GLOBIOM-forest documentation

1. GLOBIOM-forest model

Global Biosphere Management Model (GLOBIOM) is a global spatially-explicit agricultural and forest sector model (Havlik et al. 2011, 2014). GLOBIOM-forest is a version of GLOBIOM where the forest sector is modeled more detailed than in the main model (Lauri et al. 2014, 2017, 2019). The model includes two simplifications relative to main model: 1) No food and feed production. 2) Land-use is based on geographical grids instead of simulation units. The model is solved recursively for each 10-year period by maximizing the economic surplus. The supply side of the model is based on the 0.5° grid resolution while the demand side and trade on 59 economic regions. The simplified structure of the GLOBIOM-forest allows to solve the model also by intertemporal optimization instead of recursive optimization and by higher resolution than 0.5° grid, but these features are currently under development.

The model separates between coniferous (C), non-coniferous (NC) and recycled (R) biomass and includes altogether 38 wood-based products. The forestry module includes 10 harvested products (C/NC pulpwood, C/NC sawlogs, C/NC other industrial roundwood, C/NC fuelwood, C/NC logging residues) and 2 non-harvested products (C/NC deadwood). The forest industry module includes 4 paper and paperboard grades (newsprint, printing and writing papers, packaging materials, other papers), 6 pulp grades (C/NC chemical pulp, C/NC mechanical pulp, recycled pulp, other fiber pulp), 5 mechanical forest industry products (C/NC sawnwood, C/NC plywood, fiberboard[1]), 6 forest industry by-products (C/NC woodchips, C/NC sawdust, bark, black liquor) and 2 recycled products (recycled paper, recycled wood). The bioenergy module includes 2 final products (traditional bioenergy, modern bioenergy) and one intermediate product (wood pellets).

2. Model structure

The model's optimization problem for forest sector is formally written as:

$$\underset{x_{ik}, y_{if}, y_{iho}, e_{ijk}, z_{imno}, I_{if}}{Max} W = \sum_{ik} \int_0^{x_{ik}} D_{ik}(x_{ik}) \mathrm{d}x_{ik} - \sum_{iho} c_{iho}^{tran} y_{iho} - \sum_{iho} c_{iho}^{harv} y_{iho} - \sum_{if} c_{if}^{proc} y_{if}$$
$$- \sum_{if} c_{if}^{inv} I_{if} - \sum_{ijk} \int_0^{e_{ijk}} C_{ijk}^{trade}(e_{ijk}) de_{ijk} - \sum_{imn} \int_0^{z_{imn}} C_{imn}^{luc}(\sum_o z_{imno}) dz_{imn} \quad (1)$$

subject to

[1] Fiberboard includes different fiberboard types (OSB, hardboard, MDF/HDF, other fiberboard) and particleboard.

$$x_{ik} - \sum_{f} a_{ifk} y_{if} - \sum_{ho} a_{ihk} y_{iho} - \sum_{j} (e_{ijk} - e_{jik}) \leq 0 \qquad \forall\ i,k \qquad (2)$$

$$y_{iro} \leq \sum_{m} b_{irmo} L_{rmo} \qquad \forall\ i,r,o \qquad (3)$$

$$y_{ilo} \leq \sum_{r} \phi_{irlo} d_{irlo} y_{iro} \qquad \forall\ i,l,o \qquad (4)$$

$$y_{if} \leq K_{if} \qquad \forall\ i,f \qquad (5)$$

$$K_{tif} = (1-\delta) K_{(t-1)if} + I_{tif} \qquad \forall\ i,f,t \qquad (6)$$

$$L_{timo} = L_{(t-1)imo} + \sum_{n} z_{tinmo} - \sum_{n} z_{timno} \qquad \forall\ i,m,o,t \qquad (7)$$

$$y_{if} \leq \sum_{k} \phi_{ifk} x_{ik} \qquad \forall\ i,f \qquad (8)$$

$$L_{imo} \geq \bar{L}_{imo} \qquad \forall\ i,m,o \qquad (9a)$$

$$\sum_{o} L_{imo} \geq \bar{L}_{im} \qquad \forall\ i,m \qquad (9b)$$

$$e_{ijk} \geq \bar{e}_{ijk} \qquad \forall\ i,j,k \qquad (9c)$$

$$K_{if} \geq \bar{K}_{if} \qquad \forall\ i,f \qquad (9d)$$

where

i, j =economic regions
k= product
f=forest industry production activity
h=harvest activity
r=roundwood harvest activity (r $\subset$ h)
l=logging residues harvest activity (l $\subset$ h)
m,n= land-use/management types
o=grid
t=time (not used if same for all variables of the equation)
W=welfare
x=consumption quantity
y=production quantity
e=trade quantity
z=area of land-use change
K=capacity
I=investments
L=land area

c^{tran} = transport costs
c^{proc} = process costs
c^{harv} = harvest costs
c^{inv} = investment costs
δ=depreciation rate
a=input-output coefficient
b=increment per area
d=biomass expansion factor
ϕ=recovery ratio
D(x) = inverse demand function
$C^{trade}(e)$ = trade cost function
$C^{luc}(z)$=land-use change cost function

Equation (1) is the sum of consumers' and producers' surpluses. The first term of equation (1) is the area underneath the demand curve, which represents the value of final products consumption to the consumers. The remaining terms of equation (1) are the areas underneath the marginal cost curves, which represent the compensations paid to the producers. The second term is the transport costs of woody biomass from forest to the mill gate within each region. The third term is the harvest costs of woody biomass. The fourth term is the process costs of woody biomass. The fifth term is the investment costs. The sixth term is the trade costs between the regions. The last term is the land-use change costs. Transport, harvest and land-use change costs are spatially-explicit, i.e., they are indexed with regions i and grids o. Process, investment and trade costs are not spatially-explicit, i.e., they are indexed with regions i (in case of trade costs or with import region i and export region j).

Equation (2) is the material balance. It guarantees that products are not consumed or used as inputs in the production activities more than they are produced and traded. A production activity f uses product k as input if $a_{ifk}<0$ and produces product k as output if $a_{ifk}>0$. A harvest activity h produces just outputs, i.e., $a_{ihk}>0$. Production activities are Leontief production technologies, which implies that production activities use inputs in fixed proportions. However, it is possible to combine several production activities as a convex hull of activities, which allows to define ranges where inputs are perfect substitutes and where they cannot be substituted. For example, the minimum share of C pulp is 75% in packaging materials production and the remaining 25% can be C or NC pulp.

Equations (3) and (4) determine the relationship between primary woody biomass supply and forest resources. Equation (3) is the roundwood harvest constraint. This equation ensures that roundwood harvests volumes do not exceed their harvest potential for each grid. The harvest potential is based on the yield (=increment) and forest area data from G4M. The joint-production of sawlogs and pulpwood is modeled by assuming a minimum diameter for sawlogs, which implies that sawlogs have lower yield than pulpwood. Different forest managements are implemented in the model by assuming that harvest activities, i.e., managements, have different yields and feasible forest areas. Primary and secondary forests are not harvested, which is implemented in the model by assuming that these forest types have zero increments.

Equation (4) is the logging residues harvest constraint. This equation connects logging residues harvest volumes to roundwood harvest volumes and limits logging residues extraction to some share of their total volume in each grid. The total volume of logging residues is based on the biomass expansion factors while the share of logging residues that is allowed to be extracted on recovery ratio (Lauri et al. 2014). In the current version of the model the recovery ratio of logging residues is assumed to be 0.5 for all managements with positive increments. However, the recovery ratio of logging residues could be adapted according to management intensity and grid level side conditions.

Equations (5) and (6) determine the relationship between production technologies and capital stock. Equation (5) is the capacity constraint. Equation (6) is capital accumulation constraint. Investments are undertaken as long as income of increasing capital stock is higher than the investment costs within each period. In the current version of the model the depreciation rate is assumed to be 0.3 in 10-year period and is same for all final products.

Equation (7) is the land-use balance. Forestland decreases due to deforestation, i.e., changing forestland to cropland or grassland, and increases due to afforestation, i.e., changing cropland, grassland or other natural vegetation land to forestland. For sustainability reasons forestland is not allowed to be changed energy crops plantations. Within the forestland there are three forest types: primary forests, secondary forests and managed forests. For managed forests, the model chooses between low intensity, multifunctional and high intensity managements. If forest land is never used for biomass production, then it is allocated to primary forests. If the forestland is used for biomass production, then it is allocated to managed forest. If forest land is not actively use for production but has been disturbed by human activities, then it is allocated to secondary forests.

Equation (8) is biomass recycling constraint. It limits recycled paper supply to a certain fraction of paper and board consumption and recycled wood supply to a certain fraction of sawnwood, plywood and fiberboard consumption.

Equations (9a,b,c,d) are calibration constraints, which are used to force the model to observed values of land-use, trade and capacity in 2000-2020. The land-use calibration includes regional data (equation 9a) on forest types (FRA 2015,2020) as well as grid level data (equation 9b) on forest managements (WDPA 2020). An alternative option for direct forcing would be Positive Mathematical Programming (PMP) method, where shadow prices of equations (9a,b,c,d) would be used as additional calibration costs to enforce equations (9a,b,c,d). PMP method is not used in the model since the calibration costs tend to bias to solution of the model after 2020.

The one period social welfare maximization problem (1)-(9) is first calibrated and solved for the base years 2000-2020. Then it is solved repeatedly for the desired number of periods by assuming some exogenous or model history dependent changes in the state variables. The model period is 10 years. Because most of input data is annual data, the state variables of the model are adapted to correspond to one-year periods. Because the model is solved as a social welfare maximization problem, the objective function does not include any market prices or market clearing mechanism. Market prices for products k are obtained from the shadow prices of the material balance. From programming perspective, the model is solved using the GAMS programming language and linear programming. Non-linear functions are linearized by using the piecewise-linear approximation.

3. Final products demand

Final products demands are based on the constant elasticity inverse demand functions, which are parametrized by reference volumes, reference prices and elasticity coefficients:[2]

$$D_{tik}(x_{tik}) = \bar{x}_{tik}\left(\frac{p_{tik}}{\bar{p}_{ik}}\right)^{\alpha_k} \qquad \alpha_k \le 0 \qquad (10a)$$

where x_{ik}=quantity of demand for product k at region i in year t, $\bar{x}_{ik}$=reference quantity of demand for product k at region i in year t, p_{ik} is price for product k at region i in year t, $\bar{p}_{ik}$=reference price for product k at region i and α_k=price elasticity for product k.

The reference price for exporting regions is the world export price and for importing regions the world export price plus transport costs similar to Buongiorno et al. (2003). The world export price vary in the range 50 to 1000 $/m3. Preference prices are assumed to stay constant over time. Alternative option would be to use previous period prices as in Buongiorno et al. (2003), but this might cause artificial fluctuations in the market prices.

Reference volumes are based on the FAOSTAT in 2000-2020 (FAO 2020). After 2020, the reference volumes are shifted over time by the GDP and population growth:

$$\bar{x}_{(t+1)ik} = \bar{x}_{tik}\left(\frac{pop_{(t+1)i}}{pop_{ti}}\right)\left(\frac{gdp_{(t+1)i}}{gdp_{ti}}\right)^{\beta_{ikgdp}} \qquad \beta_{ikgdp} > 0 \qquad (10b)$$

where pop_{ti}=population at region i in year t, gdp_{ti}=per capita gross domestic product (GDP) at region i in year t and β_{tigdp}=GDP elasticity for product k at region i in year t. GDP elasticity depends on the level of GDP so that $\beta_{lowincome} > \beta_{middleincome} > \beta_{highincome}$ where income classes are based on World Bank classification. It follows that GDP elasticities of low-income regions decrease over time, because their GDP increases and eventually, they move to the higher income class.

The development of GDP and population is based on the SSP-RCP scenario data (IIASA 2020). The elasticity parameters of demand functions are based on econometric estimates from Buongiorno et al. (2003, 2015) and Morland et al. (2018). Income-elasticities vary in the range 0 to 1 depending on the product category, and they differentiate by low-, middle- and high-income regions (Table 1). Exception is fuelwood, which is assumed to be constant or has negative income-elasticity depending on the version of the model. Newsprint and printing and writing papers are assumed to have 0 income elasticity for all regions based on information technology development, which will decrease the demand for these paper grades in the future (Latta et al. 2013). Population elasticity is always 1. Price-elasticities vary in the range -0.1 to -0.5 depending on the product category.

Table 1: Income-elasticities used in GLOBIOM-forest

	Sawnwood_C	Sawnwood_NC	PlyWood_C	PlyWood_NC	Fiberboard
LowIncome	0.5	0.25	0.5	0.5	1.0
MidIncome	0.35	0.175	0.35	0.35	0.7
HghIncome	0.2	0.1	0.2	0.2	0.4

[2] Exceptions are modern bioenergy demand, which is based on the SSP-RCP scenario data (IIASA 2020), and fuelwood, which is usually assumed to be constant over time (see chapter 4).

	Newsprint	PrintingWriting	Packaging	Otherpaper
LowIncome	0	0	1.0	1.0
MidIncome	0	0	0.7	0.7
HghIncome	0	0	0.4	0.4

	OW_biomass_C	OW_biomass_NC	FW_biomass_C	FW_biomass_NC
LowIncome	0	0	-0.25	-0.25
MidIncome	0	0	-1	-1
HghIncome	0	0	-2	-2

Table 2: Price-elasticities used in GLOBIOM-forest

Sawnwood_C	-0.3
Sawnwood_NC	-0.3
PlyWood_C	-0.3
PlyWood_NC	-0.3
Fiberboard	-0.5
Newsprint	-0.3
PrintingWriting	-0.3
Packaging	-0.3
Otherpaper	-0.3
OW_biomass_C	-0.1
OW_biomass_NC	-0.1
FW_biomass_C	-0.1
FW_biomass_NC	-0.1

4. The future demand for fuelwood

The future demand for fuelwood is modelled in different ways depending on the version of the model. First option is to assume that fuelwood demand stays constant over time. This can be justified by historical development, which has been relatively stable during the last 70 years (FAO 2020). Second option is to use negative income elasticities for fuelwood so that fuelwood demand follows the SSP-RCP scenario data fuelwood demand patterns. It is not possible to force GLOBIOM fuelwood demand directly to SSP-RCP data, because SSP-RCP data includes also residential sector non-woody biomass use for energy, which is not modelled explicitly in GLOBIOM. In the SSP-RCP scenario data fuelwood demand in 2010 is 30 EJ ≈4200 Mm3 (conversion 1 m3=7.2 GJ) which is about two times higher than in the FAOSTAT data. This indicates that about half of SSP-RCP scenario data fuelwood is non-woody biomass.

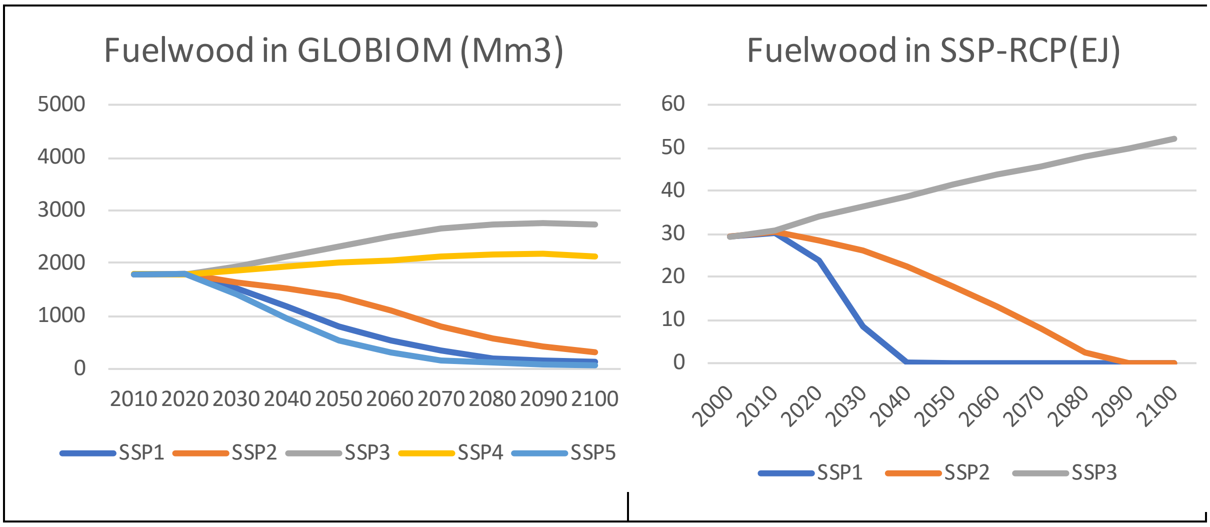

Figure 1: Fuelwood demand based on the negative income-elasticities and in SSP-RCP scenario data.

5. Trade modelling

The trade is modelled by using bilateral trade flows. For periods 2000-2020 bilateral trade quantities are forced to reference trade quantities based on the BACI trade data (Gaulier and Zignago 2010):

$$e_{tijk} \geq \bar{e}_{tijk} \qquad \text{(11a)}$$

where e_{tijk}=trade quantity for product k from region i to region j in year t, $\bar{e}_{tijk}$=reference trade quantity for product k from region i to region j in year t.

After 2020, trade volumes evolve according to trade dynamics, which depends on the constant elasticity trade-cost functions that are parametrized by historical trade volumes and unit trade costs:

$$C_{tijk}^{trade}(e_{tijk}) = \bar{c}_k \left(\frac{e_{tijk}}{\bar{e}_{tijk}}\right)^{\varepsilon} \qquad \varepsilon \geq 0 \qquad \text{(11b)}$$

$$\bar{e}_{(t+1)ijk} = e_{tijk} \qquad \text{(11b)}$$

where $\bar{c}_k$=unit trade costs for product k and ε=trade elasticity.

Trade elasticity is assumed to be 0.5 feedstocks and 3 for final products for all products and regions. Pellets trade-elasticity is 0.1. Reference trade costs are based on Buongiorno et al. (2003) and they vary in the range 20 to 80 \$/m3 or ton depending on the product. Reference trade costs stay constant over time, and they are same for all regions. If there is no trade in the previous period then it is assumed that trade costs are linearly increasing function of the periodic trade quantity (similar to the land-use change cost function).

5. Biomass supply from forests

Biomass supply is based on spatially explicit harvest potentials, spatially explicit harvest costs, spatially explicit transportation costs and forest/management type specific land-use change costs. The harvest potentials are based on the increment data from the Global Forest Model (G4M) (Kindermann et al. 2006, 2008, Gusti and Kindermann 2011). In the long-rotation forestry, the whole increment (excluding harvest loss) can be used for pulpwood, but only part of it for sawlogs. The reason is the joint production of sawlogs and pulpwood, which implies that part of the harvest potential is biomass from thinning, which does not qualify as sawlogs. This increases the relative price of sawlogs and makes pulpwood as a by-product of sawlogs production. In the short-rotation forestry, sawlogs and pulpwood are produced separately, and the whole increment (excluding harvest loss) can be used for pulpwood or sawlogs. The short-rotation forestry can be used only in the tropical zone while the long-rotation forestry in all regions. The harvest costs are based on G4M data. The transportation costs are based on Fulvio et al. (2016).

Land-use change costs are linearly increasing and they are based on historical land-use change patterns:

$$C_{imn}^{luc}(z_{timn}) = \bar{c}_{imn} + \eta_{imn} z_{timn} \qquad \eta_{imn} > 0 \qquad (12)$$

where z_{timn}=change of land area from type m to type n at region i in period t, $\bar{c}_{imn}$=fixed costs of land-use change from type m to type n at region i and η_{imn}=slope of land-use change cost function from type m to type n at region i.

The forest management is modelled through land-use changes between different forest types (primary forests, secondary forests, managed forests) and different management types (low intensity, multifunctional, high intensity) instead of changes in rotation times, stocking densities and other forest management activities. Primary forests are forestland that has not been used historically for production. Managed forests are forest land that is currently actively used for production while secondary forests are abandoned managed forests. Management types differ in the proportion of increment that is allowed to be harvested. In the high intensity management, the whole increment can be harvested while in the multifunctional and low intensity management, only part of the increment is allowed to be harvested. Consequently, harvest volumes can be increased by increasing the managed forest area or by intensifying forest management within the managed forest area, i.e., changing the management type.

The allocation of forest area to different forest and management types is based on the economic tradeoffs, i.e., the model chooses optimal spatial allocation of different forest and management types by maximizing the economic surplus given the spatially-explicit harvest potentials and spatially explicit harvests and transportation costs. The economic downscaling typically allocates high intensity management to the most productive and easily accessible forest areas while low intensity management and unmanaged forests are allocated to less productive and remote forest areas. The outcome of the economic downscaling can be improved by using additional data on forest and management types such as Global Forest Resources Assessment (FRA 2015), Word Database on Protected Areas (WDPA 2020) and Nature Map Explorer (IIASA 2020b). Total forest area development, i.e., deforestation and afforestation, is based on G4M data.

6. Production capacities and technologies

Forest industry and wood pellets production capacities are based on the FAOSTAT production data in 2000-2020 (FAO 2020). Bioenergy production (except wood pellets) does not have production capacity, i.e., it can be produced without investments in the production capacity. Main reason for this simplification is missing production data on different bioenergy feedstocks production. After 2020, the production capacities evolve according to investment dynamics, where investment decisions are made by comparing the current period income and annualized investment costs. Annuity factor is assumed to be 0.2 based on 10 years payback time and 15% IRR.

Table 2: Investment costs without annualization ($/m3 or $/ton)

InvestCost_DATA(REGION,"SawnWood_C") = 300;
InvestCost_DATA(REGION,"SawnWood_NC") = 300;
InvestCost_DATA(REGION,"PlyWood_C") = 500;
InvestCost_DATA(REGION,"PlyWood_NC") = 500;
InvestCost_DATA(REGION,"FiberBoard") = 400;
InvestCost_DATA(REGION,"ChemPulp_C") = 1000;
InvestCost_DATA(REGION,"ChemPulp_NC") = 1000;
InvestCost_DATA(REGION,"MechPulp_C") = 600;
InvestCost_DATA(REGION,"MechPulp_NC") = 600;
InvestCost_DATA(REGION,"woodpellets") = 100;
InvestCost_DATA(REGION,"RecycledPulp")=600;
InvestCost_DATA(REGION,"Newsprint")=800;
InvestCost_DATA(REGION,"PrintingWriting")=1200;
InvestCost_DATA(REGION,"Packaging")=1200;
InvestCost_DATA(REGION,"Otherpaper")=1200;

Forest industry, wood pellets and bioenergy production processes are modelled by using Leontief production technologies, which have fixed input-output coefficients. Leontief production technologies can be combined, which allows imperfect or perfect substitution between the inputs. The substitution between inputs can be further controlled by defining minimum/maximum shares for their use in combination. The model uses representative best available technologies (BAT), which are same for all regions, and which stay unchanged over time.

Table 3: Production technologies

Sawing1.productioncost	40	Sawing2.productioncost	40
Sawing1.SW_biomass_C	-1	Sawing2.SW_biomass_NC	-1
Sawing1.SawnWood_C	0.5	Sawing2.SawnWood_NC	0.5
Sawing1.SawDust_C	0.15	Sawing2.SawDust_NC	0.15
Sawing1.WoodChips_C	0.35	Sawing2.WoodChips_NC	0.35
Sawing1.Bark	0.136	Sawing2.Bark	0.136

PlywoodProd1.Productioncost	80	PlywoodProd2.Productioncost	80
PlywoodProd1.SW_biomass_C	-1	PlywoodProd2.SW_biomass_NC	-1
PlywoodProd1.Plywood_C	0.4	PlywoodProd2.Plywood_NC	0.4
PlywoodProd1.WoodChips_C	0.4	PlywoodProd2.WoodChips_NC	0.4
PlywoodProd1.Sawdust_C	0.2	PlywoodProd2.Sawdust_NC	0.2
PlywoodProd1.Bark	0.136	PlywoodProd2.Bark	0.136

FiberBoardProd1.productioncost	90	FiberBoardProd2.productioncost	90
FiberBoardProd1.PW_biomass_C	-1	FiberBoardProd2.PW_biomass_NC	-1
FiberBoardProd1.Fiberboard	0.6	FiberBoardProd2.Fiberboard	0.6
FiberBoardProd1.Bark	0.136	FiberBoardProd2.Bark	0.136
FiberBoardProd3.productioncost	90	FiberBoardProd4.productioncost	90
FiberBoardProd3.Sawdust_C	-1	FiberBoardProd4.Sawdust_NC	-1
FiberBoardProd3.Fiberboard	0.6	FiberBoardProd4.Fiberboard	0.6
FiberBoardProd5.productioncost	90	FiberBoardProd6.productioncost	90
FiberBoardProd5.Woodchips_C	-1	FiberBoardProd6.Woodchips_NC	-1
FiberBoardProd5.Fiberboard	0.6	FiberBoardProd6.Fiberboard	0.6
FiberBoardProd7.productioncost	90		
FiberBoardProd7.recycledwood	-1		
FiberBoardProd7.Fiberboard	0.6		

Chemicalpulp1.productioncost	50	Chemicalpulp2.productioncost	50
Chemicalpulp1.PW_biomass_C	-1	Chemicalpulp2.PW_biomass_NC	-1
Chemicalpulp1.ChemPulp_C	0.225	Chemicalpulp2.ChemPulp_NC	0.225
Chemicalpulp1.BlackLiquor	0.5	Chemicalpulp2.BlackLiquor	0.5
Chemicalpulp1.Bark	0.136	Chemicalpulp2.Bark	0.136
Chemicalpulp3.productioncost	50	Chemicalpulp4.productioncost	50
Chemicalpulp3.woodchips_C	-1	Chemicalpulp4.woodchips_NC	-1
Chemicalpulp3.ChemPulp_C	0.225	Chemicalpulp4.ChemPulp_NC	0.225
Chemicalpulp3.BlackLiquor	0.5	Chemicalpulp4.BlackLiquor	0.5

Mechanicalpulp1.productioncost	150	Mechanicalpulp2.productioncost	150
Mechanicalpulp1.PW_biomass_C	-1	Mechanicalpulp2.PW_biomass_NC	-1
Mechanicalpulp1.MechPulp_C	0.45	Mechanicalpulp2.MechPulp_NC	0.45
Mechanicalpulp1.Bark	0.136	Mechanicalpulp2.Bark	0.136
Mechanicalpulp3.productioncost	150	Mechanicalpulp4.productioncost	150
Mechanicalpulp3.woodchips_C	-1	Mechanicalpulp4.woodchips_NC	-1
Mechanicalpulp3.MechPulp_C	0.45	Mechanicalpulp4.MechPulp_NC	0.45

Recycledpulp1.productioncost	200	Otherfiberpulp1.productioncost	300
Recycledpulp1.recycledpaper	-1.2	Otherfiberpulp1.otherfiberpulp	1
Recycledpulp1.recycledpulp	1		

Newsprint1.productioncost	50	Newsprint2.productioncost	50
Newsprint1.mechpulp_C	-0.9	Newsprint2.recycledpulp	-0.9
Newsprint1.newsprint	1	Newsprint2.newsprint	1

Newsprint3.productioncost 50 Newsprint3.otherfiberpulp -0.9 Newsprint3.newsprint 1	Newsprint4.productioncost 50 Newsprint4.mechpulp_NC -0.9 Newsprint4.newsprint 1

PrintingWriting1.productioncost 200 PrintingWriting1.chempulp_C -0.8 PrintingWriting1.printingwriting 1	PrintingWriting2.productioncost 200 PrintingWriting2.mechpulp_C -0.8 PrintingWriting2.printingwriting 1
PrintingWriting3.productioncost 200 PrintingWriting3.otherfiberpulp -0.8 PrintingWriting3.printingwriting 1	PrintingWriting4.productioncost 200 PrintingWriting4.recycledpulp -0.2 PrintingWriting4.chempulp_C -0.6 PrintingWriting4.printingwriting 1
PrintingWriting5.productioncost 200 PrintingWriting5.recycledpulp -0.2 PrintingWriting5.mechpulp_C -0.6 PrintingWriting5.printingwriting 1	PrintingWriting6.productioncost 200 PrintingWriting6.recycledpulp -0.2 PrintingWriting6.otherfiberpulp -0.6 PrintingWriting6.printingwriting 1
PrintingWriting7.productioncost 200 PrintingWriting7.chempulp_NC -0.8 PrintingWriting7.printingwriting 1	PrintingWriting8.productioncost 200 PrintingWriting8.mechpulp_NC -0.8 PrintingWriting8.printingwriting 1
PrintingWriting9.productioncost 200 PrintingWriting9.recycledpulp -0.2 PrintingWriting9.chempulp_NC -0.6 PrintingWriting9.printingwriting 1	PrintingWriting10.productioncost 200 PrintingWriting10.recycledpulp -0.2 PrintingWriting10.mechpulp_NC -0.6 PrintingWriting10.printingwriting 1

Packaging1.productioncost 100 Packaging1.chempulp_C -1 Packaging1.packaging 1	Packaging2.productioncost 100 Packaging2.recycledpulp -1 Packaging2.packaging 1
Packaging3.productioncost 100 Packaging3.otherfiberpulp -1 Packaging3.packaging 1	Packaging4.productioncost 100 Packaging4.chempulp_C -0.75 Packaging4.chempulp_NC -0.25 Packaging4.packaging 1

Otherpaper1.productioncost 100 Otherpaper1.chempulp_C -1 Otherpaper1.otherpaper 1	Otherpaper2.productioncost 100 Otherpaper2.recycledpulp -1 Otherpaper2.otherpaper 1
Otherpaper3.productioncost 100 Otherpaper3.otherfiberpulp -1 Otherpaper3.otherpaper 1	Otherpaper4.productioncost 100 Otherpaper4.chempulp_C -0.75 Otherpaper4.chempulp_NC -0.25 Otherpaper4.otherpaper 1

Woodpellets1.Productioncost 0.1 Woodpellets1.sawdust_C -1 Woodpellets1.Woodpellets 0.4	Woodpellets2.Productioncost 0.1 Woodpellets2.sawdust_NC -1 Woodpellets2.Woodpellets 0.4
Woodpellets3.Productioncost 0.1 Woodpellets3.woodchips_C -1 Woodpellets3.Woodpellets 0.4	Woodpellets4.Productioncost 0.1 Woodpellets4.woodchips_NC -1 Woodpellets4.Woodpellets 0.4

Woodpellets5.Productioncost 0.1 Woodpellets5.IP_biomass -1 Woodpellets5.Woodpellets 0.4	Woodpellets6.Productioncost 0.1 Woodpellets6.PW_biomass_C -1 Woodpellets6.Woodpellets 0.4 Woodpellets6.bark 0.136
Woodpellets7.Productioncost 0.1 Woodpellets7.PW_biomass_NC -1 Woodpellets7.Woodpellets 0.4 Woodpellets7.bark 0.136	

WoodEnergy1.productioncost 0.1 WoodEnergy1.Sawdust_C -1 WoodEnergy1.EW_biomass 1	WoodEnergy2.productioncost 0.1 WoodEnergy2.Sawdust_NC -1 WoodEnergy2.EW_biomass 1
WoodEnergy3.productioncost 0.1 WoodEnergy3.WoodChips_C -1 WoodEnergy3.EW_biomass 1	WoodEnergy4.productioncost 0.1 WoodEnergy4.WoodChips_NC -1 WoodEnergy4.EW_biomass 1
WoodEnergy5.productioncost 0.1 WoodEnergy5.BlackLiquor -1 WoodEnergy5.EW_biomass 1	WoodEnergy6.productioncost 0.1 WoodEnergy6.Bark -1 WoodEnergy6.EW_biomass 1
WoodEnergy7.productioncost 0.1 WoodEnergy7.LR_biomass -1 WoodEnergy7.EW_biomass 1	WoodEnergy8.productioncost 0.1 WoodEnergy8.PW_biomass_C -1 WoodEnergy8.EW_biomass 1.136
WoodEnergy9.productioncost 0.1 WoodEnergy9.PW_biomass_NC -1 WoodEnergy9.EW_biomass 1.136	WoodEnergy10.productioncost 0.1 WoodEnergy10.recycledwood -1 WoodEnergy10.EW_biomass 1
WoodEnergy11.productioncost 0.1 WoodEnergy11.woodpellets -1 WoodEnergy11.EW_biomass 2.5	WoodEnergy12.productioncost 0.1 WoodEnergy12.IP_biomass -1 WoodEnergy12.EW_biomass 1

7. Representation of coniferous and non-coniferous biomass

The separation of coniferous (C) and non-coniferous (NC) biomass is applied in all products expect fiberboard, paper and paperboard and bioenergy products. The separation is not applied for these products, because they are often produced from a mixture of C and NC biomass. The separation is based on FAOSTAT data (FAO 2020). When FAOSTAT data is not available, then the separation is approximated by using regional C and NC biomass resource balances. Using wood resource balances to determine missing wood flows is common methodology in the forest sector analysis (Mantau et al. 2010, Jochem et al., 2015, Jonsson et al. 2021). In the fiberboard, newsprint, printing and writing papers and bioenergy production C and NC biomass are assumed to be perfect substitutes, which implies that the share of C and NC biomass can vary between 0 and 100%. In the packaging materials and other papers production the minimum share of C biomass is assumed to be 75%.

Harvest potential separation for C and NC biomass is based on the FRA (2015) country level growing stock data. For the EU, we use a separate spatially-explicit tree species data (Brus et al. 2012). The tree species distribution is assumed to stay fixed over time. C trees are dominant in the boreal zone while NC trees in the tropical zone. In the temperate zone, C trees are dominant in some regions while NC trees in other regions. This implies that the majority of NC biomass harvest potential is located in the tropical zone while the majority of

C biomass harvest potential in the boreal and temperate zones (Figure 2a). In the regional level[3], the majority of North-America, Russia and EU harvest potential is C biomass while the majority of South-America, Africa and Asia harvest potential NC biomass (Figure 2b).

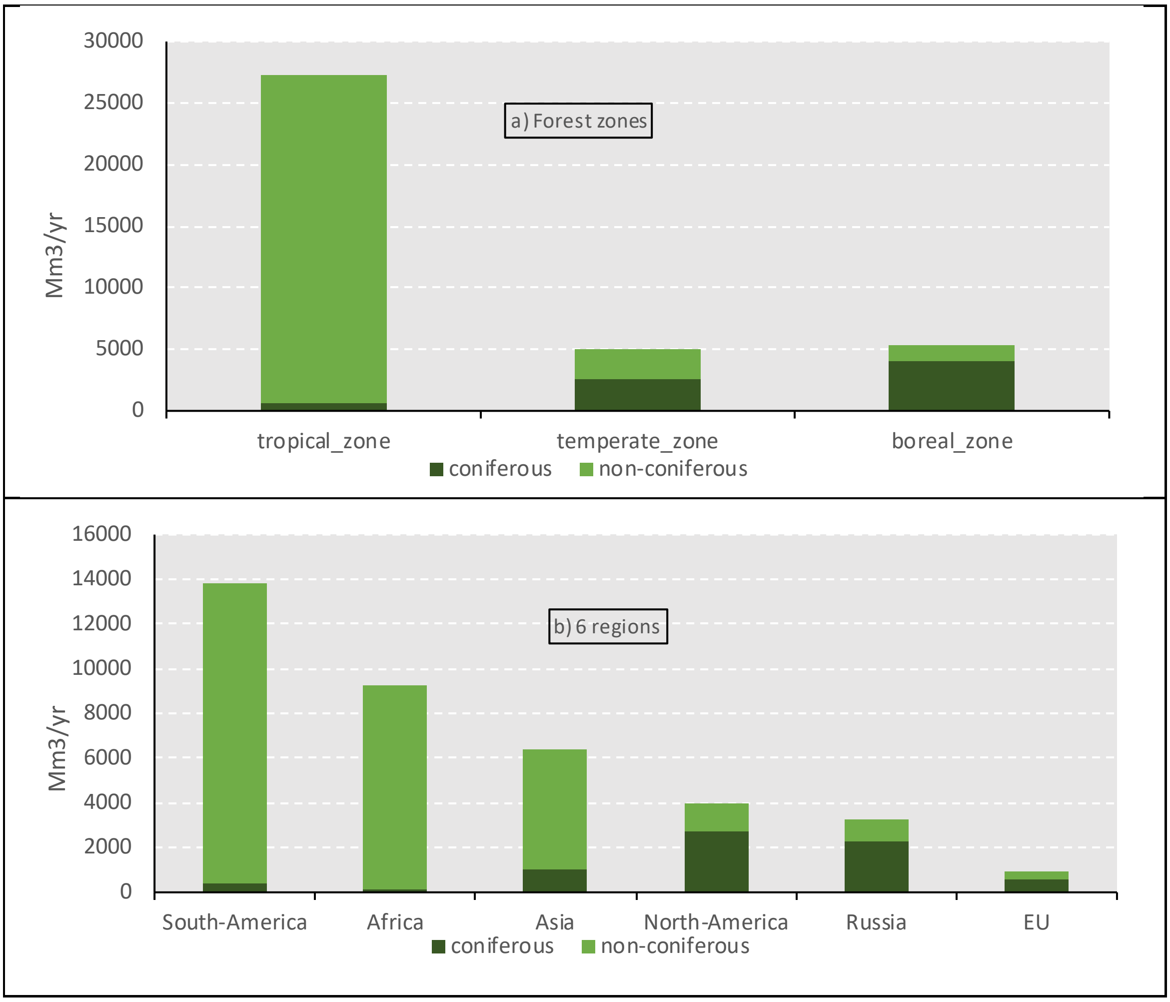

Figure 2: GLOBIOM roundwood harvest potential divided to C and NC biomass.

8. Representation of recycled biomass

Recycled (R) biomass can be used to substitute virgin fibers in the wood-based products production. Due to material losses and the ageing of recycled biomass it is not possible to substitute all virgin fibers by R biomass, but there are maximum technical shares for R biomass use. The model includes three R products: R wood, R paper and R pulp. R wood is recovered mechanical forest industry products, which are re-used as a raw material in fiberboard production or burned for energy. R paper is recovered paper and paperboard, which are re-used for R pulp production. R pulp is used as a raw material in paper and paperboard production.

[3] The world is divided to 6 regions as follows: South-America (South America + Central America +Mexico), Africa (Africa), Asia (Asia +Oceania), North-America (Canada + USA), Russia (Russia + rest of European countries), EU (EU28). The 6 regions further subdivided to traditional forest industry regions (North-America, Russia, EU) and emerging forest industry regions (South-America, Africa, Asia) based on their historical development (FAO 2020).

The supply of R wood is based on the mechanical forest industry products final consumption and R wood collection rates. The maximum R wood collection rate is assumed to be 50% based on expert opinion. The supply of R paper is based on FAOSTAT statistics in 2000-2020. After 2020 R paper supply is endogenous and it is determined by the paper and paperboard consumption and R paper collection rates. The maximum R paper collection rate is assumed to be 80% based on observed maximum national collection rates (CEPI 2019). The supply of R pulp depends on the supply of R paper and the R pulp yield from R paper. R pulp yields from R papers depend on the filler content of R papers and the ageing effect of R biomass (Stawicki and Read 2010, Van Ewijk et al. 2017). The average R pulp yield with the ageing effect is about 90%. Connecting this to filler content of different paper grades (packaging materials 0%, newsprint 10% and printing and writing papers 20%) gives recycled pulp yield of 70-90% depending on the paper grade. Other papers are assumed to have zero yields, since they include mainly sanitary papers, which are usually not recycled. Connecting the R pulp yields to the maximum collection rates and the consumption shares of different paper grades implies that the maximum technical share of R pulp varies from 60 % (current consumption shares) to 65 % (the consumption share of packaging materials increase from 50 to 70%) at the global level.

9. Calibration of the model

Model does not include production or trade costs calibration based on the Positive Mathematical Programming (PMP). Moreover, the model does not include income-elasticity calibration. However, the model includes several forcing constraints and consistency checks, which calibrate the model to match external data:

1) The consistency between harvest potentials and FAOSTAT harvest volumes is checked. If the FAOSTAT harvest volumes exceed the harvest potential in some region, then the harvest potential is increased in this region.

2) The consistency between production technologies and FAOSTAT production/consumption quantities is checked. If the regional and global material balances based on the model production technologies and FAOSTAT production/consumption quantities do not match, then FAOSTAT production/consumption quantities are corrected so that the material balances hold. Using material balances to correct wood flows is common methodology in the forest sector analysis (Mantau et al. 2010, Jochem et al., 2015, Jonsson et al. 2021). The corrections are based on goal programming, which minimize the weighted sum of deviations. The consistency check changes FAOSTAT production/consumption quantities instead of production technology parameters. Hence, the model production/consumption quantities might differ slightly from the FAOSTAT production/consumption quantities. Moreover, the consistency check changes FAOSTAT roundwood production/consumption instead of final products production/consumption. This is because roundwood production/consumption is usually less reliable data than final products production/consumption (Mantau et al. 2010, Jochem et al. 2015).

3) The consistency between BACI bilateral trade quantities and FAOSTAT net trade quantities is checked. If BACI bilateral trade quantities do not sum up to FAOSTAT net trade quantities at regional and global level, the BACI bilateral trade quantities are changed so that they sum up to FAOSTAT net trade quantities. The changes are based on goal programming, which minimizes the weighted sum of deviations.

4) Final products production quantities are forced to FAOSTAT production quantities by setting production capacities equal to FAOSTAT production quantities during 2000-2020.

5) Final products demand quantities are forced to FAOSTAT consumption quantities by setting reference quantities in the demand functions equal to FAOSTAT consumption quantities during 2000-2020.

6) Bilateral trade quantities are forced to BACI bilateral trade quantities during 2000-2020.

7) Production technology parameters that define the shares of pulpwood and by-products in pulp production are calibrated so that they are consistent with FAOSTAT pulpwood consumption quantities during 2000-2020.

8) The allocation of forest and forest management type areas is improved by using additional data such as Global Forest Resources Assessment (FRA 2015), Word Database on Protected Areas (WDPA 2020) and Nature Map Explorer (IIASA 2020b).

10. Lauri et al. (2019): carbon payments on biomass stock changes

Lauri et al. (2019) investigates the impact of carbon payments on woody biomass stock changes. Carbon payments are applied to marginal biomass stock changes, i.e., carbon payments are a function of the biomass stock change in that period. In the recursive dynamic model landowners consider only current period payments, which implies that future biomass stock changes and carbon payments does not affect their current choices. The length of the period in the GLOBIOM model is 10 years, which implies that landowners' planning horizon is 10 years.

Carbon payments depend on carbon prices and biomass stock changes

$$T_{tio}^{carbon}(v_{tio}) = p_{ti}^{carbon}(Bm_{tio} - Bm_{(t-1)io}) \tag{13a}$$

$$Bm_{tio} = Bm_{(t-1)io} + \lambda_{tio} Bm_{tio} - H_{tio} \tag{13b}$$

$$H_{tio} = \sum_h y_{thio} \tag{13c}$$

where T_{tio}^{carbon}=carbon subsidy in period t at land-use unit o and region i (if negative then carbon tax), p_{ti}^{carbon}=carbon price in period t for region i, Bm_{tio}=carbon storage of living biomass in period t at land-use unit o and region I, λ_{tio}=growth rate of biomass in period t at land-use unit o and region i (net of mortality) and H_{tio}=biomass harvest in period t at land-use unit o and region i.

If forest area is deforested, then all biomass is harvested and $T_{tio}^{carbon}=-p_{ti}^{carbon}Bm_{(t-1)io}<0$. If land area is afforested or forest area restored then there is no harvesting and $T_{tio}^{carbon}=p_{ti}^{carbon}\lambda_{tio}Bm_{tio}>0$ as long as $\lambda_{tio}>0$, i.e., until the potential maximum steady state biomass stock is achieved. If primary forest area is converted to managed forests, then harvest volumes exceed biomass growth and $T_{tio}^{carbon}=p_{ti}^{carbon}(\lambda_{tio}Bm_{tio}- H_{tio})<0$ until the managed forest steady state biomass stock is achieved. In the managed forest steady state $\lambda_{tio}Bm_{tio}=H_{tio}$ and $T_{tio}^{carbon}=0$.

11. Lauri et al. (2021): Material substitution between coniferous, non-coniferous and recycled biomass

Lauri et al. (2021) investigates material substitution between coniferous (C), non-coniferous biomass (NC) and recycled biomass (R). The majority of current forest industry raw material use is C biomass, but NC and R biomass provide a cost-effective alternative to C biomass given the development of tropical short rotation forestry and the circular economy. Consequently, an interesting question for the future development of the forest sector is how much C biomass can be substituted by NC biomass or R biomass in the future. This depends on the availability of NC and R biomass and the availability of suitable production technologies. The utilization of R biomass is constrained mainly by the availability of R biomass while the utilization of NC biomass by the availability of suitable production technologies. Taking account of this the study consider four different scenarios: baseline (C and NC biomass imperfect substitutes, high circular economy), C/NCsub (C and NC biomass perfect substitutes, high circular economy), LowCircu (C and NC biomass imperfect substitutes, low circular economy) and C/NCsubLowCircu (C and NC biomass perfect substitutes, high circular economy).

The development of circular economy depends on constraint:

$$y_{tik}^{Rbiomass} \leq \omega_{tik}^{Rbiomass} y_{tik} \qquad k = \{fiberboard, pulp\} \qquad (14)$$

where y_{tik} =production of product k in region and period t and $\omega_{tik}^{Rbiomass}$=max share of R biomass in product k production in region I and period t.

The development of circular economy is defined to be low if

$$\omega_{tik}^{Rbiomass} \leq \frac{y_{2020ik}^{Rbiomass}}{y_{2020ik}} \qquad \text{for t>2020}$$

On the other hand, the development of circular economy is defined to be high if

$$\omega_{tik}^{Rbiomass} \leq \overline{\omega}_{k}^{Rbiomass} \qquad \text{for t>2020}$$

where $\overline{\omega}_{fiberboard}^{Rbiomass}$ = 1 and $\overline{\omega}_{pulp}^{Rbiomass}$ = 0.6-0.65.

C and NC biomass are defined to be imperfect substitutes in the biomass processing and final products consumption if the model includes baseline technologies (table 3). On the other hand, C and NC biomass are defined to be perfect substitutes in the biomass processing and final products consumption if the model includes baseline and additional substitution technologies (table 3+4).

Table 4: Additional substitution technologies

biomass1.productioncost 0.1 biomass1.Sawnwood_NC -1 biomass1.Sawnwood_C 1	biomass2.productioncost 0.1 biomass2.Sawnwood_C -1 biomass2.Sawnwood_NC 1
biomass3.productioncost 0.1 biomass3.Plywood_NC -1 biomass3.Plywood_C 1	biomass4.productioncost 0.1 biomass4.Plywood_C -1 biomass4.Plywood_NC 1
biomass5.productioncost 0.1 biomass5.Chempulp_NC -1 biomass5.Chempulp_C 1	biomass6.productioncost 0.1 biomass6.Chempulp_C -1 biomass6.Chempulp_NC 1
biomass7.productioncost 0.1 biomass7.Mechpulp_NC -1 biomass7.Mechpulp_C 1	biomass8.productioncost 0.1 biomass8.Mechpulp_C -1 biomass8.Mechpulp_NC 1
biomass9.productioncost 0.1 biomass9.OW_biomass_NC -1 biomass9.OW_biomass_C 1	biomass10.productioncost 0.1 biomass10.OW_biomass_C -1 biomass10.OW_biomass_NC 1
biomass11.productioncost 0.1 biomass11.FW_biomass_NC -1 biomass11.FW_biomass_C 1	biomass12.productioncost 0.1 biomass12.FW_biomass_C -1 biomass12.FW_biomass_NC 1

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