FALLOW:
Background on a dynamic landscape model

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1. Introduction

One way to explore the simultaneous impacts of changes in land use, roads and filters at the landscape scale, is to construct a simulation model that tries to capture the most important aspects of the processes involved. Such a model should allow for analysis of scenarios and the study of trade-offs between performance indicators such as food security, returns to labour, biodiversity, C stocks and watershed functions.

Models are mental constructions that derive their value from a certain degree of similarity with the real world. For static models this similarity is a matter of 'look alike', for dynamic models primarily one of 'behave similarly'. Models derive their strength from the simplification they provide, yet that may be their greatest weakness as well. Einstein's adagium 'simplify as far as possible, but no further' is still valid. A model that captures all details and possible special cases will be at least as compli-cated as the real world, and there will be no gain in using it, rather than watching the real world itself.

Simple models, however, can lead to recognition that apparently complex and 'rich' behaviour as observed in the real world can be generated on the basis of simple rules and their logical consequences for interactions. The model that we will describe here falls into the class of 'simple' models -- not intended to simulate reality in a particular setting, but capturing overall trends that follow from the logic of a reasonable set of assumptions. The main criterion for such a model is that results are ‘sensible’ (make sense) and that model outcomes are sensitive to variation in key input parameters in a way that corresponds with what we know of the real world. No specific quantitative ‘validation’ of the model is possible as yet, but the focus is on the degree to which assumptions are reasonable as a first approach. If we accept the assumptions, we must be interested in their logical consequences.

FALLOW (Forest Agroforest Low Value, Landscape or Wasteland ?) is a landscape model simulating forest conversion to shifting cultivation or crop fallow rotation system, where staple food is produced and consumed on the basis of population density and pro-capita food demand. FALLOW simulates a 100 year period on a yearly time step.

This manual is produced to help users in understanding the basic underlying assumption used by the model. Part of the contents has been produced in other publications ([1], [2]). Currently we have two version of the model; (1) STELLA version and (2) PC-RASTER. STELLA version only deals with 10 x 10 plots, while PC-RASTER version can deal with any number of plots which can be derived from real field data through GIS work. The USERS manual for each version is currently in development.

2. Overview of the model

The FALLOW (Forest, Agroforest, Low-value Lands or Waste?) model was initially made for 'shifting cultivation' and crop-fallow rotation systems. It predicts food self-sufficiency, soil fertility, carbon stocks, plant species richness and water-shed functions, on the basis of a number of biophysical and management parameters. It also includes options for harvesting forest products and for changing the food crop based agricultural system into an 'agroforest' or tree-crop system, such as rubber or coffee. Wild fire can also occurs as a natural random occurrence.

In FALLOW model a spatial representation of a landscape mosaic is linked to a set of dynamic processes, reflecting the decisions of households in managing each plot in overall landscape. Households can choose between collecting forest products, slash-and-burn based production of food crops, or make a transition into 'agroforests' or tree-crop based systems. The outcome of these decisions is reflected in indicators of global (C stock, biodiversity), regional (watershed functions) and local (food security) performance. The model can thus be used to explore:

a. dynamic landscape consequences of landuse decisions in the forest margins
b. local and external impacts on profitability, biodiversity, watershed functions and C-stocks
c. spatially explicit or generic institutional interventions

Figure 1 shows the diagram structure of the FALLOW model.

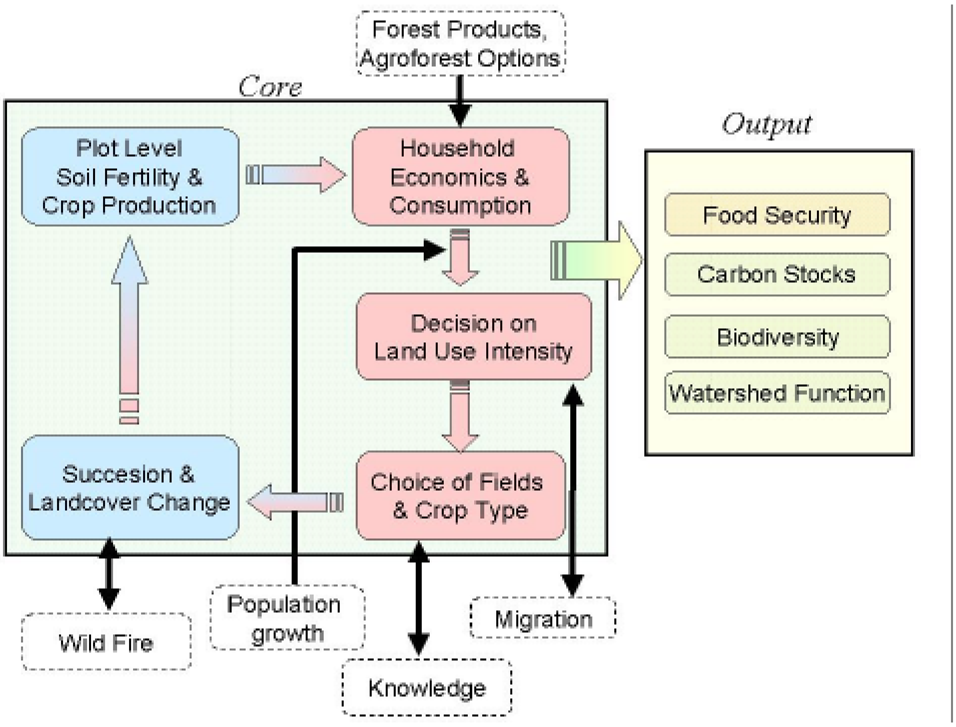


Figure 1. Structure of the FALLOW model: model core (centre left), outputs (right), and optional sectors (dashed lines).

There are basically three main types of modules:

a. Core Modules

These modules – Soil Fertility & Crop Production, Household Economics, Land Use Intensity, Decision of Crop Fields and Succession & Landuse/cover Change - are the key 'engine' of the model dynamic behaviour.

b. Optional Modules

A few other optional modules are available to produce other dynamic results as well. These modules include options on modelling farmers knowledge, population growth, dynamic migration, forest products gathering, managing agroforests system and wild fire.

c. Output Modules

Based on the outcome of core module, output modules translate the dynamic behaviour into the desirable form of 'indicators'. Food Security, Biodiversity, Watershed Functions and C-Stocks currently exists as the output indicators.

Each of these modules required its own input data and produced interesting intermediate results, useful for explorations. There are basically two ways to intialize landscape characteristics parameter:

1. using spatial data/maps
   This can be derived through available maps e.g. landcover map, soil map, topographic map.
2. using randomly generated data
   Data are generated randomly based on a few input parameters.

The following section will explain further in details of each module; its underlying assumption and available options.

3. Description of modules available in FALLOW

3.1. Core Module

3.1.1 Soil fertility and crop production

An essential module of the model is the book keeping of soil fertility in each of the plots. This core 'engine' of the model is based on a model developed by Brian Trenbath in the early 1980s ([3], [4]). Management options of fallow systems or shifting cultivation should aim to strike a balance between depletion and restoration of soil fertility. The 'Trenbath' model describes restoration of soil fertility during fallow period by two parameters: (i) a maximum level of fertility and (ii) a half-recovery time. Depletion of soil fertility occurs at cropping time as a simple proportion of current fertility (Figure 2). In FALLOW model, adding fertilizer will reduce soil fertility. The above assumptions are translated into the following equations:

Soil fertility restoration

$$F_i = \frac{(F_{max} - F_t)^2}{F_{max}(1 + k_f) - F_t}$$

where:

F_i = soil fertility increment

F_{max} = maximum soil fertility, reached after an infinitely long fallow period

F_t = current soil fertility

k_f = 'half-recovery time' or time needed to halve the difference between current and maximum soil fertility (year) as an effect of fallow time

Soil Fertility Depletion

$$F_D = F_t \; f_D \; F_{an}$$

where:

F_D = soil fertility depletion

f_D = fraction of soil fertility depleted per year

F_{an} = effect of fertilizer, defined as (1 – efficiency of fertilizer in maintaining 1 unit of soil fertility)

Soil fertility in FALLOW follows the definition used in Trenbath model, that it is a complex of effective nutrient supply and biological factor (diseases and weeds) affecting crop yield. Thus, the actual soil fertility value used in the model is not as important as the relative value to other parameters related to soil fertility; e.g. rate of fertility depletion and maximum soil fertility.

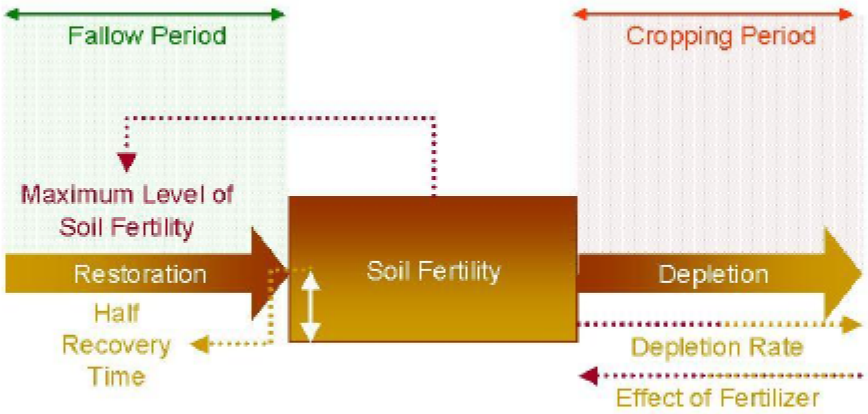


Figure 2. Soil fertility dynamic in FALLOW based on simple model of crop-fallow rotation systems of Trenbath model.

There are two ways to initialize soil fertility for each plot:

(i) through maps, which can be based from soil map.

(ii) randomly generated, using the following equations:

$$F_{init} = F_{avg} \; I[F_L, F_U]$$

where: F_{init} = initial soil fertility

F_{avg} = average soil fertility

F_L = minimum soil fertility at initial time

F_U = maximum soil fertility at initial time

$I[F_L,F_U]$ = uniformly distributed random number between F_L and F_U

van Noordwijk ([5]), explored the relationship of all the main parameters in Trenbath model as shown in Figure 3 below.

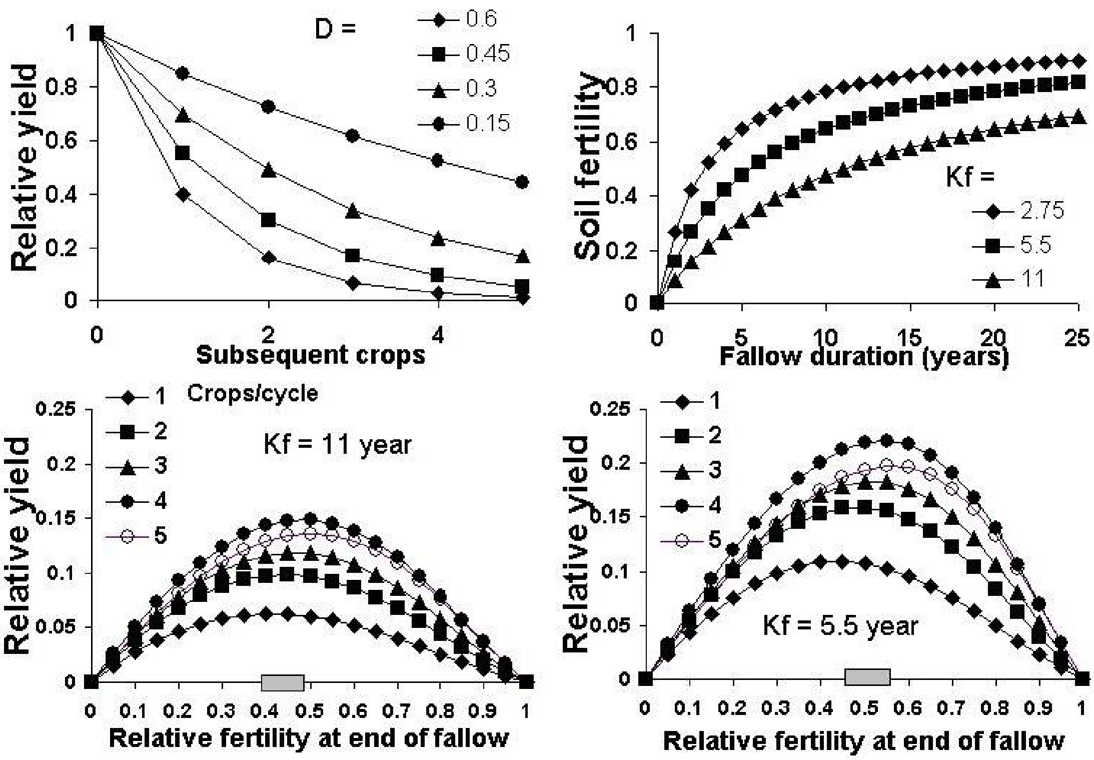


Figure 3. Soil fertility at different k_f. Taken from van Noordwijk [5]

Crop yield is assumed to be proportional to the amount of soil fertility used, taking into account the effect of crop sensitivity to climatic variability (Figure 4).

$$CP = (F_D + f_D * F_{I-An}) * Y_{eff} * W$$

where:

CP = crop production/yield ($Mg.ha^{-1}$)

F_{I-An} = soil fertility restoration by fertilizer

$= F_i = \dfrac{(F_{max} - F_t)^2}{F_{max}(1 + k_{f-An}) - F_t}$ and k_{f-An} = 'half-recovery time' or time needed to halve the difference between current and maximum soil fertility (year) as an effect of fertilizer

Y_{eff} = Conversion from soil fertility units into crop yields ($Mg.ha^{-1}.FertUnit^{-1}$)

W = Impacts of weather on crop yield

Analysis of the model equations ([5]) suggests that the highest yields per unit of land can be obtained when fallows are cleared for a new crop as soil fertility has recovered to 50-60% of its maximum value. This prediction is virtually independent of the growth rate of the fallow ('natural' or 'improved'), while the yield levels as such depend on the speed of fertility recovery by the fallow. Intensification of land use up to this point will increase returns per unit land at the likely costs of returns per unit labour. Beyond this point productivity will decline both per unit land and per unit labour, unless external inputs replace the soil fertility restoring functions of a fallow.

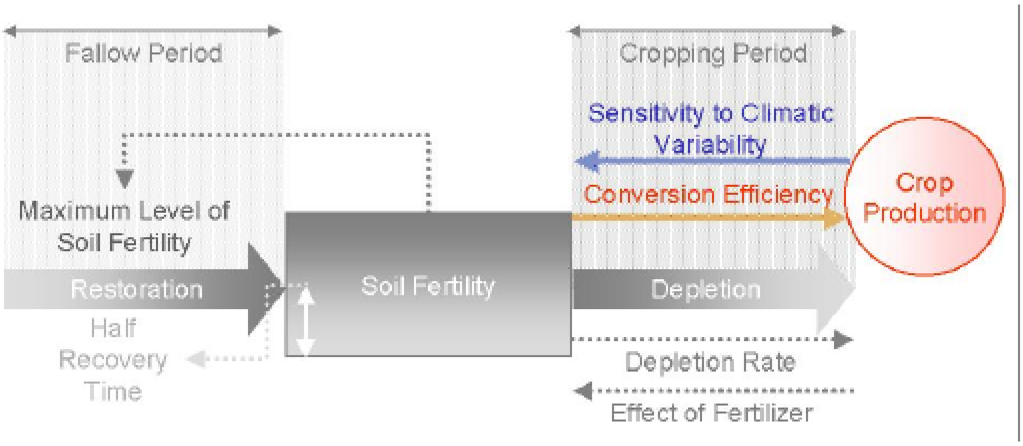


Figure 4. Crop production in FALLOW based on simple model of crop-fallow rotation systems of Trenbath model.

3.1.2. Household economics and consumption module

In this module we keep track the contents of crop storage by adding all crop yields. Crop storage are reduced due to consumption by people in the area or by pests such as rats, mice and insects (Figure 5). People can buy food in the market adding to crop storage, and vice versa people can sell their crop yield to the market adding cash into their capital. Earnings from agroforests or forest products and interest are other sources for financial capital. Capital can be reduced by non-food consumption, transaction cost and production cost.

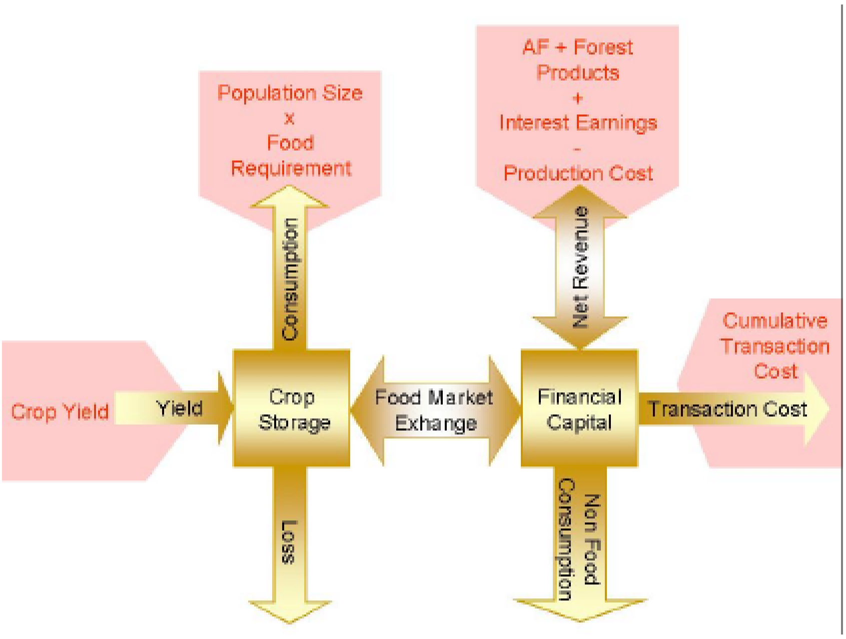


Figure 5. Diagram of household economics module in FALLOW model

3.1.3. Intensification decision module

This module controls the crooping intensification rule. The optimal crop storage should be able to meet the demand of annual consumption and buffer stock required. Deviations from this amount will trigger changes in cropping intensity or cropping ratio, that is the proportion of the landscape that is cropped. Response step in increasing or decreasing cropping intensity is bounded by maximum change of cropping ratio possible in 1 year.

There are two options on how the cropping ratio is calculated (Figure 6):

(i) amount of crop storage/reserve

(ii) amount of crop reserve and the expected yield and consumption for the following years. The number of following years influencing the decision is weighted by a memory factor (see 3.3.2. Farmers Knowledge module for more detail)

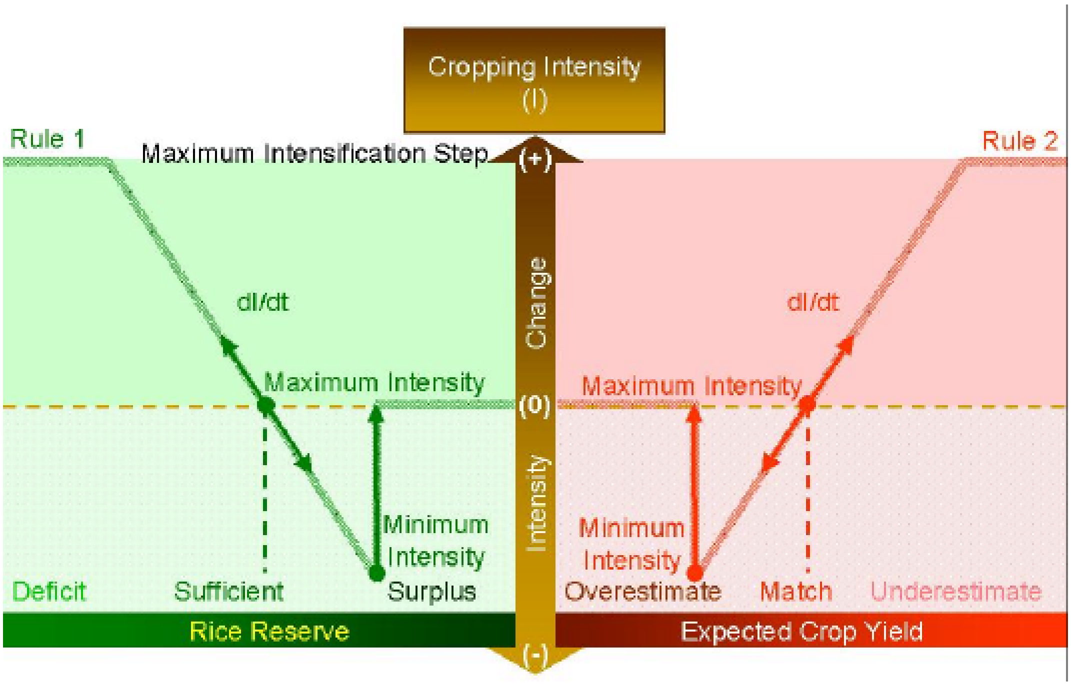


Figure 6. Intensification rules to increase crooping area.

equations

3.1.4. Field and Crop Selector module

One of the important process in FALLOW model is choosing which fields to open for cropping. The model offers two rules for this (Figure 7):

(i) Field choice rule 1, where decisions on which fields to crop are based on cycle length of FALLOW

(ii) Field choice rule 2, where decisions on which fields to crop are based on soil fertility and accesibility (distance to village, distance to settlement and land tenure).

In field choice rule B, all fields are classified by their current soil fertility into four categories: (i) below average, (ii) above average, (iii) high and (iv) very high.

The probabilities of each class being cleared depend on the total cropping intensity required (or how many more plots are needed to be open).

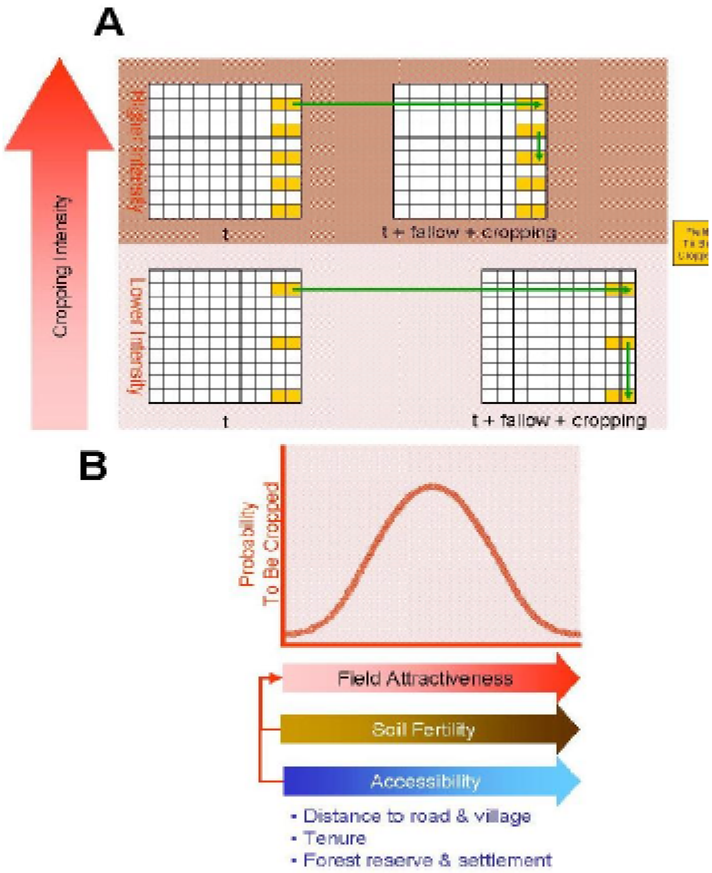


Figure 7.

Schematic diagram of

A. field choice rule 1 and

B. field choice rule 2.

Another decision rule available in this module is choosing which crop to plant. There are also two options:

(i) **Constant**. Plant one type of crop throughout the simulation

(ii) **Dynamic**. Type of crop planted can be different, depending on expected crop yield.

In 'dynamic' rule, currently there are 4 types of crop to choose from: rice, cassava, groundnut and maize. For each of these crop, we defined expected crop yield as a function of soil fertility. What crop will grow in each field will be based on the maximum expected crop yield given the current relative soil fertility ($F_{t/F}$max).

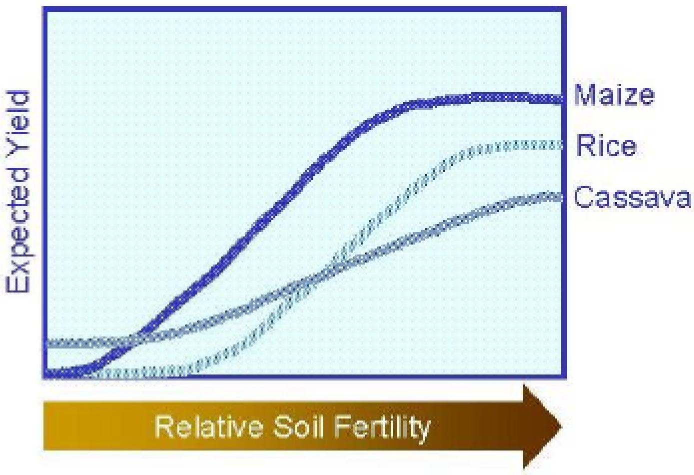


Figure 8.

Expected crop yield as a function of relative soil fertility.

3.1.5. Succession and Land Cover Change

The model has 9 types of land cover/land use as default:

(1) Crop
(2) Pioneer
(3) Young Secondary Forest
(4) Old Secondary Forest
(5) Primary Forest
(6) Agroforest (AF) Pioneer
(7) AF Early Production
(8) AF Late Production
(9) AF Post Production

The above land cover types split into two main land use succession trajectories: (1) forest and (2) agroforest (Figure 10). For each stage of succession (each land cover type) users must define period length of time (in years) before moving to the next stage. For example: 1 year for crop, 3 years for pioneer and so on. Figure 9 shows the full cycle of each trajectory using current default value.

The model will simulate the agroforest trajectory if users choose to have agroforest development occur in the model (see section 3.2.1.). Both trajectories consider period of time between cropping season as fallow period, thus soil fertility restoration period. At any point in time and at any stage of succession, a plot can become burnt plot through wildfire occurrence. It can then follow by cropping or directly to pioneer stage. In forest trajectory, slash and burn can be carried out at any point in time and at any stage of succesion. In agroforest trajectory, it can only occur when it has reached the end of AF Post Production stage.

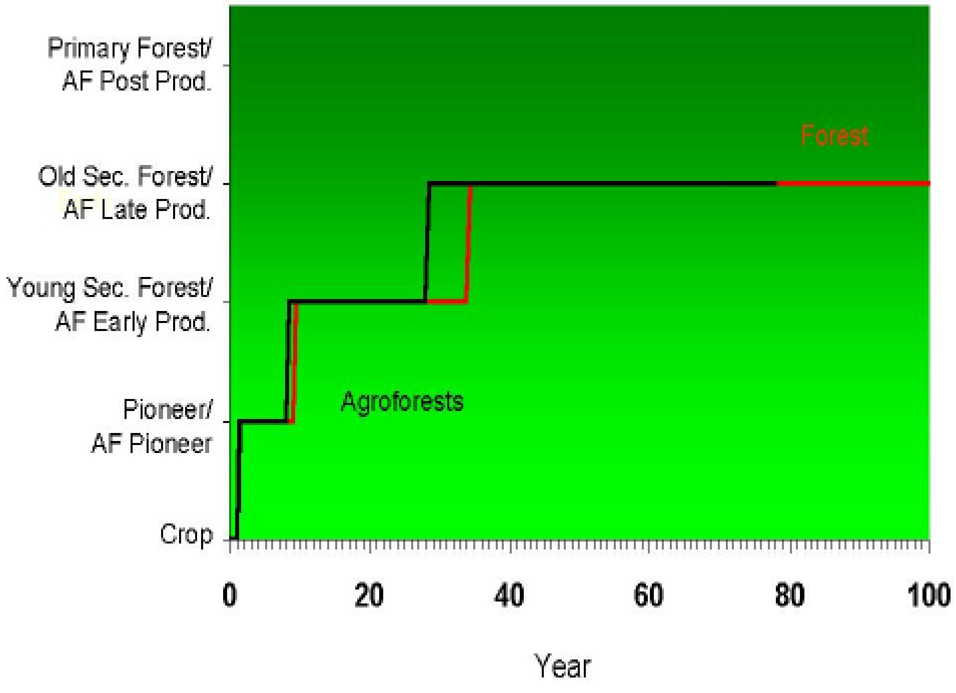


Figure 9. Full cycle of land use succession trajectories

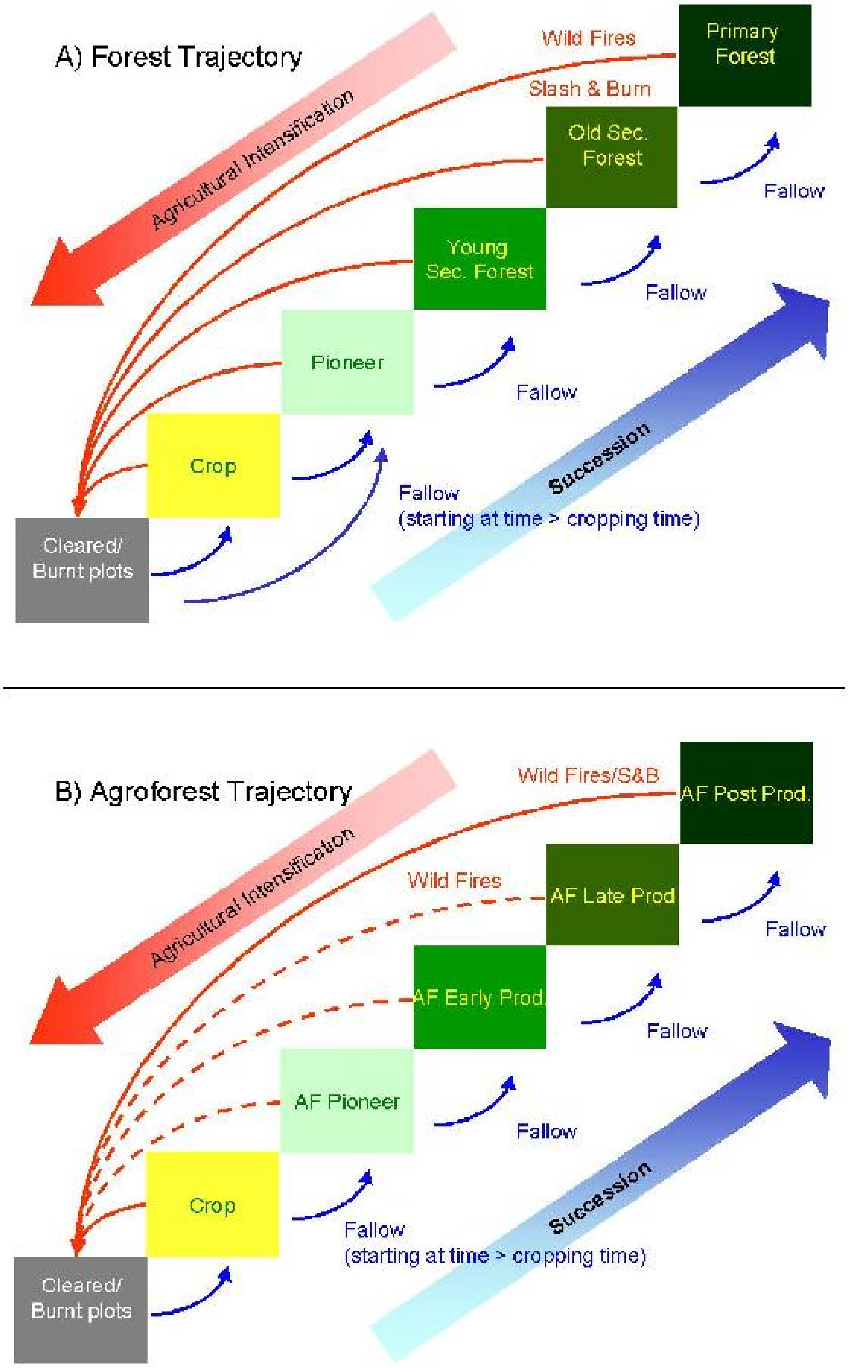


Figure 10. Schematic diagram of land use succession in FALLOW model

3.2. Optional Module

3.2.1. Forest products and Agroforest

The model also allows for the collection of forest products and for the conversion of the fallows into 'agroforest'. Both of these activities will bring cash to financial capital, if labour is allocated to them. The key is the classification of land by age since last clearing. The user can specify the expected returns to labour for fallow vegetation as well as agroforest, as a function of the vegetation class. For forest products a saturation curve is used, where the returns to labour gradually diminish as the maximum harvest intensity is approached. Amount of harvested products are contrained by labout availability and accessibility of area for gathering activities (Figure 11).

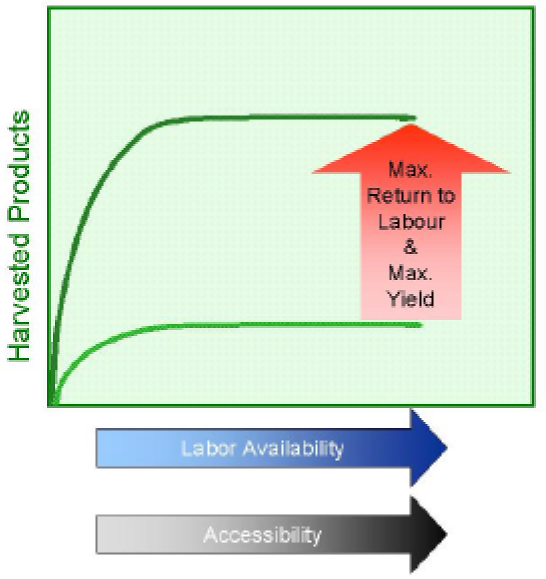


Figure 11. Harvested products as a function of labour intensity and accessibility

3.2.2. Farmers Knowledge

A number of farmer decisions are part of the simulation. We assume that these decisions are based on a weighing up of different options as they exist at that point in time. These include options on:

(i) the total number of plots to be cropped (cropping intensity)

(ii) the specific plots that will be opened by slash-and-burn in the coming year

(iii) options of how to allocate one's labour over growing food crops, collecting forest products and harvesting in one's agroforest.

We assume that the choices between these options are based on the expected outcomes, on the basis of past experience. We thus include a simple type of 'learning' into the model, where new information can update the estimates of returns to labour and crop yields.

The model user can define a parameter that indicates the type of ‘learning’. If you put the ‘Yield-memory’ parameter at 1, the traditional knowledge will always predominate over current experience. If you put the memory at 0, farmers will only use last year’s results as a basis for taking their decisions. For values in between 0 and 1, we get a mix of memory and learning.

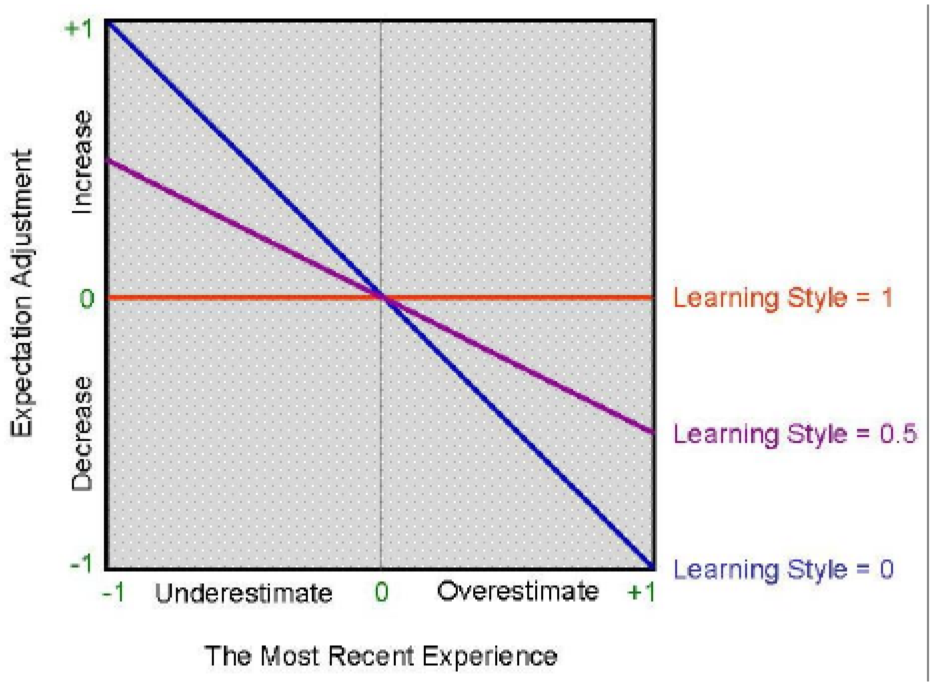


Figure 12.

equations

3.2.3. Labour allocation

If we use the forest product and/or agroforest option the model has to allocate the labour available in each year over the various activities. This is done on the basis of the expected returns to labour for each activity.

3.2.4. Human population density and migration

Human population density in the model can change as a result of births and deaths as well as migration. The birth and death rate can be specified as a function of food sufficiency. Migration decisions are supposed to be driven by a comparison of returns to labour as they actually evolve in the modelled landscape, and the returns to labour elsewhere (a constant in the current model version). A ‘quality of life’ weighting can be used to modify these decisions.

3.2.5. Wild Fire

3.2.6. Tenureship

3.3. Output Module

3.3.1. Food security

The degree to which annual food demand could be met during a simulation run is accumulated and averaged in this module.

This module also keep track the total cumulative labour time spent throughout the simulation.

3.3.2. Carbon stock

This module keep tracks of the carbon stock exist in the landscape. Output available are:

1. Maximum aboveground C stock for a forest (endpoint of fallow development), in Mg ha^{-1}
2. Yearly increment in C stock during fallow periods in Mg ha^{-1} yr^{-1}
3. Time-averaged aboveground C stock for cropping years, in Mg ha^{-1}
4. Belowground C stock at maximum soil fertility, in Mg ha^{-1}.

Input required are average carbon stock for each type of landcover.

3.3.3. Biodiversity

The biodiversity module includes explicit scaling rules from plot/field to landscape level. The maximum of species richness reached by age is determined by maximum species richness as number of species per field, with the species richness half life (in years) parameter indicating the time after major disturbance (slash-and-burn land clearing) required to reach half of the maximum richness (Figure 13). Data on plant richness for a range of tropical land cover types were indeed found to relate to time since disturbance in a similar way ([6]).

Biodiversity parameters at landscape level include the power (dimension) of the relation between number of fields and total richness for each class of vegetation. As a last step, the probability of species overlap between cover types is used to derive a landscape-level richness indicator.

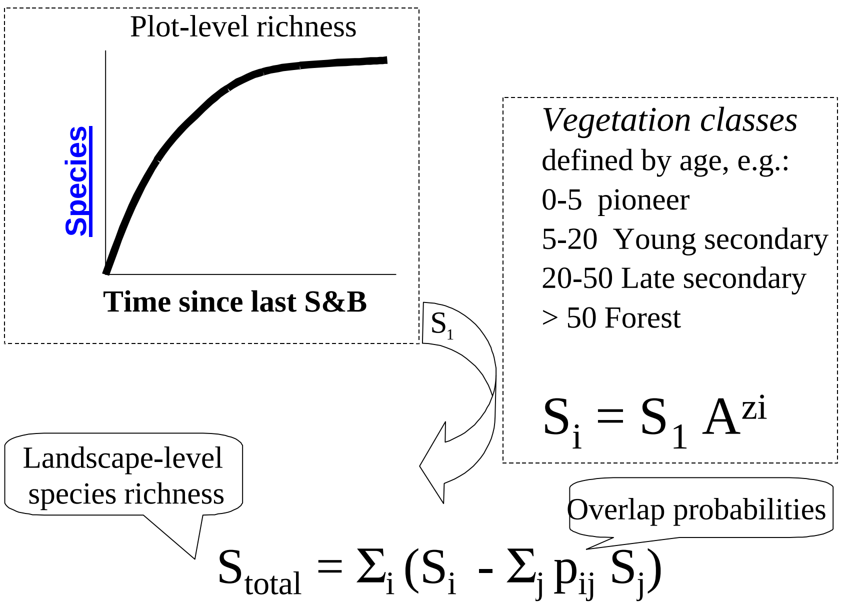


Figure 13. Relations used for deriving S_{total} as a measure of landscape level species richness

3.3.4. Watershed functions

FALLOW model has a simple water balance that predicts the impacts of the resulting landscape on the basis of the following rules:

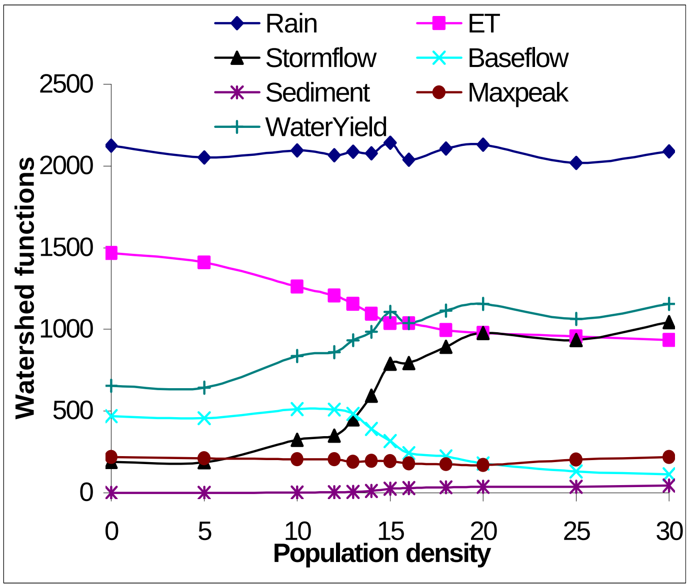
- Rainfall at patch level is independent of the land cover; no mist capture in cloud forests is considered,
- Evaporation of water intercepted by the canopy and transpiration by the vegetation is driven by a yearly total demand that the user specifies as input (e.g. varying from 140 mm month^{-1} for a primary forest to 100 mm month^{-1} for a crop, with a specified reduction factor for dry months)
- The allocation of surplus rainfall over overland flow, subsurface quickflow and baseflow is determined by slope as well as by a soil physical quality that decreases during a cropping stage and recovers (slowly) under other land cover types; if water can infiltrate but the soil water store is (nearly) saturated, the surplus will become subsurface quick-flow, that adds to the overland flow to become ‘storm flow’. From the ground water store a constant fraction contributes to ‘base-flow’.
- Overland flow of water can lead to net sediment loss, depending on a land cover factor that reflects the presence or absence of surface litter (contact cover) and intrinsic soil properties. A simple representation of sediment filter functions takes the land cover into account by distance to the streams.

4. Example of results

4.1. Exploring watershed functions: sensitivity analysis

This exercise attempts to systematically explore the response of the model to changes and to see how sensitive the overall model outcome is to a change in value. This 'sensitivity' is always dependent on the 'context' of the setting of other parameters, so you should be careful with conclusions. Some parameters only matter in particular types of circumstance. Others, however, seem to matter always, or hardly at all. This exercise is useful to see which parameters should get priority in a measurement programme. As an example we will here explore the watershed functions, at a range of population densities, and under the influence of the 'physical degradation' parameter for cropped fields.

Figure 14. Watershed functions predicted by the FALLOW model with different initial population densities, averaged over a 100 year period, using default parameter values.



An example of the model output (Figure 14) across a range of population densities shows that predicted total water yield of a subwatershed will increase if more people live there, but that this increase is based on:

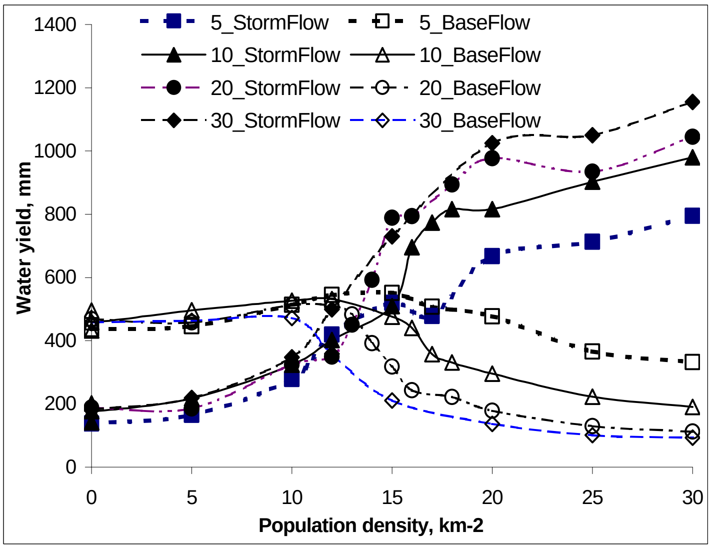
a) a slight initial increase in baseflow due to a decrease in water use by the vegetation while the infiltration capacity in the landscape is still intact

b) a more drastic increase due to stormflow, with a decline in baseflow, at higher population densities.

Net sediment loss increases along with stormflow, as the filter functions decrease with increasing cropping intensity. The maximum daily peakflow, however, is virtually independent of land cover.

The switch from baseflow to stormflow depends on the physical degradation of the soil during the cropping period. Figure 15 shows an initial parameter sensitivity study in which the SoilQChange(crop) parameter was modified from –5 to –30%.

Figure 15. Sensitivity of the FALLOW output for stormflow and baseflow to the parameter value for the soil physical deterioration in the cropping stage (SoilQChange(crop)) from –5 to –30%



The shift from baseflow to stormflow in the model output is accompanied by an increase in predicted net sediment loss (Figure 16). The relation between net sediment loss and stormflow is predicted to have an intercept on the X axis of about 250 mm. This intercept reflects landscapes where stormflow is largely due to subsurface quickflow while riparian buffer strips are still largely intact. At higher population densities, stormflow shifts to overland flow, while the filter functions decrease.

The model representation is a first approximation only, but it demonstrates that the concepts as such can be operationalised, and it points at sensitivity for specific parameters. Soil physical deterioration during cropping years will lead to a gradual loss of ‘watershed functions’ in a way that is not reflected in models that attribute soil loss or other functions to current land cover only (as is done in USLE and its various modifications). It seems likely that we will need this dynamic change in soil properties as a driver of our models, and the model outcome is clearly sensitive to the parameter values for this change. Attempts to measure the SoilQChange(crop) parameter in real watersheds will be needed.

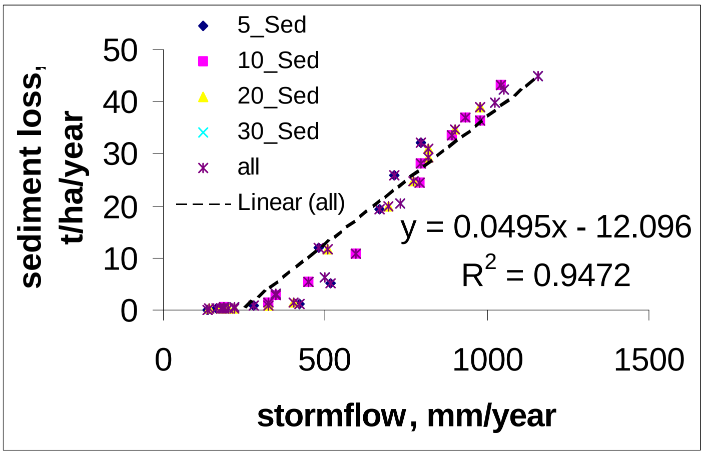


Figure 16. Predicted relationship between stormflow and net sediment loss, for a range of population density and SoilQChange(crop) values as in Figure 4.

4.2. Exploring land use change: using PC-RASTER version

<u>Opening Plot based on random choice</u>

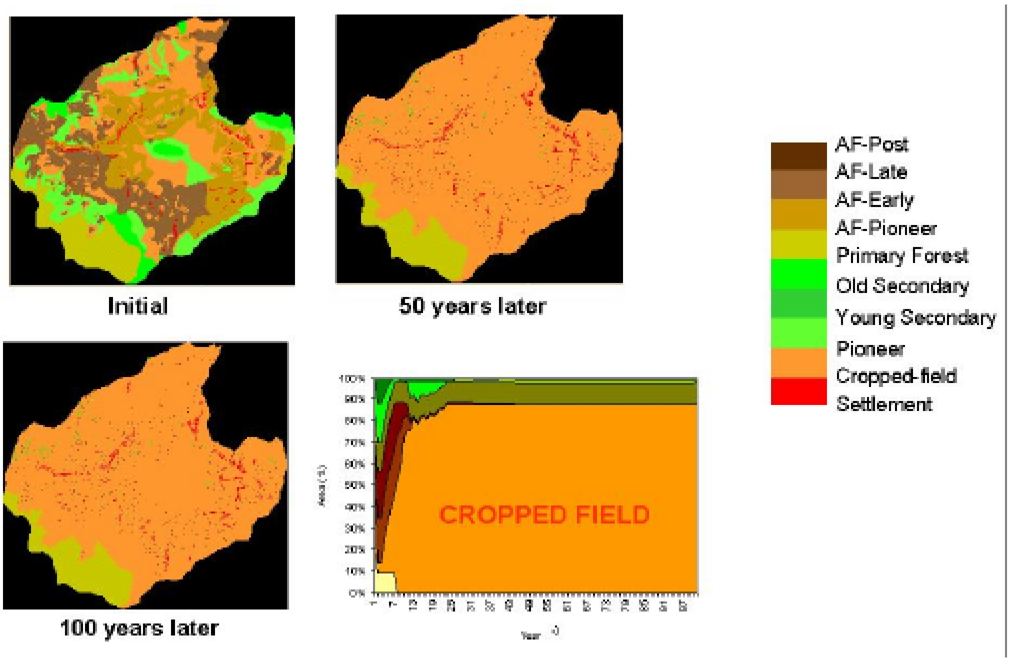


Figure 17. Landuse change and chane of cropped field area after 100 years of simulation

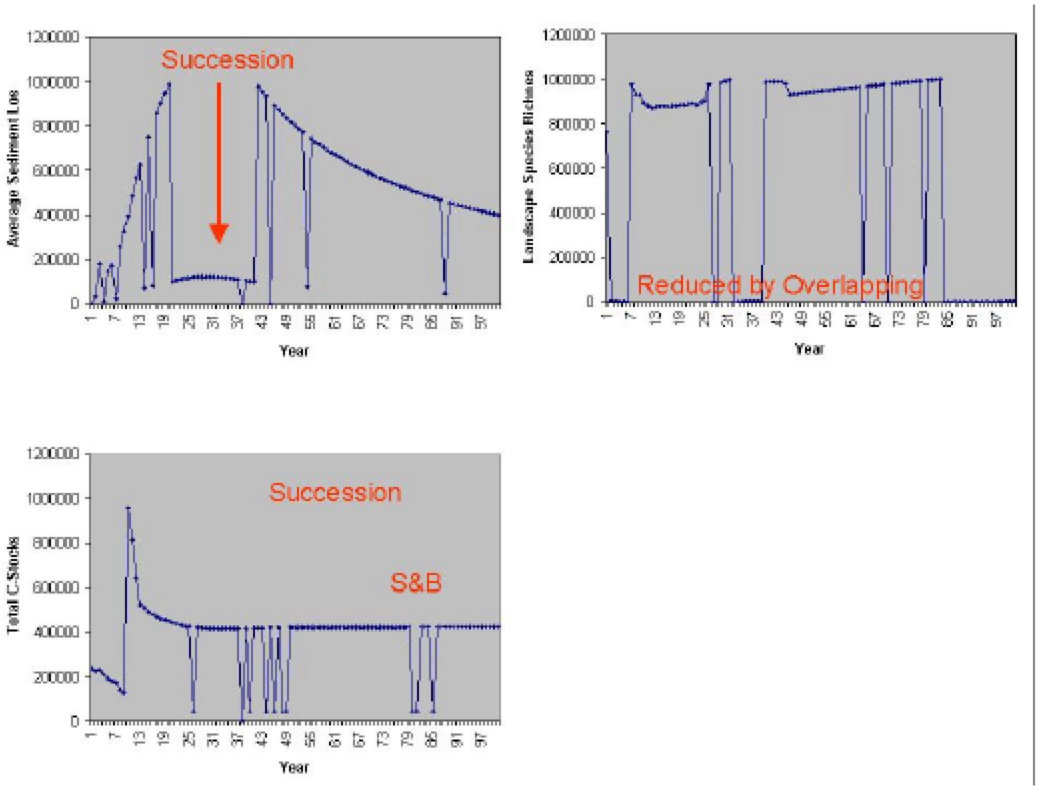


Figure 18. Consequences on watershed functions, biodiversity and carbon stock

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