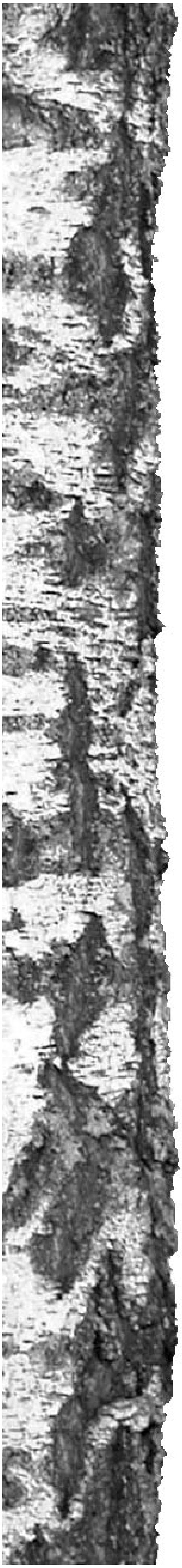

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Model overview and structure

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INA fagrapport 18

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Preface

In this report, the structure of a new forest sector model of Norway, NorFor, is described. NorFor simulates agent behavior in the sector with regard to investment in forestry, supply of timber and harvest residues, forest industrial production, consumption of products and trade between Norwegian regions and with foreign regions.

Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences, has funded the work.

We wish to thank Torjus Bolkesjø for reviewing the report.

Ås, Norway,

June 26, 2011

Summary

Sjølie, H.K., Latta, G.S., Gobakken, T., Solberg, B., 2011. NorFor - a forest sector model of Norway - Model overview and structure. INA fagrapport 18, 15 pp + app. (Sammendrag: NorFor – en skogsektormodell av Norge – modelloversikt og struktur.)

Attention to the important role of the forest sector (i.e. forestry and forest industries) in the carbon cycle and thus climate change mitigation has increased significantly in the last years. However, even though many of the principles regarding trade-offs between carbon sequestration in forests and substitution of fossil fuels and materials with high greenhouse gas (GHG) emissions seem rather clear, there is a lack of models to quantify these effects. Most models focus either on forest growth and management, i.e. the forestry part of the sector, or on industry and raw material allocation to different products. In forming *NorFor*, we attempt to develop an integrated modeling tool encompassing both forestry side and industry side in detail, which can 1) provide projections of the entire forest sector as well as its individual parts, given the objective function, assumptions and constraints; 2) project forest sector impacts of changes in political/economic factors, as well as interactions and interdependencies between the different parts of the sector; and 3) track carbon flows in the sector, from growing trees through harvest, transport and processing, through consumption, substitution and combustion. Endogenous forestry variables in NorFor are forest management and supply of timber and harvest residues. On the industry and consumer side, wood and wood products trade, industrial production and consumption of products, as well as capacity adjustments, are endogenous variables. Thus, wood and wood products prices are endogenous.

Technically, NorFor is a partial, spatial dynamic equilibrium model, based on the assumption that all agents have perfect foresight. NorFor optimizes forest sector welfare by maximizing the present value of discounted producers' and consumers' surplus, as well as environmental benefits like reduced atmospheric greenhouse gas concentration and old-growth forest amenity values, less transport and capital costs.

NorFor was developed to increase climate policy maker's knowledge about how the whole forest sector may contribute to mitigate climate change, but other applications may prove equally important. Norway has a long history of applying forest sector models to study forest policy effectiveness and sectoral impacts of a wide range of political and economic factors. Unlike models emphasizing industry (where management and investment in forestry are exogenous) or forest growth models (to which prices and allocation of timber are exogenous), this model is designed to also examine the interactions between these two

subsectors. It is the hope of the authors that NorFor will provide useful insight in political, economical and environmental aspects of the Norwegian forest sector.

Sammendrag

Sjølie, H.K., Latta, G.S., Gobakken, T., Solberg, B., 2011. NorFor - a forest sector model of Norway - Model overview and structure. INA fagrapport 15, 19 pp + app. (Sammendrag: NorFor – en skogsektormodell av Norge – modelloversikt og struktur.)

Oppmerksomheten på skogsektorens (dvs. skogbruk og skogindustri) viktige rolle i karbonsyklusen, og derved sektorens muligheter for å avhjelpe klimaproblemet, har økt betydelig de siste årene. Det har imidlertid vært utviklet få modeller som kan brukes i kvantifisering av avveiningene mellom karbonopptak i skog og substitusjon av materialer med høye klimagassutslipp, selv om prinsippene bak disse avveiningene i stor grad er klare. De fleste modeller fokuserer enten på tilvekst og skjøtsel i skog, altså på skogbruksdelen av sektoren, eller på industrien og allokeringen av råvarer til ulike produkter. *NorFor*-modellen er resultat av forsøk på å utvikle et integrert modellverktøy som inkluderer både skogbruksdelen og industridelen i detalj, og som kan 1) frembringe prognoser både for hele skogsektoren og for individuelle deler, gitt objektfunksjonen, forutsetninger og skranker; 2) estimere effekter på skogsektoren av endringer i politiske/økonomiske faktorer, i tillegg til interaksjoner og avhengighet mellom ulike deler av sektoren; og 3) følge karbonstrømmene i sektoren, fra trær i vekst via avvirkning, transport og prosessering, til konsum, substitusjon og forbrenning. Endogene variable i skogbruksdelen i NorFor er skogskjøtsel og tilbud av tømmer og hogstavfall. På industri- og konsumentsiden utgjør handel av tømmer og treprodukter, produksjon i industrien, konsum av produkter og kapasitetstilpasninger de endogene variablene. Prisene på tømmer og treprodukter er altså endogene.

Teknisk sett er NorFor en partiell og romlig dynamisk likevektsmodell, basert på forutsetningen om at alle aktører har perfekt forhåndskunnskap. NorFor optimaliserer velferden i skogsektoren ved å maksimere nåverdien av diskonterte konsument- og produsentoverskudd, i tillegg til miljøgoder som redusert akkumulering av klimagasser i atmosfæren og verdien av gammelskog, fratrukket transport- og kapitalkostnader.

Et viktig formål med utviklingen av NorFor er å øke kunnskapen til politikere og andre involvert i klimapolitikk om hvordan hele skogsektoren kan brukes til å avhjelpe klimaproblemet, men andre anvendelser kan være like viktig. Norge har lange tradisjoner for å anvende skogsektormodeller for å analysere skogpolitiske virkemidlers effektivitet, og effekter på sektoren av endringer i ulike politiske og økonomiske faktorer. Til forskjell fra modeller som kun fokuserer på industrien (som har skogskjøtsel og investeringer i skogbruk eksogent) eller tilvekstmodeller (som har priser og allokering av tømmer eksogent), er denne modellen utviklet for også å studere interaksjoner mellom disse to delsektorene. Forfatterne håper at NorFor vil gi nyttig informasjon i politiske, økonomiske og miljørelaterte spørsmål i den norske skogsektoren.

Content

Introduction

This report provides documentation of NorFor, a model of the Norwegian forest sector – i.e. the forestry and forest industries in Norway. NorFor is a partial, spatial, dynamic equilibrium model which simulates optimal agent behavior in the forest sector. The model projects harvest and investment in forestry, investment and production in industry, consumption of wood products as well as trade given the objective function for a range of assumptions and constraints. NorFor was developed in 2009-2011, at the Norwegian University of Life Sciences (UMB) and at Oregon State University (OSU) to improve the analyses of the effects of using the Norwegian forest sector to mitigate climate change, and to make possible consistent analyses of effects on the forest sector of changes in political and economic frames. The time scope of model analyses is the medium to long term (30-100 years).

Forests are a major factor in national carbon accounting in many countries, and attention on the importance of forests in the carbon balance and their potentials to further mitigate climate change has grown significantly during the last years. The forest sector contributes to climate change mitigation in two primary ways: As a carbon sink during forest growth and as a provider of materials for replacement of more carbon/energy intensive materials and fossil fuels. The trade-off between those two mitigation options has in principle been clear for long time; however few studies have looked into those effects quantitatively in a consistent way. There are several reasons why a bio-economic model like NorFor may provide useful insights into those questions: First, forests are an economic asset, providing income to forest owners and producing raw materials for industry production. In addition, the costs of mitigation are of considerable interest for the society. Thus, analyses of the forest's potential contribution in climate change mitigation have to include economic aspects in order to go beyond technical/maximum potential considerations. Third, large-scale policies may have substantial market impacts which are of interest to clarify. Fourth, forests and forest management may often involve important biological/ecological interactions which, whenever sufficient empirical data is available, should be included to get realistic analyses.

In Norway, during the last five decades, several long-range timber supply models and forest sector models have been developed and used. The first computerized long-range timber supply model (Gotaas, 1967) used rather simplified forest growth estimates. The first models to incorporate forest yield functions were AVVIRK1 and AVVIRK2, (Hobbelstad, 1979; 1981). These models had a subroutine estimating the maximum sustainable yield – i.e. the highest annual harvest quantity which, for a given forest management investment intensity, could be maintained without being reduced in later periods. The models initially dealt with timber volumes only, but Hobbelstad (1988) included revenues and costs, thus making the model AVVIRK3. This model was improved by Eid and Hobbelstad (1999) into the model AVVIRK2000, which still is in use today.

The first long-range forest optimization model applied in Norway, GAYA-LP, was introduced by Hoen (1990) and based on the GAYA stand model concept developed in Sweden by Eriksson (1987). The Norwegian version, documented in Hoen and Eid (1990), included carbon sequestration, and was one of the first optimization models to analyze optimal forest management strategies with carbon sequestration values included (Hoen and Solberg, 1994). The model initially used the MINOS solver, but later changed to the JLP solver of Lappi (1992), resulting in the model GAYA-JLP. This model evolved into the model GAYA-J/C with the addition of substitution effects, the soil model YASSO (Raymer, 2005; Raymer et al., 2009) and the J-solver (Lappi, 2003).

At the same time, several forest sector models (i.e. models which included both forestry and forest industries) emerged. The first was the SOS model, a pure simulation model based on the DYNAMO system modeling approach (Randers, 1977; Randers et al., 1978). The IBRD model, a dynamic optimization model developed by the World Bank, was later adapted to Norway by Gundersen and Solberg (1984). This model minimized the costs of producing exogenously specified quantities of forest industry products, and did as such not secure market clearance. The next models introduced were the partial equilibrium models NTM I (Trømborg and Solberg, 1995) and NTM II (Bolkesjø, 2004; Bolkesjø et al., 2006), based on the models GTM (Kallio et al., 1987), the Finnish SF-GTM (Ronnila, 1995) and the EFI-GTM (Kallio et al., 2004). These models simulate forest sector competitive markets assuming limited information, in the sense that after obtaining market equilibria through optimization in period t, the period's forest industry capacities and forest growing stocks are inputs for the equilibria calculated for period t+1. This type of models can be classified as recursive models having limited (or non-perfect) agent foresight. The primary difference between NTM I and II is that the latter has a more detailed inclusion of bioenergy. In addition to these partial modeling efforts, the full equilibrium model MSG was used in the mid 1980s to analyze how forestry and forest industries in Norway would be affected by the development of the Norwegian oil and gas activities (Solberg, 1985; 1986).

Unlike the Norwegian models described above, NorFor integrates silviculture, forest investment, harvest, industrial investment, forest products manufacturing as well as demand for final products. This is an advantage for determining potential interactions between forestry and the wood products market, as interdependences and adaptations to changes may be found, in the carbon sector, but also for other forest sector topics. Economic or political changes in the market may influence forest management, and this altered forest management may impact the market due to changes in e.g. species composition and timber quality. Because of model limitations, such interactions have been only partly studied in Norway. Some similar studies have been carried out in other countries, as the various FASOM analyses of the U.S. agriculture and forest sectors (e.g. Adams et al., 1999; Alig et al., 2010), timber market analyses in Oregon and Washington (Adams and Latta, 2005; 2007) and studies of impacts on management and markets of global forest carbon payment programs (Sohngen and Mendelssohn, 2003), although the latter study does not specifically include forest industries.

This report provides a technical description of NorFor. A report describing the data used in NorFor, as well as in the NTM III, is already published in the same series (Trømborg and Sjølie, 2011). This report is purely descriptive, but a discussion of the model is provided in Sjølie (2011).

Technical description

Overview

NorFor is an intertemporal partial, spatial equilibrium model of the Norwegian forest sector. The model maximizes welfare for all periods simultaneously implying that all agents possess perfect information of all relevant factors past and present thus providing the optimal potential of the forest sector given a set of market conditions. The model is solved by the use of linear programming in the GAMS software. The model is partial as it is built up on the assumption that the forest sector does not impact on the rest of the economy, and costs of inputs other than wood, like capital and labor, are independent of forest sector activity. Spatially, the model is divided into 19 domestic regions following the Norwegian county borders (Figure 1) and two foreign regions.

In an equilibrium model, supply and demand has to balance. Prices and quantities of final products are derived from the optimal solution, while prices of logs and intermediate products arise in the shadow prices. The demand for final products coupled with the input-output matrix of processing give the quantities of input factors (wood and non-wood). The model provides the optimal allocation of wood and products, given the objective function, assumptions and constraints. The default objective function is maximization of the welfare in the sector, i.e. consumer surplus plus producer surplus (profit + non-monetary values) plus value of net carbon sequestration minus costs of transport and investment.

NorFor is to a large extent based on three other models, the models Gaya and NTM II described above and the Regional Models of Oregon (Adams and Latta, 2005; 2007). The NTM models with their detailed representation of the forest industry have been applied extensively in Norway to study impacts of political and economic changes. However, in these models basic fiber supply is rather roughly modeled with exogenous timber supply curves based on growing stock, increment, log prices and the current forest management/investment in each region. In the NTM I and II, each period is independently optimized in a temporal recursive process, without considering future periods. The development of NorFor can be seen as an extension of the NTM with an endogenous forest growth model with various forest management options and converting the assumption of information from myopic to perfect foresight.

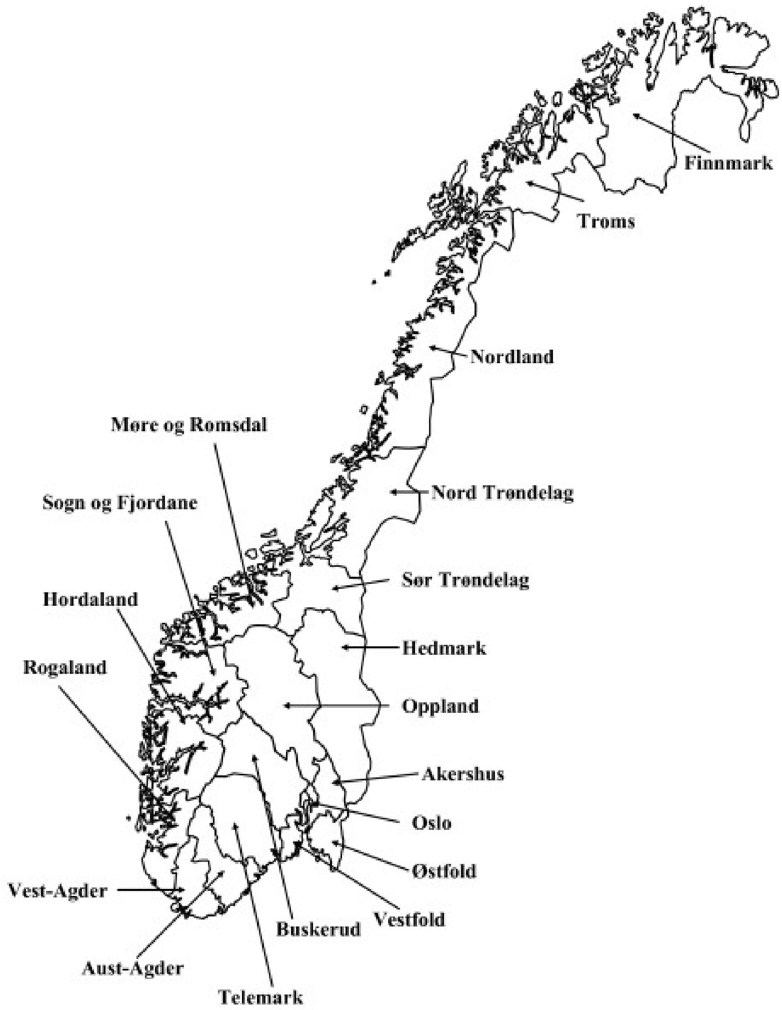

Figure 1: Norwegian counties defining the NorFor regions. Map from Johansen et al. (2007).

Gaya is a stand simulator parameterized to Norwegian forest conditions that can be applied together with the linear programming module JLP and J/C to determine the optimal stand level management. Gaya simulates the stand growth and yield with different management regimes based on preset criteria for when a certain management may take place. In Gaya-JLP, the optimal management for a forest area is found with predetermined wood prices and costs. In NorFor, Gaya is used to simulate the yield tables for a variety of different management regimes which are then incorporated in NorFor and optimally allocated incorporating the industry and consumption interactions. Thus, NorFor can also be seen as an extension of Gaya-JLP and Gaya-J/C to include industry with endogenous prices and allocation of wood.

The forest industrial structure in NorFor is based on NTM II, with the sawnwood industry represented at the regional level while the board, pulp and paper industries are represented at the mill level. Bioenergy use in industry, businesses and households is included in NorFor as in the NTM II, with some modifications.

NorFor is designed to fill a gap between the NTM's short to medium run analyses of the forest industry and consumption and Gaya's long-term planning horizon which does not take market changes into account. NorFor can also be applied to study more theoretical aspects.

The period length in NorFor is five years and the optimization horizon is adjustable according to the objective of each analysis. The model consists of four subsectors: forest growth and management; industry and consumption; transport and trade; and carbon accounting. Each of these parts is described in the following.

For clarification, primary exogenous data and variables are listed in Table 1. The appendix displays the mathematical model specification.

Table 1: Groups of data and variables in NorFor.

Sub-sector	Data	Variables
Forest growth and management	Growth and yield in different management regimes, costs of silviculture and harvest, amenity value	Land allocation to various management regimes, harvest, inventory
Forest industry production and consumption of forest industry products	Demand functions: GDP as a proxy for income and population increase, elasticity w.r.t. GDP and price; Production input factors, costs and quantity of exogenous inputs, capacity	Demand for final products; Production of industrial products
Trade	Costs	Interregional trade
Carbon	Biomass functions, carbon and decay functions; Greenhouse gas emissions from variable levels	Carbon stock and fluxes

Underlying theory

The fundamental basis for NorFor is two distinct economic theories: Samuelson's theory (Samuelson, 1952) on net social payoff represented as the basis for the interregional trade in spatial equilibrium models, and the theory for economically optimal harvest age as put forward by Faustmann (1849) and Pressler (1860) for even-aged stands and the optimal use of forest resources when the growing stock has a value in itself (Hartman, 1976). Samuelson stated formally the objective function and necessary conditions for when the net social payoff (producer surplus plus consumer surplus minus transport costs) is maximized in interconnected competitive markets with associated transport costs. By making transport between the regions endogenous, agents maximize their surplus and thereby (unintentionally) the net social pay-off.

Models that intertemporally optimize net present value assume that agents possess full information about all future conditions, anticipate all market changes perfectly, and allocate forest land accordingly. These optimal decisions inherently consider all foregone activities and thus also capture opportunity costs.

NorFor includes three distinct markets; raw materials including timber and harvest residues, intermediate goods and final products. Timber supply is determined by the optimal forest management given growth in current and future stands, current and future prices, interest rate, logging and transportation costs, silvicultural costs, as well as amenity and carbon values. Harvest residues supply is determined by supply costs and market prices for chips. Supply and demand for intermediate goods are determined by industrial input/output coefficients that describe industrial production possibilities. Final product supply and demand can be based on either fixed levels or determined endogenously through quantity dependent curves.

Dynamic features

The model simulates markets where agents are assumed to optimize their behavior over the modeling time horizon, possessing perfect information about all relevant aspects. Market shocks, by definition, are unforeseen occurrences and thus unknown to agents. Intertemporally optimizing, perfect foresight models applications to analyze market impacts of such shocks can be problematic. However, solution methods exist that limit model foresight and NorFor can be adapted to accommodate imperfect information (Sjølie et al., 2011).

Harvest scheduling problems such as the timber supply side of NorFor have notorious problems with terminal valuations. Since forest owners do not get paid within the time horizon for investments undertaken in later periods, behavior disturbances in time periods leading up to the end of the modeling time horizon may occur. We mitigate this problem in two ways: we run the model longer than the analyzed time horizon to push any terminal impact out of the ”policy relevant” period, and we include terminal conditions. A terminal condition is that the post-harvest inventory in the last period should be at least 75% of the initial inventory.

Forest growth and management

The forest growth and yield in NorFor is based on the National Forest Inventory (NFI) data ("Landsskogtakseringen") and simulations done with the stand simulator Gaya (Hoen and Eid, 1990). In Gaya, a set of criteria for each management activity[1] is exogenously set, as described in Hoen (1990). For each stand, the growth and yield is simulated for all possible combinations of management activities, management regimes. Hence, each plot has a set of management regimes.

Following the terminology of Johnson and Scheurman (1977), the forest management model applied here is of Model II type, with some modifications. In their definition, an age class forms a management unit from its regeneration until final harvest. Harvest can take place on the whole or a part of the plot. Once an area is harvested, it goes into a pool, is regenerated and forms a new management unit until it is harvested again. The new stand is completely independent on the conditions in the old stand before harvest. For some stands in NorFor, shelter wood/seed tree cut is an option, and in this case, there is inter-dependency between the units. Another distinction from the classical Model II is the pools to which the harvested areas go after harvest, which in NorFor is on plot level. Three sets of variables describing the management of subsequent stands are included; one for forest existing at the first period, one for regenerated stands and one for re-regenerated stands (stands regenerated more than once).

A management regime for existing forest stands and timing of final harvest is selected for each hectare of forest in NorFor as a part of the optimization. After each final harvest, a regeneration scheme and a new management regime is chosen. To leave the land with no regeneration is not an option. However, no clear cut is possible for all stands. For all stands, the management regime “no management” is an option.

Industry and consumption

Following Bolkesjø (2004) the NorFor’s pulp, paper and board industries are specified at the mill level, while bioenergy and the sawn wood industry are modeled at the regional level. The industry, trade and consumption designation in NorFor is primarily based on the NTM II with minor changes for the traditional forest industry, but more for the bioenergy industry. The bioenergy carriers, i.e. fire wood, pellets and chips, are here intermediate products which can be used in different combustion technologies. For each intermediate or final product, at least one technology, i.e. an input mix of production factors with endogenous

[1] "Management activity" here means one specific action undertaken in the forest stand between regeneration and final harvest (e.g. precommercial thinning). "Management regime" refers to a set of management activities which can successively be undertaken in a stand. Management activities include precommercial thinning, thinning and shelter wood/seed tree cut.

and exogenous prices, together with byproducts manufactured and capacity constraints, is given. Figure 2 displays the product flow in the industry.

Input factors are divided into price-sensitive and fixed price inputs with price sensitive wood, intermediate wood products and harvest residues, while the costs of non-wood input factors are exogenously determined. These factors include capital, labor, energy and "other costs". Upward sloping cost functions for extending distribution nets for district heating can be accommodated, yet this is not done for the current version of the model.

Industrial capacity changes are also modeled differently in NorFor than in NTM II, the investment decision being fundamentally different in the two models. For capacity adjustments in NorFor, capital costs are weighted against all future benefits of the investment. Three types of capacity costs are incorporated: capital rent, maintaining and expanding capacity. The capital rent occurs for all installed capacity. Capacity is depreciated at a fixed rate, however industry may pay a maintenance cost to avoid this depreciation. Furthermore, industrial agents can invest in new capital stock, with all investment costs paid in the year of the investment. This cost associated with expansion of capacity is more expensive than simply maintaining capacity.

Domestic and foreign demand for final products is indirectly the driver for harvest, via the forest industry. The demand is a function of the exogenous GDP and elasticity of demand with regard to GDP, as well as the price elasticity.

Domestic and international transport and trade

The 19 Norwegian counties form the domestic regions with trade in raw materials and products possible between each other. Two foreign pure trade regions with no industry production representing the western part of Sweden which traditionally has extended border trade with Norway as well as the rest of the world are also included. Trade between two counties takes place as long as the price difference of the good in the two counties exceeds the transport costs, as shown by Samuelson (1952). As long as no binding constraint is imposed, the equilibrium prices in the regions differ by only the transport costs. The transport costs in NorFor are exogenous, and for each bilateral trade, the cheapest option among road, boat and railway is chosen.

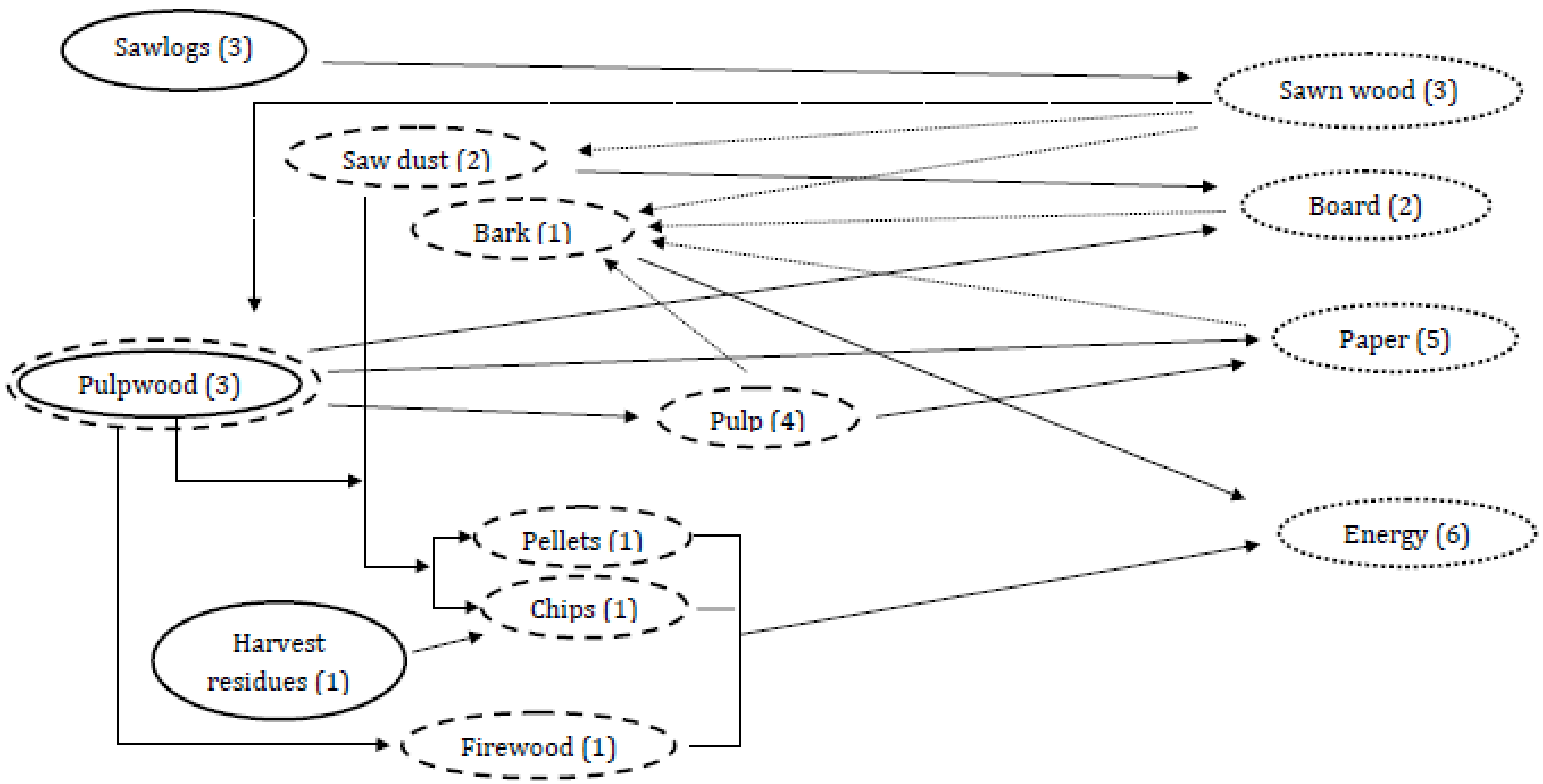

Figure 2: Product flow in the forest industry in NorFor. The solid circles refer to raw materials, the dashed to intermediate products and the dotted to end products. The lines refer to processes and the dotted lines to the production of byproducts. The numbers in parenthesis indicate the number of products in each group.

GHG accounting

GHG accounting part is an integral feature of NorFor. Detailed inclusion of the forest resource at the inventory plot level as well as accounting of industrial manufacturing along with consumption, bioenergy GHG flow and substitution in the whole sector has been included as accurately as possible. The following GHG accounts, or pools, are included in the model:

1. Forest growth and decay:

a. CO_2 sequestered during growth and stored in stem, bark, tip, branches (living and dead), needles, stump, coarse and fine roots

b. CO_2 emitted over time from harvest residues (tip, branches, needles), and from stump and roots in harvested stands

c. Reduced CO_2 emissions from harvest residues when these are taken out of the forest after harvest for energy purposes

2. Transport and machinery:

a. GHG[2] emissions from silviculture

b. GHG emissions from the use of harvester and forwarder during harvest operations

c. GHG emissions from transport of timber and wood products

3. Processing:

a. GHG emissions from industrial processing

4. End use:

a. GHG emitted over time from final products decaying on landfills or combusted in large facilities

b. Reduced GHG emissions due to substitution of fossil fuels and materials

The inclusion of GHG values in the objective function ensures that these costs and benefits are an integral part of all forest and industry decisions. GHG values are determined based on the periodic GHG flux, or change, compared to a baseline level and the assumed carbon price. GHG fluxes are calculated in two steps: First, the 5-year periodic carbon stock in each pool is found, and the annual flux is then calculated. The periodic carbon flux is computed as

[2] Included GHG are mainly CO_2, while other gases are included where provided by LCA data.

the difference between the current period's preharvest levels and the previous period's preharvest levels. This means that accounting varies by pool. Forest carbon flux is simply the preharvest level from a period minus the preharvest level from the previous period. On harvest, all removals from the forest growing stock, stems and other biomass parts alike, are emitted from the forest carbon pool. Harvest residues remaining in the forest which are not yet decayed are however added to the harvest residue pool, while harvest residues taken out of forest are added to another pool. GHG emissions from harvest, hauling and industrial processing are included based on LCA data. As all wood carbon is assumed emitted when harvested, the wood products pool includes carbon stored in products still in use. Substitution effects from utilization of solid wood and bioenergy are also included. All solid wood and paper products going out of use are assumed being combusted in heating facilities, yielding also a substitution effect.

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Appendix: Mathematical specification of the NorFor model

With the constraints and symbols defined at the end of this appendix, the NorFor model is specified as follow:

Objective function: Maximize

$$\sum_{t=1}^{T-1} [\sum_{r}\sum_{fp} D_{r,fp}\left(Q_{r,fp,t}\right) + \sum_{fr}\sum_{p} D^{F}{}_{fr,p}\left(Q^{FD}{}_{fr,p,t}\right) + \sum_{l}\sum_{r} Inv_{l,r,p} * am + \text{Carbon*CP}$$
$$-\sum_{fr}\sum_{p} S^{F}{}_{fr,p}\left(Q^{FS}{}_{fr,p,t}\right) - \sum_{r}\sum_{l}\sum_{cf} FC_{r,cf} \times H_{r,l,cf,t} - \sum_{r}\sum_{ip}\sum_{m}\sum_{f} EC_{r,t,f} \times R_{ip,r,m,f} \times PR_{ip,r,m,t}$$
$$-\sum_{r}\sum_{ip}\sum_{m} IC_{r,ip} \times (Ck \times C_{r,ip,m,t} + Cm \times CM_{r,ip,m,t} + CB_{r,ip,m,t}) - \sum_{ar}\sum_{ar2}\sum_{p} TC_{ar,ar2,p} \times TR_{ar,ar2,p,t}$$
$$] (1+i)^{-t}$$

subject to:

(1) $\sum_{XM}\sum_{t} EX_{pl,t,XM} = HA_{pl}$ $\quad\forall$ pl

(2) $\sum_{XM} EX_{pl,t,XM} = \sum_{t2}\sum_{XM}\sum_{NM} NEW\_XN_{pl,t,t2,XM,NM}$ $\quad\forall$ t, pl

(3)
$$\sum_{t2}\sum_{XM}\sum_{NM} NEW\_XN_{pl,t,t2,XM,NM} + \sum_{t2}\sum_{NM}\sum_{NM2} NEW\_NN_{pl,t,t2,NM,NM2} = \sum_{t2}\sum_{NM}\sum_{NM2} NEW\_NN_{pl,t,t2,NM,NM2}$$

$\forall$ t, pl

(4) $H_{r,l,cf,t} + Q^{FS}_{fr,p,t} + \sum_{ar2} TR_{ar2,ar,p,t} - \sum_{ar2} TR_{ar,ar2,p,t} - WD_{p,r,t} + \sum_{m} PR_{p,r,m,t} -$

$\sum_{m}\sum_{p} R_{ip,r,m,p} \times PR_{ip,r,m,t} - Q^{FD}_{ip,r,m,t} = Q_{p,r,t}$ $\quad\forall$ t, p, r

(5) $C_{ip,r,m,t-1}(1-dr) + CM_{ip,r,m,t} + CB_{ip,r,m,t} = C_{ip,r,m,t}$ $\quad\forall$ t, ip, r, m

(6): $CM_{r,ip,m,t} \le C_{ip,r,m,t-1}(1-dr)$ $\quad\forall$ t, ip, r, m

(7): $PR_{ip,r,m,t} \le C_{ip,r,m,t}$ $\quad\forall$ t, ip, r, m

(8): $CB_{r,ip,m,t} \leq CMax_{r,ip,m}$ $\forall$ t, ip, r, m

Explanation of constraints:

(1): Allocation of existing forest

(2): Harvested existing stands go into a new management regime

(3): Regenerated and re-regenerated stands go into a new management regime

(4): Balance of wood inputs and outputs in industry

(5): Capacity adjustments between periods

(6): Maximum capacity maintenance

(7): Production cannot exceed capacity

(8): Maximum limit for new capacity

Definition of symbols:

Sets

ar, ar2: all regions, within and outside Norway

cf: Forestry cost factor, i.e. costs of logging (final harvest and thinning) and silviculture

f: costs in industry of input with exogenously determined prices

fp: final products, i.e. with a demand function in Norwegian regions

fr: foreign regions

ip: industrial product, i.e. intermediate and final products from industrial production

l: log products

NM, NM2: Management regimes for forest land harvested at least once

r: regions within Norway

t: periods

T: last period

XM: Management regimes for existing forest lands, i.e. lands which have not yet been clear-cut

Scalars

am: amenity value

Ck: Costs of keeping capacity as a share of IC

Cm: Costs to maintain capacity as a share of IC

CP: carbon price

dr: depreciation rate in industry

i: discounting rate

Parameters

$CMax_{r,ip,m}$: Maximum capacity for all periods

$FC_{r,cf}$: Forestry costs in region *r* and of cost factor *cf*

$EC_{r,t,f}$: Exogenous costs in industry, in region *r*, period *t* and of factor *f*

HA_{pl}: Area in each forest plot

$IC_{r,ip}$: Costs of building new capacity in region *r* and for industrial product *ip*

$R_{ip, m, f}$: Input ratio of factor *f* to production of industrial product *ip* and in technology *m*

$TC_{ar,ar2,p}$ *:* Costs of transport a product from region *ar* to region *ar2*

Variables

$C_{r,ip,m,t}$: Capacity level in region *r*, of industrial product *ip* and of machines *m*

$CB_{r,ip,m,t}$: New capacity in region *r*, of industrial product *ip* and of machines *m*

$CM_{r,ip,m,t}$: Maintained capacity in region *r*, of industrial product *ip* and of machines *m*

Carbon: Net carbon sequestrated in the last period

$D_{r,fp}\left(Q_{r,fp,t}\right)$: Area under the demand curve for final product *fp* in region *r* as a function of volume *Q*

$D^{F}{}_{fr,p}\left(Q^{FD}{}_{fr,p,t}\right)$: Area under the demand curve for product *fp* in the foreign region *fr* as a function of volume Q^{FD}

$EX_{pl,t,XM}$: Area in plot *pl* allocated to management regime *XM* and harvested in period *t*

$H_{r,l,cf,t}$: Harvest in region *r*, of log product *l* with forestry cost factor *cf* in period *t*

$Inv_{l,r,p}$: Growing stock of log product *l*, in region *r* in period *p*

$NN_{pl,t,t2,NM}$: Area in plot *pl* allocated to management regime *NM*, re-regenerated in period *t* and harvested in period *t2* (after been through XN) $NN_{pl,\ t,\ t2,\ XM,}$

p: products, including logs, and industrial products (intermediate and final products)

$PR_{ip,r,m,t}$: Production of industrial product *ip*, in region *r*, in machines *m* in period *t*

$S^{F}{}_{fr,p}\left(Q^{FS}{}_{fr,p,t}\right)$: Supply function for product *p* in the foreign region as a function of volume Q^{FS}

$TR_{ar,ar2,p,t}$: Transport of product *p* from region *ar* to region *ar2* in period *t*

$WD_{p,r,t}$: Wood debris of product *p*, in region *r* and in period *t*

$NEW\_XN_{pl,t,t2,XM,NM}$: Area in plot *pl* allocated to management regime *NM*, allocated to management regime XM before harvest, harvested and regenerated in period *t* and harvested in period *t2*

$NEW\_NN_{pl,t,t2,NM,NM2}$: Area in plot *pl* allocated to management regime *NM2*, allocated to management regime NM before harvest, harvested and regenerated in period *t* and harvested in period *t2*