Understanding local action and its consequences for global concerns in a forest margin landscape:

the FALLOW model as a conceptual model of transitions from shifting cultivation

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INTERNATIONAL CENTRE FOR RESEARCH IN AGROFORESTRY

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Towards integrated natural resource management in forest margins of the humid tropics: local action and global concerns

Meine van Noordwijk, Sandy Williams and Bruno Verbist (Editors)

Humanity stands at a defining moment in history. We are confronted with a perpetuation of disparities between and within nations, a worsening of poverty, hunger, ill health and illiteracy, and the continuing deterioration of the ecosystems on which we depend for our well-being. However, integration of environment and development concerns and greater attention to them will lead to the fulfilment of basic needs, improved living standards for all, better protected and managed ecosystems and a safer, more prosperous future. No nation can achieve this on its own; but together we can - in a global partnership for sustainable development. (Preamble to the United Nations' Agenda21 on Sustainable Development; http://www.un.org/esa/sustdev/agenda21chapter1.htm).
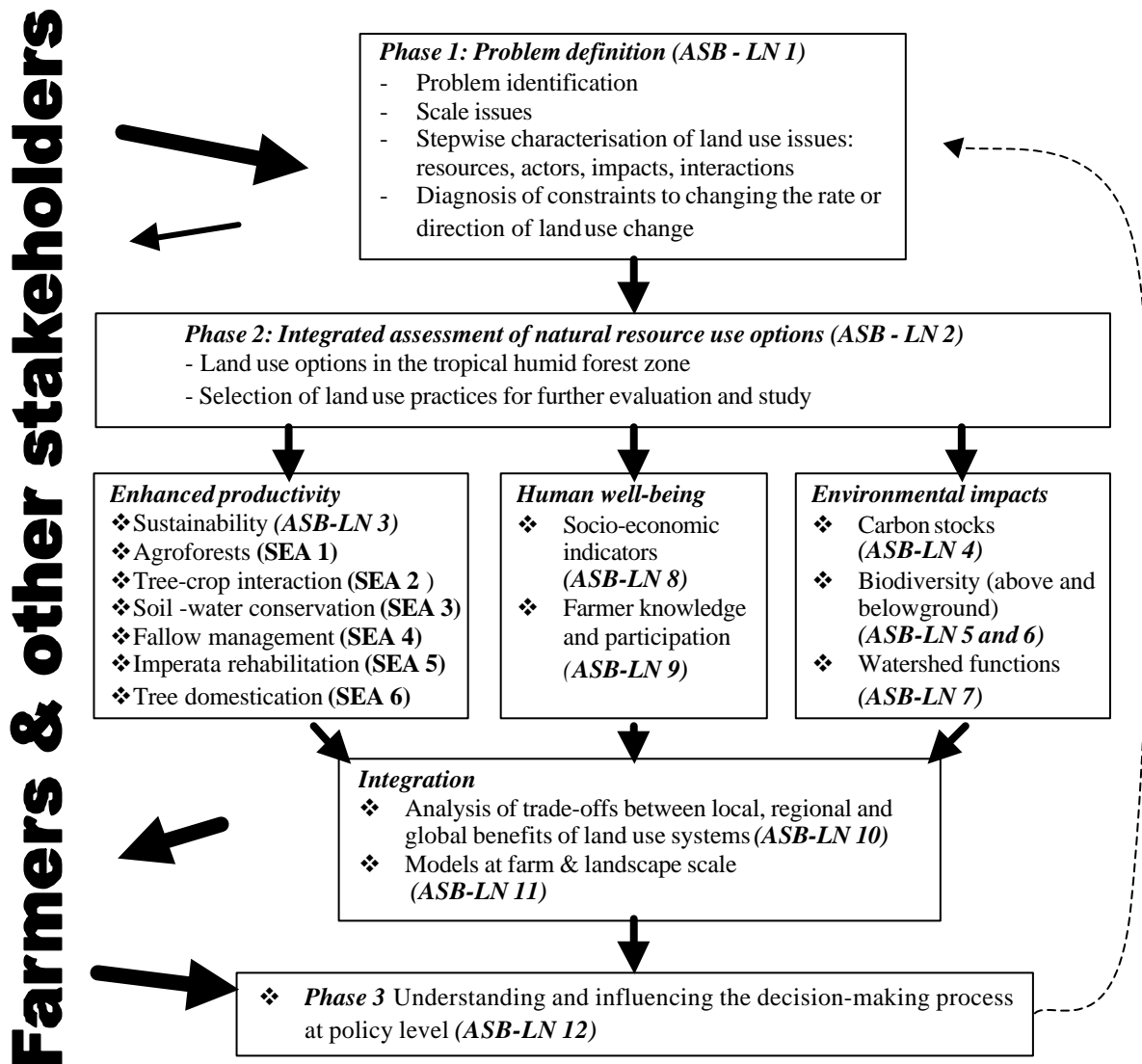
Background to this series of lecture notes

Much of the international debate on natural resource management in the humid tropics revolves around forests, deforestation or forest conversion, the consequences it has and the way the process of change can be managed. These issues involve many actors and aspects, and thus can benefit from many disciplinary perspectives. Yet, no single discipline can provide all the insights necessary to fully understand the problem as a first step towards finding solutions that can work in the real world. Professional and academic education is still largely based on disciplines – and a solid background in the intellectual capital accumulated in any of the disciplines is of great value. If one wants to make a real contribution to natural resource management issues, however, one should at least have some basic understanding of the contributions other disciplines can make as well. Increasingly, universities are recognising the need for the next generation of scientists and policymakers to be prepared for interdisciplinary approaches. Thus, this series of lecture notes on integrated natural resource management in the humid tropics was developed.

The lecture notes were developed on the basis of the experiences of the Alternatives to Slash and Burn (ASB) consortium. This consortium was set up to gain a better understanding of the current land use decisions that lead to *rapid* conversion of tropical forests, shifting the forest margin, and of the *slow* process of rehabilitation and development of sustainable land use practices on lands deforested in the past. The consortium aims to relate local activities as they currently exist to the global concerns that they raise, and to explore ways by which these global concerns can be more effectively reflected in attempts to modify local activities that stabilise forest margins.

The Rio de Janeiro Environment Conference of 1992 identified deforestation, desertification, ozone depletion, atmospheric CO_2 emissions and biodiversity as the major global environmental issues of concern. In response to these concerns, the ASB consortium was formed as a system-wide initiative of the Consultative Group on International Agricultural Research (CGIAR), involving national and international research institutes. ASB's objectives are the development of improved land-use systems and policy recommendations capable of alleviating the pressures on forest resources that are associated with slash-and-burn agricultural techniques. Research has been mainly concentrated on the western Amazon (Brazil and Peru), the humid dipterocarp forests of Sumatra in Indonesia, the drier dipterocarp forests of northern Thailand in mainland

Southeast Asia, the formerly forested island of Mindanao (the Philippines) and the Atlantic Congolese forests of southern Cameroon.

The general structure of this series is

Farmers & other stakeholders

Phase 1: Problem definition (ASB - LN 1)
- Problem identification
- Scale issues
- Stepwise characterisation of land use issues: resources, actors, impacts, interactions
- Diagnosis of constraints to changing the rate or direction of land use change

Phase 2: Integrated assessment of natural resource use options (ASB - LN 2)
- Land use options in the tropical humid forest zone
- Selection of land use practices for further evaluation and study

Enhanced productivity
- ❖ Sustainability *(ASB-LN 3)*
- ❖ Agroforests **(SEA 1)**
- ❖ Tree-crop interaction **(SEA 2)**
- ❖ Soil -water conservation **(SEA 3)**
- ❖ Fallow management **(SEA 4)**
- ❖ Imperata rehabilitation **(SEA 5)**
- ❖ Tree domestication **(SEA 6)**

Human well-being
- ❖ Socio-economic indicators *(ASB-LN 8)*
- ❖ Farmer knowledge and participation *(ASB-LN 9)*

Environmental impacts
- ❖ Carbon stocks *(ASB-LN 4)*
- ❖ Biodiversity (above and belowground) *(ASB-LN 5 and 6)*
- ❖ Watershed functions *(ASB-LN 7)*

Integration
- ❖ Analysis of trade-offs between local, regional and global benefits of land use systems *(ASB-LN 10)*
- ❖ Models at farm & landscape scale *(ASB-LN 11)*

- ❖ **Phase 3** Understanding and influencing the decision-making process at policy level *(ASB-LN 12)*

This latest series of ASB Lecture Notes (**ASB-LN 1 to 12**) enlarges the scope and embeddes the earlier developed ICRAF-SEA lecture notes (**SEA 1-6**) in a larger framework. These lecture notes are already accessible on the website of ICRAF in Southeast Asia: http://www.icraf.cgiar.org/sea

In this series of lecture notes we want to help young researchers and students, via the lecturers and professors that facilitate their education and training, to grasp natural resource management issues as complex as that of land use change in the margins of tropical forests. We believe that the issues, approaches, concepts and methods of the ASB program will be relevant to a wider audience. We have tried to repackage our research results in the form of these lecture notes, including non-ASB material where we thought this might be relevant. The series of lecture notes can be used as a basis for a full course, but the various parts can also 'stand alone' in the context of more specialised courses.

Acknowledgements

ASB-consortium members

Details of the ASB consortium members and partner organisations can be found at:
http://www.asb.cgiar.org/

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Lecture note 11B

UNDERSTANDING LOCAL ACTION AND ITS CONSEQUENCES FOR GLOBAL CONCERNS IN A FOREST MARGIN LANDSCAPE:
The FALLOW model as a conceptual model of transitions from shifting cultivation

By Meine van Noordwijk

Contents

I. Objectives

- To get hands-on experience with the use of an existing simulation model, learn how to modify parameters and evaluate model output
- To introduce simulation modelling as a tool to understand how apparently complex results can be derived on the basis of simple assumptions
- To introduce the "FALLOW" model as a representation of a landscape mosaic where shifting cultivation can be compared to other land uses, with consequences for environmental service functions and productivity
- To explore scenarios, such as the consequences of migration on otherwise promising alternatives to slash and burn agriculture
- To learn how to add structure to the model itself

To run the model you will need :
- The computer program STELLA 5.0 (or later) installed on your computer, as well as MS Excel.
- First open the file FALLOW.xls (and answer **yes** to the question whether or not you want to enable the macros that are used in this spreadsheet),
- Then open FALLOW.stm, the STELLA model, and answer **yes** to the question whether or not you want to establish links to the spreadsheet.

Switch on your computer and load the Excel and STELLA files as indicated in the box -- read the following text while the files are loaded into the computer's memory.

II. Lecture

1. Introduction

In the preceding lecture notes we have described how shifting cultivation systems can gradually intensify with shorter and shorter fallows (lecture note 2), how we can assess the sustainability of such crop-based land use systems relative to options based on tree crops ('agroforest') or collection of forest products (lecture note 3), what the consequences may be for C stocks (lecture note 4), biodiversity (lecture notes 5 & 6), watershed functions (lecture note 7) and socio-economic indicators such as returns to labour and returns to land (lecture note 8). In practice, however, all these impacts occur together and to some extent farmers' decisions on intensification interact with all of these.

One way to explore the simultaneous impacts at the landscape scale, is to construct a simulation model that tries to capture the most important aspects of the processes involved, and that allows the 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 constructs 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 complicated as the real world, and there will be no advantage in using it – you might be as well just watch the real world instead.

Simple models, however, can lead to recognition that the apparently complex and 'rich' behaviour as observed in the real world can actually be generated on the basis of simple rules and the logical interactions implied by these. 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.

1.1 How to use the FALLOW model

This is a model of shifting cultivation and crop-fallow rotations, that predicts food self-sufficiency, soil fertility, carbon stocks, plant species richness and watershed functions, on the basis of a number of biophysical and management parameters, for a 100 grid-cell landscape. We will first see what the model can do in terms of output and how it responds to modifications in the input, before we 'open the black box' and look at how it comes to these 'predictions', and what 'assumptions' it uses.

If you open FALLOW in STELLA, you will see some explanatory text and a number of buttons that allow you to navigate through the model, to save your (modified) version of the program under a new name and to quit.
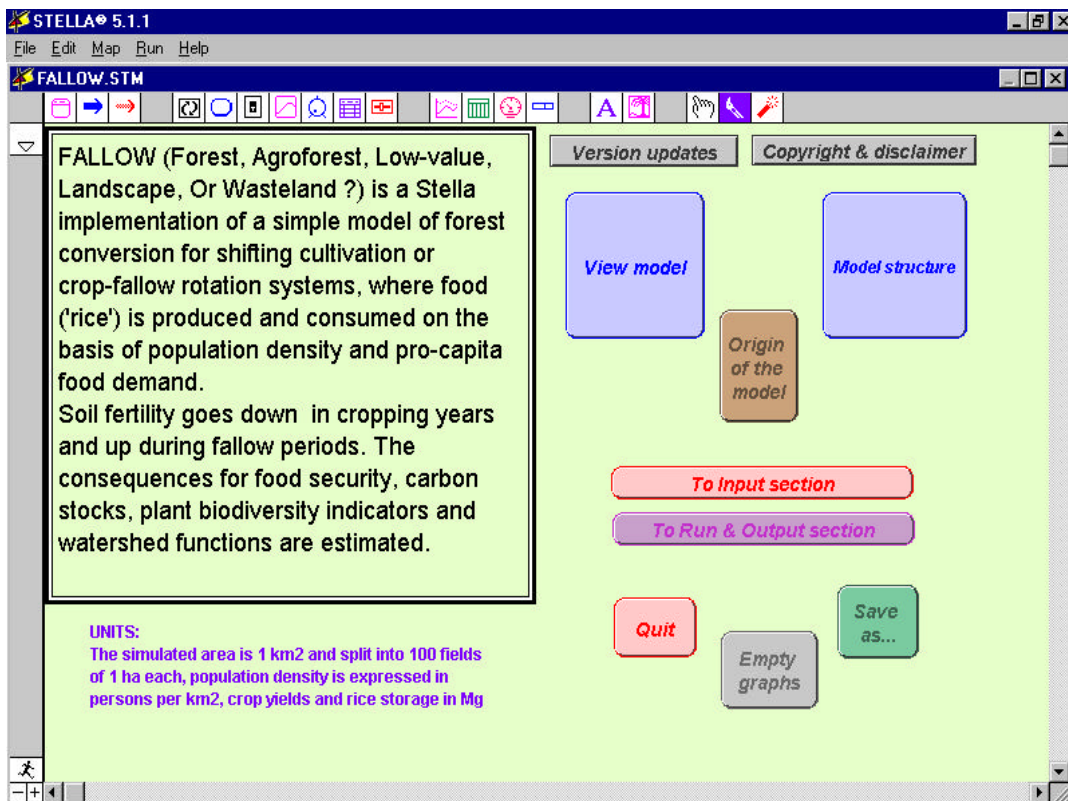
2. Running the model with default parameter values

Let's first make a run of the program and see what type of output we can obtain. Click on the ***To_run_section*** button.

The main control screen in the model allows you to run the model, set a number of key parameters (by moving sliders) and to look at the output via some direct screen output, a stack of graphs and tables. From this screen you can also go to a number of parameter input screens to modify parameter settings before making a new run.
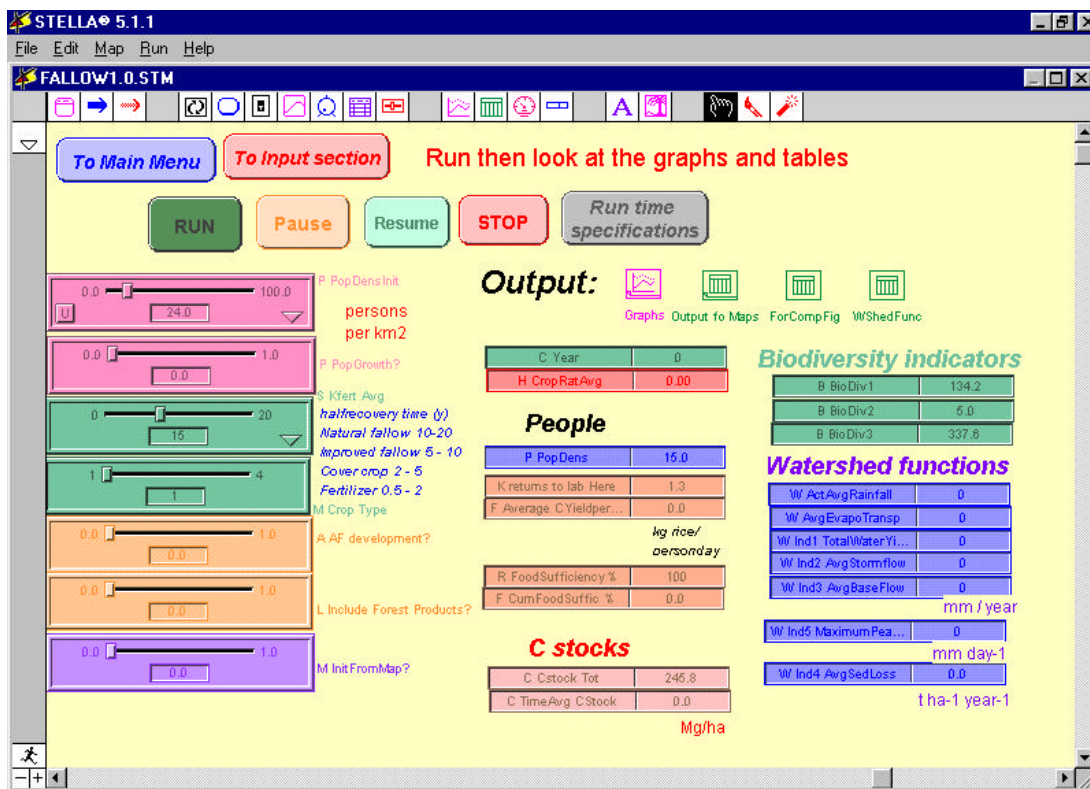
Click on the **Run** button, and see how long it takes to make a simulation over 100 years, for the default set of parameters (the time this takes depends on the clock speed of your computer).

While the simulation is going, you will notice that the output indicators on the screen keep changing, year by year. The output indicators tell you the current year, the **'crop fraction'** (fraction of plots currently cropped), and indicators under the following headings: People, C stocks, Biodiversity and Watershed functions (see Box).

At the end of a default simulation run (with 15 persons per km^2), most indicators look pretty bleak: there's not enough to eat, returns to labour are low, as are the C stocks and biodiversity indicators. The watershed functions have also degraded considerably from the forested condition where we started.

The key output indicators have the following definitions

P_PopDens (#/ km^2) = human population density in the current (last) year of the simulation,

K_Returns_to_lab_here (kg rice_eq day^{-1}) = average returns to labour in growing food crops, collecting forest products or harvesting from agroforests, converted to rice equivalents),

F_Average_C_Yieldperha (Mg ha^{-1}) = crop yield per ha of cropped field, averaged over the whole simulation period,

R_FoodSufficiency% = percentage of local food demand that could be met from the rice store or current production in the <u>current (last) year</u> of the simulation,

F_CumFoodSuffic_% = *idem*, averaged over the whole simulation period,

C_Cstock_Tot (Mg ha^{-1}) = total amount of carbon stored in aboveground vegetation plus soil in the current (last) year of the simulation,

C_TimeAvg_C_Stock (Mg ha^{-1}) *idem*, averaged over the whole simulation period,

B_Biodiv1 = Average number of plant species per plot,

B_Biodiv2 = Standard deviation of variation in vegetation age across the landscape,

B_Biodiv3 = Expected number of plant species for the landscape as a whole,

W_ActAvgRainfall (mm year^{-1}) = average rainfall amount that actually fell,

W_AvgEvapoTransp (mm year^{-1}) = averaged use of water by vegetation and evaporation from the soil surface,

W_Ind1_TotalWaterYield(mm year^{-1}) = average total river flow from the catchment,

W_Ind2_AvgStormflow (mm year^{-1}) = average storm flow from the catchment

W_Ind3_AvgBaseflow (mm year^{-1}) = average base flow from the catchment

W_Ind5_MaximumPeakFlow (mm day^{-1}) = highest peak flow recorded during the whole simulation

W_Ind4AvgSedLoss (t ha^{-1} year^{-1}) = net sediment loss from the catchment averaged over the whole simulation period

If you click on the **Graphs** button, you get a stack of graphs that can be used to understand what happened. Imagine you come to this village where the landscape is degraded, people are poor, and you start your detective work to reconstruct the history over the preceding century. Luckily, some people in the village had a perfect memory, so we can get the whole story:

A

B

C

D

E

F
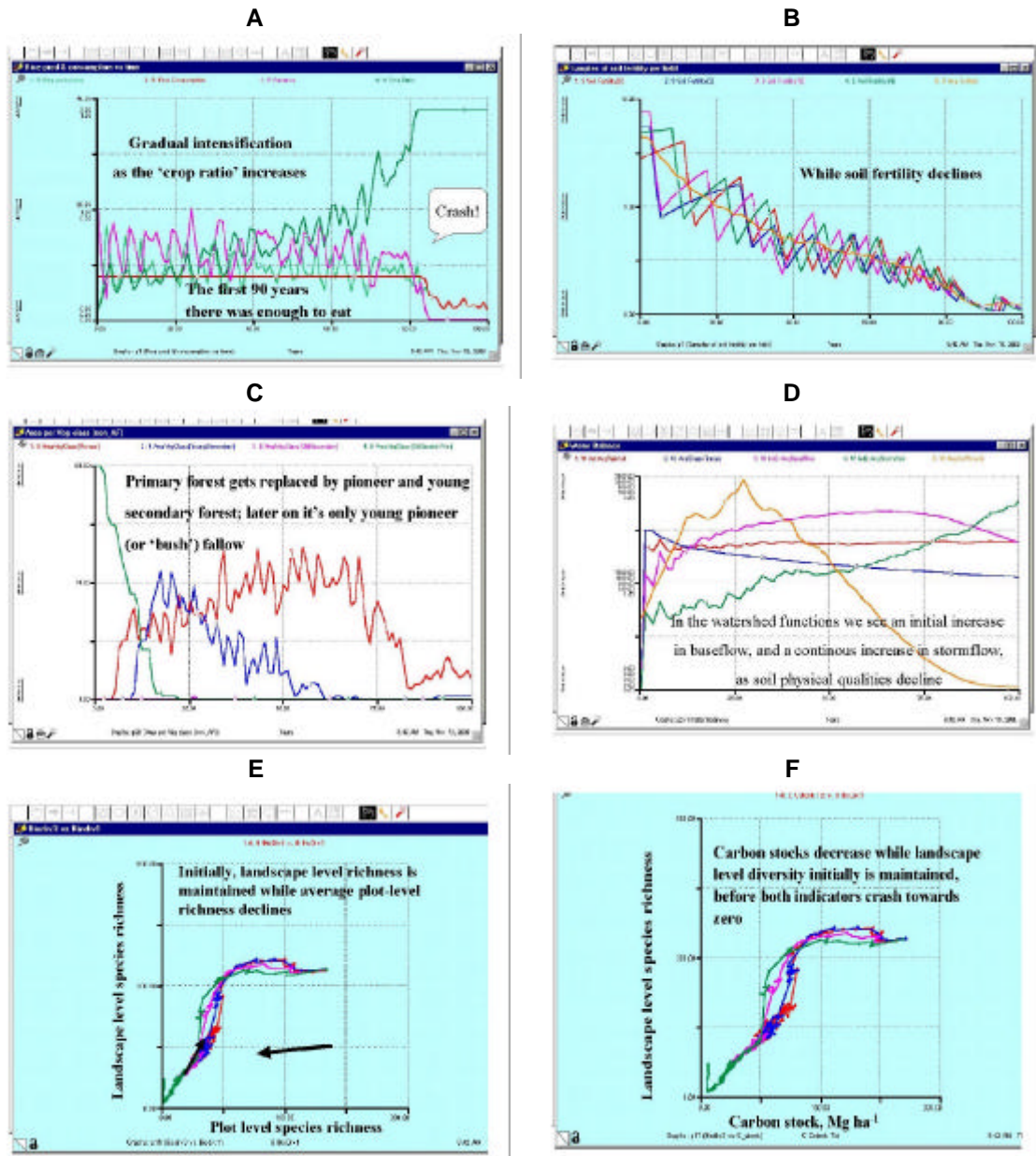
So, do you get a picture of what happened? If you had arrived here in year 50, would you have been able to predict that not everything was in order? What indicators could you have used?

We can see that there are two phases in the 'trade-off' curves between the various indicators: there is a phase that certain environmental qualities start to degrade while others are still constant or even improving, and the 'people-based' indicators are fine. So we would conclude that there are negative trade-offs between environment and 'development' indicators. But, once we get close to or beyond the 'crash' point, all indicators start to move towards zero. In that phase both environment and development objectives suffer...

At this point, we suggest that you try the following **exercises:**

1. take note of the main output indicators in the default run, and change the population density to 5, 10, 20 or 25 persons km^{-1}

2. keeping all parameters at their 'default' values, find out which human population densities will still allow for food self sufficiency after 100 years

3. compare the results for the two types of management decisions on intensification (see 'management' input screen) at a population density close to the critical one (see exercise 1)

4. choose a population density which is above the critical value established in exercise 1 and test the impact of 'improved fallows' on the various types of output indicators by reducing the S_Kfert_avg value (see 'soil fertility' input screen); will improved fallows improve environmental quality as well as human livelihoods?

5. what is the impact on food self sufficiency and landscape level biodiversity (biodiv3) if you make 10% of the plots inaccessible?

A second set of exercises allows you to explore other options that exist in the model:

6. What is the impact on the various output indicators of allowing for the harvesting of forest products?
   - at low population density
   - close to the 'carrying capacity'?

7. What is the impact on the various output indicators of allowing for the 'agroforest' option?
   - at low population density
   - close to the carrying capacity?

8. What is the impact on the various output indicators of allowing for population growth and human migration?


Segregate-Integrate Exercise

Within the FALLOW model you can change the fraction of land allocated to a 'forest reserve' and thus explore the consequences of the whole segregate-integrate continuum, especially when you allow for 'agroforest' development.

3. The model structure and its assumptions

While you learn how to operate the model and change the parameter values, you may wonder what the basis is for all these 'predictions' -- the number of possible outcomes of a simulation is nearly infinite, once we consider the range of output indicators we have and their patterns over time; it may seem to be almost as rich and confusing as the real world we know.

Yet, all these simulation results are derived from a relatively small set of rules ('assumptions'), that are applied consistently in every time step for each of the 100 cells that our landscape is supposed to have. What are these assumptions?

If you go to the Main Menu, you can click on a button that will bring you to a schematic diagram of the model. In each of the sectors there's a 'Please explain' button, that provides you with a few clues.
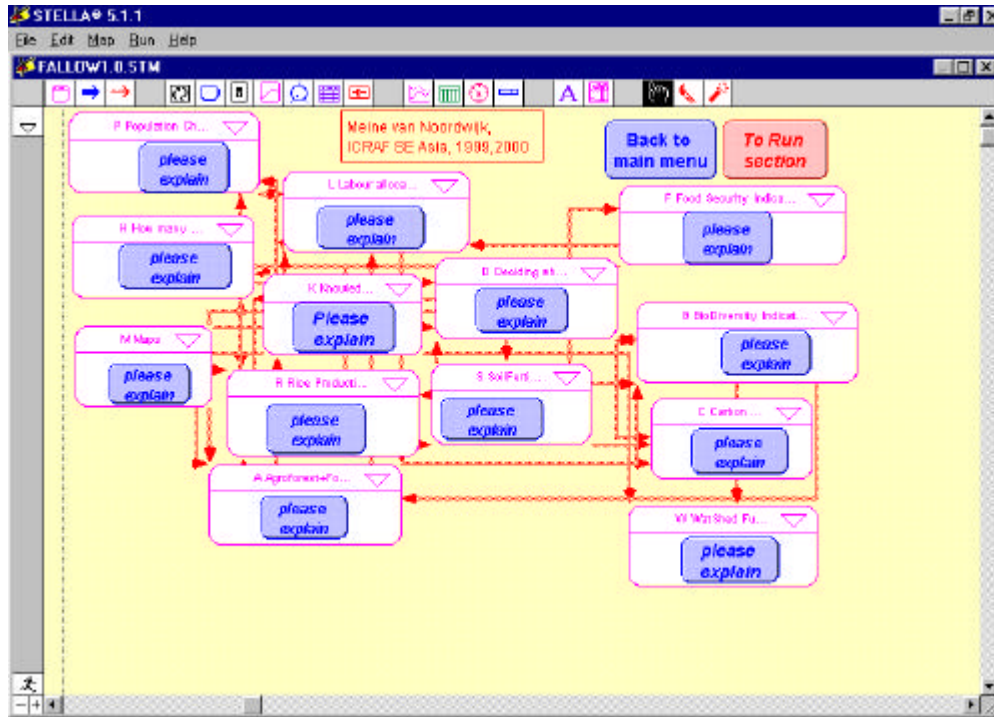
In fact there are only four essential sectors in the model that together form the key 'engine' of the dynamic behaviour. A number of other sectors only translate the dynamic behaviour into the desirable form of 'indicators'. A few further sectors are optional and can be brought to bear on the dynamic results as well.

In the following sections the four 'core' sectors of the model (Figure 1) are introduced (section 3.1), then the outputs are explained (section 3.2), and finally the five optional sectors are described (section 3.3).
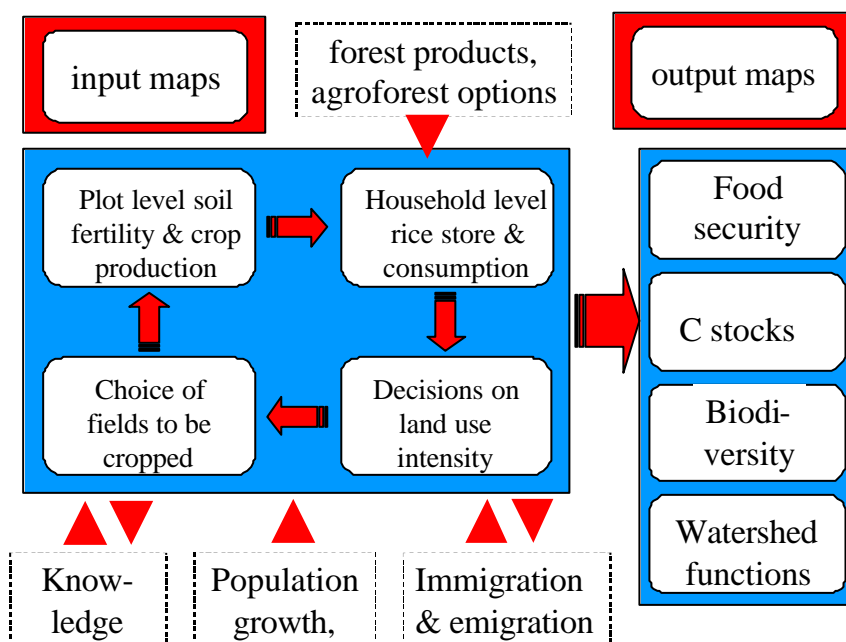
Figure 1. Structure of the FALLOW model: model core (centre left), outputs (right), and optional sectors (dashed lines).

3.1 The core of the model

Model core: Soil fertility sector

An essential sector of the model is the book-keeping of soil fertility in each of the 100 fields. This core 'engine' of the model is based on a model developed by Brian Trenbath in the early 1980s (Trenbath 1984, 1989). Management options of fallow systems ('shifting cultivation') should strike a balance between exploitation and restoration of soil fertility. The 'Trenbath' model describes build-up ('re-creation') of soil fertility by two parameters (a maximum level F-infinity and a half-recovery time K-fertrec) and decline during cropping as a simple proportion (FertDepletion).

Analysis of the model equations (Van Noordwijk, 1999) suggests that the highest yields per unit of land can be obtained when fallows are cleared for a new crop when 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, but 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.

A point of clarification on the model diagrams: in the STELLA 'language' we see a double-lined arrow going into the box marked 'soil fertility' and a double lined arrow going out from here. Which arrow is currently active for a given cell, depends on the 'switch' that indicates whether the particular field is currently 'Cropped?', yes (=1) or no (=0).
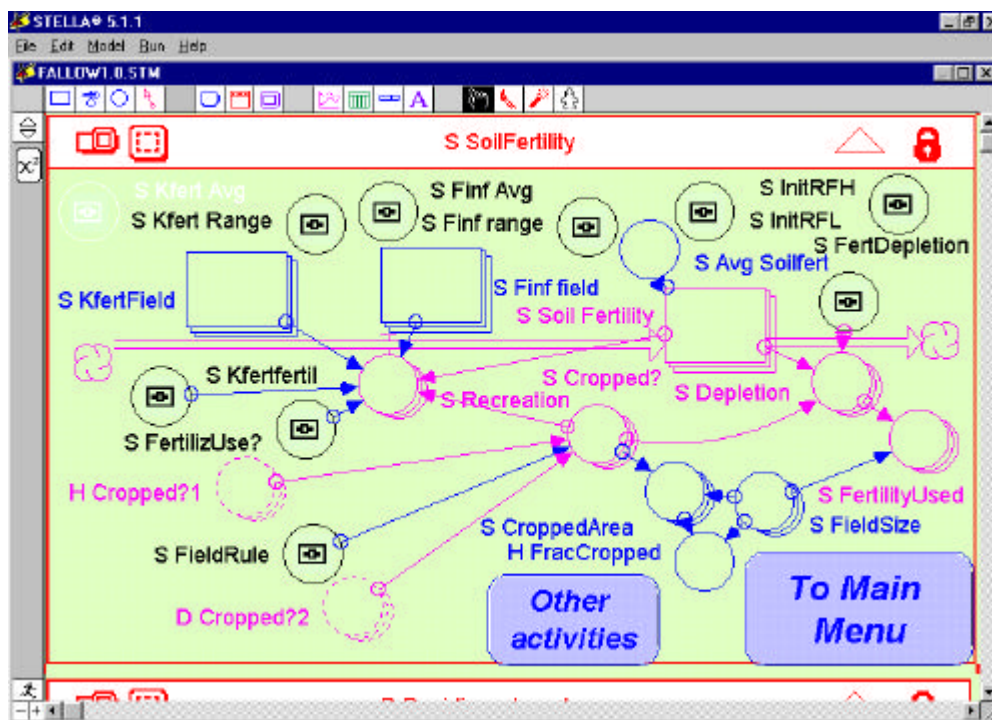
Key parameters in this sector are:

F_inf_Avg = Soil fertility (in FertUnit) to which the soil returns after an infinitely long fallow period;

Finf_Range = Range (Init RFL(ow) - InitRFH(igh)) in which initial soil fertility is varied between fields, relative to F_inf_Avg

Kfert = halfrecovery time (y) for soil fertility during fallow periods; suggested value domains: Natural fallow 10 - 20; Improved fallow 5 - 10; Cover crop 2 - 5 and Fertilizer 0.5 - 2 y

Kfert_Range = Range (InitKfL(ow) - InitKfH(igh)) in which Kfert parameter varies between fields, relative to Kfert_Avg

TimeCrop = Number of consecutive years that a field is cropped, once the fallow vegetation has been removed

FertDepletion = Fraction by which soil fertility decreases during 1 year of cropping

ConvEff[croptype] = Conversion from soil fertility units into crop yields (Mg ha^{-1} per FertUnit) e.g. for Finf = 10 & FertDeplet = 0.2, a ConvEff of 3 will lead to a maximum yield of 6 Mg ha^{-1}. For crop type = 1 (landrace), 2 (new selection), 3 (HYV1) and 4 (HYV2), default values for ConvEff are 0.5, 0.8, 1.2 and 2, respectively.

CropSens = impacts of variable weather are drawn from the range [CropWorstW, 1] and raised to the power CropSens. For crop type = 1 (landrace), 2 (new selection), 3 (HYV1) and 4 (HYV2), default values for CropSense are 1, 1.5, 2 and 2.5, respectively.

Model core: Rice_store and consumption sector

In the Rice_Store sector, we keep track of the contents of the rice store, adding all crop yields and using it to feed people, unless it is lost from the store because of rats, mice and insects. Decisions on 'intensification' or increasing the cropping ratio (the proportion of the landscape that is cropped) are based on the amount of rice in the store, relative to the annual consumption, with thresholds defined by the model user (RiceStTargL and RiceStTargH).

Parameters here include:

Labour (persondays) for growing one crop (LabCrop) or clearing 1 ha (LabClear)

PopDensInit = persons per km^2

ProCapFoodReq = Annual food requirement per capita (Mg per person per year), default value = 0.5

LossStoreFrac = Fraction of rice lost from the store per year due to rats, mice, insects etc.

Model core: Intensification decision sector

For Field_rule = 1 the number of fields to be cropped is derived from the current cropping intensity, but the choice of fields does not depend on soil fertility

RiceStocktarg = Target number of years in which annual rice consumption can be met from the rice store; deviations from this target trigger changes (+ or -) in cropping intensity, with a response step (fraction of total area) bounded by MaxStep * IntensificationStep

RegulMeth: Options are given for adjusting the cropping intensity: RegulMeth = 1 means that decisions are based on the rice store only, RegulMeth = 2 includes consumption and yield estimates, based on recent experience (the function YieldMemory gives weight to previous years)

Model core: Best field selector

In the 'Best_field_selector' section all fields are classified by their current soil fertility into 'below average', 'above average', 'high' and 'very high' categories; the probabilities of each class being cleared depend on the total cropping intensity required. The 'best field selector' part is only used when 'Field rule = 2' is chosen.

Fieldrule = 1 Decisions on which fields to crop are based on cycle length *per se*;

Fieldrule = 2 Farmers classify fields by soil fertility and distance to the village, and choose the best fields to crop
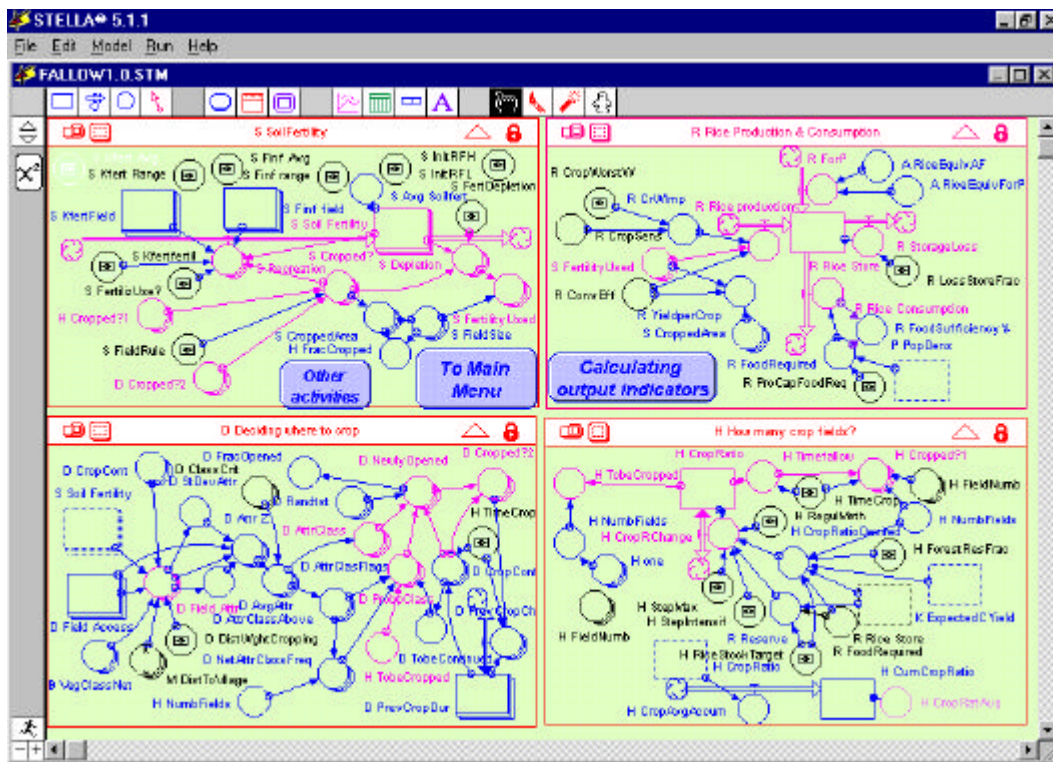
3.2 Model outputs

Output indicators: Food security sector

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

Output indicators: Carbon stock sector

Max C Stock AG gives the maximum aboveground C stock for a forest (endpoint of fallow development), in Mg ha^{-1}

FallowCAccumRate gives yearly increment in C stock during fallow periods Mg ha^{-1} yr^{-1}

CropY Cstock gives the time-averaged aboveground C stock for cropping years

Cstock BGmax gives the belowground C stock at maximum soil fertility, in Mg ha^{-1}.
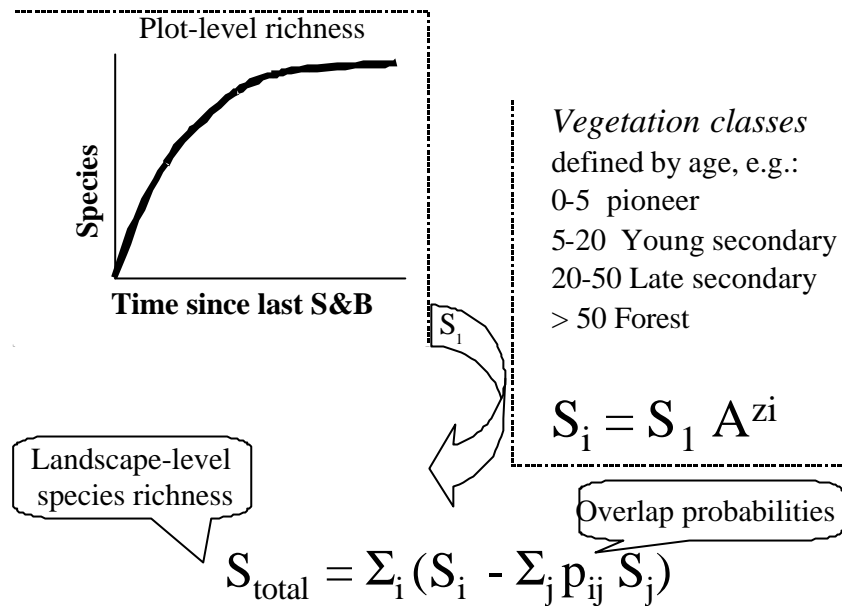
Figure 2. Relations used for deriving S_{total} as a measure of landscape level species richness

Output indicators: Biodiversity sector

The biodiversity sector includes explicit scaling rules from plot/field to landscape level. The maximum of species richness reached by age is determined by SpecRichMax as number of species per field, with the SpecRichK (year) parameter indicating the time after major disturbance (slash-and-burn land clearing) required to reach half of the maximum richness. 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 (lecture note 5).

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.

Output indicators: Watershed functions

A simple water balance was added 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 with a value of SoilQChange(crop) 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.
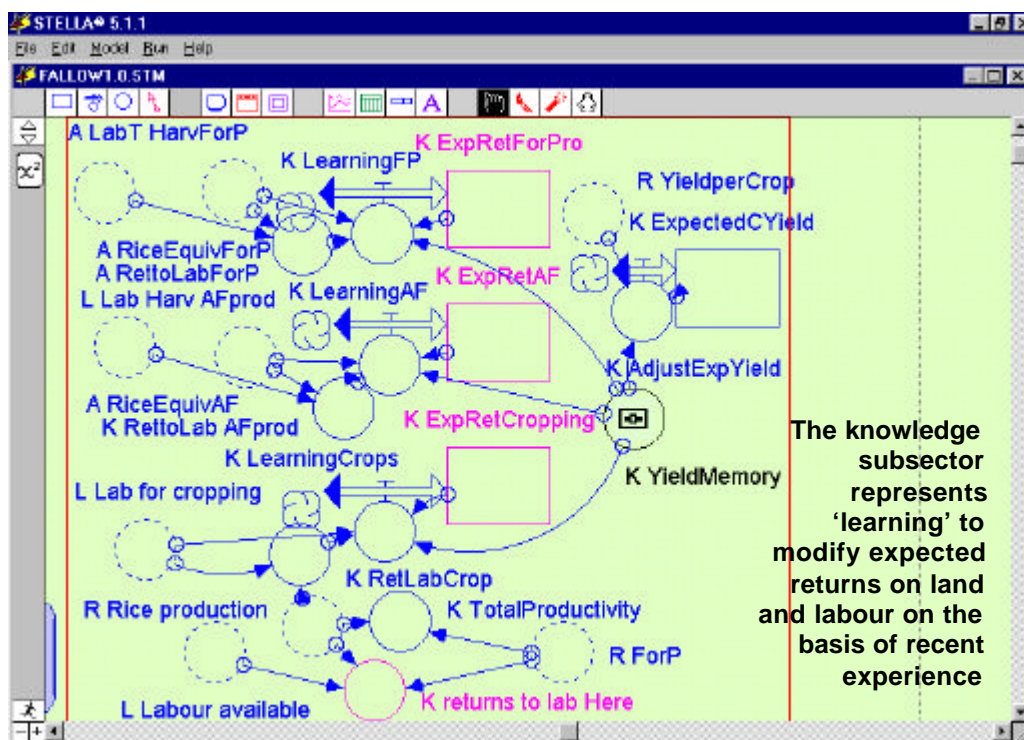
3.3 Optional sectors

Optional sectors: 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 can yield rice equivalents to the store, 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.

Optional sectors: 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 of the total number of plots to be cropped and the specific plots that will be opened by slash-and-burn in the coming year, and 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.

The knowledge subsector represents 'learning' to modify expected returns on land and labour on the basis of recent experience

Optional sectors: 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, with a preference for local food crop production, that the user can give a weight to.
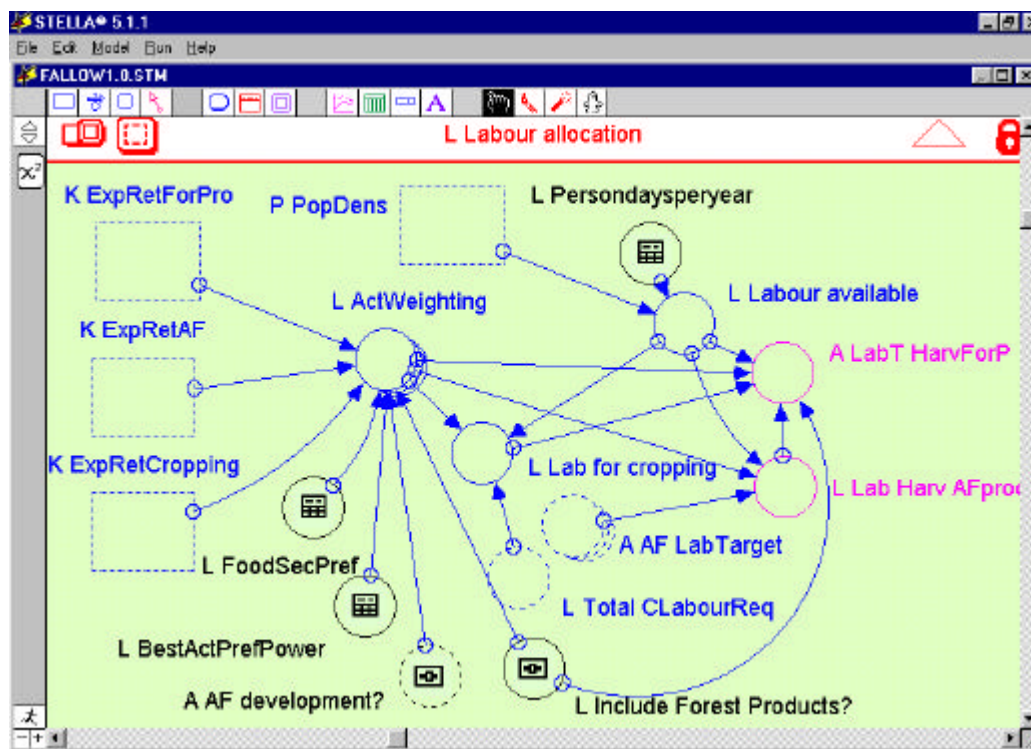
Optional sector: Human population density and migration

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.
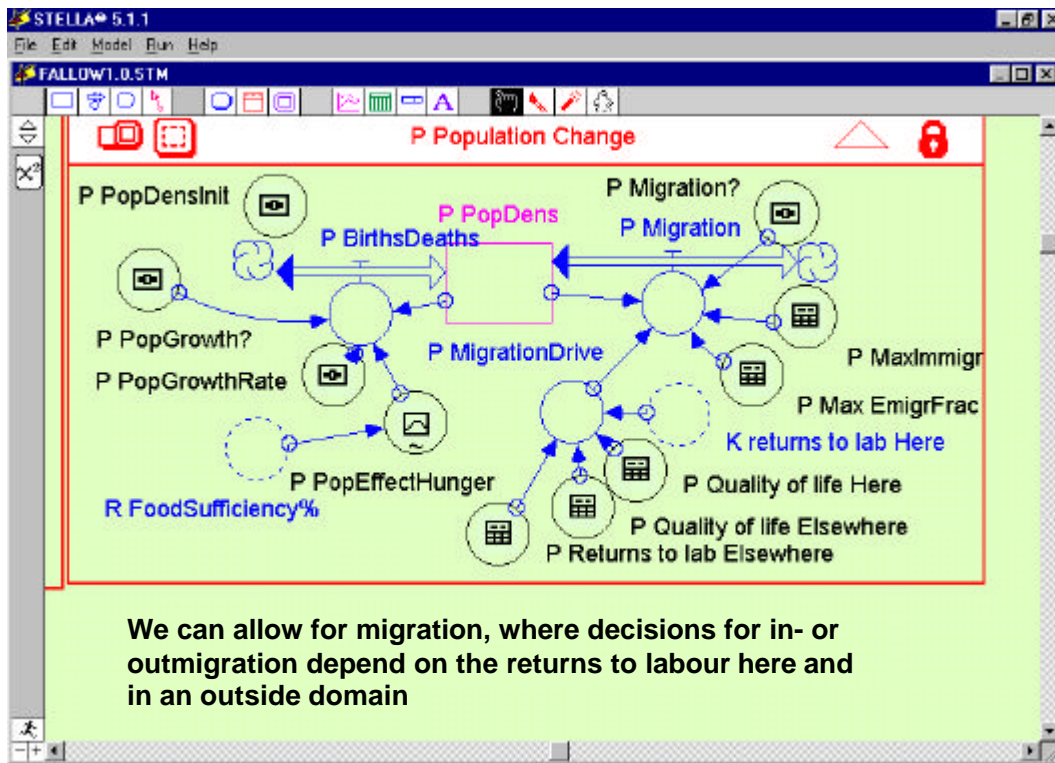
Optional sector: Spatial output and spatial inputs

In the default setting of the model the landscape has 100 plots, but without a spatial structure. The Excel spreadsheet FALLOW.xls can provide this miniature 'geographic information system' (GIS) functionality, by viewing the outputs as maps, and providing input parameters as maps (set the slider 'Use_maps?' to 'on' (= 1)).

To get the output 'developed' as a map:

- make a run
- open the table 'Mapoutput'
- copy all of its contents into the buffer by CTRL_A, CTRL_C
- go to the Excel file and the Output data sheet therein, paste the contents of the buffer (CTRL_V) into the relevant fields
- Go to the 'select data' sheet and select the years for which you want to see the map.
- Go to the 'Maps' sheet and tun the CTRL+Sh+I macro that develops the map (on computers with a limited amount of RAM (<128 kB) it is better to close the Stella file while running this macro, as otherwise progress is very slow

An example of an output map is:
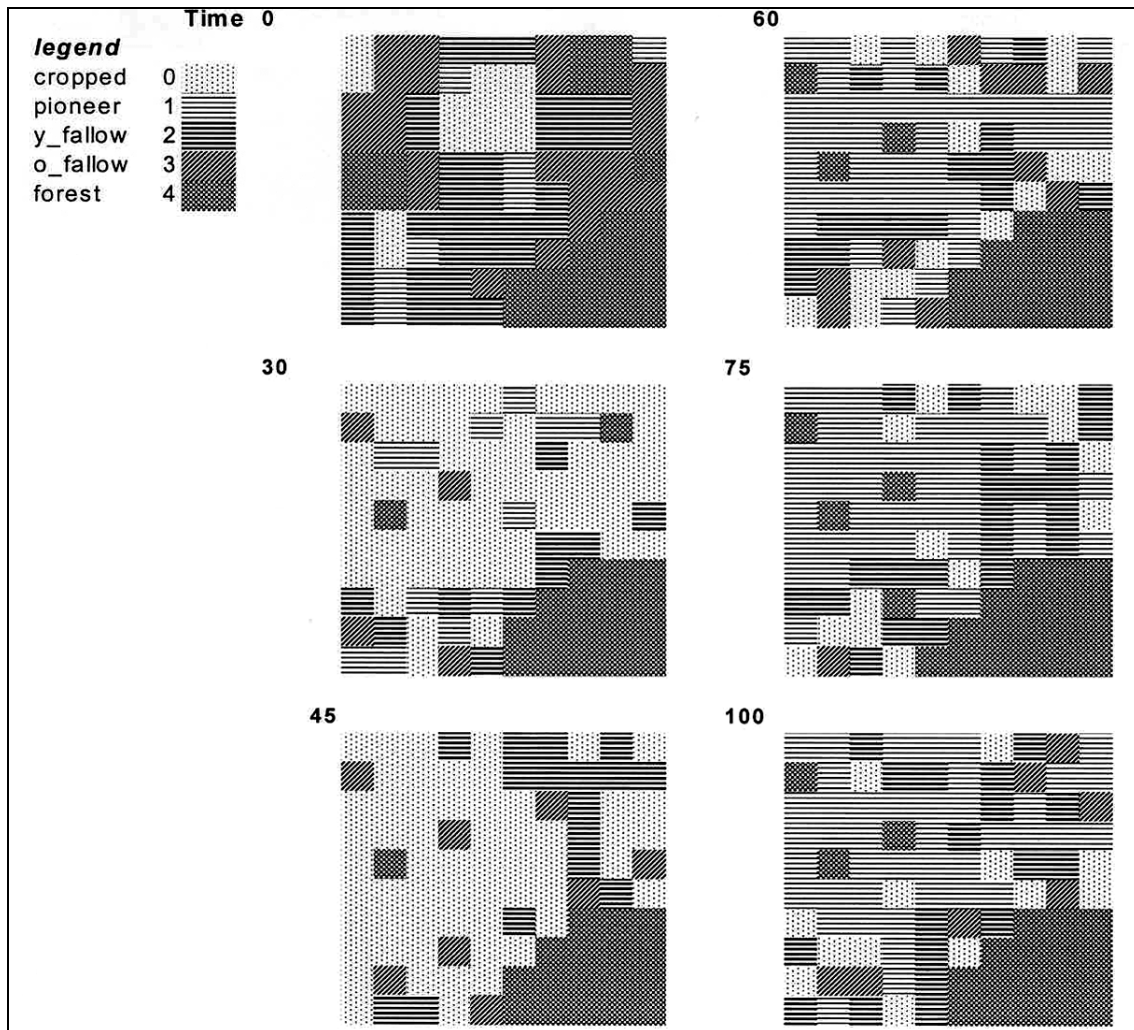
You can now explore the consequences of landscape structure in the model, by modifying the input maps (e.g. the location of the villages or forest reserve) and view the outputs.

4. An example of parameter 'sensitivity' analysis: exploring watershed functions

You can now start to systematically explore the response of the model to changes in one or a couple of parameters, 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…. You can use this type of model analysis 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 3. Watershed functions predicted by the FALLOW model with different initial population densities, averaged over a 100 year period, using default parameter values.
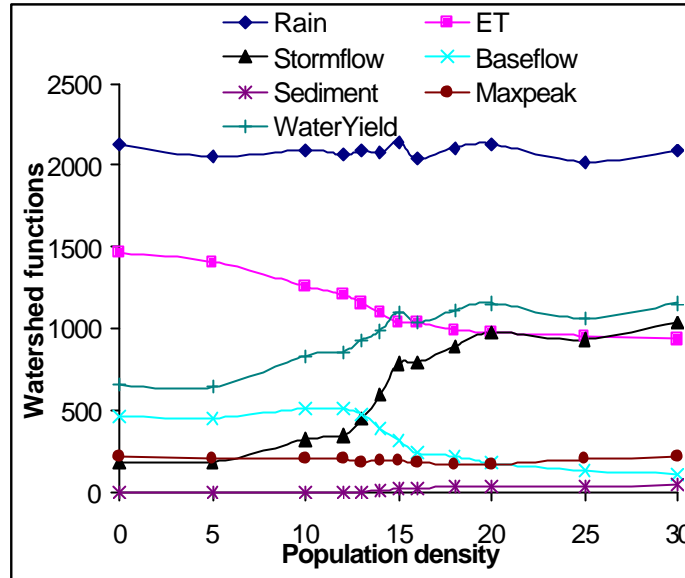
An example of the model output (Figure 3) across a range of population densities shows that predicted total water yield of a subwatershed will increase if more people live there, but that this increase is based on:

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 4 shows an initial parameter sensitivity study in which the SoilQChange(crop) parameter was modified from –5 to –30%.

Figure 4. 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%
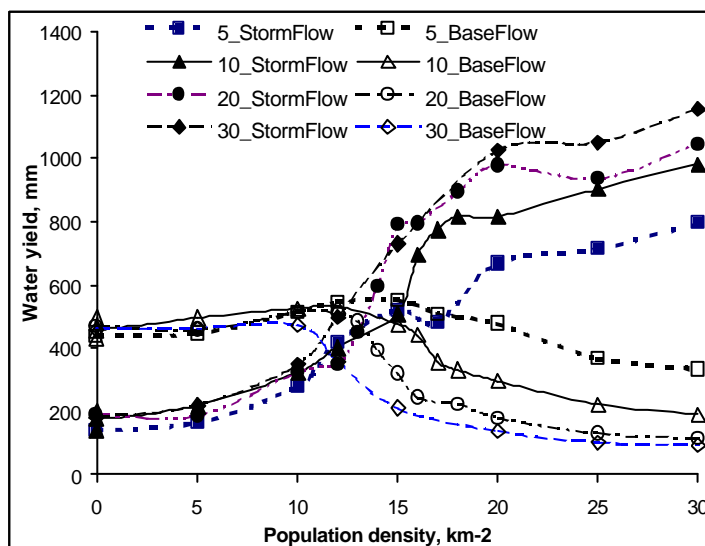
The shift from baseflow to stormflow in the model output is accompanied by an increase in predicted net sediment loss (Figure. 5). The relation between net sediment

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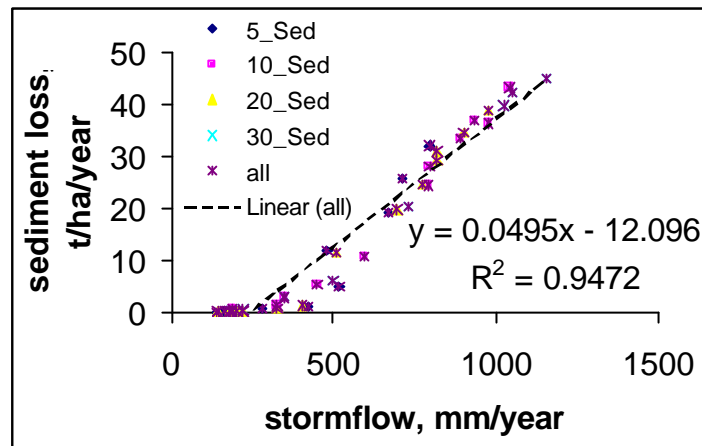
5. Further options

The model was developed in STELLA, and that means that it is easy to modify (see Appendix 1). You can add parameters and structures to the model, modify equations that you don't like, and so on – the sky is the limit. But, please go through it slowly, step-by-step, otherwise the complexity will rapidly grow beyond what you can cope with….

III. Reading Materials

Trenbath BR. 1984. Decline of soil fertility and the collapse of shifting cultivation systems under intensification. AC Chadwick and SL Sutton (eds.) Tropical Rain-Forest: the Leeds Symposium, Leeds Philosophical and Literary Society, Leeds. pp 279-292.

Trenbath BR. 1989. The use of mathematical models in the development of shifting cultivation. In: J. Proctor (Ed.) Mineral Nutrients in Tropical Forest and Savanna Ecosystems, Blackwell, Oxford. pp 353-369.

Van Noordwijk M. 1999. Productivity of intensified crop fallow rotations in the Trenbath model. Agroforestry Systems 47: 223-237.

Van Noordwijk M. 2001. Scaling trade-offs between crop productivity, carbon stocks and biodiversity in shifting cultivation landscape mosaics: the FALLOW model. Ecological Modelling (*in press*).

Appendix 1

Model construction in STELLA

STELLA is a flowchart-based modelling software package. It enables users to construct models by drawing boxes, circles and arrows.

During this session you will learn how to build a model, step by step using **STELLA**. The purpose of this session is to familiarise yourself with **STELLA** and to learn how to use basic features of **STELLA** for simulation modelling.

Initiating **STELLA**

- Start **STELLA** by clicking on its icon on the window screen. You will be automatically go into a new file.

STELLA is a multi-level hierarchical environment. It consists of 3 layers:

(1st)   the High Level Mapping Layer; which contain input output relationship
(2nd)   the Model Construction Layer; where you construct the model
(3rd)   an Equation View; to view lists of all model elements and relations

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Move between layers

- Currently you are in the second layer. You can move between layers by clicking on the arrow at the top left hand corner.
- You will find all the layers are still empty because you have not constructed anything yet

---

Let's try building a simple model based on Trenbath (1984).

Trenbath formulated a simple model of restoration and depletion of 'soil fertility' during fallow and cropping periods, respectively. 'Soil fertility' is defined as a complex of effective nutrient supply and biological factors (diseases, weeds) affecting crop yield. Crop yield is assumed to be directly proportional to 'soil fertility'.

Assume that during a cropping period soil fertility declines with a fraction 'D' per crop, while during a fallow period soil fertility can be recreated with a fraction of 'R'.

Constructing a model

- Make sure you are in the second layer. You will notice a globe (world) icon underneath the arrow at the top left hand corner. On the top you will see 14 icons, starting with 'box' icon at the furthest left and 'ghost' at the furthest right.
- Make a variable for soil fertility. To do this, click on the box icon then click again anywhere on the empty space. Change the name from 'Noname1' into 'Soil Fertility' or any variable name you like. There are no restrictions on length. What you have just made is called a **building block.**
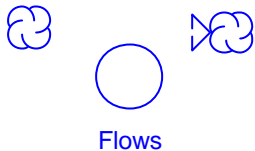
STELLA has 4 types of building block:

1. Stocks
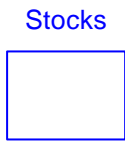
Stocks

Stocks are accumulations. They collect whatever flows into and out of them

2. Flows

Flows

The job of flows is to fill and drain accumulations. The unfilled arrow head on the flow pipe indicates the direction of the flow.
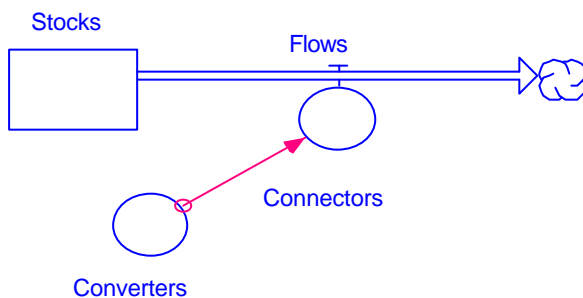
3. Converters

Converters

The converter serves a practical and handy role. It holds values for constants, defines external inputs to the model, calculates algebraic relationships and serves as the repository for graphical functions. In general it converts inputs into outputs.

4. Connectors

Stocks

Flows

Connectors

Converters

The job of the connector is to connect model elements

Above is an example of how building blocks are used.

Constructing a model (continued)

- Since 'Soil Fertility' will decrease during the cropping year, you will have to make an outflow from 'Soil Fertility'. Name the flow 'Depletion'
- 'Depletion' depends on the depleting factor (D), length of the cropping period (in years) and the length of fallow period (number of years). If it is a fallow year, depletion will not occur. Make 3 converters and name them D, TimeCrop and TimeFallow. Connect all 3 converters to 'Depletion'
- Now you will need to define the relationship between those parameters into an equation in 'Depletion'. See what happen if you click twice on 'Depletion'
- Click Cancel and see what happen if you click on the globe icon then click twice on 'Depletion'.

- • You are now in the equation box. Type out the following equation:

IF(MOD(TIME, (TimeCrop+TimeFallow)) <TimeCrop)THEN(Soil_Fertility*D) ELSE(0)[1]

Make sure there is a connection from 'Soil Fertility' to 'Depletion'

- • You will see that all building blocks except 'Depletion' have a question mark in them. They are asking for a value. Put in the following values just as an example.

D=0.4, Soil fertility=10, TimeFallow=3, TimeCrop=3

- • Now, repeat the same step for the re-creation factor, which is an inflow to 'Soil Fertility'. What do you think the equation in 'Recreation' should be? First try a constant value e.g. type in

IF(MOD(TIME, (TimeCrop+TimeFallow)) >TimeCrop)THEN(0.2) ELSE(0)

- • The Trenbath model used a 'saturation' function in which the recreation depends on the difference between current fertility and a maximum value (Finf), modified by a 'half-recovery time' Kfert, so we make converters for Finf (value e.g. 10) and Kfert (value e.g. 5):

IF(MOD(TIME, (TimeCrop+TimeFallow)) >TimeCrop)THEN((Finf-Soil_Fertility)*Soil_Fertility/(Finf-Soil_Fertility+Kfert*Finf)) ELSE(0)

- • Now go to the third layer. You will now see the values and equations within your model.

Two types of output can be generated from **STELLA:** graphs and tables.

Making an Output
- • To make a graph click on graph icon (7th icon from left) and click again anywhere. A box named 'untitled graph' will emerge.
- • Click twice on the graph then select 'Soil Fertility' from the Allowable Box. Click the arrow pointing to the right. Then click OK.
- • You may do the same thing with the table icon (8th icon from left)

Running the Program
- • To run the program choose **Run** from the Run Menu. You can also run the program by pressing **Ctrl-R** or clicking the running-man icon in the bottom left hand corner, then clicking an arrow pointing to the right.
- • To see the simulation result, click twice on the graph or table.
- • You will notice that the simulation runs until time 12 with Delta Time (DT)=0.25. You can change this by choosing **Time Spec** on Run Menu. Try putting DT=1 and simulation length to 50.
- • Run the model again and see what happen.
- • Try changing R and D value. At what value would they result in a stable condition?

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[1] MOD(TIME,(TimeCrop+TimeFallow)) will give current time minus the already completed cycles. The early part of a new cycle is cropped, the latter part is fallow.

Exercises

The model you have built is very simple. Now try adding other variables to add some more complexity to it. Below are several exercises you may like to try out.

1. Add crop production to the model. Assume crop production is linearly proportional to the decrease in 'soil fertility'/depletion. Find the total crop production during the simulation.
2. Assume that the sum of cropping time and fallow time is constant over time (a constant-length cycle). Fallow time is a function of total cumulative production. If the cumulative production meets a certain target then continue with the same length of fallow time. If cumulative production is below the target you need to shorten the length of fallow time to make up for this.
3. Assume that the target production is a function of population density and the food needed per capita

'Scaling up' from a one-plot model to a landscape model

STELLA has the option to define array dimensions and thus have 'multiple copies' of the elements of the model. For this model we may now want to apply the equations we developed simultaneously to say 100 fields. We first have to define an array dimension with the name 'field' and 100 elements (named 1...100). We then go back to the box 'Soil fertility' and click on the 'Array' function, selecting 'Field' as the array dimension we want to use. On returning to the diagram we see some question marks appearing, as the equations in which 'Soil fertility' plays a role have to be re-assessed. Do we want the equations to apply to all array elements in the same way? The answer can be yes in our case.

If we would leave the model like this, we have simply made the number of fields to which the model applies 100 times larger, but we have not 'scaled up'. Real scaling up includes consideration of the interactions between the elements at a larger scale, interactions that were not noticeable at the scale previously studied. In our case, interactions may first of all come through the farmers' management decisions on which plots to open in which year. So, we need to get some variation in the way the crop/fallow clock ticks for each field. A simple way to do this is to start all fields at a different point in the cycle.

You have now seen the basis of version zero of FALLOW. In version 2 (which you used at the beginning of the tutorial), a lot of other sectors have been added, along with more parameters, and more options for the user to select the complexity of the simulation they want to make. The basic building blocks of the model, however, are easy to understand
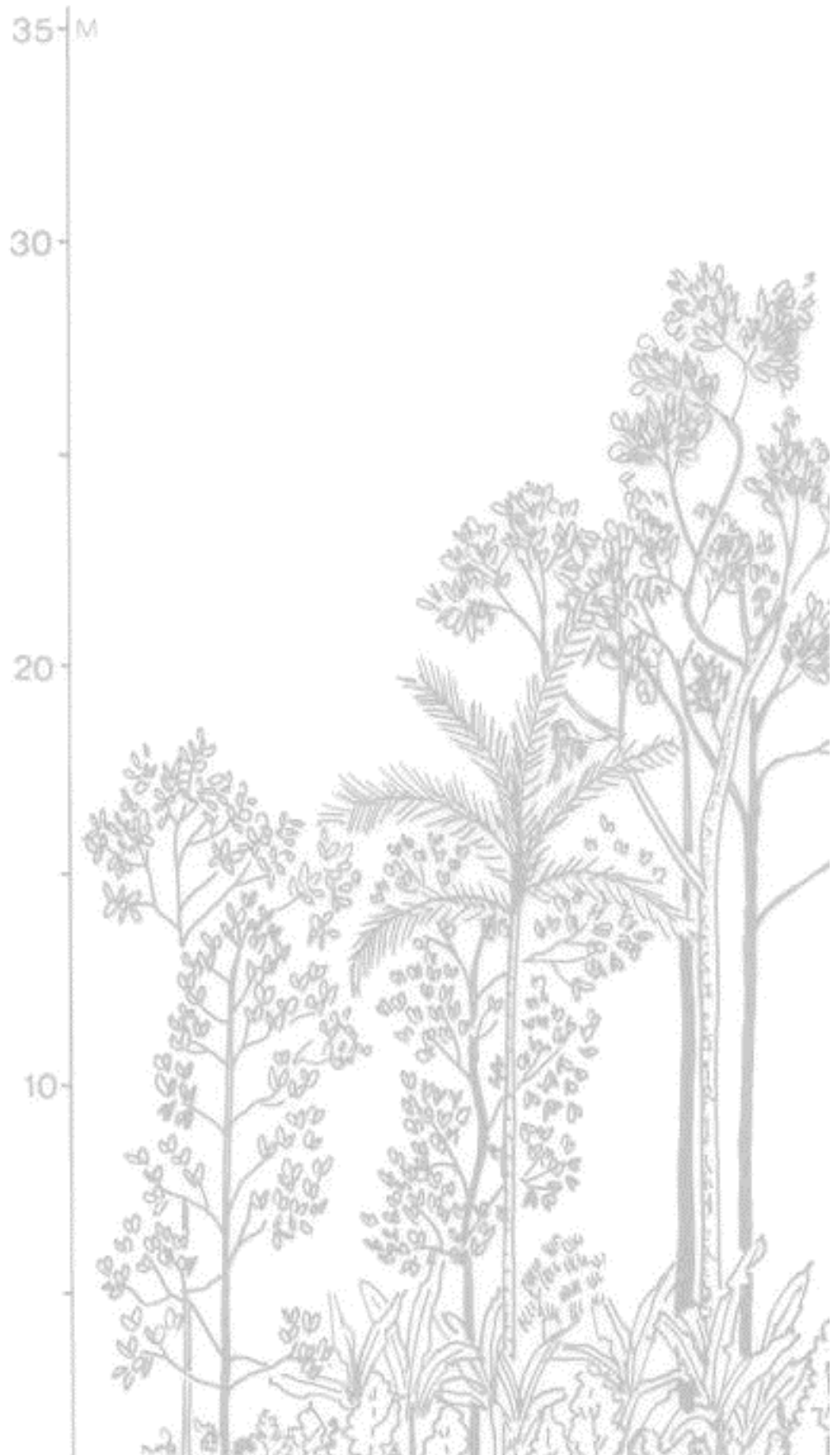
and it should be no problem to add a little structure. For example, in the FALLOW model a random variable is affecting crop yields. This factor, however, is not related to the rainfall (also a random variable used in the water balance). Could you think of a way to make crop yields partially dependent on rainfall?

Contents of this series of lecture notes

35 M

30

20

10

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