APPENDIX 1: Global Timber Model Description

The global timber model used in this analysis has been developed over a number of years and used widely for policy analysis, including conservation policy (1), carbon policy (2,3,4), and exchange rates (5). The model maximizes the net present value of consumer's plus producer's surplus in timber markets. Because forestry land competes with agriculture for land, it models the interaction between the two markets via land supply functions that account for the costs of renting forestland. These land supply functions are specified for each timber supply region in the model. They either are constant or shift over time, depending on assumptions about future development of agriculture in each region.

Timber is supplied from 146 distinct timber types. The model solves explicitly for harvesting (e.g., rotation ages), management intensity (e.g., $/ha spent regenerating and managing sites), and the area of land in each timber type. For expositional purposes, the results from these many forest types are aggregated into 13 regions. The 13 regions are the United States, Canada, Central America, South America, Europe, Russia, China, Japan, Southeast Asia, Oceania, Africa, Central Asia, and Japan.

For the purposes of describing the model, each of the 146 timber types modeled can be allocated into one of three general types of forest stocks. Stocks S^i are moderately valued forests, managed in optimal rotations, and located primarily in temperate regions. Stocks S^j are high value timber plantations that are managed intensively. Subtropical plantations are grown in the southern United States (loblolly pine plantations), South America, southern Africa, the Iberian Peninsula, Indonesia, and Oceania (Australia and New Zealand). Stocks S^k are relatively low valued forests, managed lightly if at all, and located primarily in inaccessible regions of the boreal and tropical forests. The inaccessible forests are harvested only when timber prices exceed marginal access costs[1].

Formally, the following is solved numerically:

$$\textbf{(1)}\ Max\sum_{0}^{\infty}\rho^{t}\left\{\begin{array}{l}\int_{0}^{Q^{*}(t)}\left\{D(Q_{t},Z_{t})-C_{H^{i}}(\cdot)-C_{H^{j}}(\cdot)-C_{H^{k}}(\cdot)\right\}dQ(t)-\\ \sum_{i,k}C_{G}^{i,k}(G_{t}^{i,k},m_{t}^{i,k})-\sum_{j}C_{N}^{j}(N_{t}^{j},m_{t}^{j})-\sum_{i,j,k}R^{i,j,k}(X_{t}^{i,j,k})+CC(t)\end{array}\right\}$$

where

$$\textbf{(2)}\ Q_{t}=\sum_{i,j,k}\left(\sum_{a}H_{a,t}^{i,j,k}V_{a,t}^{i,j,k}(m_{t0})\right)$$

In equation **(1)**, $D(Q_t,Z_t)$ is a global demand function for industrial wood products given the quantity of wood, Q_t, and income, Z_t. The quantity of wood depends upon $H^{i,j,k}$, the area of land harvested in the timber types in i, j, or k, and $V_a^{i,j,k}(m_{t0})$, the yield function of each plot. The yield per hectare depends upon the species, the age of the tree (a), and the management intensity at the time of planting (m_{t0}). $C_H(\cdot)$ is the cost function for harvesting and transporting logs to mills from each of timber type. Marginal harvest costs for temperate and subtropical plantation forests (i and j) are constant, while marginal harvest costs for inaccessible forests rise as additional land is accessed. $C^{i,k}{}_G(\cdot)$ is the cost function for planting land in temperate and previously inaccessible forests, and $C^j{}_N(\cdot)$ is the cost function for planting forests in subtropical plantation regions. $G^{i,k}{}_t$ is the

[1] In this study, forests in inaccessible regions are harvested when marginal access costs are less than the value of the standing stock plus the present value of maintaining and managing that land as an accessible forest in the future.

area of land planted in types i and k, and N^j_t is the area of land planted in plantation forests. The planting cost functions are given as:

(3) $$C_G^{i,k}(\cdot) = p_m^{i,k} m_t^{i,k} G_t^{i,k}$$

$$C_N^{j}(\cdot) = p_m^{j} m_t^{j} N_t^{j} + f(N_t^j, X_t^j)$$

where $m^{i,j,k}_t$ is the management intensity of those plantings purchased at price p^i_m, p^j_m, or p^k_m. $f(N^j_t, X^j_t)$ is a function representing establishment costs for new plantations. The cost function for establishing new plantations rises as the total area of plantations expands.

The yield function has the following properties typical of ecological species: $V_a>0$ and $V_{aa}<0$. We assume that management intensity is determined at planting. The following two conditions hold for trees planted at time t_0 and harvested "a" years later $(a+t_0) = t_{ai}$:

(4) $$\frac{dV^i(t_{a_i} - t_0)}{dm^i(t_0)} \geq 0 \text{ and } \frac{d^2V^i(t_{a_i} - t_0)}{dm^i(t_0)^2} \leq 0$$

The total area of land in each forest type is given as $X^{i,j,k}_t$. $R^{i,j,k}(\cdot)$ is a rental function for the opportunity costs of maintaining lands in forests. Two forms of the rental function are used:

(5) $R(X) = \alpha(t)X + \beta(t)X^2$ for temperate and boreal regions

$$R(X) = \alpha(t)X^2 + \beta(t)X^3 \qquad \text{for tropical regions}$$

The marginal cost of additional forestland in tropical forests is assumed to be non-linear to account with relatively high opportunity costs associated with shifting large areas of land out of agriculture and into forests. The parameters of the rental function are calibrated initially so that the elasticity of land supply is 0.25 initially, the reported relationship between forests and agriculture in the US (6,7). There are no similar estimates of the elasticity of land supply for other regions of the world, although empirical work is currently being undertaken on this topic. The calibration procedure utilizes the initial land area in each forest type, X, and the initial rental value for the forest type, R(X) and chooses the parameters $\alpha(t)$ and $\beta(t)$ so that the elasticity will be 0.25. This elasticity implies that the area of forests could increase by 0.25% if forests can pay an additional 1% rental payment per year.

The parameters $\alpha(t)$ and $\beta(t)$ are assumed to be constant over time for temperate regions. For tropical regions, they are assumed to change over time in order to simulate conversion of forestland to agriculture. The rental functions shift inward, thus raising the rental costs of maintaining forestland. The shift in the rental functions is an assumption in the model, and the assumptions are developed with scenario analysis. Specifically, the scenario developed for the analysis in this paper was to simulate similar deforestation rates as observed in the past 10 years during the first decade of the model run, and to simulate a decline in deforestation over the rest of the century. An alternative to this scenario analysis, of course, would be to explicitly model the agricultural sector.

The sensitivity of these assumptions about the land rental functions have been tested elsewhere. Sohngen and Sedjo (3) examined sensitivity around the assumed path of deforestation in tropical regions. Not surprisingly, they found that stronger increases in deforestation over the projection period in their analysis (100 years) raised the costs of deforestation. The results in the analysis of this paper are consistent with the higher marginal cost estimates in their study. Sohngen and Mendelsohn (4) have examined adjustments in assumptions over land supply elasticity. More elastic land supply functions reduce the costs of carbon sequestration, including reduced emissions from avoided deforestation, and vice-versa. Specifically, they found that cutting the elasticity assumption in half would reduce the global quantity of carbon sequestered by 10-20%. It is not clear

The stock of land in each forest type adjusts over time according to:

(6) $$X^{i}_{a,t} = X^{i}_{a-1,t-1} - H^{i}_{a-1,t-1} + G^{i}_{a=0,t-1} \qquad i = 1 - I$$

$$X^{j}_{a,t} = X^{j}_{a-1,t-1} - H^{j}_{a-1,t-1} + N^{j}_{a=0,t-1} \qquad j = 1 - J$$

$$X^{k}_{a,t} = X^{k}_{a-1,t-1} - H^{k}_{a-1,t-1} + G^{k}_{a=0,t-1} \qquad k = 1 - K$$

Stocks of inaccessible forests in S^k are treated differently depending on whether they are in tropical or temperate/boreal regions. All inaccessible forests are assumed to regenerate naturally unless they are converted to agriculture. In tropical regions, forests often are converted to agriculture when harvested, so that $G^{k}_{a=0}$ is often 0 for tropical forests in initial periods when the opportunity costs of holding land in forests are high. As land is converted to agriculture in tropical regions, rental values for remaining forestland declines, and land eventually begins regenerating in forests in those regions. This regeneration is dependent on comparing the value of land in forests versus the rental value of holding those forests. Inaccessible forests in temperate/boreal regions that are harvested are converted to accessible timber types so that $G^{k}_{a=0}$ is set to 0. The stock of inaccessible forests in S^{k} is therefore declining over time if these stocks are being harvested. Each inaccessible boreal timber type has a corresponding accessible timber type in S^{i}, and forests that are harvested in inaccessible forested areas in temperate/boreal regions are converted to these accessible types. Thus, for the corresponding timber type, we set $G^{i}_{a=0} \geq H^{k}_{a-1}$. Note that the area regenerated, $G^{i}_{a=0}$, can be greater than the area of the inaccessible timber type harvested because over time, harvests and regeneration occurs in forests of the accessible type.

The term CC(t) represents carbon sequestration rental payments. Rental payments are made on the total stock of carbon in forests, thus, the form for CC(t) is given as:

(7)

$$CC_t = CR_t \sum_{i,j,k} \gamma_{i,j,k} \sum_a \left\{ V_{a,t}^{i,j,k}(m^{i,j,k}(t_0)) \right\} X_{a,t}^{i,j,k} +$$

$$PC_t \sum_{i,j,k} \theta_{i,j,k} \sum_a \left\{ V_{a,t}^{i,j,k}(m^{i,j,k}(t_0)) \right\} H_{a,t}^{i,j,k} - E_t^b ,$$

where CR(t) is the annual rental value on a ton of carbon, PC(t) is the price of a ton of carbon, $\gamma_{i,j,k}$ is a conversion factor to convert forest biomass into carbon, $\theta_{i,j,k}$ is a conversion factor to convert harvested biomass into carbon stored in products, and E^{t}_{b} is baseline carbon sequestration. For this model, we assume that product storage in long-lived wood products is 30% of total carbon harvested (8).

The model is programmed into GAMS and solved in 10 year time increments. Terminal conditions are imposed on the system after 150 years. These conditions were imposed far enough into the future not to affect the study results over the period of interest. For the baseline case, $P^C_t = 0$, there is no sequestration program, and the term CC_t has no effect on the model. Baseline carbon sequestration is then estimated, and used for E^b_t in the carbon scenarios. The sequestration program scenarios are based on the assumed prices for P^C_t.

Data on initial forest area and inventories the model is obtained from multiple sources (Table 1). For most developed countries and temperate forests, inventories are obtained from original sources within the countries or regions because those sources often also contain age class information. For most developing countries in tropical regions, information on forest areas are obtained from the United Nations Food and Agricultural Organization (9).

Table 1: Sources of forest area and inventory data.

Region	Data Source
US	United States Department of Agriculture, Forest Service Forest Inventory and Analysis (http://www.fia.fs.fed.us/)
Europe	(10)
Russia	(11,12)
Canada	(13)
Australia	(14,15)
New Zealand	New Zealand Ministry of Agriculture and Forestry (www.maf.govt.nz)
China	Ministry of Forestry. Dynamic Changes in China's Forest Resources. Working Report, Center for Forest Inventory, Ministry of Forestry, Beijing, China.
All other Countries	(9)

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Appendix 2:

Model description of the Dynamic Integrated Model of Forestry and Alternative Land Use (DIMA)

Model

The model is based mainly on the global afforestation model of [1] and calculates the net present value of forestry with equation **1** − **16** and the net present value of agriculture with equation **17** − **20**. Main drivers for the net present value of forestry are income from carbon sequestration, wood increment, rotation period length, discount rates, planting costs and wood prices. Main drivers for the net present value of agriculture on current forest land are population density, agricultural suitability and risk adjusted discount rates.

These two values are compared against each other and deforestation is subsequently predicted to occur when the agricultural value exceeds the forest value by a certain margin. When the model comes to the result, that deforestation occurs, the speed of deforestation was constraint by estimates given by equation **24**. The speed of deforestation is a function of sub-grid forest share, agricultural suitability, population density and economic wealth of the country.

All symbols in the following equations are explained in the section “List of abbreviations used”.

Net present value of forestry

The net present value of forestry is determined by the planting costs, the harvestable wood volume, the wood-price and benefits from carbon sequestration.

For existing forests which are assumed to be under active managment the net present value of forestry given multiple rotations (F_i) over the simulation horizon is calculated from the net present value for one rotation (f_i) (equation **1**). This is calculated by taking into account the planting costs (cp_i) at the begin of the rotation period and the income from selling the harvested wood ($pw_i \cdot V_i$) at the end of the rotation period. Also the benefits from carbon sequestration are included denoted as (B_i).

The planting costs (eq. **3**) are calculated by multiplying the planting costs of the reference country (cp_{ref}) with a price index (px_i) and a factor which describes the share of natural regeneration (pr_i). The ratio of plantation to natural regeneration is assumed to increase with increasing yield for the respective forests eq. **4**). The price index (eq. **5**) is calculated using the purchasing power parity of the respective countries.

The stumpage wood price (eq. **6**) is calculated from the harvest cost free income range of wood in the reference country. This price is at the lower bound when the population density is low and the forest share is high and at the higher bound when the population density is high and the forest share is low. The price is also multiplied with a price index converting the price range from the reference country to the examined country. The population-density and forest-share was standardized between 1 and 10 by using equation **7** and equation **8** respectively.

The harvested volume (V_i) is calculated by multiplying the mean annual increment (MAI_i) with the rotation period length (R_i) accounting for harvesting losses (eq. **9**).

The rotation period length (eq. **10**) depends on the yield. Fast growing stands have a short and slow growing sites a long rotation length. In this study the rotation length is in the range between 5 and 140 years.

The mean annual increment (eq. **11**) is calculated by multiplying the estimated carbon uptake (ω_i) and a transformation factor which brings the carbon weight to a wood volume ($C2W_i$). The carbon uptake (ω_i) is calculated by multiplying the net primary production (NPP_i) with a factor describing the share of carbon uptake from the net primary production (eq. **12**).

The benefits of carbon sequestration (eq. **13**) are calculated by discounting the annual income from additional carbon sequestration and subtracting the expenses incurred from harvesting operations and silvicultural production. At the end of a rotation period the harvested carbon is still stored in harvested wood products and will come back to atmosphere with a delay. This is considered in the factor (θ_i) which shares the harvested wood volume to short and long living products(eq. **14**).

The effective carbon price represents the benefit which will directly go to the forest owner. In equation **16** a factor describing the percentage of the transaction cost free carbon price is used. A factor $leak_i$ is calculated as the average of the percentile rank from “political stability”, “government effectiveness” and “control of corruption” [2].

$$F_i = f_i \cdot [1 - (1+r)^{-R_i}]^{-1} \tag{1}$$

$$f_i = -cp_i + pw_i \cdot V_i + B_i \tag{2}$$

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

$$pr_i = \begin{cases} 0 & MAI_i < 3 \\ (MAI_i - 3)/6 & 3 \leq MAI_i \leq 9 \\ 1 & MAI_i > 9 \end{cases} \tag{4}$$

$$px_i = \frac{PPP_i}{PPP_{ref}} \tag{5}$$

$$pw_i = pw_{min} - \frac{pw_{max} - pw_{min}}{99} + \frac{pw_{max} - pw_{min}}{99} \cdot SPd \cdot SNFs \cdot px_i \tag{6}$$

$$SPd = \begin{cases} 1 + \frac{Pd \cdot 9}{100} & Pd \leq 100 \\ 10 & Pd > 100 \end{cases} \tag{7}$$

$$SNFs = 1 + (1 - Fs) * 9 \tag{8}$$

$$V_i = MAI_i \cdot R_i \cdot (1 - HL_i) \tag{9}$$

$$R_i = \begin{cases} 5 & MAI_i > 180/10 \\ \frac{600 - |MAI_i - 6| \cdot 50}{MAI_i} & \frac{10}{3} \leq MAI_i \leq \frac{180}{10} \\ 140 & MAI_i < 10/3 \end{cases} \tag{10}$$

$$MAI_i = \omega_i \cdot C2W \tag{11}$$

$$\omega_i = NPP_i \cdot CU \tag{12}$$

$$B_i = epc_i \cdot \omega_i \cdot (1 - b_i) \cdot \{r^{-1} \cdot [1 - (1+r)^{-R_i}] - R_i \cdot (1 - \theta_i) \cdot (1+r)^{-R_i}\} \tag{13}$$

$$\theta_i = (1 - \frac{dec_{llp} \cdot frac_{llp}}{dec_{llp} + r} - \frac{dec_{slp} \cdot frac_{slp}}{dec_{slp} + r}) \cdot (1 - frac_{sb}) + (1 - frac_{sb}) * frac_{sb} \tag{14}$$

$$frac_{slp} = 1 - frac_{llp} \tag{15}$$

$$epc_i = pc_i \cdot leak_i \tag{16}$$

Net present value of agriculture

The net present value of agriculture (A_i) is calculated with a two-factor Cobb-Douglas production function (equation **17**). It depends on the agriculture suitability and the population density. A high agriculture suitability and a high population density causes high agricultural values. The value ranges between a given minimum and a maximum land price. The parameters α_i and γ_i determine the relative importance of the agriculture suitability and the population density and ν_i determines the price level for land. The agriculture suitability and the population density are normalized between 1 and 10.

$$A_i = \nu_i \cdot SAgS_i^{\alpha_i} \cdot SPd_i^{\gamma_i} \tag{17}$$

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

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

$$\gamma_i = \alpha_i \tag{20}$$

Decision of deforestation

The deforestation decision is expressed by equation **21**. It compares the agricultural and forestry net present values corrected by values for deforestation and carbon sequestration. For the deforestation decision the amount of removed biomass from the forest is an important variable. The agricultural value needed for deforestation increases with the amount of timber sales and its concomitant flow to the HWP pool. On the other hand the agriculture value will be decreased by the amount of released carbon to the atmosphere. This mechanism is expressed by a deforestation value (DV_i, eq. **22**). The model also allows for compensation of ancillary benefits from forests. This additional income is modeled either as a periodical income or a one time payment and will increase the forestry value by (IP_i). If it is a periodic payment it has to be discounted, which has been done in equation **23**.

$$\text{Defor} = \begin{cases} \text{Yes} & \begin{array}{l} A_i + DV_i > F_i \cdot H_i + IP_i \\ \wedge \text{not Protected} \end{array} \\ \text{No} & \begin{array}{l} A_i + DV_i \leq F_i \cdot H_i + IP_i \\ \vee \text{Protected} \end{array} \end{cases} \tag{21}$$

$$DV_i = \tag{22}$$

$$BM_i \cdot \left\{ pw_i \cdot C2W \cdot (1 - HL_i) - epc_i \cdot \left[(1+r) \cdot \left(\frac{frac_{llp} \cdot dec_{llp}}{dec_{llp} + r} + \frac{frac_{slp} \cdot dec_{slp}}{dec_{slp} + r} \right) \cdot (1 - frac_{sb}) + frac_{sb} \right] \right\}$$

$$IP_i = (BM_i + BMP_i) \cdot pca_i \cdot \frac{(r+1)^{fr_i}}{(r+1)^{fr_i} - 1} \tag{23}$$

There exist several ways of how financial transfers can be handled. Two mechanisms are realized in equation **21**. One is to pay the forest owner to avert from the deforestation, the other is to introduce a carbon price that the forest owner gets money by storing carbon and paying for releasing it. The introduction of a carbon price focuses the money transfer to the regions where a change in biomass takes place. Payments to avoid emissions from deforestation can be transfered to cover all of the globe's forests, target to large "deforestation regions" or individual grids.

Deforestation rate

Once the principle deforestation decision has been made for a particular grid cell (i. e. the indicator variable $Defor_i = 1$) the actual area to be deforested within the respective grid is to be determined. This is done by the auxillary equation **24** − **25** computing the decrease in forest share. We model the deforestation rate within a particular grid as a function of its share of forest cover, agricultural suitability, population density and gross domestic product. The coefficients c_1 to c_6 were estimated with a generalized linear model of the quasibinomial family with a logit link. Values significant at a level of 5 % were taken and are shown in table 1. The parameters of the regression model were estimated using R [3]. The value of c_0 was determined upon conjecture and directly influences the maximum possible deforestation rate. For our scenarios the maximum possible deforestation is set to 5 % of the total land area per year. That means, a $0.5° \times 0.5°$ grid covered totally with forests can not be deforested in a shorter time period than 20 years.

$$Fdec_i = \begin{cases} 0 & \text{Defor} = \text{No} \\ Fs_i & Ftdec_i > Fs_i \wedge \text{Defor} = \text{Yes} \\ Ftdec_i & Ftdec_i \leq Fs_i \wedge \text{Defor} = \text{Yes} \end{cases} \quad (24)$$

$$Ftdec_i = \begin{cases} 0 & Fs_i = 0 \vee AgS_i = 0 \\ x_i & Fs_i > 0 \wedge AgS_i > 0 \end{cases} \quad (25)$$

$$x_i = \frac{c_0}{1 + e^{-(c_1 + \frac{c_2}{Fs_i} + \frac{c_3}{AgS_i} + c_4 \cdot Pd_i + c_5 \cdot Pd_i^2 + c_6 \cdot GDP_i)}} \quad (26)$$

The deforestation rates (Ft_{dec}) were taken from [4], where the forest area from 1990, 2000 and 2005 for each country was given. For the estimation of the model parameters the area difference between 1990 and 2005 was used to infer the deforestation rate. All values which showed an increase of the forest area have been set to 0, because the model should only predict the deforestation. Countries with an increasing forest area have a deforestation rate of 0. It should be mentioned that the change rate is based on the total land area in the grid i and not on the current forest area.

By using c_2/F_s the model can only be used on grid's where there is some share of forest. This makes sense, because on places where there is no forest, no deforestation can appear. The model will only be usable on grids where forests occur. Therefore, for parameterization, the average agricultural suitability and the population density of a country are also only taken from grids which indicate forest cover.

Development of forest share

After calculating the deforestation rate, the forest share has to be updated each year with equation **27** assuring that the forest share stays within the permissible range of 0–1.

$$Fs_{i,year} = \begin{cases} fsx_{i,year} & fsx_{i,year} \leq 1 - (Bul_i + Crl_i) \\ 1 - (Bul_i + Crl_i) & fsx_{i,year} > 1 - (Bul_i + Crl_i) \end{cases} \quad (27)$$

$$fsx_{i,year} = Fs_{i,year-1} - F_{i,dec} \quad (28)$$

Aboveground carbon in forest biomass

The model describes the area covered by forests on a certain grid. It can also describe the forest biomass if the average biomass on a grid is known and the assumption was made, that the biomass in forests on the grid is proportional to the forest area.

For this reason a global carbon map of aboveground carbon in forest biomass, was created, based on country values from [4]. By dividing the given total carbon, for each country, with the forest area of the country, the average biomass per hectare can be calculated. Now the assumption was made, that the stocking biomass per hectare on sites with a higher productivity is higher than on sites with a low productivity. Not for every country with forests [4] gives values of the stocking biomass. So a regression, describing the relation between tC/ha and NPP, was calculated and the biomass of grids of missing countries have been estimated to obtain a complete global forest biomass map.

Data

The model uses several sources of input data some available for each grid, some by country aggregates and others are global. The data supporting the values in table 2 are known for each grid. Some of the values are also available for time series.

Beside the datasets, available at grid level, the purchasing power parity PPP [5] from 1975–2003, the discount rates [6] for 2004, the corruption in 2005 [2] and the fraction of long living products for the time span 2000-2005 [4] are available for each country (table 3).

The values of table 4 are used globally. Monetary values are transformed for each country with their price index. Brazil was taken as the price-reference country as described in [6] and [7].

In figure 1 the net primary productivity taken from [8] is shown. The values range up to $0.75\,\text{gC/m}^2\text{/year}$. The highest productivity is near the equator.

In figure 2 the population density in 2000 and in figure 3 in the year 2100 is shown. It can be seen, that the highest population densities are reached in India and in south-east Asia. The densities are also quite high in Europe and Little Asia, Central Africa and the coasts of America. The map of 2100 shows an increase in India and in south-east Asia.

Figure 4 shows a map of the current forest, crop and buildup land cover. Large regions are covered by forests. Adjacent to the forests, large areas, used for crop production, can be seen.

In figure 5 the suitability for agriculture is shown. Most of the high suitable land is used today for crop production (see figure 4).

Figure 6 shows the carbon in forests. It can be seen, that the highest densities are located near the tropical belt. One reason for this is, that the biomass in tropical forests is high. Note that this picture shows the tons of carbon per grid and the grid size is $0.5° \times 0.5°$ so the grid has it's largest size near the equator.

Figure 7 shows the purchasing power parity which was used to calculate a price-index. It can be seen that the poorest countries are in Africa and the richest in North America, Europe, Australia and Japan.

Figure 8 shows the discount-rates given in [6]. Here also the richest countries have the lowest discount rates.

Figure 9 shows the effectiveness of the carbon incentives. In low risk countries nearly all of the spent money will be used for maintaining forest sinks in risky countries not all of the money will come to the desired sink.

Figure 10 shows the proportion of harvested wood entering the long living products pool [4].

List of abbreviations used

α_i: Importance of agriculture

γ_i: Importance of population

ν_i: Land price level = minimum land price of reference country $\times$ price index (px_i) [$/ha]

ω_i: Carbon uptake per year [tC/year/ha]

θ_i: Fraction of carbon benefits in products [1]

A_i: Net present value of agriculture [$/ha]

AgS_i: Agricultural suitability [0-1]

b_i: Baseline, how much carbon uptake will be if there is no forest, e.g. 0.1 [1]

BMP_i: Biomass in Products [tC/ha]

BM_i: Aboveground living wood biomass [tC/ha]

B_i: Present value of carbon benefits [\$/ha]

Bul: Share of buildup land [1]

$C2W$: Conversion factor form 1t Carbon to 1m^3 wood [m^3/tC]

cp_i: Planting costs [\$/ha]

cp_{ref}: Planting costs reference country [\$/ha]

CU: Carbon uptake, share of NPP stored in wood [1]

Crl: Share of crop land [1]

dec_{llp}: Decay rate of long living products e.g. 0.03 [1]

dec_{slp}: Decay rate of short living products e.g. 0.5 [1]

DV_i: Deforestation Value [\$/ha]

epc_i: Effectiv carbon price [\$/tC]

f_i: Net present value of forestry for one rotation period [\$/ha]

F_i: Net present value of forestry [\$/ha]

F_s: Actual share of forest [0-1]

F_{dec}: Decrease of the forest share

fr_i: Frequency of incentives money payment [Years]

$frac_{llp}$: Fraction of long living products e.g. 0.5 [0-1]

$frac_{sb}$: Fraction of slash burned area e.g. 0.9 [0-1]

$frac_{slp}$: Fraction of short living products e.g. 0.5 [0-1]

Fs: Forest area share [0-1]

Fs_{year}: Forest share of a certain year [1]

fsx_{year}: Theoretical forest share of a certain year [1]

Ft_{dec}: Theoretical decrease of the forest share

GDP: Gross domestic product [\$$_{1995}$/Person]

H_i: Hurdle e.g. 1.5 [1]

HL_i: Harvesting losses e.g. 0.2 [1]

i: Grid number

$leak_i$: Factor of money which will in real reach the forest [1]

IP_i: Incentive payment [\$/ha]

MAI_i: Mean annual wood volume increment [m^3/ha]

NPP_i: Net primary production [tC/ha/year]

pc_i: Carbon price [\$/tC]

pca_i: Incentives carbon price [\$/tC/fr_i]

Pd_i: Population density [People/km^2]

PL_{max}: Maximal land price of reference country × price index (px_i) [\$/ha]

PL_{min}: Minimal land price of reference country × price index (px_i) [\$/ha]

PPP_i: Purchasing power parity [\$]

PPP_{ref}: Purchasing power parity of reference country [\$]

pr_i: Ratio of area planted [0–1]

pw_i: Stumpage wood price [\$/m^3]

pw_{max}: Maximum revenue of wood, e.g. 35\$/fm [\$/fm]

pw_{min}: Minimum revenue of wood, e.g. 5\$/fm [\$/fm]

px_i: Price index [1]

r: Discount rate [e.g. 0.05]

R_i: Rotation interval length [years]

$SAgS_i$: Standardized agricultural suitability [1-10]

SFs: Standardized not forest area share [1-10]

SPd: Standardized population density [1-10]

V_i: Harvest wood volume [m^3]

x_i: Theoretical decrease of the forest share if $Fs_i > 0 \wedge AgS_i > 0$

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Figure 1 - Net Primary Production (NPP)

Areas with a high increment have a high net primary productivity and are indicated by dark green. Sites with low productivity are indicated by light green.

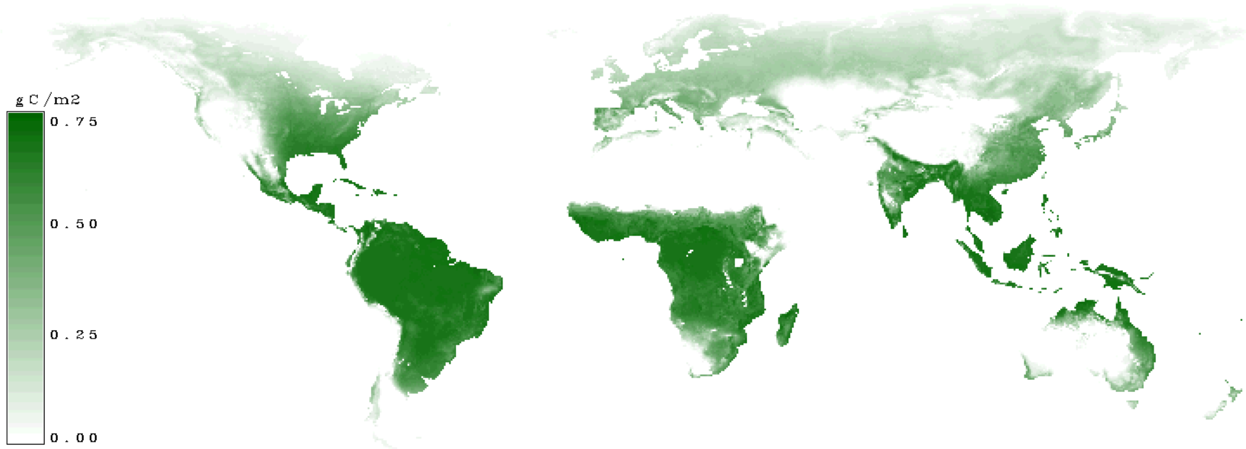

Figure 2 - Population density in Year 2000

Grids with few people are given in white. A rising population density is marked by grey up to high population densities (≥1000 people/km^2) which are indicated by black.

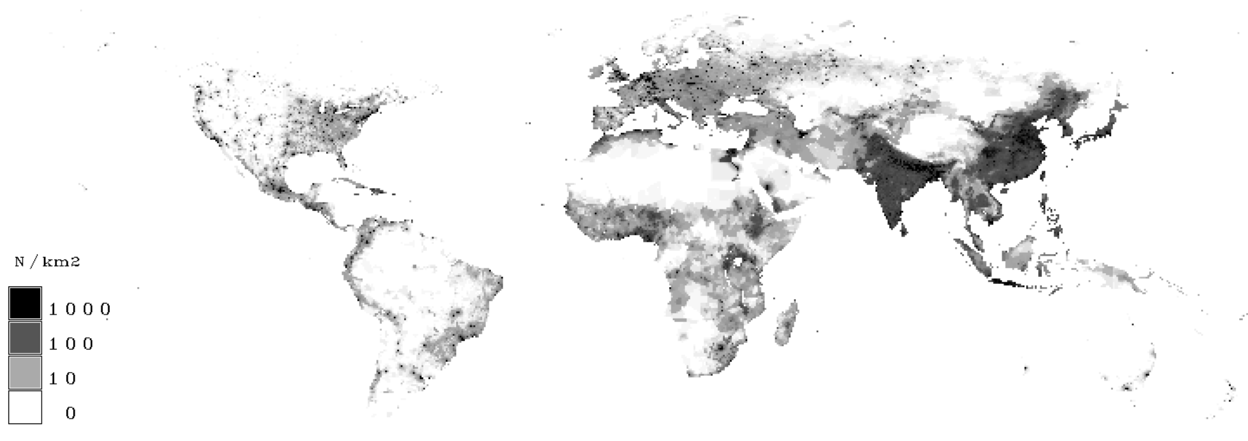

Figure 3 - Population density in Year 2100

Grids with few people are given in white. A rising population density is marked by grey up to high population densities (≥1000 people/km^2) which are indicated by black.

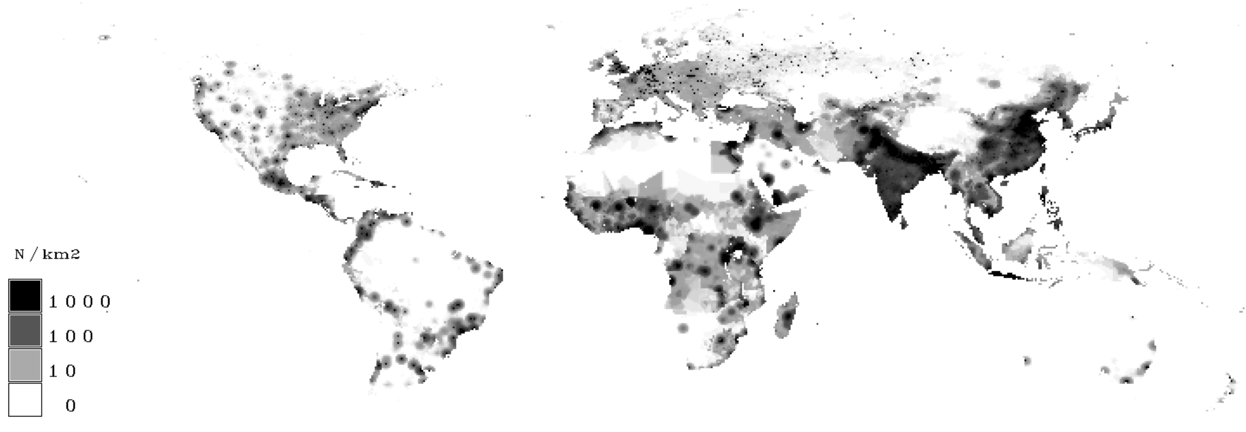

Figure 4 - Forest, Crop and Buildup Land cover

Forests are shown in green, crop in red and buildup land in grey.

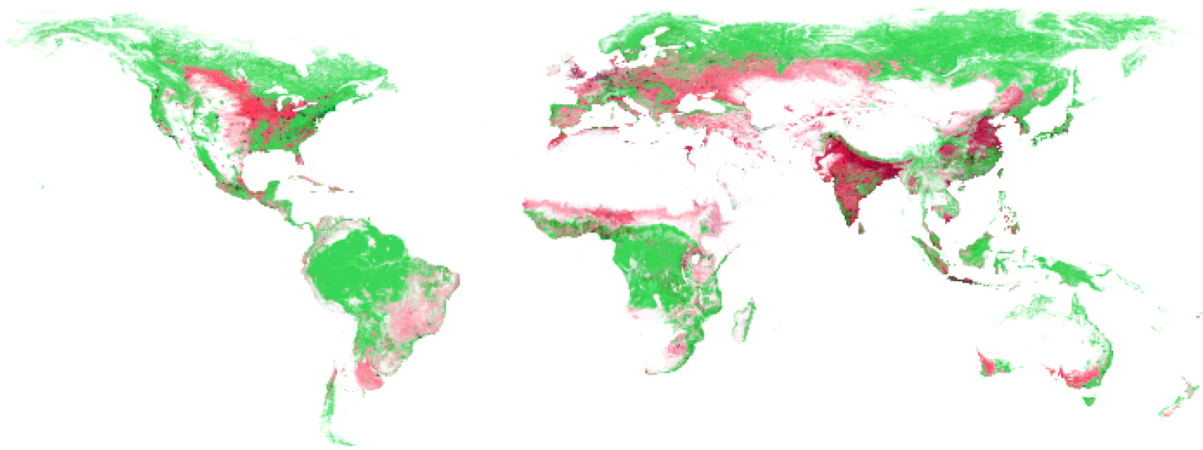

Figure 5 - Agriculture suitability

High suitability for agriculture is marked in dark red. White areas are not suitable for agriculture.

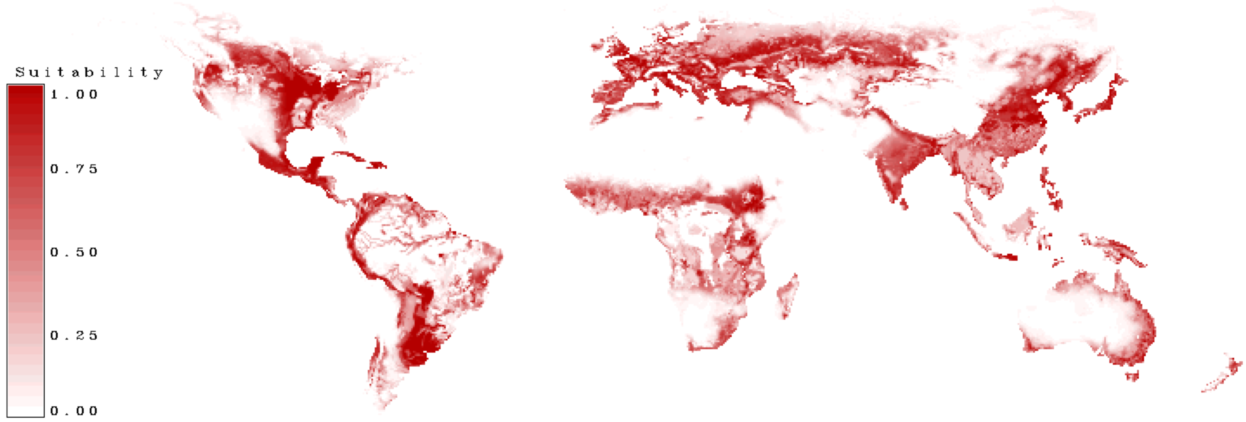

Figure 6 - Carbon in Forest biomass

Regions with no carbon in forests are white. Regions with high values of carbon in forests are dark green.

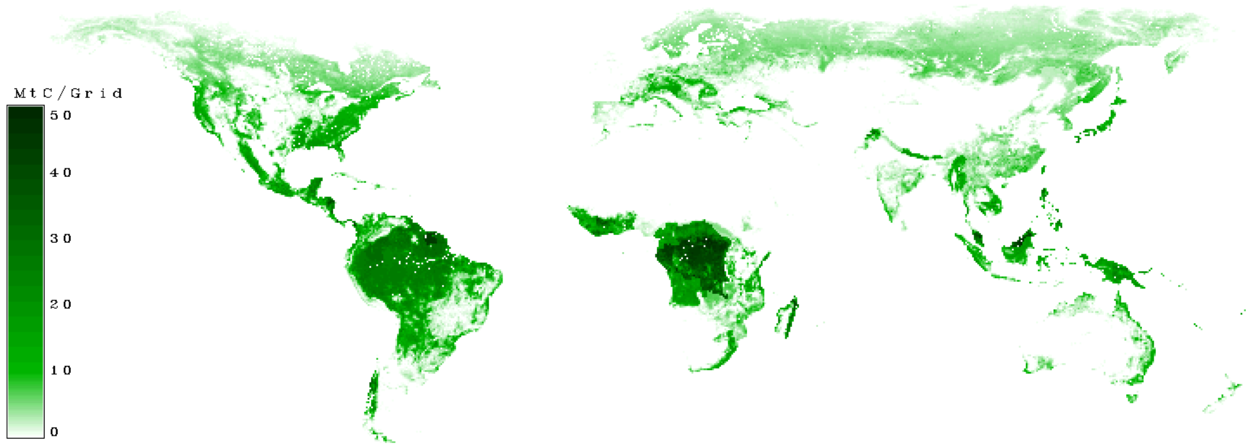

Figure 7 - Purchasing Power Parity (PPP)

Countries with a low purchasing power parity are marked in red, moderate is in green, high values in blue and very high in magenta.

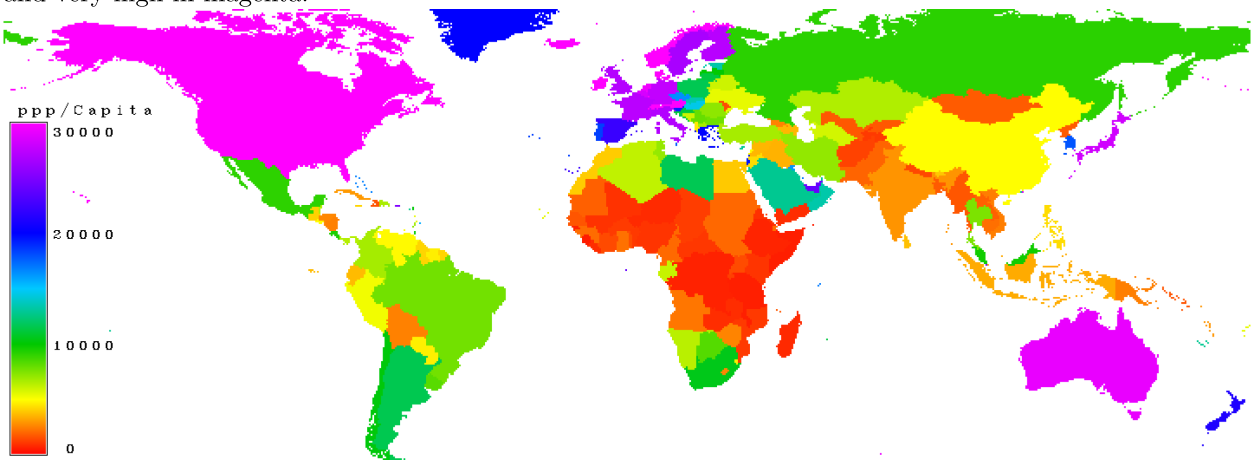

Figure 8 - Discount Rate

Countries with a low discount rate are marked in dark green, moderate countries in yellow and countries with a high rate in red.

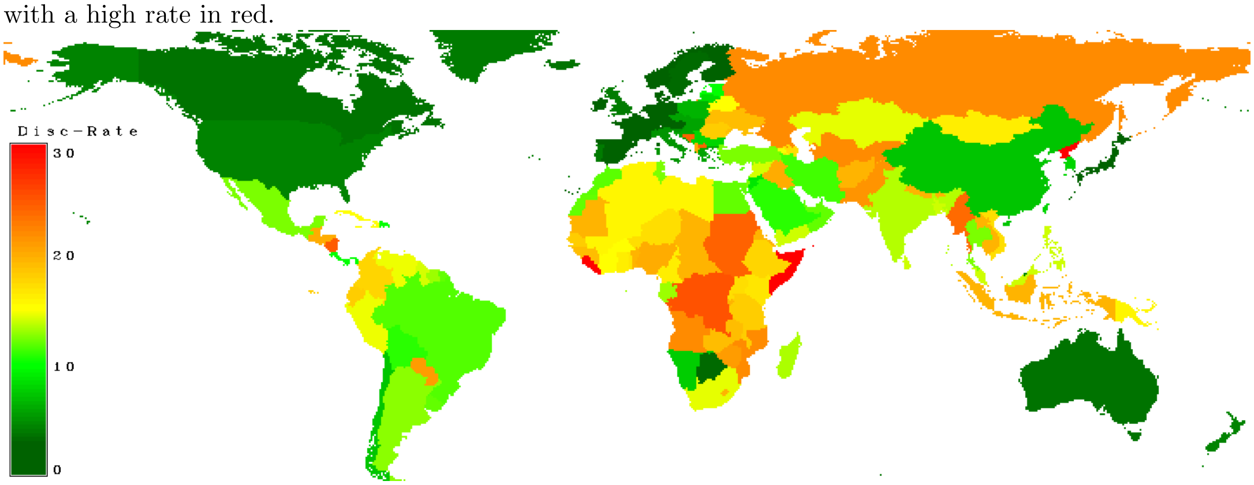

Figure 9 - Effectiveness (Corruption)

Countries with high values of corruption are marked in red, moderate countries in yellow and low values in green.

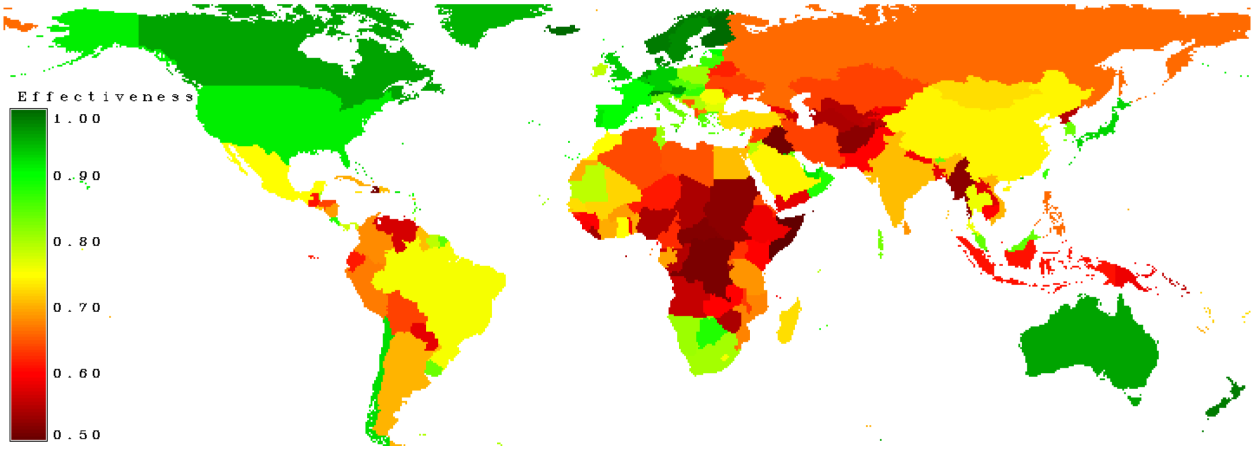

Figure 10 - Share of long living products

Countries which use their wood mainly for fuel-wood are marked in blue, those who use it for sawn-wood are in green.

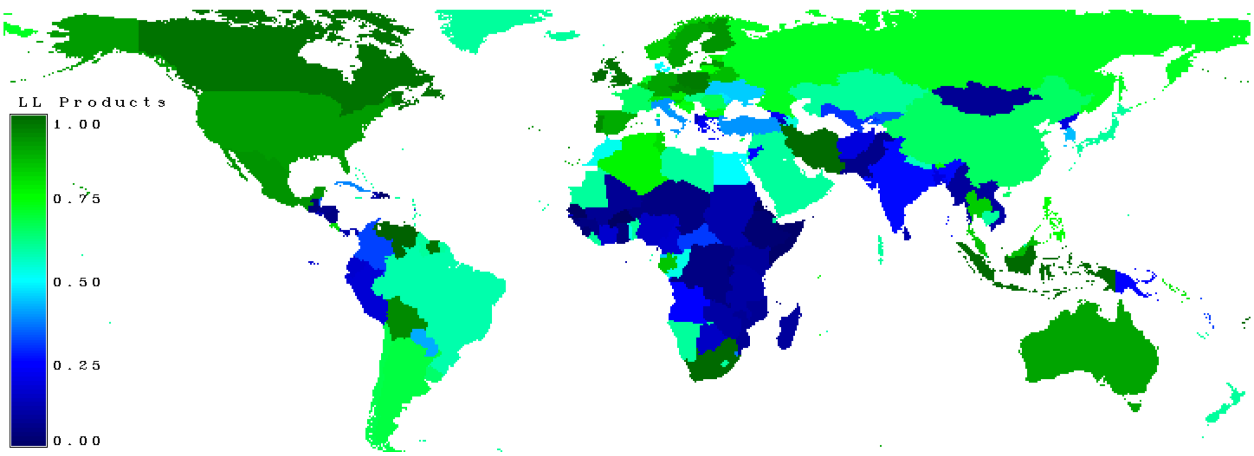

Table 1 - Coefficients for equation 25 – Deforestation speed

Signif. codes: '***'... ≤ 0.001, '**'... 0.001–0.01, '*'... 0.01–0.05

Coef	Estimate	Std. Error	Pr(> $\|t\|$)	
c_0	0.05	—	—	
c_1	-1.799e+00	4.874e-01	0.000310	***
c_2	-2.200e-01	9.346e-02	0.019865	*
c_3	-1.663e-01	5.154e-02	0.001529	**
c_4	4.029e-02	1.712e-02	0.019852	*
c_5	-5.305e-04	1.669e-04	0.001789	**
c_6	-1.282e-04	3.372e-05	0.000206	***

Table 2 - Spatial dataset available on a $0.5° \times 0.5°$ grid

Value	Year	Ref.
Land area	2000	9
Country	2000	10
NPP	—	8
Population density	1990 – 2015	11
Population density	1990 – 2100	12
GDP	1990 – 2100	12
Buildup	2010 – 2080	13
Crop	2010 – 2080	13
Protected	2004	14
Agriculture suitability	2002	15
Biomass	2005	Self
Forest area	2000	9

Table 3 - Country level values

Value	Ref.
Discount rate	6
Fraction of long living products	4
Corruption	2
PPP	5

Table 4 - Global values

Baseline	0.1
Decay rate long	ln(2)/20
Decay rate short	0.5
Factor carbon uptake	0.5
Frequency of incentives payment	5 years
tC to m^3	4
Harvest losses	0.3
Hurdle	1.5
Maximum rotation interval	140 years
Minimum rotation interval	5 years
Planting costs	800 $/ha
Carbon price	0–50 $/tC
Carbon price incentives	0–50 $/tC
Minimum Land price	200 $/ha
Maximum Land price	900 $/ha
Minimum wood price	5 $/ha
Maximum wood price	35 $/ha

Appendix 3: GCOMAP Model Description

In this paper, we use a dynamic partial equilibrium model (Generalized Comprehensive Mitigation Assessment Process, GCOMAP) built to simulate the response of the forestry sector to changes in future carbon prices. A major goal of GCOMAP is to make use of detailed country-specific activity, demand, and cost data available to the authors on mitigation options and land use change by region. The model permits explicit analysis of the carbon benefits of reducing deforestation in tropical countries. However, it does not consider the impact of increasing carbon dioxide concentration (i.e., CO_2 fertilization) on changes in the carbon cycle, and its effect on biomass growth.

The GCOMAP model establishes a reference case level of land use, absent carbon prices, for 2000 to 2100. It then simulates the response of forest land users (farmers) to changes in prices in forest land and products, and prices emerging in carbon markets. The objective is to estimate the land area that land users would plant above the reference case level, or prevent from being deforested, in response to carbon prices. The model then estimates the net changes in carbon stocks while meeting the annual demand for timber and non-timber products. Table 1 provides a list of the key features of the model. The ten world regions covered by the model and as utilized in the EMF 21 modeling process are listed in Table 2.

Table 1: GCOMAP Model Features

Feature	**GCOMAP**
Temporal coverage	2000 to 2100; changes tracked annually.
Land-use change scenarios	Reference scenario — Historical trends, modified government plans. Mitigation scenarios — Driven by land use response to six future carbon price scenarios
Timber and non-timber forest product output and prices	Use supply and demand elasticities to estimate timber price and quantity changes. Five timber and non-timber products. Separate domestic and international markets.
Discount rates	Rate of return (ROR) remains unchanged between reference and mitigation scenarios. Reference case ROR is derived from input costs, product price, and output levels.
Model mechanics	Region-specific for 10 regions. Perfect foresight; based on investment theory. Permits sensitivity and alternative scenario analyses. Software: Excel, Visual Basic.
Macro-economic implications	Estimates total outlays and changes in consumer and producer surpluses and net social pay-off (welfare)

Table 2: Mitigation options, regions , and carbon pools in GCOMAP

<table>
<tr><th>Mitigation Option</th><th>GCOMAP Reporting Regions</th><th>Carbon Pools (All Regions)</th></tr>
<tr><td>Forestation
• Short rotation
• Long rotation
• Biofuels (not reported in this paper)</td><td>• China
• India
• Rest of Asia
• Africa
• South America
• Central America
• USA
• EU (Incl. E Europe and Baltic States)
• Russia
• Oceania (Australia/NZ/Japan/PNG)</td><td rowspan="2">Above/below ground biomass
Soil organic carbon
Litter
Post-harvest residues
Products:
- Domestic timber products
- International timber products
- Fuelwood products
Biofuels (mill-waste) – used as a substitute for coal in power plants</td></tr>
<tr><td>Avoided deforestation</td><td>• Rest of Asia
• Africa
• South America
• Central America
(Minimal or no deforestation assumed for other regions)</td></tr>
</table>

Earlier studies have grouped forestry mitigation activities into three categories (1, 2). One category, carbon sequestration, includes activities that store carbon, for example through afforestation, reforestation and agroforestry. A second one, conservation, includes activities that avoid the release of emissions from carbon stock, such as forest conservation and protection, and a third category, substitution, which involves the substitution of carbon-intensive products and fossil fuels with sustainably harvested wood products and wood fuel. Activities and products in these categories may be interlinked.

We analyze three mitigation options: 1) short-rotation forestry, i.e., new or replanted tree crops or forests managed on a rotation of growth and harvest between 6-60 years; varying by region and forest type; 2) long-rotation forestry, i.e., planting and management for rotations between 20-100 years; and 3) avoided deforestation, i.e., land use management that extends rotations and prevents deforestation. The first two options conform to the first IPCC category, carbon sequestration, and the third conforms to the conservation category. These options currently are practiced in many countries in a wide range of biophysical and socioeconomic conditions, and often co-exist on similar lands, especially in the tropics. Afforestation and reforestation are difficult to define and track separately, especially in the tropics, so they are combined into two forestation options analyzed for each of the ten regions. The option to avoid deforestation is analyzed for four developing regions where deforestation is significant – Africa, Central America, Rest of Asia, and South America. We did not analyze the forest management option in the model and hence vintages of carbon stocks were not tracked for managed or unmanaged forests.

The model is composed of three modules.[1] The carbon stock module tracks annual changes in carbon stocks in ten carbon pools (Table 2): above- and below-ground biomass, soils, litter, post-harvest residues, and wood products – domestic and international timber, non-timber products (fuelwood, resin, honey, and fruits), mill waste, and biofuels (though not reported in this analysis). Product decay and deforestation releases carbon and other greenhouse gas emissions and causes carbon stocks to decline. The same carbon stock dynamics apply to each parcel of forest or planted land in a region over the model time horizon. Vintages of future carbon stock are tracked on planted land. Data for each option represent the characteristics of a representative species for a given region.

The financial module tracks the annual monetary flows associated with the implementation of each of the three mitigation options. The costs of forestation activity include the value of inputs used during establishment (or during deforestation), usually in the first three years or so (e.g., opportunity cost of land, machinery, labor and materiel), as well as expenditures on periodic operations thereafter (e.g., thinning, harvest, and annual overheads like management, maintenance, and monitoring). Costs of deforestation include the cost of harvesting trees and transporting timber from the deforested site, and the opportunity cost, which is estimated as the value of economic activity on deforested land. The benefits from forestation include the revenues derived from the sale of domestic and international timber, non-timber products and fuelwood that have no associated carbon storage, and other mill-waste products. The benefits from deforestation include the above components, except non-timber products.

The land use change module tracks the annual changes in land use in the forestry sector for each of the three mitigation options. Based on the price elasticity values for land supply and demand, the model computes the price of land and the area to be planted or not deforested annually in response to a carbon price. The module ensures that the cumulative planted land area does not exceed the estimated maximum available area suitable for that option in a region.

Each mitigation option is analyzed separately for each region in the model. The analysis begins with the specification of a land use change scenario for the reference case. Using input data on biophysical characteristics of the region -- biomass yield, carbon content of the biomass and soils, product shares, etc., -- the first module computes the annual changes in carbon stock over the model time horizon. It tracks both the accumulation of carbon and its release due to the decay of vegetation and products separately on lands planted each year. Simultaneously, using input data on fixed and variable costs, and product prices, the second module computes the financial viability of the forestry option. While the model is capable of computing several financial parameters, we are mainly interested in the estimate of the rate of return. Since the carbon dynamics are the same on

[1] Equations that describe the carbon stored in each pool, monetary costs and benefits, and the amount of land area planted in response to a carbon price scenario are described in Estimating Global Forestry GHG Mitigation Potential and Costs: A Dynamic Partial Equilibrium Approach. by Sathaye, Makundi, Dale, Chan, and Andrasko (3).

land planted each year, as are costs and product prices, the rate of return remains unchanged on lands planted in subsequent years.

The third module of the model then estimates the changes in land use that result from a carbon price scenario. The rate of return is maintained the same as in the reference case scenario, which decides the additional land area to be planted in the mitigation case each year. The first module is then rerun to compute the annual changes in carbon stock brought about by the change in mitigation land use. Finally, the model computes the difference in carbon stocks in the mitigation and reference cases and reports the carbon and land area gain for each decade between 2000 and 2100. This module also estimates the change in social welfare in the forestry sector.

Our estimated historical rates of return for forestation options reflect the prevailing returns at which land markets are in equilibrium. In the reference case, we project future planting using the historical planting rate, and assume that the current equilibrium conditions will hold over the model time horizon.

Two approaches to discounting -- prescriptive and descriptive-- may be used in climate change modeling (4). The former approach leads to lower, and the latter to higher, rates of discount. The descriptive approach is based on the private or social rates of discount that, savers and investors actually apply in their daily decisions. Private rates of discount typically range between 10% and 25%, and social rates of discount between 4% and 12% (5). The rates are lower for developed countries and higher for developing ones. We estimate private rates of discount from data on cost and revenue profiles in forestry land use activities.

The estimated rates of return (ROR) for land use activities may also depend on the capital markets from which a land user may borrow funds for investment in forestry projects. The estimation of changes in capital markets between the reference and mitigation cases and their influence on interest rates is outside the scope of a partial equilibrium framework. Instead, we assume a conservative rule that the land user would demand at least the same rate of return in a mitigation case as the ROR in the reference case — or the user would have no monetary incentive to plant additional land area or reduce the area being deforested.

Within a region, the model may compute different rates of return for short- and long-rotation forestation options, each of which satisfies demand for different wood products. The differences among land users in their access to financing, timing of revenue streams, biophysical conditions of their lands, etc., results in the coexistence of both options in each region. The model allows both forestry options to persist in the future, consistent with historical and current land use trends. Forestry options also co-exist with other land uses, with comparable implicit effective rates of return after taking into account specific factors like taxes, subsidies and risk. A carbon price allows the landowner to increase the land under forestry by enabling them to plant on higher marginal cost lands. The higher costs of this incremental planting are offset by the carbon price subsidy such that the rate of return from the new areas is maintained at its reference case value.

The rates of return vary across regions but are held constant over time. For short rotation forestry, the rates range from 6% to 12% for the three OECD regions and Russia, between 12% and 19% for Africa and Latin America, and between 26% and 30% for the Asian countries. These rates are derived from sources specific to these regions, and are higher than societal discount rates[2]. The rates for long-rotation forestry are uniformly lower, between 3% to 7% for the three OECD regions and Russia, from 6% to 11% for Africa and Latin America, and from 9% to 13% for the Asian countries. The higher rates of return in Asia also correspond to significantly higher planting rates in those countries. In each region, the rates of return for long rotation are lower than those for short rotation due to the temporal distribution of costs and revenues, with costs occurring in the beginning in both options but revenues coming in much later for long rotation. The price differential (with long rotation species generally having higher product prices), is not sufficient to defray the temporal effect.

The model represents international (timber products) and domestic markets (three types of products -- timber, fuelwood, and non-timber products) with separate demand curves and product prices by region, using International Tropical Timber Organization (ITTO) and other data. There is no single global timber clearing price, but rather a separate demand curve for each product in each region. Demand is exogenous, and supply of products meets it by region.

Consistent with historical data, this analysis assumes that real timber price remains unchanged in the reference case, mostly due to technological improvements and substitution effects. Future timber demand increases over time as population and economies continue to expand, but timber supply continues to increase to meet this demand. Data from the last 40 years suggest that real prices of forest products have remained static over this period (6, 7, 8), with the exception of tropical logs, whose real prices have been slowly increasing. Prices for wood-based panels, paper, and paperboard had been declining since the early 1960s, but have remained constant since the 1980s (7). This may be because substitution of other materials for wood products and technological improvements have reduced the quantity of wood demanded per unit of GDP over time.

Data on land use change, biomass stocks and growth, carbon pools, forestation and deforestation activity, emission factors, and costs and benefits of forestation and avoiding deforestation were gathered for each region. By their very nature, data from various sources may use similar but not identical definitions. For the tropical countries, country-specific data were gathered over a period of years by the F7 network on tropical forestry.

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[2] These rates of return are higher than the societal discount rates that are used in national and global models of climate change. LBNL's review of 23 forestry projects in the tropics shows societal discount rates to range from 1% to 12%, with the median value at 10% and the average at 7%. Other studies have used a 10% rate for short-rotation forestry and arrived at a high positive net present value of benefits. For example, D. Xu (9) using a discount rate of 10% report NPV estimates for China of $540 - $740 and $410 - $610 per hectare for short- and long-rotation forestry respectively. Likewise, Masera et al. (10) reported NPV of $497 and $5780 per ha for short- and long-rotation respectively, using a 10% real discount rate.

Definitions of various activities and data differences were reconciled by network researchers through workshops and meetings beginning in the early 1990s (11, 12, 13).

Data on land use change (forestation and deforestation) for the tropical and temperate/boreal countries were gathered largely from the FAO 2002 Forest Resource Assessment (14) and FAO 1990 FRA - Tropical Countries (15). The regional data on forestland cover, biomass volume, planting and deforestation rates, and industrial roundwood production were based on FAO and ITTO statistics. The FAO and ITTO data collection and publishing process involves some standardization, thus enhancing comparability across regions.

The afforestation and reforestation costs/benefits data as well as carbon sequestration data for the tropical countries are drawn from earlier studies for the COMAP model (16), and supplemented with country- or region-specific sources (17, 18, 19, 20, 21, 22, 23, 24). When data were not available for other countries in a region, these sources then were applied to represent tropical regions in geographic proximity. The yield data were adjusted to ensure that all biomes are appropriately covered. Country-specific labor costs are used where available or adjusted by wage index for a given region, as detailed in Table A1 in the Appendix. Domestic prices of timber and non-timber products were scaled using regional average values weighted by volume for these parameters. The regionalization approach provides coverage of tropical countries in Asia, Africa, and Latin America.

Some of the data for the industrialized regions were obtained from common international sources (7, 25, 26). However, the bulk of the data were gathered from sources unique to each region (see Appendix 1) (27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40). Country-specific data were scaled to regional values using ratios of regional averages to country-specific values for the industrialized regions -- the EU countries, Russia, and Oceania. These were supplemented with additional country-specific data for the US. Although Canada has a large forested area, it is not included in this analysis since we do not analyze the forest management option, and we assume that there is no net deforestation in non-tropical regions. Further more, we do not analyze Canada's forestation potential since there is negligible area under industrial plantations, a key element in initializing the forestation module in the model.

Data on price elasticity of timber demand and supply were obtained from the literature; these are relatively sparse and dated and were applied to each region. This lack of differentiation by region, and constancy over time, of the elasticities is conceptually sub-optimal, but the few data available seem inadequate to justify a range of values by region. A very elastic demand for exported timber, -33.3 was used (41), while price elasticity of -1.0 was used for domestic timber demand (42, 43, 44). The supply of timber was assumed to be much more inelastic, +0.5 (45, 46). In this analysis we used the US forestland supply price elasticity, 0.25, and applied it to all regions over the 100-year horizon, since few studies of such elasticities exist. This value is also the average price

elasticity of forestland reported in Sohngen and Mendelsohn (47) for eight of the ten regions in GCOMAP.[3] Cost and price data were adjusted to 2000 US dollars.
The supply of woodfuel was determined as a residual from the harvested biomass after extracting timber and an estimate of a proportion of onsite post-harvest wood waste. This estimate varies across regions depending on the level of woodfuel use in the country, with developing regions having a much higher proportion than the developed regions. As mentioned above, the proportion of firewood from industrial plantations is about 5%, but in some regions e.g., Africa and Asia, some plantations are dedicated for firewood. The demand for woodfuel and mill-waste for fuel in the reference case is modeled as a residual in the combined multiple-product demand function (international timber, domestic timber and woodfuel).

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