Technical description of the IIASA model cluster

Mykola Gusti, Petr Havlik and Michael Obersteiner

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INTRODUCTION[1]

The quantitative analysis of REDD supply schedules were carried out in a global total land-use context. The Global Model cluster combines geographically explicit biophysical models with economic modelling. The model cluster covers all land-use types and thus allows for fully integated analysis of competitive interactions between different land uses and land use change types. Combining the different models allows for geographic explicit analysis of REDD policies in a global context. The geographic explicit analysis of REDD policy options is carried out using the G4M (former DIMA) model (e.g. Rokitiansky et al., 2007; Kindermann et al., 2006, 2008b). G4M is driven by exogenous market price assumptions for land and commodities without taking market feedbacks into account. The partial equilibrium model GLOBIOM generates endogenous prices. GLOBIOM has global geographic coverage and accounts for all land uses and thus allows for REDD policy analysis in a wider land use and global change context. When the two models are coupled the G4M model serves a double purpose. First it informs GLOBIOM on basic biophysical forest growth information and engineering costing of various forest management options. Second, results from GLOBIOM, such as endogenous commodity and land prices and trade, are used as exogenous drivers for the geographically explicit modeling using G4M. In the latter G4M becomes a “sophisticated” downscaling algorithm for GLOBIOM results facilitating “visual validation” of results and geographic REDD hot spotting.

In the following the two models are described. In the description of G4M we provide a detailed description of the improved carbon accounting and calibration methods departing from (Kindermann et al., 2006). Changes in the calibration methodology have necessarily created considerable differences in baseline emissions and thus REDD costs as published in (Kindermann et al., 2006). Baselines in (Kindermann et al., 2006) are determined mainly by future GDP and population development assuming low institutional barriers for expansion of the agricultural and forestry sectors whereas the latter is mainly driven by the continuation of historical emissions and the continuation of institutional barriers of agricultural and forestry sector development. The version of G4M presented in this document was calibrated to the global emissions estimates provided by the IPCC while the one in (Kindermann et al., 2006) was calibrated to the estimates provided by global analysis using remote sensing methods. Differences in the results of these two model versions of G4M provide valuable insights on the impact of changes in methodologies on REDD costs. The description of GLOBIOM is provided with less detail due to space limitations.

METHODS

General Description of G4M

The <u>G</u>lobal <u>F</u>orestry <u>M</u>odel (G4M) is a geographically explicit agent-based model to assess land use change decision making. A series of papers by Benitez et al. (2004); Benitez and Obersteiner (2006); Rokityanskiy et al. (2007) and Kindermann et al. (2006, 2008b) document the evolution

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[1] This paper was commissioned by the Office of Climate Change as background work to its report 'Climate Change: Financing Global Forests' (the Eliasch Review). It describes the IIASA model cluster that was used to provide the Eliasch Review with marginal abatement cost curves (MACCs) used to calculate opportunity costs of reducing forest emissions. Further information about the Eliasch Review is available at: www.occ.gov.uk.

of the model starting from modeling afforestation in Latin America to global forestry scenario analysis covering avoided deforestation, afforestation and forest management decision making. The basic deforestation module of the G4M model is described in (Kindermann et al., 2006). This model was extended by more thorough representation of emissions from belowground biomass, dead trees, litter and organic soil carbon (SOC), which is described in detail in this paper. New afforestation module is developed and described in this paper. In G4M land use change decisions are calculated geographically explicit for $0.5x0.5^{o}$ grid cells, which approximately correspond to a 50x50 km grid taking sub-grid information into account as described in (Kindermann et al., 2006).

Land use change decisions are modeled on the basis of comparing net present value of forestry vis-à-vis the net present value of land use from agriculture. Deforestation is modeled to take place in a grid, if the net present value of agriculture together with benefits from selling wood after the clear-cut of the forest is greater than net present value of forestry (sustainable production of wood during multiple rotation periods) multiplied by a hurdle coefficient. The net present value of agriculture is modeled with an agricultural land price in a form of Cobb–Douglas production function, in which agricultural suitability and population density are independent variables (Benitez et al., 2004). In the model deforestation is prohibited in conservation and nature protection areas. Afforestation takes place in a grid, in which there is land that can be afforested (i.e., not under buildings and roads or secured for agriculture), the environmental conditions are suitable for forestry and the net present value of forestry multiplied by a hurdle coefficient is greater than the net present value of agriculture. Economic policies, e.g. carbon tax in case of deforestation or payments for carbon accumulated additionally in forest ecosystem in case of a/re-fforestation, add value to the maintenance of keeping the forest carbon stock. The hurdle coefficient is derived from applying a calibration method to match base year predictions to FAO and IPCC values. The hurdle rate can be interpreted as an endogenously determined transaction cost factor to LUC. The other two parameters which are endogenously determined in the calibration phase are the country specific adjustment factors for deforestation and afforestation rates. The deforestation rate (amount of forest land that can be converted to agricultural land during one year), and afforestation rate (amount of agricultural land on which forest can be planted during one year) represent more differences in capacity to implement land use changes e.g. technical, infrastructural and financial capabilities of deforesting or establishing new forests. Thus, deforestation and afforestation rates are modeled to be also a function of gross domestic product (GDP), population density and agricultural suitability.

Emissions from deforestation include emissions from burning of slash, dead wood and coarse roots, and from decomposition of wood products, litter and soil organic matter. To assess carbon losses from deforestation we track all carbon pools over time. Likewise, the evolution of carbon pools resulting from afforestation are tracked over time for all respective carbon pools. When modeling the impacts of climate policies all of the carbon pools are credited or debited. Thus, all the emissions when multiplied by the carbon price enter the net present value comparison for land use change decision making.

Information entering the model is available on different levels of aggregation. While some model parameters are global (e.g., decay rate of long/short living products, carbon price), some are region specific (e.g., relative stumpage wood price and net present values of agriculture), some are country specific (e.g., corruption factor, risk-adjusted discount rate, forest planting costs, GDP, hurdle, afforestation and deforestation rate adjustment coefficients) and other are grid specific (e.g., population density, agricultural suitability, NPP, forest biomass, litter and coarse woody debris, potential vegetation, protected areas, etc.). A number of exogenous model parameters change over time following the B2 IPCC scenario story line (e.g., population density, GDP (GGI Scenario Database, 2007)), area of agricultural extend assuming full food security, and development of build-up land (Tubiello and Fisher, 2007), etc).

Previous versions of the model were calibrated globally and tested by comparing global results with FAO deforestation data, global deforestation emissions or results of other models (see, e.g. Kindermann et al., 2006 and Rokityanskiy et al., 2007). In current version of the model we calibrate the model parameters (i.e., country-specific hurdle rates, deforestation and afforestation rate correction coefficients) such a way that country net forest area change (afforested minus deforested) rate and total afforestation and deforestation rates match respective FAO data (FAO, 2006) for the period 2000-2005.

General Description of GLOBIOM

GLOBIOM is a bottom-up partial equilibrium model of total land use. G4M uses endogenously calculated information from the GLOBIOM model, i.e., changes of stumpage wood prices, $pwGB_{reg}$, and net present values of agriculture (agricultural land prices), AGB_{reg}, relative to the year 2000 for 11 world regions, *reg*, are estimated in the GLOBIOM model. The GLOBIOM model determines equilibrium commodity prices, for both the agricultural and forest sectors, matching supply quantities with demand quantities for regional aggregates accounting for interregional trade. Population and GDP trajectories are exogenous to GLOBIOM driving basic demand for forest products and agricultural commodities. The socio-economic drivers are in line with the "central" IPCC B2 scenario. Demand functions for agricultural products are shifted by these two parameters, leading to different equilibrium points over the time. The wood demand system was calibrated recently for a global forest sector study (Rametsteiner et al., 2007). Baseline land prices are consistent with the average regional values used in G4M. In the scenarios, land prices/land rents are determined endogenously by the model. Land is not fixed to the amount of observed managed area, but in order to enable simulation of land expansion into marginal, currently not managed areas, land availability is represented by an explicit supply function. In the G4M model the prices for each grid are estimated by multiplication of the grid's prices for the base year and respective price changes for the respective region of the GLOBIOM model.

Detailed Description of the latest version of the G4M model

Preceding versions of the G4M model were developed by Benitez et al. (2004), Benitez and Obersteiner (2006), Rokityanskiy et al. (2007) and Kindermann et al. (2006)[2]. The deforestation part of the current version is based on the version by Kindermann et al. (2006). In the current version of G4M (1) exogenous prices were used from the global land use model GLOBIOM to drive G4M results (2) carbon pools of belowground biomass, dead trees, litter and soil organic carbon (SOC) were added, (3) the afforestation module was redesigned, (4) a new calibration method was deployed and new calibration data was used.

For every grid cell *i* calculations are done for a number of years. Calculations listed below are done every year. In most cases index *year* is omitted, this means the variables belong to a current year. Some model parameters are global[3] (decay rate of long/short living products, harvest losses, carbon price, etc. – they do not have a subscript index *i*, *reg* or *c*), some are region specific (e.g., relative stumpage wood price and net present values of agriculture – they have subscript index *reg*), some are country specific (corruption factor, risk-adjusted discount factor, forest planting costs, GDP, hurdle, afforestation and deforestation rate adjustment coefficients etc. – they have subscript index c) and other are grid specific (population density, agricultural suitability, net primary production (NPP), forest biomass, litter and coarse woody debris, potential vegetation, protected areas, etc. – they have subscript index *i*). A number of exogenous model parameters change with time following B2 IPCC scenario (e.g., population density, GDP

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[2] Equations 1-23 and 27-30 are taken from (Kindermann et al., 2006), equations 9, 17, 22, 28 and 30 are modified.

[3] In fact all parameters can be specified for a certain grid if respective information is available.

(market) (GGI Scenario Database, 2007)), minimum agricultural land secured to feed the population, buildup land (Tubiello and Fisher, 2007), etc).

Decision on deforestation, afforestation or no action in each cell i and every year is made by comparing net present value of forestry, F_i, (defined in equations 1-16) with net present value of agriculture, A_i, (defined in equations 17-20) and also considering economic measures giving additional value to stored carbon B_i (equations 13-14) and DV_i (equations 22-26).

Net present value of forestry for multiple rotations R_i and country specific risk-adjusted discount factor (Benitez et al., 2004), r_c, is defined with the following equation (Kindermann et al., 2006)

$$F_i = f_i \cdot \left[1-\left(1+r_c\right)^{-R_i}\right]^{-1} \qquad 1)$$

f_i is the net present value of forestry for one rotation defined as a sum of stumpage wood price, pw_i (equation 6), multiplied by harvested wood volume, V_i (equation 9), present value of stored carbon, B_i (equation 13), minus planting costs, cp_i (equation 3):

$$f_i = -cp_i + pw_i \cdot V_i + B_i \qquad 2)$$

Planting costs, cp_i, (\$/ha) are defined as planting costs multiplied by share of natural regeneration, pr_i, which is a function of mean annual increment MAI_i, and price index, px_i, defined as a ratio of purchasing power parities (World Bank, 2005) in cell i and reference country (equations 3-5).

$$cp_i = cp_{ref} \cdot pr_i \cdot px_i \qquad 3)$$

$$pr_i = \begin{cases} 0 & MAI_i < 3 \\ \left(MAI_i - 3\right)/6 & 3 \le MAI_i \le 9 \\ 1 & MAI_i > 9 \end{cases} \qquad 4)$$

$$px_i = \frac{PPP_i}{PPP_{ref}} \qquad 5a)$$

The stumpage price, pw_i, is defined with expression below

$$pw_i = pw_{\min} - \frac{pw_{\max} - pw_{\min}}{99} + \frac{pw_{\max} - pw_{\min}}{99} \cdot SPd_{i,2000} \cdot SNFs_{i,2000} \cdot px_{i,2000} \cdot pwGB_{reg} \qquad 6)$$

where pw_{min} and pw_{max} are minimum (4.4\$/m^3) and maximum (30.8\$/m^3) wood prices[4] (Kindermann et al., 2006), SPd_i is standardized population density depending on population density Pd_i (people/km^2, CIESIN 2005, Grubler et al., 2007; equation 7) and $SNFs_i$ is standardized non-forest share depending on forest share Fs_i in the grid cell i (equation 8).

$$SPd_i = \begin{cases} 1 + \dfrac{Pd_i \cdot 9}{100} & Pd_i \le 100 \\ 10 & Pd_i > 100 \end{cases} \qquad 7)$$

$$SNFs_i = 1 + \left(1 - Fs_i\right) \cdot 9 \qquad 8)$$

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[4] Originally Kindermann et al. (2006) uses 5\$/m^3 and 35\$/m^3 in the year 2000 USD as minimum and maximum prices respectively, which we converted to the year 1995 USD applying the deflator 0.8807

Harvested wood volume, V_i (m^3), depends on mean annual increment, MAI_i (m^3/ha), rotation interval, R_i (years; equation 10), and harvest losses, HL_i (0.2 (IPCC, 2001)):

$$V_i = MAI_i \cdot R_i \cdot (1 - HL_i) \qquad 9)$$

Rotation interval, R_i, is a function of mean annual increment, MAI_i (m^3/ha):

$$R_i = \begin{cases} 5 & MAI_i \geq \frac{170}{10} \\ \frac{600 - |MAI_i - 6| \cdot 50}{MAI_i} & \frac{10}{3} \leq MAI_i < \frac{170}{10} \\ 140 & MAI_i < \frac{10}{3} \end{cases} \qquad 10)$$

The mean annual increment equals to carbon uptake per year, ω_i (tC/ha/year, equation 12), which equals net primary production, NPP_i (tC/ha/year; Alexandrov et al., 1999) multiplied by share of NPP stored in wood, CU, converted to cubic meters of wood using a respective conversion factor, $C2W$:

$$MAI_i = \omega_i \cdot C2W \qquad 11)$$

$$\omega_i = NPP_i \cdot CU \qquad 12)$$

The present value of carbon stored in aboveground forest biomass and forest products, B_i, is determined with the following expression (Benitez and Obersteiner, 2006; Kindermann et al., 2006):

$$B_i = epc_c \cdot \omega_i \cdot (1 - b_i) \cdot \left\{ r_c^{-1} \cdot \left| 1 - (1 + r_c)^{-R_i} \right| - R_i \cdot (1 - \theta_i) \cdot (1 + r_c)^{-R_i} \right\} \qquad 13)$$

where b_i is the baseline carbon uptake, θi considers carbon stored in short living ($frac_{slp}$) and long living ($frac_{llp}$) wood products (FAO, 2006) and carbon release to the atmosphere when the products decompose with decomposition rates dec_{slp} and dec_{llp} (0.5 and 0.03 year^{-1} (IPCC 2001); equation 14). The equation also accounts for fraction of slash burn area (Kindermann et al., 2006), $frac_{sb}$.

$$\theta_i = \left(1 - \frac{dec_{llp} \cdot frac_{llp}}{dec_{llp} + r_c} - \frac{dec_{slp} \cdot frac_{slp}}{dec_{slp} + r_c} \right) \cdot (1 - frac_{sb}) + (1 - frac_{sb}) \cdot frac_{sb} \qquad 14)$$

All wood products are divided to short living and long living fractions:

$$frac_{slp} = 1 - frac_{llp} \qquad 15)$$

A price of ton of carbon, which is applied as carbon tax in case of deforestation or as payments for carbon accumulated in a forest ecosystem (above and belowground biomass, litter, soil organic carbon and coarse woody debris) and woody products (see section on carbon price scenarios) if a new forest is planted, is denoted by pc. In fact, the money which the forest owners pay as tax for a ton of lost carbon or get for a ton of accumulated carbon, epc_i, is smaller than the carbon price because it is reduced by country specific factor, $leak_c$, considering corruption in countries (Kaufmann et al., 2005):

$$epc_c = pc \cdot leak_c \qquad 16)$$

In case of deforestation the tax paid by the forest owner is adjusted according to equation 16 respectively.

Net present value of agriculture, A_i, is modeled using the functional form of a Cobb-Douglas production function using the standardized agriculture suitability, $SAgS_i$ (equation 18; agricultural suitability, AgS_i, from (Ramakutty et al., 2002), and standardized population density SPd_i (equation 7), parameters α and υ_i (price level of land, \$/ha) are defined with equations 19 and 20:

$$A_i = v_{i,2000} \cdot SAgS_{i,2000}^{\alpha} \cdot SPd_{i,2000}^{\alpha} \cdot AGB_{reg} \tag{17}$$

$$SAgS_i = \begin{cases} 10 & AgS_i \geq 0.5 \\ 1 + 9 \cdot AgS_i / 0.5 & AgS_i < 0.5 \end{cases} \tag{18}$$

$$\alpha = \frac{\ln\left(PL_{\max}\right) - \ln\left(PL_{\min}\right)}{2 \cdot \ln\left(10\right)} \tag{19}$$

$$\nu_i = PL_{\min} \cdot px_i \tag{20}$$

PL_{min} and PL_{max} are minimum (176.1\$/ha) and maximum (792.6\$/ha) land prices in reference country[4] (see Kindermann et al., 2006).

Decision on deforestation or no action in each cell i at every year is made by comparing net present value of forestry F_i (defined in equations 1-16) multiplied by country specific hurdle, H_c, with net present value of agriculture A_i (defined in equations 17-20) plus revenue from selling clearcut wood, DV_i, (equations 22-26) if the area is not under protection (e.g., nature reserve; WDPA Consortium, 2004):

$$Defor = \begin{cases} True & A_i + DV_i > F_i \cdot H_c \wedge notProtected \\ False & A_i + DV_i \leq F_i \cdot H_c \vee Protected \end{cases} \tag{21}$$

Deforestation value, DV_i, considers revenue from selling harvested wood and paying money for carbon being lost in the case of clearing the forest (BM_i is aboveground forest biomass, tC/ha, estimated from FAO statistics by Kindermann et al. (2008a):

$$\begin{aligned} DV_i = {} & BM_i \cdot pw_i \cdot C2W \cdot \left(1 - HL_i\right) - \\ & - epc_i \cdot \left[ProdLoss_i + LitterLoss_i + SOCLoss_i + blBM_i + Dead_i + BM_i \cdot frac_{sb}\right] \end{aligned} \tag{22}$$

The deforestation value also considers carbon lost due to emissions associated with decomposition of wood product discounted over infinite time horizon (for details see Benitez and Obersteiner, 2006):

$$ProdLoss_i = BM_i \cdot \left(1 + r_c\right) \cdot \left(\frac{dec_{llp} \cdot frac_{llp}}{dec_{llp} + r_c} + \frac{dec_{slp} \cdot frac_{slp}}{dec_{slp} + r_c} \right) \cdot \left(1 - frac_{sb}\right) \tag{23}$$

decomposition of forest litter (woody, $frac_{wlp}$=0.3, and herbaceous, $frac_{hl}$=0.7, litter fractions), which decompose at rates dec_{wli} and dec_{hli}):

$$LitterLoss_i = Litter_i \cdot \left(1 + r_c\right) \cdot \left(\frac{dec_{wli} \cdot frac_{wlp}}{dec_{wli} + r_c} + \frac{dec_{hli} \cdot frac_{hl}}{dec_{hli} + r_c} \right) \tag{24}$$

decomposition of soil organic carbon at rate dec_{SOCi}:

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[4] Originally Kindermann et al. (2006) uses 200\$/ha and 900\$/ha in the year 2000 USD as minimum and maximum prices respectively, which we converted to the year 1995 USD applying the deflator 0.8807

$$SOCLoss_i = (1 + r_c) \cdot \frac{SOC_i \cdot dec_{SOCi}}{dec_{SOCi} + r_c} \qquad 25)$$

burning of extracted coarse roots (70% of belowground biomass, *blBM$_i$*, which is proportional to aboveground biomass, see equation 51) and decomposition of fine roots left onsite (30% of belowground biomass) at decomposition rate *dec$_{hli}$*:

$$blBMLoss_i = blBM_i \cdot \left[0.7 + (1 + r_c) \cdot \frac{0.3 \cdot dec_{hli}}{dec_{hli} + r_c} \right] \qquad 26)$$

burning of coarse woody debris, *Dead$_i$*, stored in forest (tC/ha, estimated from FAO statistics by Kindermann et al. (2008a)).

The decomposition rates *dec$_{wli}$*, *dec$_{hli}$* and *dec$_{SOCi}$* are functions of long-term average annual temperature and precipitations in each grid cell (climate database by Willmott et al., 1998) according to (Esser, 1991).

The **deforestation rate** is defined by equations 27-29 (for details see Kindermann et al., 2006). The country specific parameter *DefRate$_c$* is introduced to calibrate the model to match FAO statistics (see section on model parameterization). The initial forest share is taken from GLC 2000 (JRC, 2003), GDP rate is taken from GGI Scenario Database, 2007 and adjusted to match 1995 GDP.

$$Fdec_i = \begin{cases} 0 & Defor = False \\ Fs_i & Ftdec_i > Fs_i \wedge Defor = True \\ Ftdec_i & Ftdec_i \le Fs_i \wedge Defor = True \end{cases} \qquad 27)$$

$$Ftdec_i = \begin{cases} 0 & Fs_i = 0 \vee AgS_i = 0 \\ x_i & Fs_i > 0 \wedge AgS_i > 0 \wedge x_i \le Fs_i \\ Fs_i & x_i > Fs_i \end{cases}$$

28)

$$x_i = \frac{0.05 \cdot DefRate_c}{1 + \exp\left(-1.799 + \frac{0.22}{Fs_i} + \frac{0.1663}{AgS_i} - 4.029e-2 \cdot Pd_i + 5.305e-4 \cdot Pd_i^2 \cdot 1.282e-4 \cdot GDP_i \right)}$$

29)

Development of forest share in case of deforestation is determined with equation

$$Fs_{i,year} = Fs_{i,year-1} - Fdec_i \qquad 30)$$

Decision on afforestation in each cell *i* and every year is made if there is area for new forest (share of buildup land, *Bul$_i$*, land reserved for cropland, *Clr$_i$*, and current forest share, *Fs$_i$*, is less than 1), the potential vegetation is forest (*VegType$_i$*, see Table 1; Ramankutty and Foley, 1999)), and the net present value of forestry *F$_i$* (defined in equations 1-16) multiplied by country specific hurdle, *H$_c$*, with net present value of agriculture, *A$_i$* (defined in equations 17-20), plus revenue from selling clearcut wood, *DV$_i$*, defined in equations 22-26, is as follows:

$$Affor = \begin{cases} True & Fs_i + Bul_i + Clr_i < 1 \wedge VegType < 9 \wedge A_i + DV_i < F_i \cdot H_c \\ False & otherwise \end{cases} \qquad 31)$$

The **afforestation rate** is defined with equations 32 and 33. It is a function of agricultural suitability, *AgS$_i$*, determining natural conditions of planting and gross domestic product, *GDP$_i$*, approximating the state of development of transport infrastructure and other technical capacities in the grid. The country specific parameter, $AffRate_c$, is introduced to tune the model to match FAO statistics (see section on model parameterization).

$$Faff_i = \begin{cases} 0 & Affor = False \\ 1-(Fs_i + Bul_i + Crl_i) & Ftaff_i > (Fs_i + Bul_i + Crl_i) \wedge Affor = True \\ Ftaff_i & Ftaff_i \le (Fs_i + Bul_i + Crl_i) \wedge Affor = True \end{cases} \qquad 32)$$

$$Ftaff_i = \frac{0.01 \cdot AffRate_c}{1+\exp\left(\dfrac{0.1}{AgS_i} + \dfrac{1000}{GDP_i}\right)} \qquad 33)$$

Development of forest share in case of afforestation is determined with equation

$$Fs_{i,year} = \begin{cases} Fs_{i,year-1} + Faff_i & Fs_{i,year-1} + Faff_i \le 1-\left(Bul_i + Crl_i\right) \\ 1-\left(Bul_i + Crl_i\right) & otherwise \end{cases} \qquad 34)$$

Carbon Emissions from deforestation

We consider the following carbon dioxide emissions caused by deforestation: emissions from wood product decomposition ($EmProduct_i$, equation 37), emissions from litter decomposition ($EmLitter_i$, equation 38), emissions from soil organic carbon decomposition ($EmSOC_i$, equation 39), emissions from fine root decomposition ($EmFRoot_i$, equation 40), emissions from burning of coarse roots ($EmCRoot_i$, equation 41), coarse woody debris ($EmDead_i$, equation 42) and slash ($EmSlashBurn_i$):

$$Em_i = EmProduct_i + EmLitter_i + EmSOC_i + EmFRoot_i + EmCRoot_i + EmDead_i + EmSlashBurn_i \qquad 36)$$

To estimate the emissions from decomposition in each grid cell we consider cohorts, k, characterized by age of deforested forest carbon pool portions in each grid. The maximal possible age of the oldest cohort, CA, equals to number of years passing from initial until the current calculations year.

$$EmProduct_i = \sum_{k=1}^{CA}\left(Prodll_{i,k} \cdot dec_{llp} + Prodls_{i,k} \cdot dec_{slp}\right) \qquad 37)$$

$$EmLitter_i = \sum_{k=1}^{CA} Litter_{i,k} \cdot \left(frac_{wl} \cdot dec_{wli} + frac_{hl} \cdot dec_{hli}\right) \qquad 38)$$

$$EmSOC_i = \begin{cases} \sum_{k=1}^{CA} SOC_{i,k} \cdot dec_{SOC} & SOC_{i,k} \ge 0.6 \cdot SOC_i \cdot Fdec_{i,k} \cdot Area_i \\ 0 & otherwise \end{cases} \qquad 39)$$

$$EmFRoot_i = \sum_{k=1}^{CA} FRoot_{i,k} \cdot dec_{hl} \qquad 40)$$

$$EmCRoot_i = 0.7 \cdot blBM_i \cdot Fdec_{i,year} \cdot Area_{i,year} \qquad 41)$$

$$EmDead_i = Dead_i \cdot Fdec_{i,year} \cdot Area_{i,year} \qquad 42)$$

$$EmSlashBurn_i = BM_i \cdot frac_{sb} \cdot Fdec_{i,year} \cdot Area_{i,year} \qquad 43)$$

The re-estimation of pools every year ($k = 0..CA$) follows the following roles:

$$Prodll_{i,k} = Prodll_{i,k} \cdot \left(1 - dec_{llp}\right) \qquad 44)$$

$$Prodsl_{i,k} = Prodsl_{i,k} \cdot \left(1 - dec_{slp}\right) \qquad 45)$$

$$Litter_{i,k} = Litter_{i,k} \cdot \left[frac_{wli} \cdot \left(1 - dec_{wli}\right) + frac_{hli} \cdot \left(1 - dec_{hli}\right)\right] \qquad 46)$$

$$FRoot_{i,k} = FRoot_{i,k} \cdot \left(1 - dec_{hli}\right) \qquad 47)$$

We assume that after deforestation eventually up to 40% of SOC is lost (Czimczik et al., 2005) in the following manner

$$SOC_{i,k} = \begin{cases} SOC_{i,k} \cdot \left(1 - dec_{SOCi}\right) & SOC_{i,k} \cdot \left(1 - dec_{SOCi}\right) \geq 0.6 \cdot SOC_i \cdot Fdec_{i,k} \cdot Area_i \\ 0.6 \cdot SOC_i \cdot Fdec_{i,k} \cdot Area_i & otherwise \end{cases}$$

48)

‘Negative’ emissions from afforestation

If forest is planted carbon accumulates in biomass (*EmBMAff$_i$*, equation 50-52), litter (*EmBMAff$_i$*, equation 53) and soil organic carbon (*EmSOCAff$_i$*, equation 54):

$$EmAff_i = EmBMAff_i + EmLitterAff_i + EmSOCAff_i \qquad 49)$$

Forest growth in a cohort, *k*, is a function of NPP and cohort age (*CA-k*, cohort with the smallest number is the oldest). We assume that maximum aboveground biomass in industrial plantations is 100 tC/ha. Forest can be planted on recently deforested areas and all planted forests are managed:

$$abBMAff_i = 100 \cdot \sum_{k=1}^{CA} \left\{ \left[1 - \exp\left(-0.1 \cdot NPP_i \cdot [CA - k]\right)\right]^3 \cdot Faff_{i,k} \right\} \cdot Area_i \qquad 50)$$

The amount of belowground biomass depends on the ecological zone the forest belongs to (the coefficients are estimated using data from (Penman et al., 2003, Table 3A.1.8)):

$$blBMAff_i = \begin{cases} 0.18 \cdot abBMAff_i & Tropical\ forest \\ 0.22 \cdot abBMAff_i & Temperate\ forest \\ 0.25 \cdot abBMAff_i & Boreal\ forest \end{cases} \qquad 51)$$

The carbon sink strength to forest biomass accumulation in each year is estimated as a difference of current year biomass and previous year biomass:

$$EmBMAff_i = \left(abBMAff_{i,year} - abBMAff_{i,year-1}\right) + \left(blBMAff_{i,year} - blBMAff_{i,year-1}\right) \qquad 52)$$

Carbon in litter accumulates with maximum speed 0.95tC/ha/year (Czimczik et al., 2005), and the accumulation rate depends on aboveground biomass in forest age cohorts:

$$EmLitterAff_i = \begin{cases} 0.95 \cdot \sum_{k=1}^{CA} \left\{ \left[1 - \exp\left(\frac{-0.1 \cdot abBmAff_{i,k}}{Faff_{i,k} \cdot Area_i} \right) \right]^3 \cdot Faff_{i,k} \right\} \cdot Area_i & LitterAff_{i,k} < 5 \cdot Faff_{i,k} \cdot Area_i \\ 0 & otherwise \end{cases}$$

53)

Carbon in soil accumulates until reaching 140% of its initial value (almost maximal value according to data by Czimczik et al., 2005). The maximum accumulation speed is 0.04 tC/(ha year) for coniferous (*VegType*=4,6), 0.2 tC/(ha year) for mixed (*VegType*=8) and 0.35 tC/(ha year) for deciduous forests (*VegType*=1-4,7; see Table 1) (Czimczik et al., 2005):

If $SOCAff_{i,k} \leq 1.4 \cdot Faff_{i,k} \cdot Area_i$:

$$EmSOCAff_i = \begin{cases} 0.04 \cdot \sum_{k=1}^{CA} \left\{ \left[1 - \exp\left(\frac{1.2 \cdot LitterAff_{i,k}}{Faff_{i,k} \cdot Area_i} \right) \right]^3 \cdot Faff_{i,k} \right\} \cdot Area_i & VegType = 4 \vee 6 \\ 0.2 \cdot \sum_{k=1}^{CA} \left\{ \left[1 - \exp\left(\frac{1.2 \cdot LitterAff_{i,k}}{Faff_{i,k} \cdot Area_i} \right) \right]^3 \cdot Faff_{i,k} \right\} \cdot Area_i & VegType = 8 \\ 0.35 \cdot \sum_{k=1}^{CA} \left\{ \left[1 - \exp\left(\frac{1.2 \cdot LitterAff_{i,k}}{Faff_{i,k} \cdot Area_i} \right) \right]^3 \cdot Faff_{i,k} \right\} \cdot Area_i & VegType = 1 \vee 2 \vee 3 \vee 5 \vee 7 \end{cases}$$

54)

The re-estimation of pools every year ($k = 0..CA$) follows the following rules:

$$LitteAffr_{i,k,year} = LitterAff_{i,k,year-1} + \\ + \begin{cases} 0.95 \cdot \left[1 - \exp\left(\frac{-0.1 \cdot abBmAff_{i,k}}{Faff_{i,k} \cdot Area_i} \right) \right]^3 \cdot Faff_{i,k} \cdot Area_i & LitterAff_{i,k} < 5 \cdot Faff_{i,k} \cdot Area_i \\ 0 & otherwise \end{cases}$$

55)

If $SOCAff_{i,k} \leq 1.4 \cdot Faff_{i,k} \cdot Area_i$:

$$SOCAff_{i,k} = SOCAff_{i,k,year-1} + \\ + \begin{cases} 0.04 \cdot \left[1 - \exp\left(\frac{1.2 \cdot LitterAff_{i,k}}{Faff_{i,k} \cdot Area_i} \right) \right]^3 \cdot Faff_{i,k} \cdot Area_i & VegType = 4 \vee 6 \\ 0.2 \cdot \left[1 - \exp\left(\frac{1.2 \cdot LitterAff_{i,k}}{Faff_{i,k} \cdot Area_i} \right) \right]^3 \cdot Faff_{i,k} \cdot Area_i & VegType = 8 \\ 0.35 \cdot \left[1 - \exp\left(\frac{1.2 \cdot LitterAff_{i,k}}{Faff_{i,k} \cdot Area_i} \right) \right]^3 \cdot Faff_{i,k} \cdot Area_i & VegType = 1 \vee 2 \vee 3 \vee 5 \vee 7 \end{cases}$$

56)

Calibration of the model

Previous versions of the model were calibrated globally and tested by comparing global results with FAO deforestation data or results of other models (see, e.g. Kindermann et al., 2006 and Rokityanskiy et al., 2007). The G4M model version used here adds calibration of net forest area change (afforested minus deforested) and total afforestation and deforestation areas to match respective FAO data (FAO, 2006) for the period 2000-2005 for individual countries.

The calibration algorithm is designed to find country specific hurdle coefficients (H_c), deforestation and afforestation rates. First, hurdle coefficients are determined while deforestation and afforestation rates from global parameterization are used. Then deforestation and afforestation rates of the grids were tuned with country specific multipliers ($DefRate_c$ and $AffRate_c$) to further minimize the squared differences between FAO data (FAO_c^{net}, FAO_{total}^{affor} and FAO_{total}^{defor} respectively) and corresponding model results (M_c^{net}, M_{total}^{affor} and M_{total}^{defor}, respectively)

$$\sum_c \left(\left(FAO_c^{net} - \sum_{year=2000}^{2005} M_{c,year}^{net} \right)^2 + \left(FAO_{total}^{affor} - \sum_{year=2000}^{2005} M_{year,total}^{affor} \right)^2 + \right. \\ \left. + \left(FAO_{total}^{defor} - \sum_{year=2000}^{2005} M_{year,total}^{defor} \right)^2 \right) \xrightarrow[H_c, DefRate_c, AffRate_c]{} \min ,$$

where c corresponds to country number and runs through all countries.

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