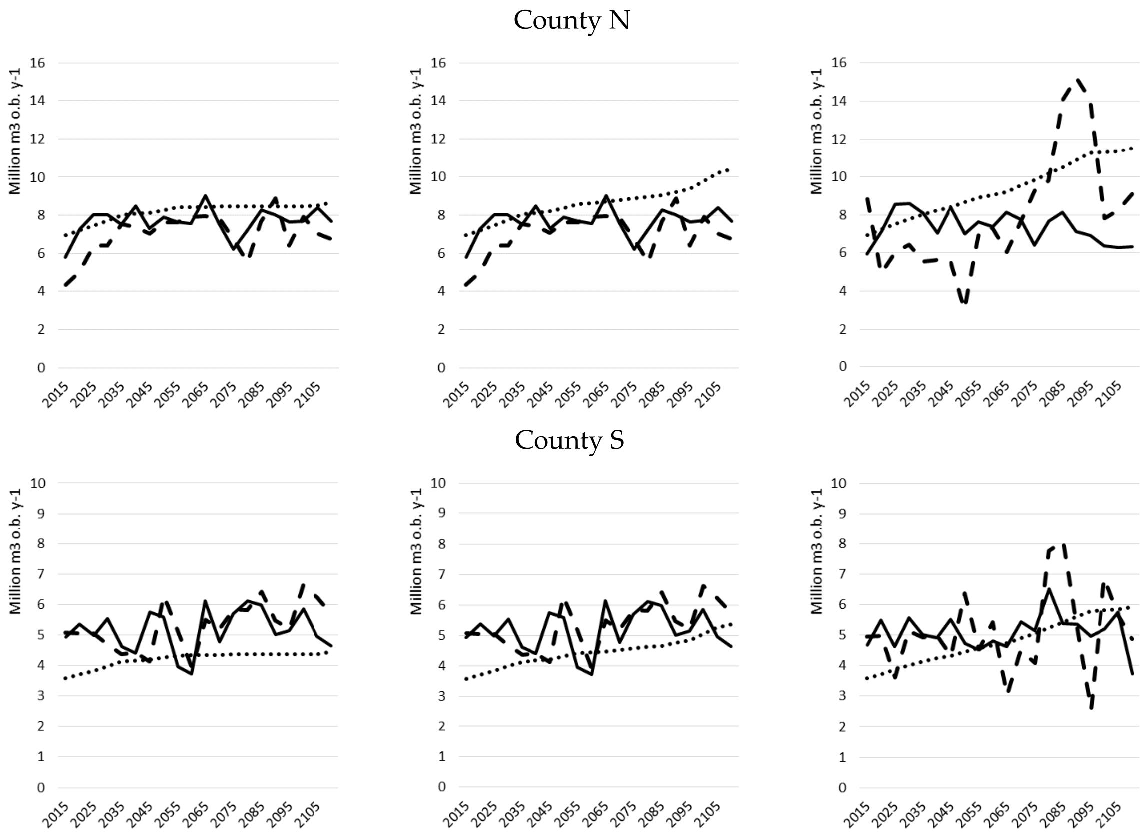

Figure 4. *Cont*.

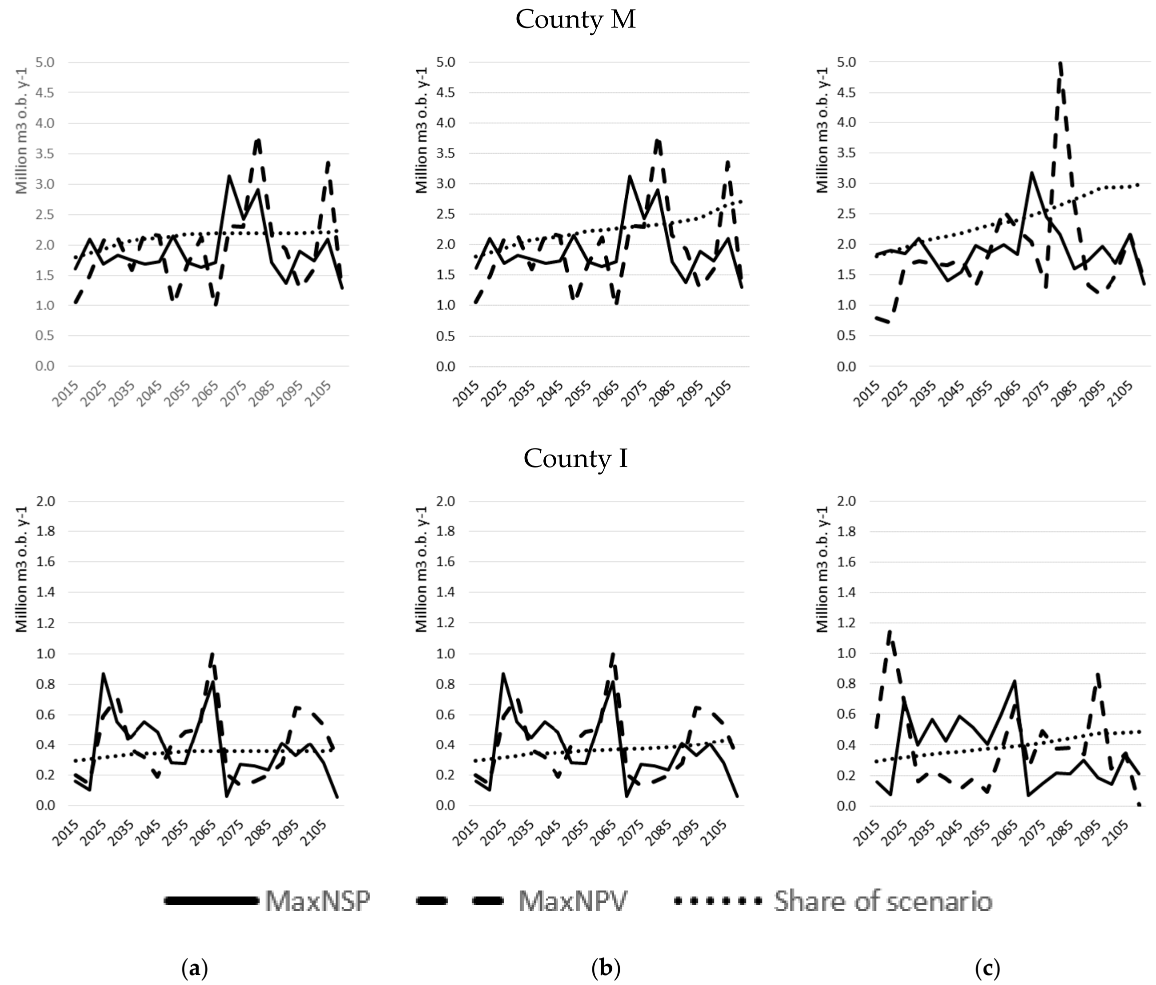

Figure 4. Harvest volumes (m^3 o.b. including treetops) for counties Västerbotten (N), Kronoberg (S), Västmanland (M), and Gotland (I) for scenarios RCP4p5.SSP3, RCP2p6.SSP4, and RCP2p6.SSP5 (left, middle and right panel) according to solutions for MaxNSP and MaxNPV, and as a constant share of the national GLOBIOM scenario volume. (**a**) Scenario RCP4p5.SSP3; (**b**) scenario RCP2p6.SSP4; (**c**) scenario RCP2p6.SSP5.

Harvests in the first period in the larger regions deviate considerably from the current level. First-period harvest deviates more from the current level for MaxNPV than for MaxNSP for all counties. This may reflect that MaxNPV solutions have larger variation and therefore tend to show larger deviations from a specific value.

Due to the variation of harvests on the county level, the trend of the FSM specifications is not easily compared to the trajectory given as a constant share of national harvests. The MaxNSP specification has a general tendency to provide trajectories that are fairly on the same level throughout the time horizon, which is in agreement with the solution on a national level. Thus, the more harvests change over time, the more the MaxNSP specification would deviate from the MaxNPV specification. For the MaxNPV specification county N has a reduction of harvests after the initial cut, county S is more on the same level throughout, and county I shows a reduction over time. None of these observations is in line with the scenario trend despite the fact that harvests with this specification are forced to follow the scenario on a national level. County M, though, appears to give a similar trend as the national share.

To test the importance of the number of plots for the variation over time noticed above, scenario RCP2p6.SSP4 was run with 2 years NFI material, i.e., a total of 10,663 plots. This had essentially no discernable effect for the larger counties except that method MaxNPV shows a larger variation than with one-year NFI material (Figure 5). The smaller counties M and I do show a somewhat reduced variation as a result of the increase in number of plots.

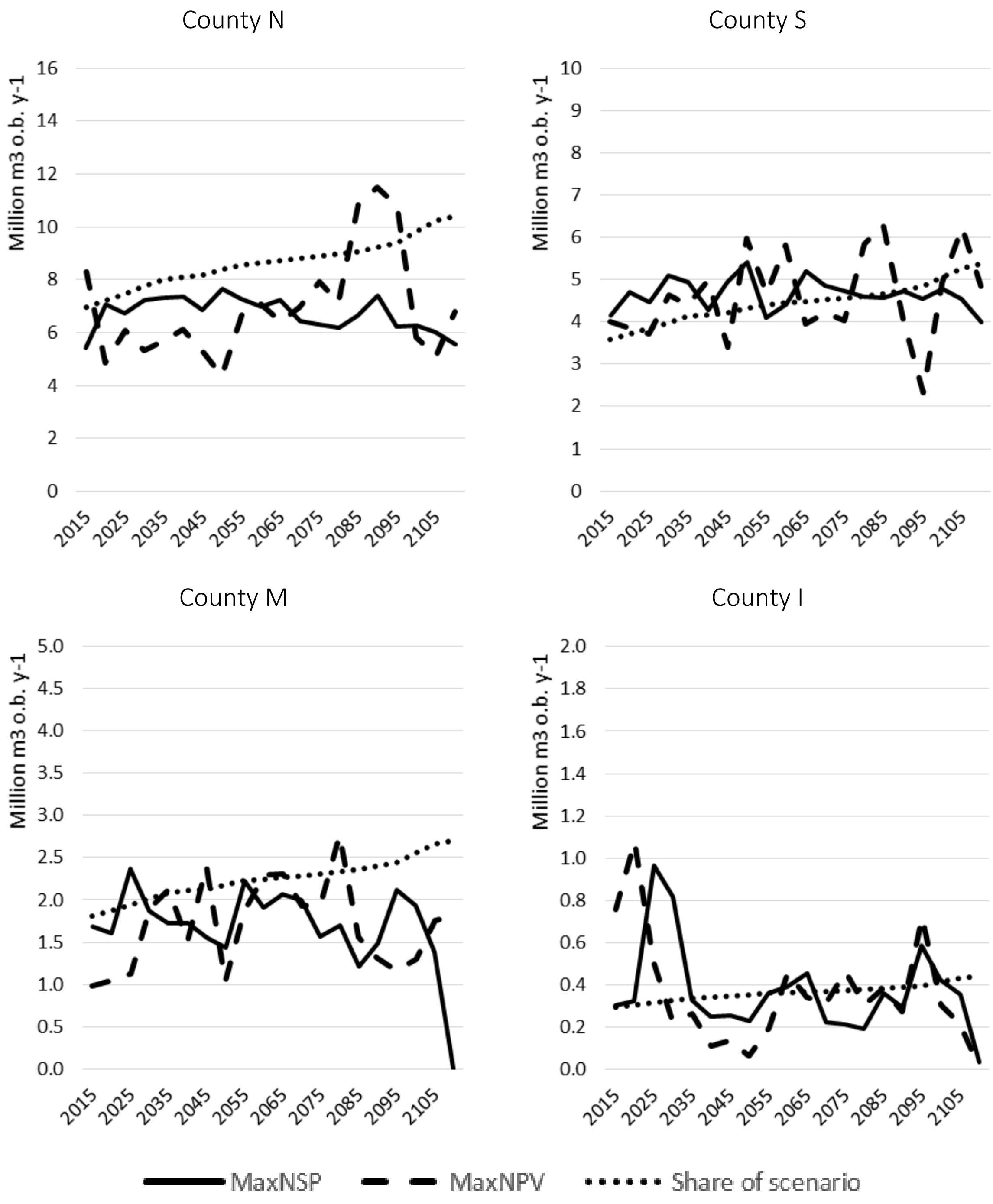

Figure 5. Harvest volumes (m^3 o.b. including treetops) for counties Västerbotten (**N**), Kronoberg (**S**), Västmanland (**M**), and Gotland (**I**) for scenario RCP2p6.SSP4, using NFI plots measured during two years.

4. Discussion

The discussion will first investigate the general properties of the FSM method as tools for modelling the national forest sector. Thereafter, we trace the implications of the method for identifying frame conditions for regional studies, including the case where the resolution of the data is inadequate for representing the region.

The MaxNSP model formulation is the standard formulation for PEMs [20] with a strong footing in economic theory [31]. MaxNPV can be characterized as a standard harvest scheduling problem, in this case with an attached industrial model, and is therefore operating with much more restrictive assumptions than the MaxNSP model. The argument for the use of the MaxNPV model over the MaxNSP model would be that it enables a strict prolongation of the global scenario to the national level. In this respect, the MaxNPV model resembles the method used by [1]. With the market elasticities used with the MaxNSP model in this study, rather different trajectories emanate compared to the ones from GLOBIOM (Figure 3). This may be a serious complication if the very aim of the analyses is to investigate the consequences of satisfying scenario requirements stemming from the global model.

Two criteria are the focus at the regional level; variation over time of the harvest volumes and first-period harvests. Starting with variation, the results indicate that two factors are at play when it comes to explaining varying harvests over time; the constraints on solution space and the size of the area in terms of number of NFI plots. MaxNPV has a more constrained solution space compared to MaxNSP since the former locks volume to certain values whereas MaxNSP varies activity more according to economic conditions. Thus, less weight is put on economic factors and more on the volume production aspect for MaxNPV than for MaxNSP. Forestry is, to a large extent, a matter of transportation. Bigger variations imply that catchment areas of industries will vary more and on average be more costly due to longer transport distances. Thus, economic factors incentivize limited variation in harvests over time. Assuming that forestry over a larger area, such as a region, is characterized by a certain stability, this would favor the MaxNSP formulation over the MaxNPV formulation.

The smaller counties express harvest patterns with greater variation than the larger areas. County I for instance, with only 59 NFI plots, comes close to a zigzag pattern. The problem is difficult to avoid. Models built to handle forest management problems on a national level are with few exceptions, if any, built on NFI data, where a sparse grid of plots represents NFI data. The two smaller counties are the ones where variation is reduced with adding plots. Of course, the more years of inventories that can be used, the better. There is a limit to this remedy, both with respect to the pedigree of the data and the constraints of computing capacity to solve the SFM. Another approach to get around this problem would be to identify a larger area that consists of enough plots to represent the region, a master area. The master area could be checked for having properties, such as age class structure, average standing volume, and species distribution, as the target region. A complementary approach to the problem would be smoothing the time profile.

The first-period harvest has to do with the ability of the method to reflect actual conditions. If the model predicts harvests far from the current levels, it indicates that data are flawed or some essential aspect is missing challenging the realism of the results. The current implementations of the MaxNSP and MaxNPV formulations are problematic in this respect. To avoid large deviations from the current activity level, one could anchor the first-period harvests to the current level and let the regional model follow the relative variation of the FSM solution for the master area. The drawback is that the average harvest level will change. This, for instance, could result in an unmotivated buildup of standing volume when shifting the level down and infeasible solutions when shifting the level up. Another way to control first-period harvest would be to introduce a constraint for each county (or comparable area unit for which there is data) in the FSM model to ensure that current harvests are met. In the current case, where the GLOBIOM model is harmonized to arrive at current harvests for countries and regions in the first period, this could make for better consistency between the two levels of analysis.

The results are here focused on the total harvest. A good reason for that is that in managed forests, it would normally be the measure of the largest impact. More detailed forest management specifications could, of course, be found in the solution from the national FSM, like different establishment methods or the distribution of harvests on different forms of felling and management methods. However, those would be even more dependent on the density of NFI pots than total harvest volumes as they concern smaller areas or smaller fractions of the harvest.

There will most likely always be inconsistencies between the specifications of the scenario model, in this case GLOBIOM, and those of the national FSM, in this case SweFor. These could include differentiation among timber assortments, the exact definitions of forest areas, the reference year for data, growth functions, etc. In this particular case, we have scenarios prescribing industry gate prices and volumes, whereas SweFor operates with prices and quantities for forest products markets (i.e., sawn wood, pulp and energy). This makes a direct translation of the national scenario to the national model difficult. This relates in particular to the different descriptions of how forest energy is defined. Another reason MaxNSP solutions differ from scenario values is probably that there is an ending standing volume constraint in SweFor, but not in GLOBIOM. This constraint is binding for all scenarios for both MaxNSP and MaxNPV models. It is, of course, possible to get a better alignment of GLOBIOM and SweFor results if the constraint is removed. However, the conditions set by the government for forest policy analysis states an even stronger constraint, i.e., standing volume is not allowed to diminish at any future point [12]. Thus, it would probably be difficult to leave out the standing volume constraint, or a comparable construct, and still have a valid model. To conclude, different models are different (that is the very idea behind using them) and the consequences of model inconsistencies have to be observed.

5. Conclusions

The use of a national FSM allows the regional conditions to be reflected in the analysis in a way that is consistent with global scenarios. The deviations of harvest volume trajectories formed by the solutions to the FSM-based models from those formed under the assumption of a constant national share constitute evidence in this direction. However, it requires making a number of choices and analyses. One is choosing between different model formulations. In this study, the standard formulation of a PEM with demand functions is contrasted against a modified harvest scheduling model, the former with more economic logic and resulting in less temporal variation and the latter with more regional variation but conforming better with the national scenario given by the global model. The tendency of larger temporal variation for smaller regions would make it necessary to analyze the performance at the larger region before implementing framework conditions for the smaller region.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Appendix A.1. Material—Scenarios

Demand projections as estimated by the GLOBIOM model for the set of global scenarios are as follows. It should be notes that each scenario is a combination of assumptions concerning the shared socioeconomic pathways (SSP) and the representative concentration pathways (RCP). For further details concerning how the SSP and RCP scenarios are implemented in the GLOBIOM model, we refer to [9,55].

Appendix A.2. Scenario Estimates for Sweden

Table A1. Total national harvest (millions of m^3/year, excluding bark, harvesting losses and branches).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP8p5.SSP1	69.73	76.36	82.83	86.22	89.93	91.87	94.04	96.00	97.95	100.03
RCP8p5.SSP2	69.73	76.28	82.83	84.54	89.57	91.34	93.34	95.17	97.31	99.61
RCP8p5.SSP3	69.73	75.66	82.57	84.15	87.38	87.75	88.13	88.17	88.18	88.32
RCP8p5.SSP4	69.73	75.95	82.83	84.85	88.97	90.58	92.24	93.51	94.90	96.15
RCP8p5.SSP5	69.73	76.55	82.83	87.45	93.29	96.73	103.51	110.88	117.49	122.95
RCP4p5.SSP1	69.73	76.36	82.83	86.22	89.92	91.86	94.04	95.94	97.89	100.37
RCP4p5.SSP2	69.73	76.29	82.83	84.55	88.96	90.73	92.82	94.68	97.06	99.88
RCP4p5.SSP3	69.73	75.66	82.58	84.16	87.37	87.74	88.12	88.16	88.18	88.41
RCP4p5.SSP4	69.73	75.95	82.83	84.85	89.42	91.11	92.69	94.16	95.33	96.98
RCP4p5.SSP5	69.73	76.55	82.83	87.45	93.28	96.73	103.51	110.86	117.36	122.95
RCP2p6.SSP1	69.73	76.36	82.83	86.22	89.93	92.06	94.75	97.86	102.31	112.56
RCP2p6.SSP2	69.73	76.30	82.83	84.55	88.96	90.91	93.36	96.89	103.33	115.23
RCP2p6.SSP3	69.73	75.70	82.64	84.18	87.38	88.05	88.90	90.06	96.04	107.92
RCP2p6.SSP4	69.73	75.95	82.83	84.82	89.36	91.07	93.10	95.36	99.40	109.68
RCP2p6.SSP5	69.73	76.55	82.83	87.45	93.29	97.34	104.70	113.03	122.22	123.00

Table A2. Industrial roundwood harvest (millions of m^3/year, under bark).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP8p5.SSP1	63.83	68.76	73.58	76.11	78.88	80.33	81.95	83.42	84.87	86.42
RCP8p5.SSP2	63.83	68.70	73.58	74.85	78.61	79.94	81.43	82.79	84.39	86.11
RCP8p5.SSP3	63.83	68.24	73.38	74.56	76.98	77.25	77.54	77.57	77.57	77.68
RCP8p5.SSP4	63.83	68.46	73.58	75.09	78.16	79.37	80.61	81.56	82.59	83.53
RCP8p5.SSP5	63.83	68.90	73.58	77.03	81.39	83.97	89.03	94.55	99.48	103.56
RCP4p5.SSP1	63.83	68.76	73.58	76.11	78.88	80.32	81.95	83.37	84.82	86.68
RCP4p5.SSP2	63.83	68.71	73.58	74.86	78.16	79.48	81.04	82.43	84.21	86.31
RCP4p5.SSP3	63.83	68.24	73.39	74.57	76.97	77.24	77.53	77.56	77.57	77.74
RCP4p5.SSP4	63.83	68.46	73.58	75.08	78.50	79.77	80.95	82.04	82.91	84.15
RCP4p5.SSP5	63.83	68.90	73.58	77.03	81.39	83.96	89.03	94.53	99.38	103.56
RCP2p6.SSP1	63.83	68.76	73.58	76.11	78.88	80.47	82.48	84.81	88.13	95.79
RCP2p6.SSP2	63.83	68.72	73.58	74.86	78.16	79.61	81.44	84.08	88.89	97.79
RCP2p6.SSP3	63.83	68.27	73.43	74.58	76.97	77.48	78.11	78.98	83.45	92.33
RCP2p6.SSP4	63.83	68.46	73.58	75.06	78.45	79.73	81.25	82.94	85.95	93.65
RCP2p6.SSP5	63.83	68.90	73.58	77.03	81.40	84.42	89.92	96.15	103.01	103.60

Table A3. Industrial roundwood harvest assortments—Sawlogs (millions of m^3/year, under bark).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP8p5.SSP1	33.00	36.29	40.28	42.37	43.46	44.63	45.97	46.57	47.16	48.01
RCP8p5.SSP2	33.00	36.24	40.07	40.99	42.78	43.82	45.02	45.55	46.29	47.28

Table A3. *Cont*.

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP8p5.SSP3	33.00	35.92	39.35	40.54	41.25	41.45	41.65	41.65	41.65	41.65
RCP8p5.SSP4	33.00	36.03	39.91	40.97	42.48	43.44	44.45	44.83	45.25	45.63
RCP8p5.SSP5	33.00	36.31	40.06	42.37	44.96	47.27	50.89	54.36	57.18	59.51
RCP4p5.SSP1	33.00	36.29	40.28	42.37	43.47	44.64	45.98	46.56	47.16	48.02
RCP4p5.SSP2	33.00	36.24	39.92	40.84	42.43	43.46	44.74	45.31	46.05	47.06
RCP4p5.SSP3	33.00	35.92	39.35	40.54	41.25	41.45	41.65	41.65	41.65	41.65
RCP4p5.SSP4	33.00	36.03	39.91	40.96	42.51	43.54	44.48	44.93	45.28	45.79
RCP4p5.SSP5	33.00	36.31	40.05	42.37	44.96	47.27	50.89	54.35	57.12	59.51
RCP2p6.SSP1	33.00	36.29	40.28	42.37	43.47	44.79	46.06	47.01	49.17	50.83
RCP2p6.SSP2	33.00	36.25	39.92	40.84	42.44	43.61	44.97	46.05	48.15	49.92
RCP2p6.SSP3	33.00	35.95	39.39	40.55	41.27	41.60	41.95	41.95	41.95	41.95
RCP2p6.SSP4	33.00	36.03	39.91	40.94	42.45	43.48	44.55	45.24	46.17	46.83
RCP2p6.SSP5	33.00	36.31	40.05	42.37	44.96	47.59	51.64	55.27	59.20	59.53

Table A4. Industrial roundwood harvest assortments—Pulpwood (millions of m^3/year, under bark).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP8p5.SSP1	30.33	31.98	32.81	33.27	34.95	35.22	35.51	36.37	37.23	37.94
RCP8p5.SSP2	30.33	31.97	33.02	33.38	35.36	35.64	35.94	36.76	37.62	38.36
RCP8p5.SSP3	30.33	31.83	33.54	33.54	35.25	35.32	35.40	35.43	35.43	35.53
RCP8p5.SSP4	30.33	31.93	33.18	33.64	35.21	35.45	35.68	36.24	36.87	37.42
RCP8p5.SSP5	30.33	32.10	33.04	34.19	35.96	36.23	37.68	39.72	41.84	43.60
RCP4p5.SSP1	30.33	31.98	32.81	33.27	34.93	35.21	35.49	36.33	37.19	38.19
RCP4p5.SSP2	30.33	31.97	33.17	33.54	35.26	35.54	35.82	36.64	37.68	38.78
RCP4p5.SSP3	30.33	31.83	33.55	33.55	35.24	35.31	35.39	35.42	35.43	35.60
RCP4p5.SSP4	30.33	31.93	33.18	33.64	35.52	35.75	35.99	36.63	37.15	37.88
RCP4p5.SSP5	30.33	32.10	33.04	34.19	35.96	36.23	37.67	39.72	41.80	43.60
RCP2p6.SSP1	30.33	31.98	32.81	33.27	34.93	35.21	35.95	37.32	38.48	44.49
RCP2p6.SSP2	30.33	31.97	33.17	33.54	35.25	35.53	36.00	37.55	40.27	47.41
RCP2p6.SSP3	30.33	31.83	33.56	33.56	35.22	35.39	35.67	36.54	41.02	49.92
RCP2p6.SSP4	30.33	31.93	33.18	33.64	35.54	35.77	36.22	37.22	39.31	46.35
RCP2p6.SSP5	30.33	32.10	33.04	34.19	35.97	36.36	37.82	40.42	43.36	43.64

Table A5. Harvest of forest residues (millions of m^3/year).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP8p5.SSP1	9.88	16.04	26.19	27.31	31.60	31.60	31.60	31.60	31.60	31.60
RCP8p5.SSP2	9.88	16.21	26.22	27.64	31.50	31.50	31.50	31.50	31.50	31.50
RCP8p5.SSP3	9.88	16.40	25.56	27.05	30.88	30.88	30.88	30.88	30.88	30.88
RCP8p5.SSP4	9.88	15.85	25.66	27.01	31.33	31.33	31.33	31.33	31.33	31.33
RCP8p5.SSP5	9.88	15.94	26.06	26.80	30.65	30.65	30.65	30.65	30.65	30.65
RCP4p5.SSP1	9.88	16.04	26.19	27.31	31.60	31.60	31.60	31.60	31.60	31.60

Table A5. *Cont*.

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP4p5.SSP2	9.88	15.87	25.70	27.12	31.33	31.33	31.33	31.33	31.33	31.33
RCP4p5.SSP3	9.88	16.38	25.54	27.03	30.87	30.87	30.87	30.87	30.87	30.87
RCP4p5.SSP4	9.88	16.19	26.02	27.36	31.46	31.46	31.46	31.46	31.46	31.46
RCP4p5.SSP5	9.88	15.94	26.06	26.80	30.65	30.65	30.65	30.65	30.65	30.65
RCP2p6.SSP1	9.88	16.04	26.19	27.31	31.60	31.60	31.60	33.85	35.12	38.02
RCP2p6.SSP2	9.88	15.87	25.70	27.12	31.33	31.33	31.33	33.58	35.40	38.78
RCP2p6.SSP3	9.88	16.37	25.51	27.01	30.88	30.88	30.88	31.64	33.34	36.71
RCP2p6.SSP4	9.88	16.19	26.02	27.37	31.44	31.44	31.44	33.14	34.29	37.21
RCP2p6.SSP5	9.88	15.94	26.06	26.80	30.64	30.64	30.64	37.25	40.76	40.99

Table A6. Prices—Sawlogs (National average price per m^3, in USD (exchange rate in 2010)).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP8p5.SSP1	64.85	70.52	74.88	82.43	91.12	85.49	86.40	85.95	87.05	87.86
RCP8p5.SSP2	64.85	70.39	72.66	80.36	84.94	82.19	85.49	86.27	85.66	88.89
RCP8p5.SSP3	64.85	70.39	71.61	77.65	80.56	74.21	74.21	74.21	72.56	69.16
RCP8p5.SSP4	64.85	70.39	72.88	81.52	85.18	80.63	81.54	79.53	80.15	79.40
RCP8p5.SSP5	64.85	71.23	78.90	88.63	93.67	92.77	96.10	103.15	130.51	171.57
RCP4p5.SSP1	64.85	70.52	74.84	82.43	91.12	85.49	86.40	85.95	87.05	90.21
RCP4p5.SSP2	64.85	70.39	73.77	81.52	85.06	82.37	85.40	83.87	83.89	90.85
RCP4p5.SSP3	64.85	70.39	71.61	77.65	80.56	74.21	74.21	74.21	71.53	70.41
RCP4p5.SSP4	64.85	70.39	72.66	81.52	85.06	81.04	81.79	79.03	78.48	82.46
RCP4p5.SSP5	64.85	71.23	78.85	88.64	93.67	92.77	96.15	103.26	130.43	173.80
RCP2p6.SSP1	64.85	70.52	74.80	82.43	91.16	86.17	90.46	92.20	89.01	96.93
RCP2p6.SSP2	64.85	70.39	73.79	81.52	85.06	84.14	86.94	91.58	90.44	99.75
RCP2p6.SSP3	64.85	70.39	71.60	77.96	80.56	74.21	74.21	74.36	83.44	93.51
RCP2p6.SSP4	64.85	70.39	72.66	81.52	84.99	82.34	84.24	84.21	88.55	97.07
RCP2p6.SSP5	64.85	71.23	78.89	88.63	93.67	92.77	96.95	119.01	146.46	210.47

Table A7. Prices—Pulpwood (National average price per m^3, in USD (exchange rate in 2010)).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP8p5.SSP1	48.99	54.56	58.93	65.69	68.73	63.11	64.02	63.56	64.67	65.48
RCP8p5.SSP2	48.99	54.44	56.70	64.40	66.63	63.88	63.10	63.88	66.31	67.06
RCP8p5.SSP3	48.99	54.44	55.65	61.69	64.61	58.25	58.25	58.25	56.61	53.20
RCP8p5.SSP4	48.99	54.44	56.93	65.57	66.87	62.32	63.19	61.23	61.85	61.10
RCP8p5.SSP5	48.99	55.27	62.95	68.12	71.28	70.39	73.71	74.85	84.14	90.66
RCP4p5.SSP1	48.99	54.56	58.89	65.69	68.74	63.11	64.01	63.57	64.67	67.82
RCP4p5.SSP2	48.99	54.44	57.82	65.57	66.75	64.07	65.46	65.57	65.57	68.46
RCP4p5.SSP3	48.99	54.44	55.65	61.69	64.61	58.25	58.25	58.25	55.58	54.46
RCP4p5.SSP4	48.99	54.44	56.70	65.57	66.75	62.73	59.40	60.73	60.17	64.16

Table A7. *Cont.*

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP4p5.SSP5	48.99	55.27	62.90	68.12	71.28	70.39	73.76	74.38	82.31	91.24
RCP2p6.SSP1	48.99	54.56	58.85	65.69	68.78	63.79	68.07	69.82	66.62	74.55
RCP2p6.SSP2	48.99	54.44	57.83	65.57	66.75	65.83	66.91	69.19	68.05	77.37
RCP2p6.SSP3	48.99	54.44	55.65	62.01	64.61	58.25	58.25	58.41	67.48	77.56
RCP2p6.SSP4	48.99	54.44	56.70	65.57	66.69	64.03	63.41	65.91	66.26	74.68
RCP2p6.SSP5	48.99	55.27	62.93	68.11	71.28	70.39	74.57	84.34	94.09	138.06

Appendix A.3. Scenario Estimates for Germany

Table A8. Total national harvest (millions of m^3/year, excluding bark, harvesting losses and branches).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP8.5.SSP1	77.57	86.51	90.91	96.56	101.58	106.75	111.96	114.50	116.84	119.07
RCP8.5.SSP2	77.57	86.35	90.37	94.43	98.85	102.77	107.66	110.44	113.44	116.95
RCP8.5.SSP3	77.57	86.04	88.72	91.17	91.74	91.76	91.78	91.78	91.78	91.78
RCP8.5.SSP4	77.57	86.22	90.04	95.10	98.62	102.69	106.15	107.23	108.53	109.55
RCP8.5.SSP5	77.57	86.79	92.65	100.14	109.06	119.26	130.78	131.00	131.01	131.01
RCP4p5.SSP1	77.57	86.51	90.91	96.52	101.55	106.75	111.95	114.43	116.69	120.08
RCP4p5.SSP2	77.57	86.25	90.19	94.27	98.71	102.60	107.56	110.24	113.33	118.16
RCP4p5.SSP3	77.57	86.04	88.72	91.17	91.74	91.76	91.78	91.78	91.78	91.78
RCP4p5.SSP4	77.57	86.27	90.49	95.36	98.96	102.90	106.60	107.61	108.82	110.75
RCP4p5.SSP5	77.57	86.79	92.65	100.15	108.98	119.14	130.47	131.00	131.01	131.01
RCP2p6.SSP1	77.57	86.51	90.88	96.48	101.46	108.66	114.36	122.43	130.94	131.01
RCP2p6.SSP2	77.57	86.25	90.19	94.28	98.71	104.94	110.64	122.19	130.94	131.01
RCP2p6.SSP3	77.57	86.09	88.77	91.24	91.80	92.66	92.69	106.69	129.32	130.99
RCP2p6.SSP4	77.57	86.27	90.51	95.35	99.39	105.27	109.32	119.25	130.92	131.01
RCP2p6.SSP5	77.57	86.79	92.65	100.13	109.00	120.40	130.93	131.01	131.01	131.01

Table A9. Industrial roundwood harvest (millions of m^3/year, under bark).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP8.5.SSP1	64.70	71.40	74.69	78.93	82.69	86.57	90.47	92.37	94.13	95.80
RCP8.5.SSP2	64.70	71.28	74.29	77.33	80.65	83.59	87.25	89.33	91.58	94.21
RCP8.5.SSP3	64.70	71.05	73.05	74.89	75.32	75.34	75.35	75.35	75.35	75.35
RCP8.5.SSP4	64.70	71.18	74.04	77.84	80.48	83.52	86.11	86.93	87.90	88.66
RCP8.5.SSP5	64.70	71.61	76.00	81.61	88.30	95.94	104.57	104.74	104.74	104.74
RCP4p5.SSP1	64.70	71.40	74.69	78.90	82.67	86.56	90.46	92.33	94.02	96.56
RCP4p5.SSP2	64.70	71.20	74.16	77.21	80.54	83.46	87.17	89.18	91.50	95.12
RCP4p5.SSP3	64.70	71.05	73.05	74.89	75.32	75.34	75.35	75.35	75.35	75.35
RCP4p5.SSP4	64.70	71.22	74.38	78.03	80.73	83.68	86.45	87.21	88.12	89.57
RCP4p5.SSP5	64.70	71.61	76.00	81.61	88.23	95.85	104.34	104.74	104.74	104.74
RCP2p6.SSP1	64.70	71.40	74.67	78.87	82.60	88.00	92.27	98.32	104.69	104.74
RCP2p6.SSP2	64.70	71.20	74.16	77.22	80.54	85.21	89.48	98.14	104.69	104.74

Table A9. *Cont.*

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP2p6.SSP3	64.70	71.08	73.09	74.95	75.37	76.01	76.03	86.52	103.48	104.73
RCP2p6.SSP4	64.70	71.22	74.39	78.03	81.05	85.46	88.49	95.94	104.68	104.74
RCP2p6.SSP5	64.70	71.61	76.00	81.60	88.25	96.80	104.68	104.74	104.74	104.74

Table A10. Industrial roundwood harvest assortments—Sawlogs (millions of m^3/year, under bark).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP8.5.SSP1	42.04	46.41	49.67	53.85	57.53	61.01	64.25	65.29	66.62	67.97
RCP8.5.SSP2	42.04	46.24	49.22	52.24	55.45	57.99	61.26	62.39	64.09	66.22
RCP8.5.SSP3	42.04	45.99	47.99	49.83	50.22	50.24	50.25	50.25	50.25	50.25
RCP8.5.SSP4	42.04	46.19	49.03	52.78	55.35	57.81	59.89	60.27	60.97	61.55
RCP8.5.SSP5	42.04	46.76	51.10	56.57	62.39	68.57	75.99	76.60	76.60	76.60
RCP4p5.SSP1	42.04	46.41	49.67	53.81	57.50	61.00	64.24	65.24	66.51	68.12
RCP4p5.SSP2	42.04	46.24	49.16	52.20	55.41	57.93	61.18	62.30	64.05	66.65
RCP4p5.SSP3	42.04	45.99	47.99	49.83	50.22	50.24	50.25	50.25	50.25	50.25
RCP4p5.SSP4	42.04	46.19	49.32	52.92	55.50	57.87	60.13	60.46	61.09	61.62
RCP4p5.SSP5	42.04	46.76	51.10	56.57	62.33	68.49	75.77	76.60	76.60	76.60
RCP2p6.SSP1	42.04	46.41	49.65	53.79	57.44	61.14	64.73	66.93	68.44	68.57
RCP2p6.SSP2	42.04	46.24	49.16	52.20	55.42	58.71	62.21	63.62	66.41	66.58
RCP2p6.SSP3	42.04	46.03	48.04	49.88	50.27	50.82	50.84	50.84	50.85	50.86
RCP2p6.SSP4	42.04	46.19	49.33	52.92	55.88	58.73	60.92	61.72	62.34	62.46
RCP2p6.SSP5	42.04	46.76	51.10	56.56	62.35	68.57	75.15	76.02	76.60	76.60

Table A11. Industrial roundwood harvest assortments—Pulpwood (millions of m^3/year, under bark).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP8.5.SSP1	22.66	25.02	25.02	25.08	25.16	25.56	26.22	27.08	27.51	27.84
RCP8.5.SSP2	22.66	25.07	25.07	25.09	25.20	25.60	25.99	26.94	27.50	27.99
RCP8.5.SSP3	22.66	25.06	25.06	25.06	25.06	25.06	25.06	25.06	25.06	25.06
RCP8.5.SSP4	22.66	25.01	25.01	25.06	25.13	25.71	26.23	26.62	26.89	27.08
RCP8.5.SSP5	22.66	24.88	24.90	25.04	25.94	27.40	28.65	28.43	28.46	28.49
RCP4p5.SSP1	22.66	25.02	25.02	25.08	25.16	25.56	26.22	27.09	27.51	28.44
RCP4p5.SSP2	22.66	24.99	24.99	25.01	25.13	25.52	25.99	26.89	27.45	28.47
RCP4p5.SSP3	22.66	25.06	25.06	25.06	25.06	25.06	25.06	25.06	25.06	25.06
RCP4p5.SSP4	22.66	25.06	25.06	25.10	25.23	25.81	26.33	26.72	26.99	27.95
RCP4p5.SSP5	22.66	24.88	24.90	25.04	25.93	27.39	28.64	28.43	28.46	28.46
RCP2p6.SSP1	22.66	25.02	25.02	25.08	25.16	26.86	27.54	31.42	36.36	36.36
RCP2p6.SSP2	22.66	24.99	24.99	25.01	25.13	26.50	27.27	34.57	38.41	38.42
RCP2p6.SSP3	22.66	25.06	25.06	25.06	25.06	25.16	25.16	35.74	52.75	54.06
RCP2p6.SSP4	22.66	25.06	25.06	25.10	25.17	26.73	27.57	34.25	42.47	42.47
RCP2p6.SSP5	22.66	24.88	24.90	25.04	25.93	28.28	29.64	29.07	28.56	28.56

Table A12. Prices—Sawlogs (National average price per m^3, in USD (exchange rate in 2010)).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP8.5.SSP1	67.88	70.40	68.67	69.69	69.68	69.73	69.76	68.47	68.49	68.47
RCP8.5.SSP2	67.88	70.38	68.40	68.60	68.94	68.90	69.48	68.43	68.70	69.24
RCP8.5.SSP3	67.88	70.10	67.52	67.40	66.19	66.13	66.10	66.10	66.10	66.10
RCP8.5.SSP4	67.88	70.25	68.36	69.19	68.63	68.93	68.68	67.19	67.58	67.54
RCP8.5.SSP5	67.88	70.54	69.61	70.56	71.73	73.67	77.84	120.92	168.22	213.40
RCP4p5.SSP1	67.88	70.40	68.67	69.69	69.68	69.69	69.76	68.47	68.49	69.35
RCP4p5.SSP2	67.88	70.38	68.40	68.62	68.95	68.77	69.46	68.31	68.71	70.07
RCP4p5.SSP3	67.88	70.10	67.52	67.40	66.19	66.13	66.10	66.10	66.10	66.10
RCP4p5.SSP4	67.88	70.38	68.64	69.15	68.61	68.90	68.68	67.39	67.44	67.91
RCP4p5.SSP5	67.88	70.54	69.59	70.56	71.72	73.70	77.77	120.81	166.35	212.86
RCP2p6.SSP1	67.88	70.40	68.67	69.69	69.68	70.56	70.41	72.34	81.46	96.74
RCP2p6.SSP2	67.88	70.38	68.40	68.62	68.95	69.86	69.98	74.14	84.09	104.49
RCP2p6.SSP3	67.88	70.11	67.52	67.42	66.19	66.36	66.13	73.91	82.98	93.05
RCP2p6.SSP4	67.88	70.38	68.69	69.15	68.89	69.77	69.12	72.88	82.27	93.80
RCP2p6.SSP5	67.88	70.54	69.61	70.56	71.72	74.38	83.23	135.97	180.44	231.77

Table A13. Prices—Pulpwood (National average price per m^3, in USD (exchange rate in 2010)).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP8.5.SSP1	50.88	53.23	51.29	52.30	52.22	52.01	52.04	50.75	50.76	50.74
RCP8.5.SSP2	50.88	53.23	51.01	51.22	51.56	51.47	51.76	50.76	50.98	51.52
RCP8.5.SSP3	50.88	52.96	50.35	50.23	49.02	48.96	48.96	48.96	48.96	48.96
RCP8.5.SSP4	50.88	53.10	51.19	51.80	51.24	51.50	51.16	49.72	50.03	49.88
RCP8.5.SSP5	50.88	53.23	52.22	52.97	53.95	55.76	58.73	94.20	102.71	112.45
RCP4p5.SSP1	50.88	53.23	51.29	52.30	52.22	51.96	52.04	50.75	50.77	51.63
RCP4p5.SSP2	50.88	53.23	51.02	51.23	51.56	51.33	51.75	50.65	50.99	52.35
RCP4p5.SSP3	50.88	52.96	50.35	50.23	49.02	48.96	48.96	48.96	48.96	48.96
RCP4p5.SSP4	50.88	53.23	51.25	51.76	51.22	51.47	51.16	49.92	49.90	50.25
RCP4p5.SSP5	50.88	53.23	52.21	52.97	53.93	55.79	58.66	93.34	103.03	107.21
RCP2p6.SSP1	50.88	53.23	51.29	52.31	52.22	52.89	52.69	54.62	63.74	79.02
RCP2p6.SSP2	50.88	53.23	51.02	51.23	51.56	52.39	52.32	56.49	66.42	86.81
RCP2p6.SSP3	50.88	52.96	50.35	50.17	49.02	49.02	48.96	56.77	65.85	75.92
RCP2p6.SSP4	50.88	53.23	51.30	51.76	51.50	52.30	51.57	55.23	64.62	76.15
RCP2p6.SSP5	50.88	53.23	52.22	52.97	53.94	56.51	64.12	116.87	144.24	142.85

Appendix A.4. Scenario Estimates for Finland

Table A14. Total national harvest (millions of m^3/year, excluding bark, harvesting losses and branches).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCPref.SSP1	51.86	52.74	55.77	59.74	62.80	64.29	66.62	69.29	71.85	74.47
RCPref.SSP2	51.86	52.40	55.05	57.74	60.37	61.73	64.02	66.52	69.88	73.02

Table A14. *Cont.*

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCPref.SSP3	51.86	52.59	54.66	56.75	57.24	57.43	57.71	57.75	57.76	57.76
RCPref.SSP4	51.86	51.91	55.11	58.13	60.90	62.24	63.76	65.03	66.65	67.85
RCPref.SSP5	51.86	52.83	56.60	62.46	67.82	72.33	78.59	87.16	94.31	94.93
RCP4p5.SSP1	51.86	52.74	55.76	59.74	62.78	64.25	66.53	69.13	71.75	75.94
RCP4p5.SSP2	51.86	51.91	54.88	57.40	60.18	61.68	64.24	66.72	70.06	75.09
RCP4p5.SSP3	51.86	52.59	54.66	56.72	57.21	57.40	57.68	57.71	57.72	57.73
RCP4p5.SSP4	51.86	52.65	55.40	58.43	61.26	62.50	63.94	65.22	66.83	69.64
RCP4p5.SSP5	51.86	52.83	56.60	62.46	67.82	72.33	78.64	87.47	94.71	94.93
RCP2p6.SSP1	51.86	52.74	55.76	59.74	62.78	64.98	67.98	73.46	80.72	92.54
RCP2p6.SSP2	51.86	51.91	54.88	57.40	60.18	62.51	65.80	71.27	81.31	92.58
RCP2p6.SSP3	51.86	52.59	54.66	56.75	57.24	57.57	58.43	64.05	75.59	89.36
RCP2p6.SSP4	51.86	52.65	55.40	58.41	61.08	62.85	65.08	69.13	78.22	90.56
RCP2p6.SSP5	51.86	52.83	56.60	62.46	67.82	73.38	80.90	92.54	94.93	95.28

Table A15. Industrial roundwood harvest (millions of m^3/year, under bark).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCPref.SSP1	46.45	47.10	49.35	52.31	54.59	55.69	57.43	59.42	61.30	63.20
RCPref.SSP2	46.45	46.85	48.82	50.82	52.78	53.79	55.50	57.35	59.85	62.15
RCPref.SSP3	46.45	46.99	48.53	50.09	50.45	50.59	50.79	50.82	50.82	50.82
RCPref.SSP4	46.45	46.48	48.87	51.11	53.17	54.16	55.30	56.25	57.45	58.34
RCPref.SSP5	46.45	47.17	49.97	54.34	58.32	61.65	66.19	72.42	77.63	78.09
RCP4p5.SSP1	46.45	47.10	49.35	52.31	54.57	55.66	57.36	59.29	61.23	64.27
RCP4p5.SSP2	46.45	46.48	48.69	50.57	52.64	53.75	55.66	57.50	59.99	63.65
RCP4p5.SSP3	46.45	46.99	48.53	50.06	50.42	50.56	50.77	50.79	50.80	50.80
RCP4p5.SSP4	46.45	47.04	49.08	51.34	53.44	54.37	55.44	56.38	57.58	59.68
RCP4p5.SSP5	46.45	47.17	49.97	54.34	58.32	61.65	66.23	72.65	77.92	78.09
RCP2p6.SSP1	46.45	47.10	49.35	52.31	54.57	56.21	58.44	62.47	67.74	76.33
RCP2p6.SSP2	46.45	46.48	48.69	50.57	52.64	54.37	56.81	60.89	68.17	76.37
RCP2p6.SSP3	46.45	46.99	48.53	50.08	50.45	50.69	51.33	55.52	64.01	74.02
RCP2p6.SSP4	46.45	47.04	49.08	51.32	53.30	54.62	56.28	59.29	65.92	74.90
RCP2p6.SSP5	46.45	47.17	49.97	54.34	58.32	62.41	67.87	76.33	78.09	78.34

Table A16. Industrial roundwood harvest assortments—Sawlogs (millions of m^3/year, under bark).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCPref.SSP1	21.08	21.73	23.03	25.00	26.34	27.27	28.51	29.61	30.65	31.89
RCPref.SSP2	21.08	21.48	22.62	23.85	24.93	25.76	26.87	27.87	29.29	30.79
RCPref.SSP3	21.08	21.62	22.53	23.31	23.60	23.69	23.84	23.84	23.84	23.84
RCPref.SSP4	21.08	21.11	22.58	23.93	24.96	25.81	26.73	27.16	27.71	28.17
RCPref.SSP5	21.08	21.80	23.36	26.35	28.78	31.50	34.73	38.67	41.44	41.69
RCP4p5.SSP1	21.08	21.73	23.03	25.00	26.32	27.24	28.45	29.56	30.58	32.68

Table A16. *Cont.*

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP4p5.SSP2	21.08	21.11	22.49	23.60	24.69	25.61	26.92	27.87	29.32	31.92
RCP4p5.SSP3	21.08	21.62	22.53	23.29	23.57	23.66	23.81	23.81	23.81	23.81
RCP4p5.SSP4	21.08	21.67	22.79	24.16	25.19	25.97	26.83	27.26	27.81	28.96
RCP4p5.SSP5	21.08	21.80	23.36	26.35	28.78	31.53	34.76	38.78	41.60	41.69
RCP2p6.SSP1	21.08	21.73	23.03	25.00	26.32	27.38	28.77	31.77	34.49	36.89
RCP2p6.SSP2	21.08	21.11	22.49	23.60	24.69	25.79	27.33	30.28	32.85	36.12
RCP2p6.SSP3	21.08	21.62	22.53	23.31	23.60	23.80	23.97	23.97	23.97	23.98
RCP2p6.SSP4	21.08	21.67	22.79	24.14	25.17	26.04	27.06	28.92	30.19	31.39
RCP2p6.SSP5	21.08	21.80	23.36	26.35	28.78	31.61	35.76	40.75	41.69	41.82

Table A17. Industrial roundwood harvest assortments—Pulpwood (millions of m^3/year, under bark).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCPref.SSP1	25.37	25.37	26.32	27.31	28.25	28.42	28.91	29.81	30.65	31.31
RCPref.SSP2	25.37	25.37	26.20	26.97	27.85	28.03	28.63	29.48	30.56	31.35
RCPref.SSP3	25.37	25.37	26.00	26.77	26.85	26.90	26.96	26.98	26.99	26.99
RCPref.SSP4	25.37	25.37	26.29	27.18	28.21	28.36	28.57	29.08	29.74	30.17
RCPref.SSP5	25.37	25.37	26.61	27.99	29.55	30.15	31.46	33.76	36.19	36.40
RCP4p5.SSP1	25.37	25.37	26.32	27.31	28.25	28.42	28.91	29.74	30.65	31.58
RCP4p5.SSP2	25.37	25.37	26.20	26.97	27.95	28.14	28.74	29.63	30.67	31.73
RCP4p5.SSP3	25.37	25.37	26.00	26.77	26.85	26.90	26.96	26.98	26.99	26.99
RCP4p5.SSP4	25.37	25.37	26.29	27.18	28.25	28.40	28.61	29.12	29.77	30.72
RCP4p5.SSP5	25.37	25.37	26.61	27.99	29.55	30.12	31.46	33.86	36.32	36.40
RCP2p6.SSP1	25.37	25.37	26.32	27.31	28.25	28.83	29.67	30.70	33.25	39.44
RCP2p6.SSP2	25.37	25.37	26.20	26.97	27.95	28.58	29.48	30.60	35.32	40.25
RCP2p6.SSP3	25.37	25.37	26.00	26.77	26.85	26.90	27.35	31.54	40.03	50.05
RCP2p6.SSP4	25.37	25.37	26.29	27.18	28.14	28.58	29.22	30.37	35.73	43.51
RCP2p6.SSP5	25.37	25.37	26.61	27.99	29.55	30.79	32.12	35.58	36.40	36.52

Table A18. Prices—Sawlogs (National average price per m^3, in USD (exchange rate in 2010)).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCPref.SSP1	57.95	59.00	61.75	63.11	61.85	59.91	60.93	61.27	62.86	62.60
RCPref.SSP2	57.95	58.81	61.37	61.59	61.39	59.76	61.11	61.49	62.30	63.29
RCPref.SSP3	57.95	59.00	60.38	60.95	58.56	58.33	58.46	57.95	57.95	57.95
RCPref.SSP4	57.95	58.05	62.48	62.19	61.36	59.43	59.93	59.86	60.30	59.73
RCPref.SSP5	57.95	59.00	63.13	65.55	65.01	65.21	72.41	88.14	117.52	172.52
RCP4p5.SSP1	57.95	59.00	61.75	63.11	61.85	59.91	60.93	61.28	62.88	66.98
RCP4p5.SSP2	57.95	58.05	61.81	61.59	61.41	60.03	61.11	61.00	62.27	66.18
RCP4p5.SSP3	57.95	59.00	60.38	60.95	58.56	58.33	58.46	57.95	57.95	57.95
RCP4p5.SSP4	57.95	59.00	61.76	62.22	61.91	59.40	59.92	59.86	59.82	61.76
RCP4p5.SSP5	57.95	59.00	63.13	65.55	65.01	65.21	72.41	87.60	116.05	175.27

Table A18. *Cont.*

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP2p6.SSP1	57.95	59.00	61.75	63.11	61.85	61.03	61.94	66.60	72.31	81.09
RCP2p6.SSP2	57.95	58.05	61.81	61.59	61.41	61.21	62.17	66.47	74.59	83.91
RCP2p6.SSP3	57.95	59.00	60.38	60.95	58.56	58.46	58.89	64.93	74.01	84.08
RCP2p6.SSP4	57.95	59.00	61.76	62.05	61.35	60.46	61.03	63.39	72.78	81.20
RCP2p6.SSP5	57.95	59.00	63.13	65.55	65.01	66.63	76.17	99.70	143.12	205.38

Table A19. Prices—Pulpwood (National average price per m^3, in USD (exchange rate in 2010)).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCPref.SSP1	40.40	41.46	44.21	45.57	44.31	42.37	43.38	43.73	45.32	45.06
RCPref.SSP2	40.40	41.26	43.82	44.04	43.85	42.21	43.56	43.95	44.76	45.75
RCPref.SSP3	40.40	41.46	42.83	43.40	41.02	40.78	40.91	40.40	40.40	40.40
RCPref.SSP4	40.40	40.51	44.93	44.65	43.82	41.88	42.39	42.32	42.76	42.19
RCPref.SSP5	40.40	41.46	45.58	48.01	47.47	47.67	54.21	54.13	58.07	94.76
RCP4p5.SSP1	40.40	41.46	44.21	45.57	44.31	42.37	43.38	43.73	45.33	48.78
RCP4p5.SSP2	40.40	40.51	44.26	44.05	43.87	42.48	43.56	43.46	44.73	48.63
RCP4p5.SSP3	40.40	41.46	42.83	43.40	41.02	40.79	40.91	40.40	40.40	40.40
RCP4p5.SSP4	40.40	41.46	44.21	44.67	44.36	41.86	42.38	42.31	42.28	44.22
RCP4p5.SSP5	40.40	41.46	45.58	48.01	47.47	47.67	54.21	55.82	64.11	99.61
RCP2p6.SSP1	40.40	41.46	44.21	45.57	44.31	43.49	44.40	49.06	54.35	63.53
RCP2p6.SSP2	40.40	40.51	44.26	44.05	43.87	43.67	44.63	48.93	57.03	66.35
RCP2p6.SSP3	40.40	41.46	42.83	43.40	41.02	40.91	41.34	47.39	56.46	66.54
RCP2p6.SSP4	40.40	41.46	44.21	44.51	43.80	42.91	43.48	45.85	55.24	63.66
RCP2p6.SSP5	40.40	41.46	45.58	48.01	47.47	49.09	57.97	63.02	90.74	130.31

Appendix A.5. Scenario Estimates for Norway

Table A20. Total national harvest (millions of m^3/year, excluding bark, harvesting losses and branches).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCPref.SSP1	10.63	10.95	11.73	12.76	13.64	14.36	15.06	15.80	16.67	16.67
RCPref.SSP2	10.63	10.88	11.51	12.27	13.03	13.76	14.85	15.72	17.01	17.01
RCPref.SSP3	10.63	10.78	10.90	10.97	11.01	11.09	11.13	11.14	11.15	11.15
RCPref.SSP4	10.63	10.93	11.71	12.45	12.92	13.62	14.03	14.67	15.23	15.23
RCPref.SSP5	10.63	11.13	12.56	14.10	15.87	18.13	20.96	24.73	28.95	28.95
RCP4p5.SSP1	10.63	10.95	11.73	12.70	13.63	14.35	15.14	15.84	17.03	17.03
RCP4p5.SSP2	10.63	10.88	11.52	12.26	13.02	13.75	14.84	15.72	17.00	17.00
RCP4p5.SSP3	10.63	10.78	10.99	10.99	11.00	11.07	11.07	11.09	11.24	11.24
RCP4p5.SSP4	10.63	10.93	11.71	12.48	12.97	13.68	14.08	14.62	15.27	15.27
RCP4p5.SSP5	10.63	11.14	12.57	14.10	15.87	18.13	20.96	24.82	29.21	29.21
RCP2p6.SSP1	10.63	10.95	11.73	12.70	13.82	14.90	16.83	18.90	21.93	21.93
RCP2p6.SSP2	10.63	10.88	11.53	12.27	13.16	14.26	16.32	18.86	22.54	22.54

Table A20. *Cont.*

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP2p6.SSP3	10.63	10.78	10.90	11.03	11.25	11.54	12.67	16.03	20.25	20.25
RCP2p6.SSP4	10.63	10.93	11.70	12.46	13.18	13.92	15.64	18.02	21.22	21.22
RCP2p6.SSP5	10.63	11.14	12.58	14.10	16.24	18.99	23.28	27.82	31.46	31.46

Table A21. Industrial roundwood harvest (millions of m^3/year, under bark).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCPref.SSP1	8.27	8.27	8.49	9.01	9.47	9.95	10.38	10.86	11.34	11.84
RCPref.SSP2	8.27	8.27	8.45	8.84	9.19	9.62	10.06	10.72	11.28	12.02
RCPref.SSP3	8.27	8.27	8.38	8.46	8.51	8.54	8.60	8.62	8.63	8.63
RCPref.SSP4	8.27	8.27	8.48	8.97	9.30	9.60	9.99	10.24	10.64	10.99
RCPref.SSP5	8.27	8.27	8.61	9.47	10.20	11.21	13.01	15.22	17.78	20.58
RCP4p5.SSP1	8.27	8.27	8.49	9.01	9.45	9.92	10.36	10.90	11.34	12.20
RCP4p5.SSP2	8.27	8.27	8.45	8.85	9.18	9.60	10.02	10.68	11.24	12.21
RCP4p5.SSP3	8.27	8.27	8.38	8.52	8.53	8.53	8.57	8.58	8.59	8.69
RCP4p5.SSP4	8.27	8.27	8.48	8.97	9.31	9.62	10.01	10.26	10.59	11.05
RCP4p5.SSP5	8.27	8.27	8.61	9.47	10.20	11.21	13.05	15.22	17.83	20.75
RCP2p6.SSP1	8.27	8.27	8.49	9.01	9.45	10.19	10.94	12.46	13.85	15.88
RCP2p6.SSP2	8.27	8.27	8.45	8.85	9.19	9.78	10.72	12.12	13.82	16.28
RCP2p6.SSP3	8.27	8.27	8.38	8.46	8.55	8.70	8.90	9.66	11.92	14.76
RCP2p6.SSP4	8.27	8.27	8.48	8.97	9.31	9.83	10.45	11.65	13.26	15.40
RCP2p6.SSP5	8.27	8.27	8.62	9.47	10.20	12.06	13.90	16.77	19.84	22.28

Table A22. Industrial roundwood harvest assortments—Sawlogs (millions of m^3/year, under bark).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCPref.SSP1	4.31	4.31	4.42	4.69	5.06	5.36	5.62	5.86	6.13	6.44
RCPref.SSP2	4.31	4.31	4.40	4.62	4.89	5.15	5.41	5.79	6.10	6.55
RCPref.SSP3	4.31	4.31	4.37	4.41	4.43	4.45	4.48	4.49	4.49	4.50
RCPref.SSP4	4.31	4.31	4.42	4.69	4.95	5.11	5.36	5.50	5.73	5.92
RCPref.SSP5	4.31	4.31	4.48	4.99	5.52	6.15	6.94	7.92	9.25	10.71
RCP4p5.SSP1	4.31	4.31	4.42	4.69	5.04	5.36	5.61	5.89	6.14	6.56
RCP4p5.SSP2	4.31	4.31	4.40	4.62	4.88	5.15	5.41	5.78	6.09	6.55
RCP4p5.SSP3	4.31	4.31	4.37	4.44	4.44	4.44	4.47	4.47	4.48	4.53
RCP4p5.SSP4	4.31	4.31	4.42	4.69	4.96	5.13	5.38	5.52	5.71	5.93
RCP4p5.SSP5	4.31	4.31	4.49	4.99	5.52	6.15	6.94	7.92	9.28	10.79
RCP2p6.SSP1	4.31	4.31	4.42	4.69	5.04	5.43	5.81	6.48	7.21	8.26
RCP2p6.SSP2	4.31	4.31	4.40	4.63	4.89	5.20	5.58	6.31	7.19	8.47
RCP2p6.SSP3	4.31	4.31	4.37	4.41	4.45	4.53	4.63	4.75	4.79	4.80
RCP2p6.SSP4	4.31	4.31	4.42	4.69	4.95	5.21	5.46	6.07	6.85	7.25
RCP2p6.SSP5	4.31	4.31	4.49	4.99	5.52	6.28	7.24	8.73	10.32	11.59

Table A23. Industrial roundwood harvest assortments—Pulpwood (millions of m^3/year, under bark).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCPref.SSP1	3.96	3.96	4.07	4.32	4.41	4.58	4.77	5.00	5.21	5.41
RCPref.SSP2	3.96	3.96	4.05	4.22	4.30	4.47	4.65	4.93	5.18	5.46
RCPref.SSP3	3.96	3.96	4.02	4.05	4.08	4.09	4.12	4.13	4.13	4.14
RCPref.SSP4	3.96	3.96	4.06	4.28	4.35	4.48	4.63	4.74	4.91	5.07
RCPref.SSP5	3.96	3.96	4.12	4.48	4.67	5.07	6.07	7.30	8.53	9.87
RCP4p5.SSP1	3.96	3.96	4.07	4.32	4.41	4.56	4.75	5.01	5.21	5.64
RCP4p5.SSP2	3.96	3.96	4.05	4.22	4.30	4.45	4.61	4.90	5.14	5.66
RCP4p5.SSP3	3.96	3.96	4.02	4.08	4.08	4.09	4.11	4.11	4.12	4.17
RCP4p5.SSP4	3.96	3.96	4.06	4.28	4.35	4.49	4.63	4.74	4.88	5.11
RCP4p5.SSP5	3.96	3.96	4.13	4.48	4.67	5.07	6.11	7.30	8.56	9.96
RCP2p6.SSP1	3.96	3.96	4.07	4.32	4.41	4.76	5.14	5.97	6.64	7.62
RCP2p6.SSP2	3.96	3.96	4.05	4.22	4.30	4.58	5.14	5.81	6.63	7.81
RCP2p6.SSP3	3.96	3.96	4.02	4.05	4.10	4.17	4.26	4.92	7.13	9.97
RCP2p6.SSP4	3.96	3.96	4.06	4.28	4.35	4.62	4.99	5.59	6.41	8.15
RCP2p6.SSP5	3.96	3.96	4.13	4.48	4.67	5.78	6.67	8.05	9.52	10.69

Table A24. Prices—Sawlogs (National average price per m^3, in USD (exchange rate in 2010)).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCPref.SSP1	68.33	66.67	72.48	75.28	76.67	76.51	76.59	77.77	79.92	82.04
RCPref.SSP2	68.33	66.67	71.68	74.38	74.44	74.90	76.46	78.02	80.39	84.53
RCPref.SSP3	68.33	66.28	69.71	70.28	68.21	68.09	68.25	65.23	67.47	66.34
RCPref.SSP4	68.33	66.80	71.78	74.44	74.31	74.24	74.20	74.13	74.83	74.85
RCPref.SSP5	68.33	67.41	74.08	79.18	81.41	85.93	96.59	101.77	124.77	159.07
RCP4p5.SSP1	68.33	66.67	72.45	75.10	76.67	76.52	76.38	78.51	80.37	83.98
RCP4p5.SSP2	68.33	66.93	70.76	74.38	74.32	75.05	75.71	77.82	80.05	84.53
RCP4p5.SSP3	68.33	66.28	69.70	70.97	70.64	70.64	70.64	66.63	67.99	66.81
RCP4p5.SSP4	68.33	66.54	72.61	74.98	74.71	74.24	74.19	74.13	74.82	78.14
RCP4p5.SSP5	68.33	67.41	74.08	79.18	81.48	85.91	96.59	100.97	124.43	160.18
RCP2p6.SSP1	68.33	66.67	72.41	75.11	76.67	76.82	78.16	77.77	80.54	85.74
RCP2p6.SSP2	68.33	66.93	70.76	74.38	74.32	76.58	75.93	76.89	80.52	88.37
RCP2p6.SSP3	68.33	66.28	69.71	70.31	68.79	68.69	69.57	66.28	75.36	85.43
RCP2p6.SSP4	68.33	66.51	72.57	74.38	74.65	74.24	75.00	74.70	75.41	84.43
RCP2p6.SSP5	68.33	67.43	74.08	79.17	81.48	89.28	95.89	113.78	140.02	185.54

Table A25. Prices—Pulpwood (National average price per m^3, in USD (exchange rate in 2010)).

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCPref.SSP1	34.38	36.18	34.60	34.14	33.89	33.89	33.89	33.89	33.89	34.09
RCPref.SSP2	34.38	36.18	35.47	33.89	33.89	33.89	33.89	33.89	33.89	34.09
RCPref.SSP3	34.38	36.60	35.31	34.67	36.89	37.02	36.84	40.11	37.68	38.90
RCPref.SSP4	34.38	36.04	35.36	33.89	33.89	33.89	33.89	33.89	33.89	33.89

Table A25. *Cont.*

Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCPref.SSP5	34.38	35.38	34.26	33.89	33.89	33.89	34.83	40.98	49.45	54.88
RCP4p5.SSP1	34.38	36.18	34.64	34.09	33.89	33.89	33.89	33.89	33.89	34.83
RCP4p5.SSP2	34.38	35.90	36.46	33.89	33.89	33.89	33.89	33.89	33.89	34.83
RCP4p5.SSP3	34.38	36.60	35.31	34.15	34.26	34.26	34.26	38.58	37.12	38.39
RCP4p5.SSP4	34.38	36.32	34.46	33.89	33.89	33.89	33.89	33.89	33.89	33.89
RCP4p5.SSP5	34.38	35.37	34.26	33.89	33.89	33.89	34.83	40.12	49.98	59.53
RCP2p6.SSP1	34.38	36.18	34.68	34.12	33.89	33.89	34.09	45.24	54.35	63.53
RCP2p6.SSP2	34.38	35.90	36.46	33.89	33.89	33.89	36.09	47.11	57.03	66.35
RCP2p6.SSP3	34.38	36.60	35.31	34.64	36.27	38.71	37.76	47.39	56.46	66.54
RCP2p6.SSP4	34.38	36.35	34.50	33.89	33.89	33.89	33.89	45.85	55.24	63.66
RCP2p6.SSP5	34.38	35.36	34.26	33.89	33.89	35.95	41.98	57.06	71.37	95.06

Appendix B

Material—SweFor

Parameters associated with the facilities are found in Table A26. Other parameters that relate to supply are found in Table A27 and parameters that relate to demand in Table A28 presents the demand-side parameters.

Table A26. Parameters associated with different facility types (for Leontief production function coefficients, see Table A28).

Facility Type	Investment Cost Per Output Unit (SEK) [(a)]	Operating Cost Per Input Unit (SEK) [(b)]	Capital Cost on Capacity (% of Investment Cost) [(c)]	Maintenance Cost (% on Investment Cost) [(c)]
Sawmill pine	3750	700	5%	10%
Sawmill spruce	3750	700		
Sawmill all species	3750	700		
Pulp mill chemical	6500	800		
Pulp mill mechanical	4000	800		
Heating plant	2500	300		

[(a)] Investment costs except for heating plants are from [46] and converted from NOK to SEK. The heating plant investment cost is derived from the per unit capital cost presented by [56]; [(b)] Operating cost is differentiated on input factor; however, in this application it is standardized for all inputs to the same kind of facility. Operating costs except for heating plants are from [46] and converted from NOK to SEK. Operating costs for heating plants is the average for heating plants presented by om [56] and added with 100 SEK per ton TS for fragmenting residues and logs [57]; [(c)] [46].

Table A27. Supply side model parameters including Leontief production function coefficients.

Model Item	Definition
Residues [58]	Allowed if mesic-moist or dryer and slope less or equal to 20% and distance to road less or equal to 500 m.
M^3 to ton TS [59]	0.46 tonTS m^{-3} u.b. (weighted coniferous and deciduous).
M^3 to chips [(a)] [60]	0.261 m^3 m^{-3} u.b. [(b)] after sawing
M^3 to sawdust [60]	0.1019 m^3 m^{-3} u.b. after sawing
M^3 own consumption [60]	0.1 m^3 m^{-3} u.b. used by sawmill internally
M^3 to mech. pulp [61]	0.427 ton m^{-3} u.b. (only spruce)
M^3 to chem. pulp [61]	0.230 ton m^{-3} u.b. (all species)
Ton TS to energy [59]	4.8 MWh $tonTS^{-1}$

Table A27. *Cont.*

Model Item	Definition
Residue extraction to roadside [62]	129 + 0.1879*m, SEK tonTS^{-1} where m is forwarding distance to road in meters.
Transport cost per ton TS [57]	31.824 + 1.4339*km, SEK tonTS^{-1} where km is distance in km measured by Euclidian distance multiplied with a curving coefficient of 1.25 (all transports are in ton TS)

(a) Sawn product is input in m^3 u.b. reduced by chips, sawdust, and own consumption, i.e., 0.5371; (b) Should have been 0.34 causing an overestimate of sawn wood.

Table A28. Demand-side model parameters.

Item	Sawn Wood Pine	Sawn Wood Spruce	Sawn Wood All Spec.	Mechanical Pulp	Chemical Pulp	Energy
No. of (a)	10	7	24	8	27	63
Capacity (a,b)	4.7	4.4	9.9	4.5	10.6	30.2
Price (c)		1900		3600	6400	700
Volume (d)		16		3.5	8.0	24.0
Elasticity (e)		−0.5		−0.5	−0.9	∞
Demand func. steps (f)		1000		1000	1000	1

(a) For sawmills and pulp mills see [63], and for heating plants [64]. (b) Million m^3 for sawn wood, million tons for pulp, and million MWh for energy, all y-1. (c) Price that together with volume defines the demand function for the first period (SEK) [65]. (d) See (b). (e) Can be compared with data in the following sources A = [66]; B = [67]; C = median by of nine past studies in [68]; D = [69] as interpreted by [67]: Sawn wood −0.5 A, −0.17 B, −0.35 C, −0.78 to −0.79 D; newsprint −0.5 A; −0.04 (not sign) B, −0.54 C, −0.14 to −0.24 D; printing and writing paper −0.8 A; −0.53 B, −0.38 C, −0.91; other paper and paperboard −0.3 A, −0.45 B, −0.30 C, −0.15 D. Furthermore [70] reported elasticities in the range of −0.2 to −0.3 for final products in general while [71] used much higher elasticities, −3 for sawn wood and −5 for paper products. Perfectly elastic demand for heating plants is motivated by [66] and by [72] due the lack of impact on energy prices of bioenergy production [73]. (f) The demand function is constructed so that price is divided into equidistant steps in the interval [0.5,1.5] around scenario price, and volume is assigned each step based on step price, elasticity, and scenario volume.

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