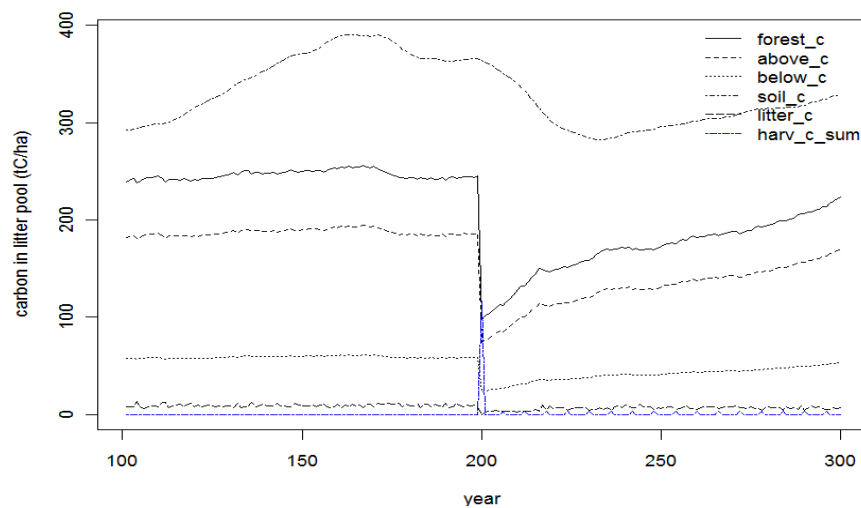


**Project on Environmental Protection and  
Management of Natural Resources in Dak Nong  
Province (EPMNR)**

**Vietnam**

**Carbon Budget and projection model V.1.1**

carbon in different pools in tC/ha



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**March 2010**

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# CARBON BUDGET AND PROJECTION MODEL

V. 1.1

## MANUAL and MODEL APPLICATION

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### Main model features

The model calculates the carbon content in a series of compartments in specific forest stands of Vietnam. At the beginning of all calculations is the estimation of the aboveground biomass with biomass expansion factors. The model simulates yearly growth of diameter at breast height with the measured mean annual diameter increment. The allocation of the aboveground carbon to the different compartments is realised with fixed fraction derived from the literature. It includes three different management strategies to analyse the carbon stocks in the forest stands. Observed data from the forest investigation were used to define the maximum stocking capacity of aboveground biomass. This maximum stocking capacity serves as an asymptote for the simulated maximum stem number that defines the mortality within the stands. The aboveground biomass is divided into three cohorts of small ( $D_{bh} < 20\text{cm}$ ), medium ( $D_{bh} \geq 20\text{cm}$  and  $D_{bh} < 50\text{cm}$ ), and big ( $D_{bh} \geq 50\text{cm}$ ) trees. The model can only be applied at the specific forest stands that were investigated within this project.

## 1 Introduction

Institutional efforts are strengthened to direct the focus on the feasibility of Reduced Emissions from Deforestation and forest Degradation (REDD) in climate change mitigation (IIED 2009). A REDD pilot study on the potential impact of sustainable forest management on foregoing carbon emissions in three communes in the Central Highlands of Vietnam has been initiated. Systematic natural forest management planning and associated participatory forest inventory have taken place in the first step to prepare for carbon accounting. Carbon accounting aims at setting the base for calculations on the offset of carbon emissions in difference harvest and management approaches. Two conceptual approaches are proposed in the literature to calculate carbon emissions (GOFC-GOLD 2008). The stock-based approach estimates the difference in carbon stocks in a particular pool at two points in time and is often applied in setting national-wide baseline degradation rates based on national forest inventories (GOFC-GOLD 2008). In contrast, the gain-loss approach estimates the net balance of additions to and removals from a carbon pool for different carbon pools (GOFC-GOLD 2008). We opt for implementing a gain-loss approach which tracks forest degradation in a simulation model for two reasons. First, cross-sectional data sets on diameter increments and diameter distributions have been appraised in a systematic terrestrial inventory for the year 2009. Second, projections are possible to incorporate harvest and management scenarios that influence the carbon stock in different pools over time and approximate the reduced carbon emissions in sustainable forest management versus a business-as-usual degradation. The simulation model of carbon stocks and flows is inspired by CO2FIX structure of modules (Schelhaas et al. 2004, Masera et al. 2003) and simplicity but deviates in treating mortality, timber harvest and financial feasibility calculations. However, the simulation of carbon stock development into the future does not claim to be as explicit and comprehensive as a process-based vegetation model (e.g. LPJmL, Sitch et al. 2003) but requires incorporating simplified mechanisms of forest regeneration, growth, mortality and harvest for the ease of understanding and application in line with limited data availability from forest inventories in many tropical and subtropical countries (Schelhaas et al. 2004, Masera et al. 2003). The model needs to be prepared to simulate the impact of observed demand for forest products (fuelwood, timber in different diameter-classes etc.) on the development of the total carbon stock. A major prerequisite in REDD studies is to precisely define forest degradation and deforestation. We use the definition of forest degradation based on IPCC (2003), extended by Griscom et al. (2009: 7) as the “direct, human-induced reduction in the forest carbon stocks from the natural carbon carrying capacity of natural forest ecosystems which persists for a specified performance period and does not qualify as deforestation”.

Therefore, the objectives are to estimate the natural carbon carrying capacity and the historical forest degradation of natural forest ecosystems based on calculating the carbon stock and flows in different carbon pools by means of a simulation model on feedback mechanisms of forest growth and forest degradation. The carbon stock and flows in different carbon pools are to be projected in policy scenarios that aim at taking business-as-usual degradation and sustainable forest management into account.

## 2 Simulation model and scenario setup

The simulation model consists of six modules – regeneration, growth, mortality, harvest, carbon budgeting and dynamic investment calculation. We loop the model over  $N$  number of years, with forest regeneration, growth and natural mortality taking place in each year. Forest regeneration (**subsection 3.1**) enters as function of the change in number of trees per hectare due to mortality and harvest events. Forest growth (**subsection 3.1**) is based on calculated mean annual diameter increment from observed current annual increment data over different diameter classes from forest inventory. Mortality due to senescence (**subsection 3.2**) is approximated by a fixed maximum diameter which can be translated to the ratio of current biomass to potential maximum biomass per tree. Tree mortality prior to mortality due to senescence is implemented as function of forest density in three diameter cohorts. Harvest and management scenarios (**subsection 3.3**) are built upon the business-as-usual harvest above a threshold growing stock per hectare without a predefined harvest interval. In addition, sustainable forest management-based harvest bases on priority given to restoring the natural carbon carrying capacity while harvest takes place at reduced magnitude at predefined harvest intervals. The carbon budgeting module (**subsection 3.4**) compiles the carbon emissions due to harvest and carbon stored in each of five pools: aboveground biomass, belowground biomass, soil, litter (aboveground, belowground and foliage dead organic matter). Dynamic investment calculations (**subsection 3.5**) apply for a predefined REDD project length and serve for contrasting the value of carbon under different carbon price scenarios minus the cost of implementing the REDD project to the value of harvested timber minus the costs of timber harvest.

A spin-up phase of 200 years is allowed to bring forest regeneration, growth and natural mortality into equilibrium, i.e. close to the prescribed asymptote of carbon carrying capacity of the forest ecosystem where the change of volume increment per hectare is close to zero. Due to missing sample plots in undisturbed natural forest, the potential biomass stock has been estimated from sample plots in village 6 with high growing stock in 2004 to define the asymptote of forest growth without human intervention. It is confirmed from forest inventory data that the human-induced degradation until 2004 had been negligible. Placing a harvest shock on undisturbed growth means that the forest strives for restoring the equilibrium condition. We shock the forest carbon stock in equilibrium by harvest intervention in 2009 which coincides with observed forest degradation between 2004 and 2009 and allows deriving two plausible scenarios on human-induced interventions. Thus, it should be clear, that both of the harvest scenarios start from the degraded forest status in 2009 while forest use can continue as business-as-usual or under sustainable forest management.

### Baseline scenario

The business-as-usual practice of wood harvest follows governmental regulations on the quantity of harvestable biomass above a prescribed minimum threshold of biomass

volume (130 m<sup>3</sup> per hectare) to be maintained on the stock (more details are provided in the report on forest inventory). In addition, the critical minimum threshold of timber harvest is 50 m<sup>3</sup> to warrant cost-efficient harvest and transport to saw mills (more details are provided in the report on forest inventory). Thus the volume of aboveground biomass is used as criterion to define sustainably-managed forests, but leaves diameter distribution out of considerations. Two major arguments for the need to adjust business-as-usual harvest practices can be addressed. First, harvest takes place in diameter classes from 30 cm to 40 cm of major marketable tree species (more details on species are provided in the report on forest inventory) which disturbs the natural diameter distribution and leads to the change in species composition from biological perspective and irregular income from timber sales from economic perspective. Second, the change in canopy layers and post-harvest mortality leads to a change in ecosystem services, e.g. change in surface runoff and soil stabilization through reduced trees in big diameter classes and the like.

### Sustainable forest management (SFM) scenario

Sustainable forest management is considered to take continuous provision of harvestable timber as well as ecosystem services into account by selective logging distributed over a range of diameter classes to minimize the impact of changed diameter distribution and canopy layers. By means of this scenario the foregone net revenues from reduced timber sales at regular intervals plus the acquired net revenues from carbon credits for carbon sequestered above the baseline degradation can be calculated.

## 3 THEMATIC MODULES, INPUTS AND OUTPUTS

### 3.1 Regeneration and biomass growth

The model uses a simple regeneration establishment rule which determines the number of individuals in regeneration ( $NIND_{reg}$ ) in each year to equal the  $NIND$  prior to mortality and harvest ( $NIND_1$ ) less the  $NIND$  after mortality and harvest ( $NIND_2$ ), (Eq. 1),

$$NIND_{t,reg} = NIND_{t,1} - NIND_{t,2} \quad (1)$$

for each  $t$  year of simulation. An initial diameter of 5 cm is assigned to regenerated trees to start growth from and the  $NIND$  are calibrated to match with the  $NIND$  in regeneration from inventory data. The base for doing so is that the model tracks the  $NIND$  in the growth process from regeneration phase to mortality and builds on intermediate updates of  $NIND_1$  and  $NIND_2$ .

Biomass growth is determined by tree diameter increment in each year of simulation. The mean annual increment (MAI) has been calculated as arithmetic mean from trunk discs of randomly selected cut trees appraised in forest inventory 2009 in village 6. The latest five years have not been regarded since harvest events influenced forest stand density and this in turn had an impact on MAI. By this means, a MAI of diameter by  $0.5 \text{ cm} \cdot \text{y}^{-1}$  has been identified for the time period before 2004 referring to a tree age up to 60 years. The

MAI has been assumed to apply for the entire forest area included in the study. The current annual increment (CAI) of a tree diameter depends on stochastic environmental parameters such as precipitation or change in stand density due to natural mortality of neighbouring trees. Thus, normal distribution of diameter variability around the MAI is assumed and a standard deviation of 0.1 has intuitively been set to restrict the amplitude of randomly selected values for each tree in each year (Eq. 2, Sachs 1999). The variable  $x$  denotes the randomly selected value on the abscissa which determines the CAI (Eq. 2).

$$CAI = \frac{1}{0.1 * \sqrt{2\pi}} * e^{-\frac{1}{2} \left[ \frac{(x-MAI)}{0.1} \right]^2} \quad (2)$$

Furthermore, decreasing CAI is assumed with increasing tree diameter and therefore randomly-determined CAI is sorted in descending order. The unsorted vector of trees is divided into three diameter cohorts <20 cm, 20 cm to 50 cm, >50 cm which the vector of decreasing CAI is applied to. This is based on the NIND in each cohort to approximate random variability among trees in a similar growth stage but general trend of decreasing CAI with diameter cohort. The update of tree diameters by random and sorted CAI values around the observed MAI in each year takes place after regeneration is established.

The CAI value prior to mortality is defined as the gross CAI in volume per hectare which is used as crucial determinant of harvest volume in the sustainable forest management scenario. To do so, CAI of tree diameters is translated into tree volume by calculating the aboveground biomass in tons dry matter per hectare via biomass expansion functions, converted to m<sup>3</sup> fresh matter per hectare via wood density conversion factor (see parameter list in Appendix). The difference in summed aboveground biomass prior to and after tree growth  $V_{above,nogrowth,t}$  and  $V_{above,growth,t}$  in each year  $t$  equals to the gross annual volume increment  $CAI_{grossV,t}$  (Eq. 3).

$$CAI_{grossV,t} = V_{above,nogrowth,t} - V_{above,growth,t} \quad (3)$$

### 3.2 Natural mortality

Mortality takes place if:

- a) the maximum diameter of a tree exceeds the maximum tree diameter and
- b) the number of trees of a cohort exceeds the maximum number (Eq.4)

$$N_{Max_i} = \left( \frac{k_i}{M_i} \right)^{\frac{2}{3}} \quad (4)$$

$N_{Max_i}$  [stems per m<sup>2</sup>] is the maximum number of trees in a cohort  $i$ ,  $k_i$  is the cohort specific parameter, and  $M$  is the mean aboveground biomass of a tree [kg dry matter] in a cohort  $i$ . The parameter  $k$  is fixed for each cohort in a way that its aboveground biomass is constant over simulation time without management. The reference maximum stem number for the fitting of  $k_i$  was taken from village 6 in 2004 with the observed maximum

stem number of a diameter class. The number of dead trees in a cohort equals the difference of number of trees in cohort  $i$  and the maximum number of trees in cohort  $i$ . The individuals were selected with a linear negative probability dependent on the diameter.

### 3.3 Harvest/Management

The conceptual setup of baseline and sustainable forest management scenarios has been described in **section 2**. The implementation and refinement in the model is explained hereafter.

The growing stock difference between 2009 and 2004 is derived from data on the NIND and diameter distribution in 2009 and 2004 via biomass expansion functions. In order to do so, the number of trees per diameter class in 2004 has been randomly reduced until the number of trees per diameter class in 2009 has been attained. The two scenarios are implemented and refined as follows:

#### Baseline scenario

Based on the minimum threshold criterion of 50 m<sup>3</sup> of timber harvest in each harvest interval, the minimum threshold criterion on policy-prescribed 130 m<sup>3</sup> of remaining growing stock and the criterion on harvest in diameter classes of 30 cm and 40 cm, the quantity of harvestable timber is calculated in the baseline scenario. The harvest decision is model-endogenous, but harvest criteria are checked on annual base. Therefore, the parameter *harv\_interval.opt* has to be set to one year. If harvest criteria are fulfilled, randomly with equal probability selected trees are cut until the sum of harvested timber volume is greater than or equal to the minimum threshold under the remaining growing stock constraint. A 10% uncertainty premium is added due to assumed non-accessibility or non-conformity of trunks to quality standards. The harvest residues, i.e. tree crown wood, foliage and stumps, remain in the area and enter the litter pool (see subsection 3.4). Throughout the harvest loop the NIND and the sum of total volume of remaining trees are updated.

#### SFM scenario

In contrast to the baseline scenario there is no prescription on the minimum threshold of harvestable timber. Harvest is prescribed to be the arithmetic mean of gross annual volume increment (biomass growth excluding natural mortality)  $CAI_{grossV,t}$  in fixed periodic harvest intervals. Only trees with a diameter of 25 cm and above qualify for being harvested. The harvest algorithm follows an intuitively selected beta probability distribution in random tree selection until  $CAI_{grossV,t}$  is attained. The beta probability distribution is calibrated to match a 0.5 probability to select a diameter of 50cm. A 10% uncertainty premium is added and calculations also take harvest residuals and biomass volume conversion into carbon into account similar to the baseline scenario.



### 3.4 Carbon budgeting

The aboveground biomass of each tree in kg dry matter was estimated with diameter-based biomass expansion factors in line with FAO methodology. Observed values for aboveground mass in kg CO<sub>2</sub> per diameter class were used to fit biomass expansion functions which were the same for the villages. The resulted regression function (Eq. 5) based on Schroeder et al. (1997).

$$M_{tree} = 0.5 + \left[ \frac{(20000 \cdot d_{bh}^a)}{(d_{bh}^a + b)} \right] \quad (5)$$

$M_{tree}$  is the aboveground biomass of a tree [kg CO<sub>2</sub>],  $d_{bh}$  [cm] is the diameter at breast height,  $a$  and  $b$  are fitting parameters and equal for all trees ( $a=2.87$ ,  $b=548300$ ).

The total aboveground biomass  $AGB_{tot}$  [t dry matter·ha<sup>-1</sup>] is calculated as the sum of all tree biomasses in all cohorts  $i$  (Eq. 6). The converting factors between t dry matter, t C and t CO<sub>2</sub> are listed in Appendix, table 2.

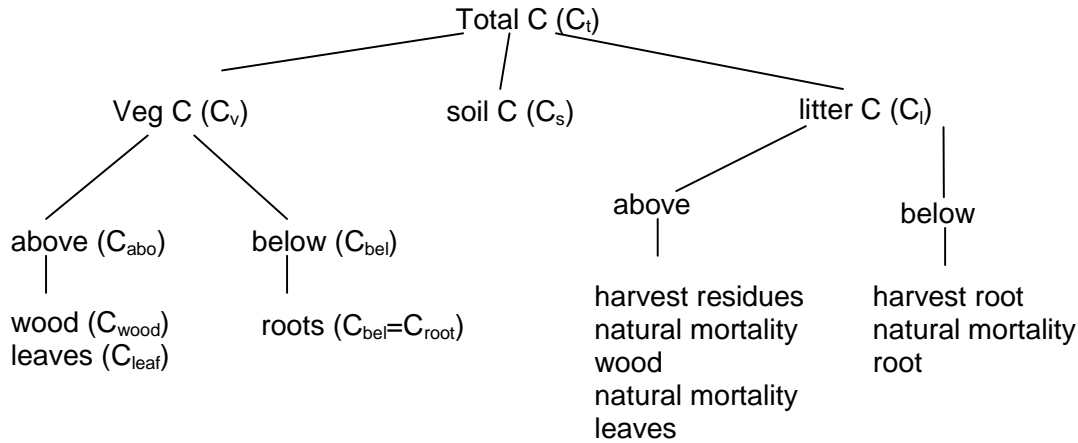
$$AGB_{tot} = \sum_{i=1}^{cohort} \sum_{tree=1}^{tree} M_{tree} \quad (6)$$

There is a fixed ratio between belowground to aboveground biomass. The root-shoot ratio from Ruesch, Gibbs (2008) is set to 0.24 for all plots and trees.

The harvest residues, i.e. tree crown wood, foliage and stumps, remain in the area and enter the litter pool (see carbon pool calculations below). Therefore, the share of crown wood at tree wood had to be determined and converted to carbon. The crown wood share is determined by means of yield tables for *Pinus sp.* monoculture for the sake of simplicity. The total aboveground biomass in m<sup>3</sup> fresh matter per hectare has been converted to tons carbon per hectare, subtracting foliage carbon fraction to obtain the aboveground wood carbon content and finally subtracting a prescribed crown carbon share at total aboveground wood carbon (parameter: *non\_harv\_wood\_perc*) whereas site- and species-dependency is neglected. As the values are age-dependent, the upper bound of yield table estimates has been taken.

Carbon pools are distinguished as follows (Figure 1).

Figure 1: Carbon allocation in pools



The total carbon pool is the sum of all components of the aboveground biomass, the belowground biomass, the soil carbon and the litter carbon due to harvest and senescence (Eq. 7).

$$C_t = C_v + C_s + C_l \quad (7)$$

The carbon stored in the vegetation (Eq. 8) consists of two components, above and belowground material. The aboveground carbon is calculated by the biomass expansion function. The belowground carbon is a fraction of aboveground carbon (Eq. 9).

$$C_v = C_{abo} + C_{bel} \quad (8)$$

$$C_{bel} = \frac{C_{abo}}{1 - 0.24} \quad (9)$$

The distinction between foliage and wood carbon is done with a fixed ratio of foliage carbon fraction at aboveground carbon. The foliage carbon fraction (parameter *leafc\_fra*) is taken from five year running mean output of LPJ global dynamic vegetation model (Sitch et al. 2003) for tropical broadleaved evergreen forest in Vietnam at growth close to natural carbon carrying capacity (Eq. 10).

$$C_{leaf} = 0.021 \cdot C_{abo} \quad (10)$$

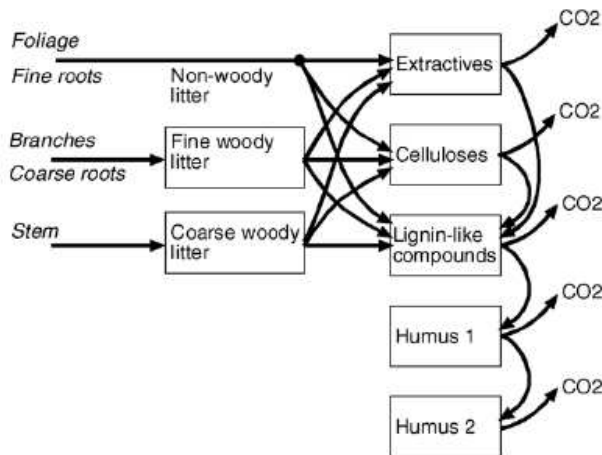
Dead trees due to natural mortality and residues from harvested trees enter the litter carbon pool ( $C_l$ ). The same constants as used for the  $C_v$ -pool are used to fractionise dead tree carbon into wood and leaf carbon from natural mortality. Furthermore 20% of harvested stems without leaves are put into the litter pool as harvest residues. In addition also 1% of  $C_{abo}$  as yearly amount of fine root litter due to senescence is added to  $C_l$

(Jackson et al. 1997). The detailed litter calculation is only needed to simulate soil carbon with the Yasso model.

The dynamic soil carbon model Yasso (Liski et al. 2005) is used to get a rough estimation for the carbon pool in the soil. The model describes decomposition and dynamics of soil carbon in well-drained soils. The current version is calibrated to describe the total stock of soil carbon without distinction between soil layers. The model can be applied for both coniferous and deciduous forests. It has been tested to describe in a wide range of ecosystems from arctic tundra to tropical rainforest. There is no interaction between the Yasso soil model with the biomass growth model. The soil model calculates the soil carbon on the base of the results of the biomass growth model separately.

The soil module consists of three litter compartments and five decomposition compartments (Figure 2). Litter is produced in the biomass module through biomass turnover, natural mortality, management mortality, and logging slash. For the soil carbon module, the litter is grouped as non-woody litter (foliage and fine roots), fine woody litter (regeneration and coarse roots) and coarse woody litter (stems). Since the biomass module makes no distinction between fine and coarse roots, root litter is separated into fine and coarse roots with a fix percentage amount of total dead root biomass (20% fine root and 80% coarse root).

Figure 2: Flow chart of the model. The boxes represent carbon compartments, the arrows carbon fluxes (from Liski et al. 2005).



The formulas given below describe the calculation of the change within the carbon compartments shown in Figure 2. The compartments are simulated on a yearly time step.

$$\frac{dx_{fwl}}{dt} = u_{fwl} - a_{fwl}x_{fwl} \quad (11)$$

$$\frac{dx_{cwl}}{dt} = u_{cwl} - a_{cwl}x_{cwl} \quad (12)$$

$$\frac{dx_{ext}}{dt} = u_{nwl}c_{nwl\_ext} + c_{fwl\_ext}a_{fwl}x_{fwl} + c_{cwl\_ext}a_{cwl}x_{cwl} - k_{ext}x_{ext} \quad (13)$$

$$\frac{dx_{cel}}{dt} = u_{nwl}c_{nwl\_cel} + c_{fwl\_cel}a_{fwl}x_{fwl} + c_{cwl\_cel}a_{cwl}x_{cwl} - k_{cel}x_{cel} \quad (14)$$

$$\frac{dx_{lig}}{dt} = u_{nwl}c_{nwl\_lig} + c_{fwl\_lig}a_{fwl}x_{fwl} + c_{cwl\_lig}a_{cwl}x_{cwl} + p_{ext}k_{ext}x_{ext} + p_{cel}k_{cel}x_{cel} - k_{lig}x_{lig} \quad (15)$$

$$\frac{dx_{hum1}}{dt} = p_{lig}k_{lig}x_{lig} - k_{hum1}x_{hum1} \quad (16)$$

$$\frac{dx_{hum2}}{dt} = p_{hum1}k_{hum1}x_{hum1} - k_{hum2}x_{hum2} \quad (17)$$

$$k_j(T, D) = k_{j0}(1 + s_j\beta(T - T_0) + \gamma(D - D_0)) \quad (18)$$

$$a_i(T, D) = a_{i0}(1 + \beta(T - T_0) + \gamma(D - D_0)) \quad (19)$$

where:

- $u_i(t)$  is the input of litter type  $i$  to the system ( $i$  = nonwoody litter (nwl), fine woody litter (fwl) or coarse woody litter (cwl)),
- $x_i(t)$  is the weight of organic carbon in woody litter compartment  $i$  at time  $t$  ( $i$  = fine or coarse woody litter),
- $a_i$  is the rate of exposure of woody litter  $i$  to microbial decomposition,
- $x_j(t)$  is the weight of organic carbon in decomposition compartment  $j$  at time  $t$  ( $j$  = extractives (ext), celluloses (cel), lignin-like compounds (lig), humus (hum1) or more recalcitrant humus (hum2)),
- $c_{ij}$  is the concentration of compounds  $j$  in litter type  $i$ ,
- $k_j$  is the decomposition rate of compartment  $j$ , and

- $p_j$  is the proportion of mass decomposed in compartment  $j$  transferred to a subsequent compartment ( $1-p_j$  is the proportion removed from the system).
- $T$  is mean annual temperature,  $D$  is climatic water balance (precipitation minus potential evapotranspiration from May to September),  $T_0$  and  $D_0$  denote the long time average of  $T$  and  $D$ ,  $a_{i0}$  and  $k_{j0}$  denote exposure and decomposition rates in these standard conditions, and  $\beta$  and  $\gamma$  are parameters quantifying the temperature and the summer drought effects

The parameter setting is almost the same as proposed for pine in the publication of Liski et al. (2005). Due to a lack of data and the shortness of time the Yasso implementation is thought as a possible extension for the future. Currently the output of the Yasso model was only tested on constancy and plausibility. The needed climate data for the climate dependent decomposition rates were estimated from a monthly temperature and precipitation time series that encompass 15 years. The selected climate station was available on the global PIK database and is located at N17.37, E102.80. The parameter list of the Yasso model is attached in Appendix: table 3.

### 3.5 Financial feasibility calculation

Based on the total carbon data calculated for sustainable forest management versus baseline scenarios over time the financial analysis links costs and revenues that accrue to the entitled institutional body in implementing a sustainable forest management -based REDD scheme. The conceptual question pertains to the required exogenously given price of CO<sub>2</sub>e at the compliance market or voluntary carbon market to make a REDD project financially feasible. Since the REDD project is treated as any other capital investment in companies interested in offsetting their carbon emissions, the dynamic investment calculation concept of the net present value of monetary flows per time unit, i.e. costs and revenues is employed. The opportunity costs of foregone timber extraction are considered as a bottom line payable to the resource owner to agree to reduce harvest activity though the value of sequestered CO<sub>2</sub>e due to sustainable forest management may exceed the value of harvestable timber. The concept is to give incentives to deviate from observed baseline forest degradation towards the increase in carbon stock while generating income to the resource owner.

IIED (2009) summarizes the average prices per ton CO<sub>2</sub>e emission reduced in 10 voluntary market avoided deforestation projects to vary from 6.3USD in 2008 to about 30USD in 2009. This gives rise to the assumption that scenarios of carbon prices in the future have to cover a great range of uncertainty. Therefore, we suggest a scenario analysis with carbon prices of 10USD, 25USD and 50USD throughout the duration of the project, which is flexibly set in 5 year time steps from 5 years to 50 years.

The model allows using scenarios on the discount rate, the future timber prices, the harvest interval, and the future price per ton CO<sub>2</sub>e.

The discount rate  $\rho$  is converted to a discount factor  $\delta$  (Eq. 20).

$$\partial = \frac{1}{(1 + \rho)^t} \quad (20)$$

with  $t$  being the time step when costs and revenues accrue. The net present value of the profit  $NPV_{\pi}$  for different management scenarios is calculated as follows (Eq. 21).

$$NPV_{\pi_{sce}} = \begin{cases} \sum_{t=1}^T (\partial * (TR_{timber,t} + TR_{carbon,t} - TOC_{timber,t} - TOC_{carbon,t} - TAX_t)) - TSC_{carbon,t=0} & \text{if } sce = \{sfm, no\} \\ \sum_{t=1}^T \partial * (TR_{timber,t} - TOC_{timber,t} - TAX_t) & \text{if } sce = \{baseline\} \end{cases} \quad (21)$$

The abbreviation  $TR$  denotes total revenues,  $TOC$  are total operating costs,  $TSC$  translates as total setup costs of the REDD project and  $TAX$  is the natural resource tax which is levied on harvested timber.

Since the model is applied to a natural forest there is no final cut for timber but continuous decision-making on the magnitude of harvestable timber. Sustainable forest management is a financially viable option to the baseline extraction of timber (Eq. 13) if

$$NPV_{\pi_{sfm}} > NPV_{\pi_{baseline}} \quad (22)$$

The financial feasibility is calculated as postprocessing to the simulation runs if is defined to be included in calculations (SCENARIO SETTING, value.module <- TRUE). Different cost types, i.e. setup costs (forest management planning) treated as fixed costs, operating costs (monitoring costs, cutting and hauling costs) and natural resource tax on harvested timber volume are defined from local data and expert guess (PARAMETER SETTING, DEFINE COST TYPES). However, several other setup costs types, i.e. feasibility study, preparing communities for participation, setting up payment scheme and operating costs, i.e. administration costs have been excluded due to missing data.

### 3.6 Outputs

The output is thematically divided into biological and economic outputs. Biological outputs comprise, *inter alia*, carbon pools for each 5-year time step for the number of time steps simulated

- a) the total forest carbon (tC\*ha-1\*ha\*t-1)
- b) the aboveground carbon (tC\*ha-1\*ha\*t-1)
- c) belowground carbon (tC\*ha-1\*ha\*t-1)
- d) soil carbon (tC\*ha-1\*ha\*t-1)
- e) litter carbon (tC\*ha-1\*ha\*t-1)
- f) harvested carbon (tC\*ha-1\*ha\*t-1)
- g) number of individuals in each diameter class

Economic outputs pertain to the NPV of the baseline scenario and scenario for comparison for three carbon price scenarios each. In a separate output file the REDD project establishment costs are taken into account.

Output is summarized in separate files for every management scenarios in csv-format for the ease of further processing. The structure of the output file name is explained; note that thematic contents are separated by dots. Examples are provided below:

v6.sfm.harvint\_10y.carbon\_nind\_calc.csv

Abbreviation	Explanation
v6	Village 6
sfm	Sfm scenario
harvint_10y(s)	Harvest interval of 10 years
carbon_nind_calc	Calculation of carbon and number of individuals in diameter classes

If the VALUE MODULE is switched on, two additional csv-files are generated. For example

v6.sfm.harvint\_10y.proj\_50y.drata\_8perc.pv\_net\_rev\_ha.csv  
v6.sfm.harvint\_10y.proj\_50y.drata\_8perc.pv\_net\_rev\_forest\_fixcost.csv

read as follows:

Abbreviation	Explanation
v6	Village 6
sfm	Sfm scenario
harvint_10y	Harvest interval of 10 years
Proj_50y	Project duration of 50 years
drata_8perc	Discount rate of 8%
pv_net_rev_ha	Present value of net revenues per hectare
pv_net_rev_forest_fixcost	Present value of net revenues incl. fixed project costs

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## APPENDIX

Though harvest scenarios are of major importance, several additional scenario options give maximum flexibility to adjust model runs to different needs (Table 1)

Table 1: Parameters for scenario setting

Option parameter	Parameter space	Value	Explanation
mult.vill	Logical, {TRUE,FALSE}	TRUE	shall all villages be processed at once?
vill_number	Integer, {4,5,6}		single-village calculation, if mult.vill=FALSE: which forest should be parameterized?
harv.scen.opt	Character, {"baseline","sfm","no"}	"sfm"	determine harvest scenario
harv_interval.opt	Integer, {1,2...N} with $N < \text{inf}$	1	harvest interval allowed for baseline or sfm scenario in years
plot_output	Logical, {TRUE,FALSE}	TRUE	shall output be plotted?
value.module	Logical, {TRUE,FALSE}	TRUE	shall carbon/forest product valuation be switched on?
dura.proj	Integer, $n=\{1,5...50\}$ with n element of Z	30	what is the duration of the REDD project in years?
c.price.sce1..3	floating point, with n element of $R < \text{inf}$ and $>0$	10,20,30	determine carbon price scenarios to be compared for the duration of the REDD project
timber.price.sce	floating point, with n element of $R < \text{inf}$ and $>0$	60	determine timber price scenario for the duration of the REDD project
rho	floating point, with n element of $R < \text{inf}$ and $>0$	0.08	determine the discount rate for calculating the capital value of net revenues from REDD
fsiz.vill4...6	Integer, {0,1,2...N}	450	size of forest to be

	with $N < \text{inf}$		included in sfm (in ha), derived from terrestrial inventory data and remote sensing
fmp.cost	Integer, $\{0,1,2\dots N\}$ with $N < \text{inf}$	4	VARIABLE SETUP COSTS: Forest Management Planning, others
oth_var_set.cost	Integer, $\{0,1,2\dots N\}$ with $N < \text{inf}$	0	VARIABLE SETUP COSTS: Forest Management Planning, others
fix_set.cost	Integer, $\{0,1,2\dots N\}$ with $N < \text{inf}$	10500	VARIABLE SETUP COSTS: feasibility study, preparing communities for participation
moni.cost	Integer, $\{0,1,2\dots N\}$ with $N < \text{inf}$	4	VARIABLE SETUP COSTS: Monitoring of forest's growing stock (forest inventory)
oth_carb_oper.cost	Integer, $\{0,1,2\dots N\}$ with $N < \text{inf}$	0	VARIABLE SETUP COSTS: other operating costs
cut.cost	floating point, with n element of $R < \text{inf}$ and $>0$	2.65	OPERATING COSTS: cutting
transp.cost	floating point, with n element of $R < \text{inf}$ and $>0$	18.53	transport
oth_timb_oper.cost	floating point, with n element of $R < \text{inf}$ and $>0$	0	other operating costs
nat.res.tax	floating point, with n element of $R < \text{inf}$ and $>0$	15.44	natural resource tax
plot_spinup	Logical, {TRUE,FALSE}	TRUE	shall spinup be plotted?

nyear	Integer, {0,1,2...N} with N < inf	300	years of simulation
start.year.readout	Integer, {0,1,2...N} with N < inf	200	start year of scenario-based shock and output read-out (spin-up period possible)

Table 2: Data initialization and parameterization (MICHA+MARTIN)

Type of data	Unit	Year	Value	Reference
Magnitude of regeneration	Number of trees/year	2009		Observation, systematic 2x2m regeneration sample plots in 3 villages
Average diameter increment over all diameter classes	cm/year	2009	0.5	Observation, systematic sample plots in 3 villages
Diameter distribution	Number of trees in diameter classes	2009, 2004 (village 6 only)		Observation, systematic sample plots in 3 villages
temperature time series	°C	1990-2005	monthly	PIK Global Time Series Database
precipitation time series	mm	1990-2005	monthly	PIK Global Time Series Database
Main parameters	Unit	Year	Value	Reference
Carbon content	tC·t DM <sup>-1</sup>		$\rho_c=0.47$	Ruesch, Gibbs (2008)
Average wood density of observed main tree species	t DM·m <sup>-3</sup> FM		$\rho_{DM}=0.64$	Zanne et al. (2009)
Root:shoot ratio			$r_{r:s}=0.24$	Ruesch, Gibbs (2008)
CO <sub>2</sub> :C ratio			$r_{CO_2:C}=3.67$	
Biomass expansion function parameters			a=2.87 b=548300	Result from fitted observed carbon content/tree in diameter classes

Mortality rule parameters $k_1, k_2, k_3$	kg DM·m <sup>-2</sup>		$k_1=2.5$ $k_2=3.1$ $k_3=1.5$	this study
Maximum tree diameter at breast height	cm		DBH <sub>max</sub> =100	this study
Minimum threshold harvest	m <sup>3</sup> aboveground stem biomass		50	Local policy regulations
Minimum threshold of remaining growing stock	m <sup>3</sup> aboveground biomass		130	Local policy regulations
Inaccessible tree % resid_non_harv_tree	Fraction of harvestable biomass		0.1	this study
Crown wood % non_harv_wood_perc	Fraction of aboveground biomass		0.2	Pinus sp. yield table, Germany
Foliage carbon share leafc_fra	fraction		0.021	LPJ simulation tropical broadleaved evergreen forest in Vietnam
Lower diameter threshold for gross CAI calculation in sfm-scenario bio_thre	cm		25	this study
Maximum diameter simulated dbh_max	cm		100	this study

Table 3: Parameterization of Yasso model

Parameter	Value	variable name in source code
<b>Invasion rates of woody litter by microbes (year<sup>-1</sup>)</b>		
Non-woody litter ( $a_{nwl}$ )	1	-
Fine woody litter ( $a_{fwl}$ )	0.6	a0.fwl
Coarse woody litter ( $a_{cwl}$ )	0.05	a0.cwl
<b>Decomposition rates (year<sup>-1</sup>)</b>		
Extractives ( $k_{ext}$ )	0.82	k0.ext
Celluloses ( $k_{cel}$ )	0.3	k0.cel
Lignin-like compounds ( $k_{lig}$ )	0.22	k0.lig
Faster humus ( $k_{hum1}$ )	0.012	k0.hum1

Slower humus ( $k_{\text{hum}2}$ )	0.0012	k0.hum2
<b>Formation of more complex compounds in decomposition (proportion of decomposed mass)</b>		
Extractives to lignin-like compounds ( $p_{\text{ext}}$ )	0.2	p.ext
Celluloses to lignin-like compounds ( $p_{\text{cel}}$ )	0.2	p.cel
Lignin-like compounds to faster humus ( $p_{\text{lig}}$ )	0.2	p.lig
Faster humus to slower humus ( $p_{\text{hum}1}$ )	0.2	p.hum1
<b>Parameter values for the effects of temperature and summer drought in the model</b>		
parameter for mean annual temperature ( $\beta$ )	0.05	beta
parameter for climatic water balance ( $\gamma$ )	0.001	gamma