Supplementary material

1. Formal description of the forest sector module

This chapter includes a formal description of the forest sector part of GLOBIOM used in the study. The model is similar to Lauri et al. (2017) except that the forestry module is extended to include different forest types and carbon payments on forest type changes. Moreover, the forest industry module is extended to include some new products (different paper grades, recycled paper, pellets). A formal description of the full model (including forest sector, agriculture sector and carbon emissions accounting) can be found in Havlik et al. (2011) and Havlik et al. (2014).

GLOBIOM is a recursive dynamic land-use model, which have two types of land-use changes: land-use change between different land types within the same land-cover ("land management change") and land-use change between different land-cover types ("land-cover change"). The forest management is modelled in GLOBIOM through land-use changes between different types of forests (primary forests, secondary forests, restored forests, low intensity managed forests, and high intensity managed forests) instead of changes in rotation times, stocking densities and other forest management activities.

1.1 Model structure

Indexes
i,j =economic regions
k= product
f=forest industry production activity
h=harvest activity
w=roundwood harvest activity ($w \subset h$)
l=logging residues harvest activity ($l \subset h$)
m,n= land-use types
o=land-use unit
t=time (not used if same for all variables of the equation)

Variables

W=welfare
x=consumption quantity
y=production quantity
e=trade quantity
K=capacity
I=investments
L=land area
z=change of land area
Bm=biomass stock
v=change of biomass stock

Parameters

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

Functions

D(x) = inverse demand function
C^{trade}(e) = trade cost function
C^{luc}(z)=land-use change cost function
T^{carbon}(bm)=carbon payments on biomass stock change

Objective function

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

subject to

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

$$y_{iwo} \leq \sum_{m} b_{iwmo} L_{wmo} \qquad \forall \ i, w, o \qquad (3)$$

$$y_{ilo} \leq \sum_{w} \varphi_{iwlo} d_{iwlo} \, y_{iwo} \qquad \forall \ i, l, o \qquad (4)$$

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

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

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

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

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 with in 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 seventh term is the land-use change costs. Transport, harvest and land-use change costs are spatial explicit, i.e., they are indexed with regions i and land-use units o. Process, investment and trade costs are not spatially explicit, i.e., they are indexed with just with regions i (or i and j in case of trade costs). The last term is carbon payments on biomass stock changes.

Equation (2) is the material balance. It guarantees that products consumed or used as inputs in production activities are less than what is 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., $a_{ihk}>0$.

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 land-use unit. The harvest potential is based on the increment and forest area data from G4M. Equation (4) is the logging residues harvest constraint. This equation connects logging residues harvest volumes to roundwood harvest volumes and limit logging residues extraction to some share of their total volume in each land-use unit. The total volume of logging residues is based on biomass expansion factors while the share of logging residues that is allowed to be extracted on a 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.

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 forest area balance, which includes land-use changes within forest area (between different forest types) and land-use changes between forest and non-forest area. 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 to energy crops plantations. Within the forestland there are three different types of forests: primary forests, secondary forests and managed forests. Primary forests are forestland that has not been used historically for production. Managed forests are forest land that is used for production while secondary forests are abandoned managed forests. Production can be increased be converting secondary and primary forests to production forests. Managed and secondary forests can be converted to primary forests by restoration. All types of forests can be deforested. Afforested areas are assumed to be secondary forests, which can be taken to production use or restored to primary forests after the minimum rotation time.

Equation (8) limits recycled wood supply to a certain fraction of sawnwood, plywood and fiberboard consumption and recycled paper supply to a certain fraction of newsprint, printing&writing papers, packing materials and other papers consumption.

The one period social welfare maximization problem (1)-(8) is first calibrated and solved for the base year. 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. However, because the data are usually based on the one year periods, the state variables of the model are adapted to correspond one-year period.

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.

The model is solved using the GAMS programming language and linear programming. Non-linear functions are linearized using the piecewise-linear approximation.

1.2 Final products inverse demand function

Final products include sawnwood, plywood, fiberboard, newsprint, printing&writing papers, packing materials, other papers, modern bioenergy and traditional bioenergy.

Final products (except modern bioenergy) have constant elasticity inverse demand function

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

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.

In the current version of the model price elasticities and reference prices are based on Buongiorno et al. (2003). Price elasticities vary in the range -0.1 to -0.5 depending on the product category. The reference price for exporting regions is the world export price and for importing regions the world export price plus transport costs. The world export price vary in the range 20 to 1000 $/m3. For simplicity the reference prices stay constant over time.

Base year reference quantities are based on FAOSTAT data. After the base year reference quantities are shifted by population and GDP growth:

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

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.

In the current version of the model GDP elasticities are assumed to be in the range 0 to 1 (except for newsprint, printing & writing papers and fuelwood, see chapter 1.5) depending on the region, the product and the level of GDP. 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.

Modern bioenergy demand is based on SSP-RCP scenario data and it is assumed to be perfectly inelastic.

1.3 Trade cost function

Trade costs are modeled using a constant elasticity trade cost function

$$C_{tijk}^{trade}(e_{tijk}) = \bar{c}_k(\frac{e_{tijk}}{\bar{e}_{tijk}})^{\varepsilon} \qquad \varepsilon \ge 0 \qquad (11a)$$

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

In the current version of the model trade elasticity is assumed to be 0.5, which is same for all products and regions. 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. For simplicity the reference trade costs stay constant over time and they are same for all regions.

The base year reference trade quantities are based on the BACI (Base pour l'analyse du commerce international) bilateral trade database (Gaulier and Zignago 2010). After the base year the reference trade quantity is assumed to be previous period trade quantity:

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

If there is no trade in the previous year then it is assumed that trade costs are linearly increasing function of the periodic trade quantity (similar to the land-use change cost function).

1.4 Land-use change cost function

Land-use change costs are modeled using a linearly increasing cost function

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

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.

In the recursive dynamic land-use change models increasing land-use change costs functions are used to stabilize land-use change development over time besides other land-use change constraints (land-suitability constraints, maximum share of conversion per period etc.). The parameters of land-use change cost function are based on historical land-use change patterns. Remark that land-use change costs are an increasing function of accumulated land-use change during the whole 10 year period.

1.5 Carbon payments on 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 $T_{tio}^{carbon}=0$.

1.5 Calibration of the model

The model includes several calibrations and consistency checks. First, 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. Second, the consistency between model 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 changed so that the material balances hold. The changes 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. This is because the model uses representative best available technologies (BAT), which are same for all regions and which stay unchanged over time. Third, 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. Fourth, final products production quantities are calibrated to FAOSTAT production quantities by setting the base year capacities equal to FAOSTAT production quantities. Fifth, final products demand quantities are calibrated to FAOSTAT consumption quantities by setting the base year reference quantities in demand functions equal to FAOSTAT consumption quantities. Sixth, bilateral trade quantities are calibrated to BACI bilateral trade quantities by setting the base year reference quantities in trade cost functions equal to BACI bilateral trade quantities. Seventh, production technology parameters that define the shares of pulplogs and by-products in pulp and fiberboard production are calibrated so that they are consistent with FAOSTAT pulplogs consumption quantities. Eight, the base forest areas are calibrated to match FRA (2015) country level data of primary forests, production forests and planted forests.

In Lauri et al. (2017) forest sector final products demand was based on the FAOSTAT data in 2000 and 2010 and thereafter shifted over time by population and GDP growth by using income elasticities from Buongiorno et al. (2003). This approach leads to increasing demand for forest products over time except for fuelwood, which has negative income elasticity. In the current version of the model we use also FAOSTAT 2017 data to adjust final products demand in 2020. The reason for this is that some paper grades demand (newsprint and printing & writing papers) has experienced a qualitative change in the demand during the last 20 years due to information technology revolution, which is difficult to take account by the demand shifting approach. Similar issue arise also with China final product demand, which has been increasing during the last 10 years more than the demand shifting approach projects. In general adjusting 2020 demand to 2017 data decreases the final products future demand in the global level somewhat (about 10%) comparing to previous results.

Income elasticities are based on Buongiorno et al. (2003) except for fuelwood, newsprint and printing&writing papers. Newsprint and printing & writing papers are assumed have negative income elasticities due to information technology development (Latta et al. 2016). Fuelwood income elasticities are adjusted so that fuelwood demand in GLOBIOM follows the SSP-RCP scenario data fuelwood demand patterns. It is not possible to adjust 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 (2000 Mm3), which indicates that about half of SSP-RCP scenario data fuelwood is non-woody biomass.

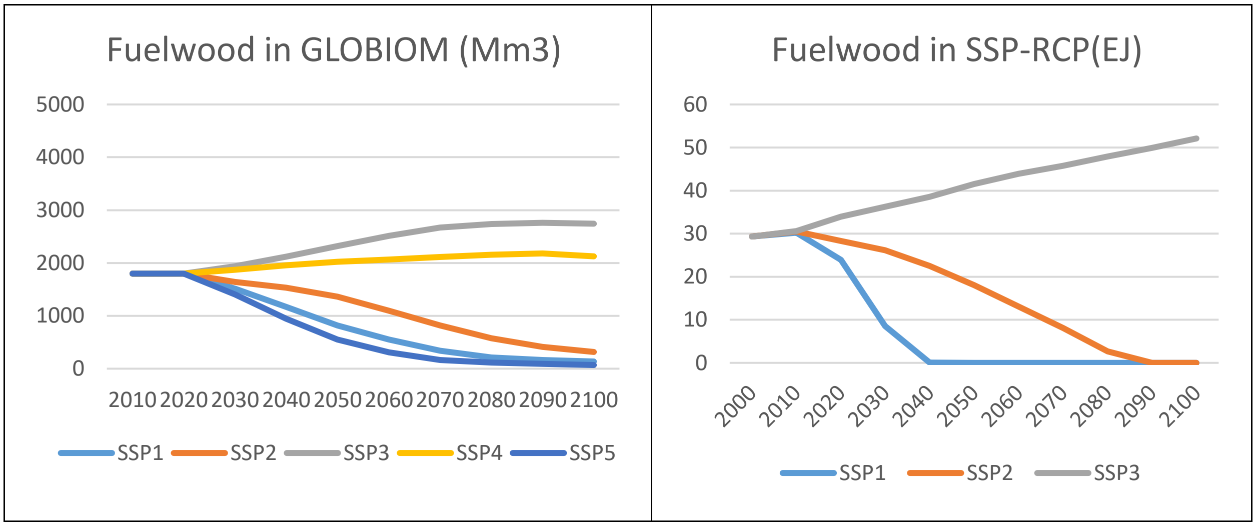

Figure s1: Fuelwood demand in GLOBIOM and in SSP-RCP scenario data

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