

A model to explore REDD payments in an agroforest landscape in South-West Ghana

Marieke Sandker, Bruce M. Campbell, Neil Collier

Abstract

We constructed a system dynamics model for a cocoa agroforest landscape in South-western Ghana to explore the likely impact of reducing emissions from deforestation and forest degradation (REDD) payments on local farmers. REDD strategies could potentially conserve forests and impact the poor. Participatory modeling was carried out with a diverse range of stakeholders to explore REDD payments as an option to local farmers. This paper describes the full structure, dynamics and information input of the model built of the Wasa Amenfi West district.

Introduction

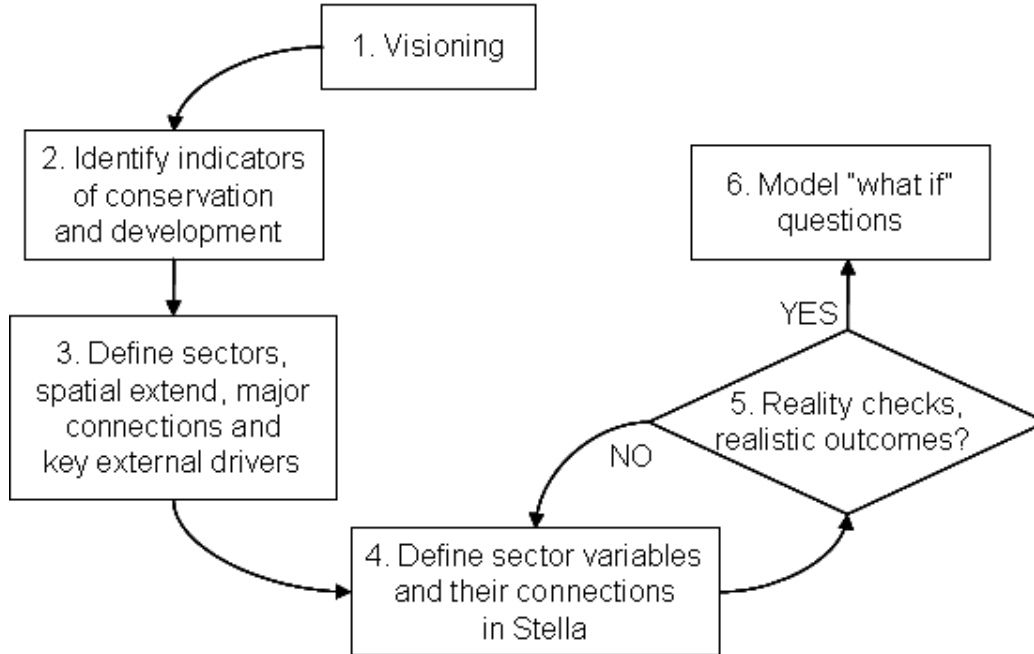
Following the United Nation's conference of parties on climate change in Bali, December 2007, reduced emissions from deforestation and forest degradation (REDD) are heavily debated. The concept in brief is this: payments are made to governments of developing countries if they decrease CO₂ emitted from deforestation and forest degradation, with payments based on the difference between realised emissions and projections from a historical baseline. Ghana's deforestation rate of 2.0% is high compared to the average of 0.7% for the sub-Saharan countries and 24% of the country is still covered with forest (WB 2008). These national statistics look promising for Ghana's REDD potential. A participatory model was built for the Wasa Amenfi West district, SW Ghana, in order to explore potential REDD payments as an option to local farmers. This paper describes in detail the full structure of the model, gives an introduction to the STELLA modeling language, the steps taken in the participatory modeling process and provides the sources of information of the data entered into the model.

Methods

Steps taken in the participatory model building process

We will describe an idealized sequence of steps in the participatory modeling process (Fig. 1) although as in many multi-stakeholder processes there was some iteration and backtracking during the workshop.

Figure 1. Sequence of steps in participatory modeling process copied from Sandker et al 2009



In the first step, we developed visions of the future around topics of interest. As a prelude to visioning, we encouraged participants to think about change by discussing historical events that affected conservation and development outcomes. We examined underlying trends in ecological and socioeconomic variables. We then identified some potential major drivers of change, and developed positive and negative scenarios from poverty and biodiversity perspectives. In so doing, we identified the key issues for modeling.

The second step consisted of identifying what model parameters we are interested in; their outcomes are plotted on graphs. For the scenario for REDD this is the amount of carbon prevented from being emitted by deforestation and forest degradation, and the cash income for the farmers that preserve this carbon on their lands.

The third step consisted of conceptualizing the landscape; this involved defining the major sectors for the model, the spatial dimensions and the major connections between sectors. This step is conducted on paper or in Stella's "map layer".

The fourth step was the detailed model building in Stella: defining the main variables (stocks and converters in model terms) in each sector, collecting the initial values for these variables, and defining how variables influenced each other. Small groups of stakeholders worked on different sectors after which they were presented and discussed as a group and linked together in one landscape model.

The fifth step consisted of reality checks, running the model under different conditions and exploring how simulations compared to what is known by stakeholders. The simulations often led to revisions of assumed variables and relationships and revealed the need for additional data; data which was collected in the beginning of 2009 by household surveys.

Once the model simulations were found to be realistic by all stakeholders, we moved to the final step of exploring scenarios and asking 'what if..' questions.

The participants and data fed into the model

The model was built with various stakeholders: a district official of the Ministry of Food and Agriculture, a cocoa farmer, a representative of a timber company and staff working for local and international environmental NGOs. In addition there were modeling and remote sensing experts, 15 persons in all. The information fed into the model is mostly information from district reports, the literature or district and national statistics.

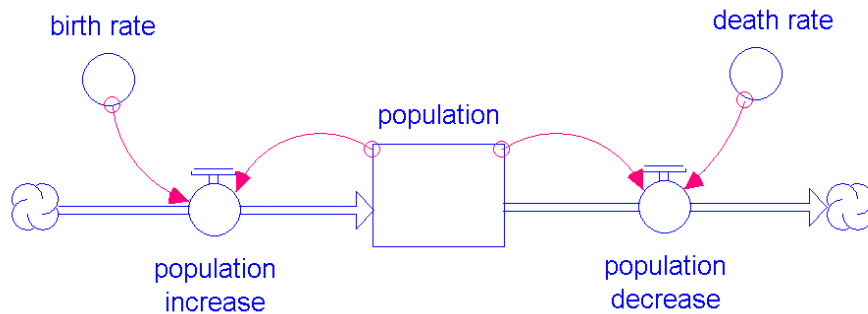
Whenever data was lacking a mediated estimate was made by the local experts either based on their knowledge or on data from comparable situations.

The modeling language STELLA

The system dynamics model of the Wasa Amenfi West district was built using the software STELLA (HPS, 1996). STELLA's interface has three levels: the equation level, the model level and the interface level. The equation level is generally the least used, the model is built at the model level and the interface level gives an overview of the different sectors of the model.

STELLA models are built using four basic elements of construction: 'stocks', 'flows', 'action connectors' and 'converters' (Fig 2).

Figure 2. A STELLA model for population (in STELLA's model level)



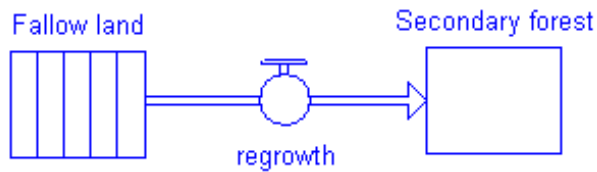
Stocks (e.g. 'Population' in Fig 2) represent conditions within a system; they are a quantity of something with one single unit (e.g. km², persons, m³). Stocks are represented with the following formula:

$$X(t) = X(t-dt) + (\text{Inflows} - \text{Outflows}) * dt$$

where t= time and dt = the time step

None of the stocks in this model can have a negative value. There are different stock variants, of which two are used in this model. We used the 'classic' stock, called a 'reservoir' ('Population' in Fig. 2 and 'Secondary forest' in Fig. 3), and a 'conveyor' to simulate aging ('Fallow land' in Fig. 3).

Figure 3. A STELLA model for re-growth of fallow land into forest using a conveyor



The initial value entered in the conveyor is considered to be of different ages spread equally over the transit time. For example, in the example of Fig. 3 we entered a transition time for re-growth of 5 years; when $t=0$ and the initial value of fallow land=100ha, then during the first 5 years of the simulation, 20 ha will grow into secondary forest each year. After the first transit time in the simulation has passed, the outflow equals the inflow with one transit time delay; in our example this would be $\text{outflow}(t) = \text{inflow}(t-5)$.

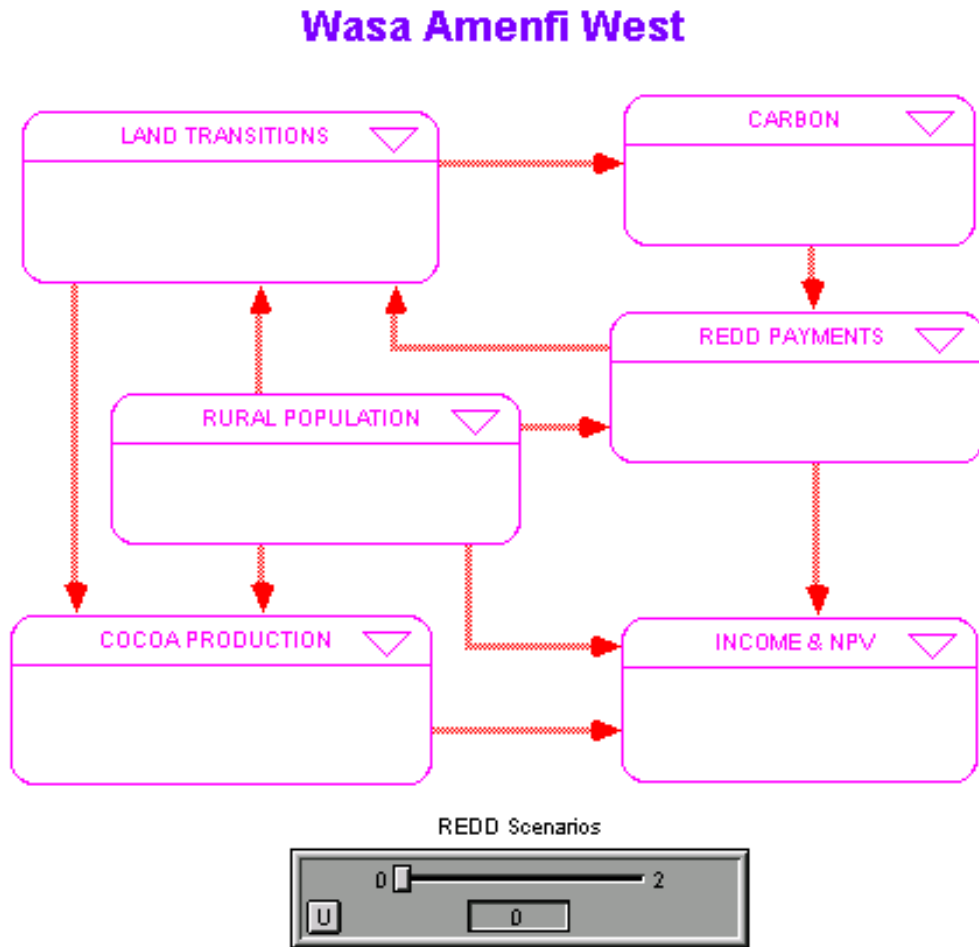
Flows ('Population increase' and 'Population decrease' in Fig. 2 and 'Regrowth' in Fig. 3) represent the activities that cause conditions to change and add dynamics to the values of stocks. Flows do not have a predetermined formula structure but have the same unit as the stock with which they are connected per time step (e.g. km^2/year , $\text{persons}/\text{year}$).

In a metaphor HPS (2003) suggests that if stocks are nouns and flows are verbs, then converters ('Birth rate' and 'Death rate' in Fig. 2) are adverbs. Converters add information and are often used to define flows and convert their units correctly. They have no predetermined formula structure and can have single (e.g. ha, elephants) or combined units (e.g. $\text{elephants}/\text{ha}$; m^3/year). Often they are constant values but their values can also be defined as functions or 'graphical functions'. When a converter is a graphical function its value can change in a non-linear manner over time or with the values of stocks, flows or other converters in the model. E.g. one can make a graphical function of Birth rate making its value depend on Population; we can enter a constant value until the population reaches a certain number after which we can lower the value of Birth rate with an S-shaped curve.

The last element of the STELLA language is the action connector (the red arrows in Fig 1). Action connectors transport information from stocks, flows and converters to flows and converters. E.g. if the flow 'Population increase' is determined by 'Birth rate' x 'Population', then action connectors are needed from 'Birth rate' and 'Population' to 'Population increase'.

A landscape model is often sub-divided in different model sectors, just to make it easier to navigate the model and to keep a degree of overview when the model gets more complex. The sectors of the Wasa Amenfi West model are displayed in Figure 4. The arrows between the sectors indicate where information from the sector from which the arrow departs is used in the sector the arrow points at.

Figure 4. Sectors of the Wasa Amenfi West model and slider for running different scenarios (in STELLA's interface level)



Located below the model sectors one can see a slider called 'REDD Scenarios'. A slider is a converter which can take different values. The slider in Fig. 4 can take the value 0, 1 and 2. The incremental step is set at 1 so the slider in this example cannot take intermediate values (e.g. 1.5). Sliders are usually used so one can easily run different scenarios or to change the value of a parameter whose influence on the model outcomes we'd like to explore.

In the Ghana model the three scenarios explored are obtained as follows:

REDD Scenarios= 0: 'Business as Usual' (BAU), forest is being converted to cocoa plantations

REDD Scenarios= 1: 'Reducing emissions from deforestation' (RED), none of the current area covered with old growth forest is converted

REDD Scenarios=2 'Reducing emissions from deforestation and forest degradation' (RED&D), none of the current area covered with old growth or secondary forest is converted

Detailed description of the model formulas

In this section the formulas used to model the landscape are described per sector. The formulas are ordered as stocks, flows and converters though some sectors only include converters (carbon, cocoa production, REDD payments and Income and NPV). The stocks, flows or converters in red originate from a different sector.

SECTOR: Rural population

Only the rural population is included in this model since the urban population is not involved in REDD and will not affect deforestation much. Rural population increase is mainly caused by births in the district as the in- and out migration was expected to be minor. There might be a possible shift from rural people becoming urban (farmers changing to the service sector) and/or one might experience an increase in rural people migrating out of the district, especially with land becoming scarce. However this is not of major importance for the outcomes of REDD and was not included in the model.

The rural households are divided into large landholders (LL Households) and smallholders (SH Households) because these households are differently affected by REDD payments.

Information in model	Source
Population size district 2008: 190,400	Mediated estimate using district report 2000 data and local expert knowledge
85% of the population is rural	
Birth rate = 4% Death rate = 1.5%	
Average household size = 5 people	Average from data collected in 2000
14% of the households are large landholders, 86% smallholders	Local expert estimates
Immigration and outmigration is assumed 0	

Stocks:

$$LL_households(t) = LL_households(t - dt) + LL_hh_increase - LL_hh_decrease$$

$$SH_households(t) = SH_households(t - dt) + SH_hh_increase - SH_hh_decrease$$

Flows:

$$LL_hh_increase = Birth_rate * LL_households * dt$$

$$LL_hh_decrease = Death_rate * LL_households * dt$$

$$SH_hh_increase = Birth_rate * SH_households * dt$$

$$SH_hh_decrease = Death_rate * SH_households * dt$$

Convertors:

$$Birth_rate = 0.04$$

$$Death_rate = 0.015$$

$$Total_hh = LL_households + SH_households$$

$$Total_rural_population = Total_hh * 5$$

$$Change_in_hh_LL = LL_hh_increase - LL_hh_decrease$$

$$Change_in_hh_SH = SH_hh_increase - SH_hh_decrease$$

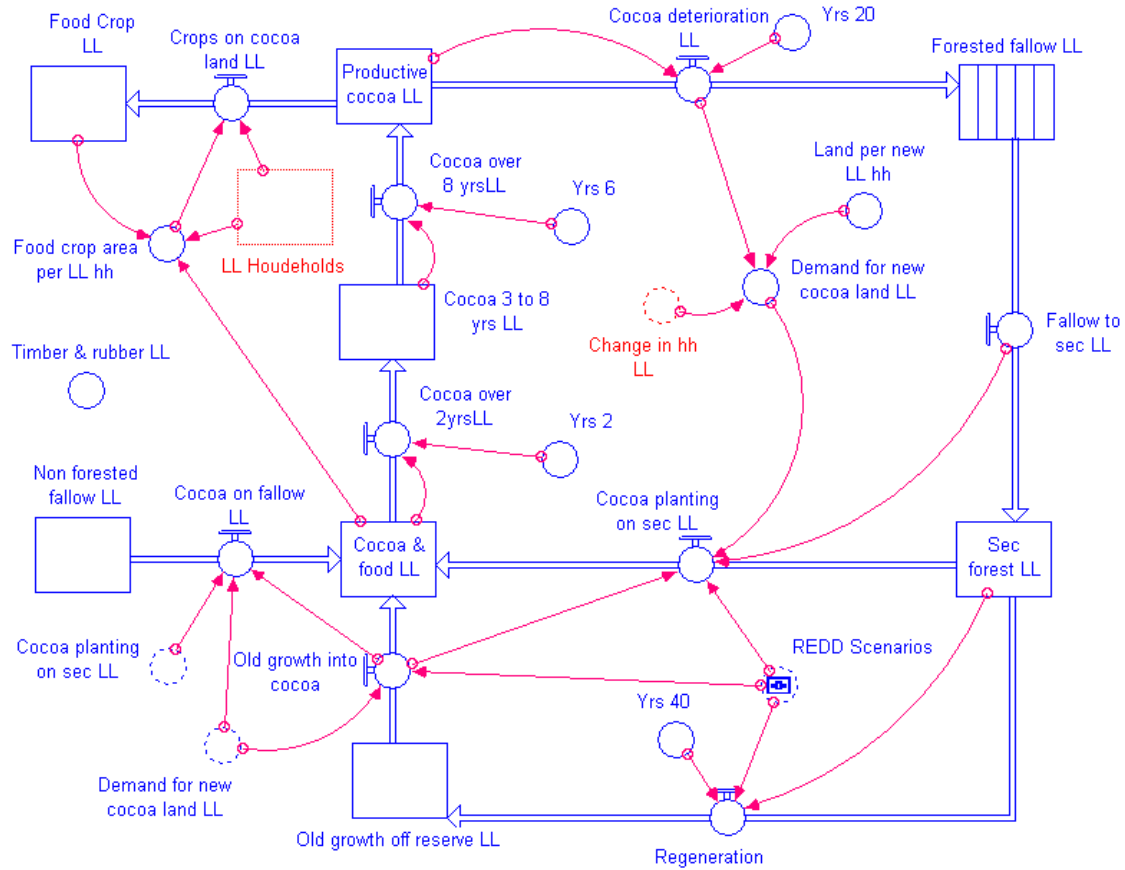
SECTOR: LAND TRANSITIONS

Deforestation in the landscape has occurred mainly outside forest reserves, driven by local farmers clearing for cocoa production. This land cover change dynamic is our main interest which is why this conversion is modeled in more detail. It is unclear whether timber and rubber plantations would increase or decrease to make way for cocoa; these areas are presumed to remain constant. The demand for new cocoa land is modeled in such a way that the cocoa area per household remains the same as long as there is enough land available to realize this condition.

Information in model	Source
District size is 346,462 ha of which 12% is forest reserve	District report 2000
Land cover outside forest reserves in 2008: 2% urban and bare soil, 3% non forested fallow, 8% food crops, 6% food crops intercropped with young cocoa, 19% 2-8 year old cocoa, 42% productive cocoa, 5% timber and rubber, 10% secondary forest and 5% old growth (of which one quarter is sacred forest), 0% forested fallow	Mediated estimates using Aster 2007 images and 2009 household surveys
Sacred forest is not converted	Local expert knowledge
We assume deforestation of old growth forest to continue to expand linearly with the same annual quantity as seen between 2000 and 2007	Mediated estimates using Aster 2007 and Landsat 2000 images
Old growth forest is located on the land of the large landholders as well as 80% of the secondary forest; 20% of the secondary forest is located on the land of the small landholders	Mediated estimates based on 2009 household surveys and local expert knowledge
40% of the total cocoa, food crop, non-forested fallow and timber and rubber land is located on the land of large landholders, 60% on the land of the small landholders	
Cocoa starts to produce after 8 years, remains productive for 20 years followed by a fallow period of 3 years	
For the first 2 years, young cocoa is intercropped with food crops	
The food crop area will be at least 1 ha per rural household	
Food crops are for subsistence use only, not for cash	
There is a preference for converting old growth forest rather than secondary forest into cocoa by large landholders. Without restrictions 90% of their demand for new cocoa land is assumed to come from old growth forest	

Large landholders' (LL) land:

Figure 5. Model for dynamics of land uses on large landholders' land (in red, dotted are model elements calculated in other model sectors and 'copied' to this sector maintaining its dynamics)



Stocks:

$$\text{Old_growth_off_reserve_LL}(t) = \text{Old_growth_off_reserve}(t - dt) + (\text{Regeneration} - \text{Old_growth_into_cocoa}) * dt$$

$$\text{Old_growth_off_reserve}(0) = 11,400 \text{ ha}$$

$$\text{Sec_forest_LL}(t) = \text{Sec_Forest_LL}(t - dt) + (\text{Fallow_to_sec_LL} - \text{Cocoa_planting_on_sec_LL} - \text{Regeneration}) * dt$$

$$\text{Sec_forest_LL}(0) = 24,406 \text{ ha}$$

$$\text{Cocoa_ \& _food_LL}(t) = \text{Cocoa_ \& _food_LL}(t - dt) + (\text{Cocoa_planting_on_sec_LL} + \text{Old_growth_into_cocoa} + \text{Cocoa_on_fallow_LL} - \text{Cocoa_over_2yrsLL}) * dt$$

$$\text{Cocoa_ \& _food_LL}(0) = 7,342 \text{ ha}$$

$$\text{Cocoa_3_to_8_yrs_LL}(t) = \text{Cocoa_3_to_8_yrs_LL}(t - dt) + (\text{Cocoa_over_2yrsLL} - \text{Cocoa_over_8yrsLL}) * dt$$

$$\text{Cocoa_3_to_8_yrs_LL}(0) = 22,842 \text{ ha}$$

$$\text{Productive_cocoa_LL}(t) = \text{Productive_cocoa_LL}(t - dt) + (\text{Cocoa_over_8yrsLL} - \text{Cocoa_deterioration_LL}) * dt$$

$$\text{Productive_cocoa_LL}(0) = 51,394 \text{ ha}$$

$$\text{Food_crop_LL}(t) = \text{Food_crop_LL}(t - dt) + \text{Crops_on_cocoa_land_LL} * dt$$

$Food_crop_LL(0) = 9,946 \text{ ha}$
 $Non_forested_fallow_LL(t) = Non_forested_fallow_LL(t - dt) - Cocoa_on_fallow_LL * dt$
 $Non_forested_fallow_LL(0) = 3,661 \text{ ha}$

Conveyor stock:

$Forested_fallow_LL(t) = Forested_fallow_LL(t - dt) + (Cocoa_deterioration_LL - Fallow_to_sec_LL) * dt$
 $Forested_fallow_LL(0) = 0$
 Transit time = 3 years

Flows:

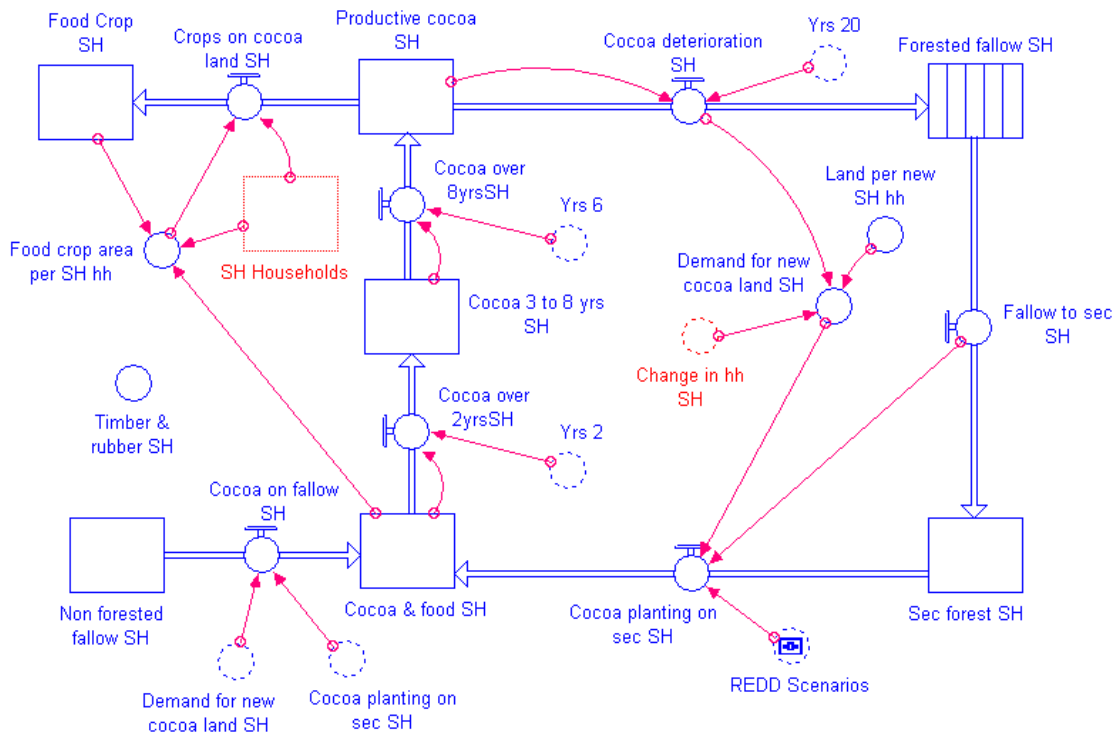
$Regeneration = \text{if } REDD_Scenarios=2 \text{ then } Sec_forest_LL/Yrs_40 \text{ else } 0$
 $Old_growth_into_cocoa = \text{if } REDD_Scenarios=0 \text{ then Demand_for_new_cocoa_land_LL} * 0.9 \text{ else } 0$
 $Fallow_to_sec_LL = CONVEYOR \text{ OUTFLOW}$
 $Cocoa_planting_on_sec_LL = \text{if } REDD_Scenarios=2 \text{ then } Fallow_to_sec_LL \text{ else Demand_for_new_cocoa_land_LL} - Old_growth_into_cocoa$
 $Cocoa_on_fallow_LL = Demand_for_new_cocoa_land_LL - Cocoa_planting_on_sec_LL$
 $Cocoa_over_2yrsLL = Cocoa_ \& _Food_LL(t) / Yrs_2$
 $Cocoa_over_8yrsLL = Cocoa_2_to_8_yrs_LL(t) / Yrs_6$
 $Cocoa_deterioration_LL = Productive_Cocoa_LL(t) / Yrs_20$
 $Crops_on_cocoa_land_LL = \text{if } Food_crop_area_per_LL_hh < 1 \text{ then } (1 - Food_crop_area_per_LL_hh) * LL_households(t) \text{ else } 0$

Convertors:

$Demand_for_new_cocoa_land_LL = Change_in_hh_LL * Land_per_new_LL_hh + Cocoa_deterioration_LL$
 $Food_crop_per_LL_hh = (Food_crop_LL + Cocoa_ \& _food_LL) / LL_households$
 $Land_per_new_LL_hh = 21 \text{ ha}$
This value is obtained by $(Cocoa_ \& _food_LL + Cocoa_2_to_8_yrs_LL + Productive_Cocoa_LL + Food_Crop_only_LL + Forested_Fallow_LL + non_forested_fallow_LL) / LL_households$ at $t=0$
 $Yrs_2 = 2 \text{ years}$
 $Yrs_6 = 6 \text{ years}$
 $Yrs_20 = 20 \text{ years}$
 $Yrs_40 = 40 \text{ years}$
 $Timber_ \& _rubber_LL = 6102 \text{ ha}$

Smallholders' (SH) land:

Figure 6. Model for dynamics of land uses on smallholders' land



Stocks:

$$\text{Sec_forest_SH}(t) = \text{Sec_forest_SH}(t - dt) + (\text{Fallow_to_sec_SH} - \text{Cocoa_planting_on_sec_SH}) * dt$$

$$\text{Sec_forest_SH}(0) = 6,102 \text{ ha}$$

$$\text{Cocoa_ \& _food_SH}(t) = \text{Cocoa_ \& _food_SH}(t - dt) + (\text{Cocoa_planting_on_sec_SH} + \text{Cocoa_on_fallow_SH} - \text{Cocoa_over_2yrsSH}) * dt$$

$$\text{Cocoa_ \& _food_SH}(0) = 11,013 \text{ ha}$$

$$\text{Cocoa_3_to_8_yrs_SH}(t) = \text{Cocoa_3_to_8_yrs_SH}(t - dt) + (\text{Cocoa_over_2yrs_SH} - \text{Cocoa_over_8yrs_SH}) * dt$$

$$\text{Cocoa_3_to_8_yrs_SH}(0) = 34,263 \text{ ha}$$

$$\text{Productive_cocoa_SH}(t) = \text{Cocoa_hh_SH}(t - dt) + (\text{Cocoa_over_8yrsSH} - \text{Cocoa_deterioration_SH} - \text{Old_cocoa_into_food_crop}) * dt$$

$$\text{Productive cocoa_hh_SH}(0) = 77,091 \text{ ha}$$

$$\text{Food_crop_SH}(t) = \text{Food_crop_SH}(t - dt) + \text{Crops_on_cocoa_land_SH} * dt$$

$$\text{Food_crop_SH}(t) = 14,918 \text{ ha}$$

$$\text{Non_forested_fallow_SH}(t) = \text{Non_forested_fallow_SH}(t - dt) - \text{Cocoa_on_fallow_SH} * dt$$

Conveyor stock:

$$\text{Forested_fallow_SH}(t) = \text{Forested_fallow_SH}(t - dt) + (\text{Cocoa_deterioration_SH} - \text{Fallow_to_sec_SH}) * dt$$

$$\text{Forested_fallow_SH}(0) = 0$$

$$\text{Transit time} = 3$$

Flows:

Fallow_to_sec_SH = CONVEYOR OUTFLOW

Cocoa_planting_on_sec_SH = if REDD_Scenarios=2 then Fallow_to_sec_SH else Demand_for_new_cocoa_land_SH

Cocoa_on_fallow_SH = Demand_for_new_cocoa_land_SH - Cocoa_planting_on_sec_SH

Cocoa_over_2yrsSH = Cocoa_&_food_SH(t)/Yrs_2

Cocoa_over_8yrsSH = Cocoa_3_to_8_yrs_SH(t)/Yrs_6

Cocoa_deterioration_SH = Productive_cocoa_SH(t)/Yrs_20

Crops_on_cocoa_land_SH = if Food_crop_area_per_SH_hh<1 then (1-Food_crop_area_per_SH_hh) * SH_households(t) else 0

Convertors:

Demand_for_new_cocoa_land_SH = Change_in_hh_SH * 5.2 + Cocoa_deterioration_SH

Food_crop_area_per_SH_hh = (Cocoa_&_food_SH+Food_crop_SH)/SH_households(t)

Land_per_new_SH_hh = 5.1 ha

This value is obtained by (Cocoa_&_food_SH + Cocoa_2_to_8_yrs_SH + Productive_Cocoa_SH + Food_Crop_only_SH + Forested_Fallow_SH + non_forested_fallow_SH)/ SH_households at t=0

Timber_&_rubber_SH = 9,152 ha

Remaining land:

Forest_reserve = 41,384 ha

Old_growth_sacred_forest = 3,813 ha

Urban & bare soil = 6,102 ha

SECTOR: CARBON

In this sector, the amount of carbon is calculated for which a payment can be received. The BAU scenario is used as the carbon baseline. All functions in this sector are convertors.

Information in model	Source
Average carbon contents (ton C/ha) per land use : Urban, bare soil= 0 ; non-forested fallow= 15; food crops= 30; food crops intercropped with young cocoa= 50; 3-8 year old cocoa= 70; productive cocoa= 100; forested fallow= 130; timber and rubber= 135; secondary forest= 160; old growth forest= 200	Mediated estimations from Swallow et al. (2007), Wauters et al (2008) and De Bruijn (2005)

Calculation of carbon (C) contents different landuses:

C_old_growth_per_ha = 200 ton C/ha

C_secforest_per_ha = 160 ton C/ha

C_timber_&_rubber_per_ha = 135 ton C/ha

C_new_cocoa_per_ha = 50 ton C/ha

C_cocoa_3to8_per_ha = 70 ton C/ha

C_prodcocoa_per_ha = 100 ton C/ha

$C_{\text{forest_fallow_per_ha}} = 130 \text{ ton C/ha}$
 $C_{\text{nonforest_fallow_per_ha}} = 15$
 $C_{\text{food_crop_per_ha}} = 30 \text{ ton C/ha}$

$\text{Total_C_old_growth_off_reserve} = C_{\text{old_growth_per_ha}} *$

$\text{Old_growth_off_reserve_LL}(t)$

$\text{Total_C_sec_forest_LL} = C_{\text{secforest_per_ha}} * \text{Sec_Forest_LL}(t)$

$\text{Total_C_timber_ \& _rubber_LL} = C_{\text{timber_ \& _rubber}} * \text{Timber_ \& _Rubber_LL}$

$\text{Total_C_new_cocoa_LL} = C_{\text{new_cocoa_per_ha}} * \text{Cocoa_ \& _food_LL}(t)$

$\text{Total_C_cocoa_3to8_LL} = C_{\text{cocoa_3to8_per_ha}} * \text{Cocoa_3_to_8_yrs_LL}(t)$

$\text{Total_C_prodcocoa_LL} = C_{\text{prodcocoa_per_ha}} * \text{Productive_Cocoa_LL}(t)$

$\text{Total_C_forest_fallow_LL} = C_{\text{forest_fallow_per_ha}} * \text{Forested_Fallow_LL}(t)$

$\text{Total_C_foodcrop_LL} = C_{\text{food_crop_per_ha}} * \text{Food_Crop_LL}(t)$

$\text{Total_C_nonfor_fallow_LL} = C_{\text{non_for_fallow_per_ha}} * \text{Non_forested_fallow_LL}(t)$

$\text{Total_C_sec_forest_SH} = C_{\text{secforest_per_ha}} * \text{Sec_Forest_SH}(t)$

$\text{Total_C_timber_ \& _rubber_SH} = C_{\text{timber_ \& _rubber}} * \text{Timber_ \& _Rubber_SH}$

$\text{Total_C_new_cocoa_SH} = C_{\text{new_cocoa_per_ha}} * \text{Cocoa_ \& _food_SH}(t)$

$\text{Total_C_cocoa_3to8_SH} = C_{\text{cocoa_3to8_per_ha}} * \text{Cocoa_3_to_8_yrs_SH}(t)$

$\text{Total_C_prodcocoa_SH} = C_{\text{prodcocoa_per_ha}} * \text{Productive_Cocoa_SH}(t)$

$\text{Total_C_forest_fallow_SH} = C_{\text{forest_fallow_per_ha}} * \text{Forested_Fallow_SH}(t)$

$\text{Total_C_foodcrop_SH} = C_{\text{food_crop_per_ha}} * \text{Food_Crop_only_SH}(t)$

$\text{Total_C_nonfor_fallow_SH} = C_{\text{non_for_fallow_per_ha}} * \text{Non_forested_fallow_SH}(t)$

Calculation of C contents for payment scenario 'RED':

The RED scenario only concerns carbon payments to LL since old growth forest is located on their land. For scenario RED, the amount of carbon for payment is obtained by calculating the carbon stock for the land uses that replace old growth forest after 20 years under BAU and subtracting this value from the calculated carbon stock in the old growth forest after 20 years (RED). In these calculations we 'distillate' only the carbon changes on the land which is currently covered with old growth forest from the total landscape carbon changes. Thus the carbon amount for the land uses replacing old growth forest under BAU is assessed by calculating the total landscape carbon changes on LL land after 20 years, minus the changes in carbon outside the current old growth area after 20 years as explained in more detail here below.

$C_{\text{cocoa_ \& _sec_ \& _fallowLL}} = \text{Total_C_new_cocoa_LL} + \text{Total_C_Cocoa_3to8_LL} +$
 $\text{Total_C_Prodcocoa_LL} + \text{Total_C_for_fallow_LL} + \text{Total_C_sec_forest_LL}$

$\text{Total_C_outside_current_area_old_growthLL} = \text{Graphical function of time (year, value Total_C_outside_current_area_old_growthLL)}$

(0, 1.1e+007), (1, 1.1e+007), (2, 1e+007), (3, 1e+007), (4, 9.9e+006), (5, 9.7e+006), (6, 9.5e+006), (7, 9.6e+006), (8, 9.7e+006), (9, 9.8e+006), (10, 9.8e+006), (11, 9.9e+006), (12, 9.9e+006), (13, 9.9e+006), (14, 9.9e+006), (15, 9.9e+006), (16, 9.9e+006), (17, 9.9e+006), (18, 9.9e+006), (19, 9.9e+006), (20, 9.9e+006)

The values in this graphical function are the carbon changes on the LL land excluding the carbon changes in the land currently covered with old growth forest. The values are obtained from the values of C_cocoa_&_sec_&_fallowLL running the model for 20 years under a BAU scenario and multiplying the following flows by zero:

Crops_on_cocoa_land_LL, Cocoa_on_fallow_LL, Old_growth_into_cocoa.

By giving these flows a value zero we calculate the carbon changes in the old growth forest area going through the different cocoa stages, we assume that the old growth forest is only converted into cocoa, not into food crops.

$$C_cocoa_ \& _sec _ \& _fallow_oldgrowthLL = Total_C_new_cocoa_LL + Total_C_Cocoa_3to8_LL + Total_C_Prodcocoa_LL + Total_C_for_fallow_LL + Total_C_sec_forest_LL + Total_C_old_growth$$

$$Total_C_scen_BAU _ \& _RED = C_cocoa _ \& _sec _ \& _fallow_oldgrowthLL - Total_C_outside_current_area_old_growthLL$$

We get the C-values for the area currently covered with old growth for the scenario BAU and RED while multiplying the following flows by zero: Crops_on_cocoa_land_LL, Cocoa_on_fallow_LL

$$Total_C_for_paymentLL_RED = 1,220,456 \text{ tonC}$$

This value is obtained from the converter value Total_C_scen_BAU_&_RED at t=20 when REDD Scenarios=1 minus the converter value Total_C_scen_BAU_&_RED at t=20 when REDD Scenarios=0. The flows Crops_on_cocoa_land_LL and Cocoa_on_fallow_LL are multiplied by zero since we want to calculate only carbon changes in the land currently covered with old growth and we assume the land currently covered with old growth forest will be converted to cocoa land, not into cropland.

Calculation of C contents for payment scenario 'RED&D':

For scenario RED&D, the amount of carbon for payment is obtained by calculating the carbon stock for the land uses that replace old growth and secondary forest after 20 years (BAU) and subtracting this value from the calculated carbon stock in the area now covered with old growth and secondary forest after 20 years (RED&D). Under RED&D this area remains covered with secondary and old growth forest and some secondary will grow into old growth forest increasing carbon contents. In these calculations we 'distillate' only the carbon changes on the land which is currently covered with old growth and secondary forest from the total landscape carbon changes. Thus the carbon amount for the land uses replacing secondary and old growth forest under BAU is assessed by calculating the total landscape carbon changes on LL and SH land after 20 years, minus the changes in carbon outside the area currently covered with secondary and old growth forest after 20 years as explained in more detail here below.

$$C_cocoa_ \& _fallowLL = Total_C_new_cocoa_LL + Total_C_Cocoa_3to8_LL + Total_C_Prodcocoa_LL + Total_C_for_fallow_LL$$

$$Total_C_cocoa_outside_current_area_old_growth _ \& _sec_LL = \text{Graphical function of time (year, value Total_C_cocoa_outside_current_area_old_growth _ \& _sec_LL)}$$

(0.00, 7.1e+006), (1.00, 7.4e+006), (2.00, 7.6e+006), (3.00, 7.8e+006), (4.00, 7.8e+006), (5.00, 7.8e+006), (6.00, 7.7e+006), (7.00, 7.7e+006), (8.00, 7.7e+006), (9.00, 7.7e+006), (10.0, 7.7e+006), (11.0, 7.7e+006), (12.0, 7.7e+006), (13.0, 7.7e+006), (14.0, 7.7e+006), (15.0, 7.7e+006), (16.0, 7.7e+006), (17.0, 7.7e+006), (18.0, 7.7e+006), (19.0, 7.7e+006), (20.0, 7.7e+006)

The values in this graphical function are obtained from the values of C_cocoa_&_fallowLL running the model under a BAU scenario and multiplying the following flows by zero: Crops_on_cocoa_land_LL, Cocoa_on_fallow_LL, Old_growth_into_cocoa, Cocoa_planting_on_sec_LL and by connecting the flow Fallow_to_sec_LL to the stock Cocoa_&_food_LL(t) instead of Sec_forest_LL(t). By giving these flows a value zero we calculate the carbon changes in the secondary and old growth forest area going through the different cocoa stages, we assume that the secondary and old growth forest is only converted into cocoa, not into food crops.

$$\begin{aligned} \text{Total_C_land_currently_old_growth_}\&_ \text{sec_LL} = & \text{Total_C_new_cocoa_LL} + \\ & \text{Total_C_prodcocoa_LL} + \text{Total_C_sec_forest_LL} + \\ & \text{Tot_C_old_growth_off_reserve} + \text{Total_C_cocoa_3to8_LL} + \\ & \text{Total_C_forest_fallow_LL} \end{aligned}$$

$$\begin{aligned} \text{Total_C_scen_BAU_}\&_ \text{REDD_LL} = & \text{Total_C_land_currently_old_growth_}\&_ \text{sec_LL} - \\ & \text{Total_C_cocoa_outside_current_area_old_growth_}\&_ \text{sec_LL} \end{aligned}$$

We get the C-values for the area currently covered with old growth for the scenario BAU and REDD while multiplying the following flows by zero: Crops_on_cocoa_land_LL, Cocoa_on_fallow_LL

$$\text{Total_C_for_paymentLL_RED\&D} = 3,221,492 \text{ tonC}$$

This value is obtained from the converter Total_C_scen_BAU_&_REDD_LL's value at t=20 when REDD Scenarios=2 minus the converter Total_C_scen_BAU_&_REDD_LL's value at t=20 when REDD Scenarios=0. The flows Crops_on_cocoa_land_LL and Cocoa_on_fallow_LL are multiplied by zero.

$$\begin{aligned} \text{C_cocoa_}\&_ \text{fallowSH} = & \text{Total_C_new_cocoa_SH} + \text{Total_C_Cocoa_3to8_SH} + \\ & \text{Total_C_Prodcocoa_SH} + \text{Total_C_for_fallow_SH} \end{aligned}$$

$\text{Total_C_cocoa_outside_current_area_sec_SH} = \text{Graphical function of time (year, value Total_C_cocoa_outside_current_area_sec_SH)}$
 (0.00, 1.1e+007), (1.00, 1.1e+007), (2.00, 1.1e+007), (3.00, 1.2e+007), (4.00, 1.2e+007), (5.00, 1.2e+007), (6.00, 1.2e+007), (7.00, 1.2e+007), (8.00, 1.2e+007), (9.00, 1.2e+007), (10.0, 1.2e+007), (11.0, 1.2e+007), (12.0, 1.2e+007), (13.0, 1.1e+007), (14.0, 1.1e+007), (15.0, 1.1e+007), (16.0, 1.1e+007), (17.0, 1.1e+007), (18.0, 1.1e+007), (19.0, 1.1e+007), (20.0, 1.1e+007)

The values in this graphical function are obtained from the values of C_cocoa_&_fallowSH running the model under a BAU scenario and multiplying the following flows by zero: Crops_on_cocoa_land_SH, Cocoa_on_fallow_SH, Cocoa_planting_on_sec_SH and by connecting the flow Fallow_to_sec_SH to the stock Cocoa_&_food_SH(t) instead of Sec_forest_SH(t).

$$\text{Total_C_land_currently_sec_SH} = \text{Total_C_new_cocoa_SH} + \text{Total_C_cocoa_3to8_SH} \\ + \text{Total_C_prodcocoa_SH} + \text{Total_C_sec_forest_SH} + \\ \text{Total_C_forest_fallow_SH}$$

$$\text{Total_C_scen_BAU_ \& _REDD_SH} = \text{Total_C_land_currently_sec_SH} - \\ \text{Total_C_cocoa_outside_current_area_sec_SH}$$

Total_C_for_paymentSH_RED&D = 403,237 tonC

This value is obtained from the converter Total_C_scen_BAU_&_REDD_SH's value at t=20 when REDD Scenarios= 2 minus the converter

Total_C_scen_BAU_&_REDD_SH's value at t=20 when REDD Scenarios =0. The flows Crops_on_cocoa_land_SH and Cocoa_on_fallow_SH are multiplied by zero.

SECTOR: COCOA PRODUCTION

Production and income from cocoa plantations is simulated in this sector. Income from cocoa makes up for about 90% of the rural population's cash income (estimation district officials 2007) which is why we use cocoa income as a proxy for total cash income excluding REDD payments. All functions in this sector are convertors.

Information in model	Source
Cocoa production per ha= 11.8 bags (767 kg)	Data from Technoserve extension office in the district
Costs are 20% of profit	
Cocoa price in Ghana: 1.57 New Ghana Cedis/kg (US\$ 1.37/kg) in 2008 and is assumed to remain fixed	Information from district official and cocoa farmer
In additional simulations we assume the cocoa price to drop with 25% in the next 12 years as prospected by the WB	WB 2008b
We assume labour is not paid and the cost of this is not included in the model	Expert judgment

Cocoa_production_per_ha = 11.8 bags

Price_per_bag = if Price_Fix_or_WB=0 then US\$89 else

Price_predicted_by_World_Bank

Price fix or WB= 0 or 1 (this convertor is a switch and can take the value 0 or 1)

Price_predicted_by_World_Bank = Graphical function of time (year, value

Price_predicted_by_World_Bank)

(0.00, 89.0), (2.00, 76.0), (4.00, 69.0), (6.00, 65.0), (8.00, 61.0), (10.0, 59.0),

(12.0, 57.0), (14.0, 55.0), (16.0, 54.0), (18.0, 53.0), (20.0, 53.0)

Profit_ratio = 0.8

Total_production_LL = Cocoa_production_per_ha * Productive_Cocoa_LL(t)

Total_cash_value_cocoa_LL = Total_production_LL * Price_per_bag

Total_cocoa_income_LL = Total_cash_value_cocoa_LL * Profit_ratio

Cocoa_income_per_LL_hh = Total_cocoa_profit_LL/LL_Houdeholds

$Total_production_SH = Cocoa_production_per_ha * Productive_Cocoa_SH(t)$
 $Total_cash_value_cocoa_SH = Total_production_SH * Price_per_bag$
 $Total_cocoa_income_SH = Total_cash_value_cocoa_SH * profit_ratio$
 $Cocoa_income_per_SH_hh = Total_cocoa_profit_SH / SH_Households$

SECTOR: REDD PAYMENTS

In this sector the payment to the farmers (LL and SH) is calculated. LL have old growth and secondary forest on their land and thus receive carbon payments under both the scenario RED and RED&D. SH only have some secondary forest on their land so they only get a carbon payment under scenario RED&D.

Information in model	Source
We assume a carbon price of US\$ 10/ton CO ₂ paid by investors	Average CO ₂ price compared to prices on the existing Clean Development Mechanism market mentioned by Capoor and Ambrosi (2008)
Transaction costs of REDD are presumed high and thus we assume only 25% will reach the farmers, the remainder going to middlemen, and national and district REDD implementers	Personal communication H. Purnomo (CIFOR) 2009
We assume a 20-year contract with: 20% paid up front; large payments paid every 5-years (10%) and 20% paid after 20 years if there is contract compliance; and regular small payments in other years (2%)	How REDD contracts will be constructed has yet to be determined. We assume a large payment up front in order to attract sellers of carbon and provide finance for start-up costs of sellers
1 ton C contains the same quantity of carbon as 3.67 ton CO ₂	Murdiyarsa and Skutsch (2006)

Conversion_factor_CO2_to_C = 1/3.67

Price_tonCO2 = 10US\$

Share_to_farmers = 0.25

Contract_payment_share_per_year = Graphical function of time (year, value

Contract_payment_share_per_year

(0, 0), (1, 0.2), (2, 0.02), (3, 0.02), (4, 0.02), (5, 0.02), (6, 0.1), (7, 0.02), (8, 0.02), (9, 0.02), (10, 0.02), (11, 0.1), (12, 0.02), (13, 0.02), (14, 0.02), (15, 0.02), (16, 0.1), (17, 0.02), (18, 0.02), (19, 0.02), (20, 0.2)

C_due_for_payment_LL = if REDD_Scenarios=1 then Total_C_for_paymentLL_RED
else if REDD_Scenarios=2 then Total_C_for_paymentLL_RED&D else 0

Total_gross_REDD_payment_LL = Price_tonC * C_due_for_payment_LL

Total_net_REDD_pay_LL = Total_gross_REDD_payment_LL * Share_to_farmers

Total_annual_REDD_LL = Total_net_REDD_pay_LL *

Contract_payment_share_per_year

REDD_per_LL_hh = Total_annual_REDD_LL/LL_Houdeholds

C_due_for_payment_SH = if REDD_Scenarios=2 then

Total_C_for_paymentSH_RED&D else 0

Total_gross_REDD_payment_SH = Price_tonC * C_due_for_payment_SH

$$\text{Total_net_REDD_pay_SH} = \text{Total_gross_REDD_payment_SH} * \text{Share_to_farmers}$$

$$\text{Total_annual_REDD_SH} = \text{Total_net_REDD_pay_SH} * \text{Contract_payment_share_per_year}$$

$$\text{REDD_per_SH_hh} = \text{Total_annual_REDD_SH} / \text{SH_Houdeholds}$$

SECTOR: INCOME & NET PRESENT VALUE

In this sector we simulate total cash income for the rural population in the district over the next 20 years and total Net Present Value (NPV) of this cash income using a 10% and 20% discount rate. The formula used for NPV is:

$$\text{NPV}_{\text{total}} = \sum_{t=1}^{20} \text{NPV}_t / (1+r)^t$$

where NPV_t is the net present value of the total rural income per year t , and r is the discount rate.

All functions in this sector are convertors.

$$\text{Total_rural_income} = \text{Total_cocoa_income_LL} + \text{Total_cocoa_income_SH} + \text{Total_annual_REDD_LL} + \text{Total_annual_REDD_SH}$$

$$\text{NPV_total_rural_income_per_year_10\%} = \text{Total_rural_income} / (\text{Discount_Rate_10\%}^{\text{time}})$$

$$\text{NPV_total_rural_income_per_year_20\%} = \text{Total_rural_income} / (\text{Discount_Rate_20\%}^{\text{time}})$$

$$\text{Income_per_capita} = \text{Total_rural_income} / \text{Total_rural_population}$$

$$\text{NPV_rural_income_pp_per_year_20\%} = \text{Income_per_capita} / (\text{Discount_Rate_20\%}^{\text{time}})$$

$$\text{NPV_rural_income_pp_per_year_10\%} = \text{Income_per_capita} / (\text{Discount_Rate_10\%}^{\text{time}})$$

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