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Scaling trade-offs between crop productivity, carbon stocks and biodiversity in shifting cultivation landscape mosaics: the FALLOW model

Meine van Noordwijk *

International Centre for Research in Agroforestry, ICRAF SE Asia, PO Box 161, Bogor 16001, Indonesia

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Abstract

Scaling rules other than those based on area ('scale-dependence') for 'environmental service functions' such as productivity, biodiversity and carbon stocks depend on spatial variability and spatial patterns within the landscape, on lateral flows and neighbourhood effects, and on the impact of scale-dependent 'actors' and 'agents'. Previous models of shifting cultivation or crop-fallow rotations have described the fate of soil fertility and crop productivity for an average plot, as a function of intensity of land use, without explicit consideration of the scaling rules between plot and landscape. Up to medium land use intensities, a negative tradeoff exists between farmers's interest in crop productivity per unit area, and environmental interests in carbon stock and other parameters related to age of the fallow vegetation such as biodiversity. If land use intensity increases beyond a critical point, land will further degrade from a farmer's as well as from environmental perspective. In the Forest, Agroforest, Low-value Lands Or Waste model ('FALLOW?') this description is applied at landscape scale to a mosaic of plots, to investigate the transient behavior under non-equilibrium conditions for different land use intensification scenario's. The FALLOW model is implemented in the STELLA environment and in the default form keeps track of the soil fertility changes in 100 fields, which may differ in initial fertility and dynamics. During any year in the simulation a number of these fields is cropped, while others are fallowed. During the fallow period aboveground C stocks accumulate and plot-level biodiversity changes in character during the succession from pioneer, via early and late secondary vegetation into 'primary' forest. The model user can define the time frames for each of these transitions, as well as determine the degree of species overlap between categories and area-based scaling rules within each category, to derive an indicator of landscape-level biodiversity. The model allows comparisons of spatially segregated as well as integrated solutions to multiple functionality of land use by applying 'forest reserve' rules. Depending on the amount of between-plot variation in parameter values, the trade-off between carbon stock and crop productivity can shift by a factor 2, even though both properties are directly related to area. The trade-off between local and external stakeholder interests for a landscape mosaic can thus differ from that derived for a 'representative landscape element'. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Agricultural intensification; Biodiversity; Carbon stock; Land use change; Scaling; Shifting cultivation

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* Tel.: +62-251-315-234; fax: +62-251-315-567.
E-mail address: m.van-noordwijk@cgiar.org (M. van Noordwijk).

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1. Introduction

Concerns over the rate of tropical deforestation have led to a renewed interest in shifting cultivation systems and early stages of agricultural intensification, and their impact on 'environmental service functions' such as productivity, biodiversity and carbon stocks in the forest margin (Perrings et al., 1995; Van Noordwijk et al., 1998; Tomich et al., 1998a,b, 2001). Efforts to 'scale up' from plot-level measurements and assessments to landscape-level impacts have to deal explicitly with the scaling relations that are likely to differ between the various land functions, leading to scale-dependence of the trade-offs between these functions as well. Scaling relations depend on spatial variability and spatial patterns within the landscape, on lateral flows and neighborhood effects, and on the impact of scale-dependent 'actors' and 'agents' (Van Noordwijk et al., in press).

Use of natural resources can only be sustained if it balances the rate of replenishment, and thus sustainable-use strategies require a detailed understanding of the replenishment processes. Yet, most resource use problems share a common dynamics, with a 'diminishing returns' or 'asymptotic' approach to a maximum resource availability when the resource is left alone (not harvested), and a proportional decrease due to harvesting, leading to decreasing returns to harvesting effort. This may apply to resources as different as fisheries, forestry, rubber tapping and soil fertility replenishment by natural vegetation in crop-fallow rotations. Here we focus on a crop-fallow model, but most of its dynamics would, *mutatis mutandis*, apply to other resources as well.

Whereas 'shifting cultivation' systems in which a long tree fallow phase alternates with a few years of cropping can sustain crop production at acceptable levels and favorable returns to labor, it has been observed in many parts of the world (Hagreis, 1930; Nye and Greenland, 1960; Ruthenberg, 1976) that with increased pressure on land and shorter fallow cycles, crop production will fall short of requirements and the 'system breaks down'.

Trenbath (1984, 1989) formulated a simple model of crop-fallow rotations, which can be solved by algebra when a single 'representative' field is followed over time (Van Noordwijk, 1999). Intensification of a crop fallow rotation can be reflected in a reduced duration of the fallow and its consequences for long term production can be evaluated. Intensification (increased use of land for crop production) can initially increase crop yield per unit area under the rotation, while reducing yield per unit cropped area, and the impacts on returns to labor depend on the ratio of labor costs for clearing a fallow and those for tending a crop. The highest returns to land are, according to the Trenbath model, obtained in systems where soil fertility under the fallow is allowed to return to around 55% of the maximum value, independent of other model parameters (Van Noordwijk, 1999). Beyond this point, further intensification will lead to a rapid degradation unless a technology shift modifies essential parameters of the model. This description on the basis of a single 'representative' field, however, is not sufficient for judging the transition period of fallow intensification, when part of the landscape still has a relatively high fertility as remnant of past fallow lengths.

Intensification of such crop-fallow systems will initially increase yields while decreasing terrestrial carbon stocks in soil and aboveground vegetation, but beyond the critical intensity both C stock and yield will decrease. The trade-off between local (productivity) and global (C stock) interests in such a system, is thus likely to be non-linear. This trade-off is relevant to the current debate on the relation between poverty alleviation and environmental protection, as articulated in the global 'Alternatives to Slash and Burn' program (Tomich et al., 1998a). Similarly, intensifying fallow rotations can have a non-linear impact on landscape level biodiversity. At low intensities, crop-fallow rotations may increase the diversity of vegetation types in the form of fallows of various ages, while allowing a substantial share of mature forest to persist. Although the average species richness per unit area at field scale is likely to decrease, landscape level diversity may initially increase; while further intensification is likely to reduce all aspects of biodiversity.

To explore these transition phases and their scale-dependence and test the robustness of the 'critical fertility' limit, a distributed model was made that: (1) applies the Trenbath model rules for depletion and restoration of soil fertility to a large number of fields, contributing to a single food (rice) store (2). Decisions on increase or decrease of crop intensity (fraction of the land cropped in a single year) are simulated on the basis of the amount of food in the store and expected to be gained per field, relative to the annual food requirement (3). Decisions on which fields are to be used in a given year can be based on a number of rules, including a partial knowledge of the actual fertility of each field (4). Four modules representing these aspects jointly drive the dynamics of a landscape mosaic, that can be evaluated in terms of carbon stock, biodiversity and food security (Fig. 1).

Here, we present results of using the spatially distributed model to explore:

- impacts of spatial heterogeneity in soil properties on the dynamics of the overall system,
- impacts of various decision rules for intensification on system dynamics,
- effects of simulating farmer knowledge in selecting the best fields for current cropping,
- effects of intensification on terrestrial C stocks and biodiversity at field and landscape scale,
- effects of scale on the trade-off between local (productivity) and global (biodiversity and C-stock) benefits.

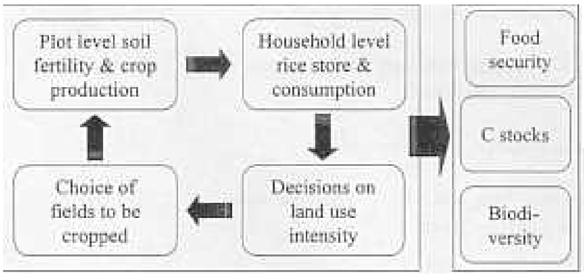

Fig. 1. Overview of the model modules in the FALLOW model.

2. Model

2.1. Model overview

The FALLOW model (available via http://www.icraf.cgiar.org/sea/AgroModels/FALLOW/fallow.htm) is a Stella implementation of a set of equations proposed by Trenbath (1984) of a shifting cultivation or crop-fallow rotation system where rice is produced on the basis of soil fertility restoration during fallows, and consumed on the basis of population density and per-capita food demand. The simulated area can be interpreted as 1 km^2, split into 100 fields of 1 ha each but individual field sizes can vary and a different total area can be simulated as well. Human population density is expressed in persons per km^2, crop yields and rice storage in mg.

The model has four core modules that represent the fate of plot-level soil fertility, the rice store, decisions on next years cropping intensity and the spatial implementation of this cropping plan (Fig. 1). In a yearly time step the program loops through these four modules. Three other modules derive the consequences of the farmers land use decisions for food security, C stocks and biodiversity. Table 1 provides the definitions, dimensions and default parameter values for the model.

2.2. Soil fertility module

The soil fertility module is based on the Trenbath (1984) model (Van Noordwijk, 1999) and describes build-up of soil fertility by two parameters, a maximum level S_*F*inf and a half-recovery time S_*K*fert, and decline during cropping as a simple proportion S_FertDepletion. There are two ways of initializing the model: specifying values for each field in a spreadsheet linked to the Stella model, or by specifying a range of values within which random choices are made. If external inputs are used as fertilizer (S_FertilUse? = 1), their effect on soil fertility is represented by the S_Kfertfertil parameter.

Table 1
Main FALLOW input parameters, their definition and default values

Acronym	Definition	Dimensions	Range of value (default value)
B_module: Biodiversity			
B_SpecOverlap (Vegetation,Vegetation)	Probability (fraction) of species overlap in species composition between two vegetation types	Dimensionless	0–1, arrays
B_SpecRich_K	Parameter influencing how species richness increase with time, indication of 'half-enrich-time'. Biodiversity parameter at plot level	Year	5–100 (30)
B_SpecRichMax	Maximum of species richness (number of species) per field reached. Biodiversity parameter at plot level	#Species/plot	50–500 (200)
B_SpecRichPowe (Vegetation)	Biodiversity parameter at landscape level: power of relation between number of fields and total richness for each vegetation class	Dimensionless	0.1–0.4 (0.2)
B_VegClassBound (Vegetation)	Minimum age of vegetation class. For young secondary forest, old secondary forest, old growth primary forest, early, full and late-productive AF stage. Values for the first three vegetation class has to be in ascending order.	Year	(5, 20, 50, 10, 20, 45)
C_module: carbon stocks			
C_AccumRateF	Yearly increment in C stock during fallow periods	mg ha^{-1} year^{-}	2–15 (8)
C_CropY_Cstock	Time-averaged aboveground C stock for cropping years	mg ha^{-1}	1–10 (5)
C_CstockAGMax	Maximum aboveground C stock for a forest (end-point of fallow development)	mg ha^{-1}	100–400 (250)
C_StockBGmax	Belowground C stock at maximum soil fertility	mg ha^{-1}	20–100 (50)
H_module: household decisions			
H_DistWgtCropping	Relative weight of the distance to the village relative to current soil fertility in determining attractiveness of a field for a new cropping cycle	Dimensionless	0–10 (0)
H_FieldRule	Parameter influencing decision on which fiel to crop. 1, Decisions on which fields to crop are not based on current fertility; 2, Farmers classify fields by soil fertility (and distance to village) and choose the best fields to crop	Dimensionless	or 2 (2)
H_ForestResFrac	Fraction of reserved forest area	Dimensionless	0–1 (0)
H_RegulMeth	Parameter to adjust cropping intensity: 0, constant cropping intensity; 1, based on the rice store only; 2, includes consumption and yield estimates, based on recent experience.	Dimensionless	0, 1 or 2 (2)
H_RiceStockTarget	Target number of years annual rice consumption can be met from the rice store	Year	
H_StepIntensif	Parameter influencing maximum changes in cropping intensity due to deviation of yield from target. Maximum changes is H_MaxStep × H_IntensificationStep	Dimensionless	0.01–0.3 (0.05)
H_StepMax	Parameter influencing maximum changes in cropping intensity due to deviation of yield from target. Maximum changes is H_MaxStep × H_IntensificationStep	Dimensionless	–5 (2.5)
H_TimeCrop	Number of consecutive years that a field is cropped, once the fallow vegetation has been removed	Year	
H_YieldMemory	Parameter governing farmer's memory of past crop yield: 0, last years results replace all memory; 1, no learning from recent experience	Dimensionless	0–1 (0.75)
R_module: rice store			
R_ConvEff	Conversion efficiency of mineralized nutrients (linked to the decrease in soil fertility in a cropping year) into crop yield	mg	0.5–2 (1)

Table *(Continued)*

Acronym	Definition	Dimensions	Range of value (default value)
R_CropWorstW	Parameter defining weather/climate in relation to crop growth. 0, weather are bad for crop; 0.99, weather are appropriate for growing crop	Dimensionless	0–0.99 (0.5)
R_LossStoreFrac	Fraction of rice lost from the store per year	Dimensionless	0.1–1 (0.15)
R_PopDens	Human population	Persons	0–100 (10)
R_ProCapFoodReq	Annual food requirement pro capita	mg per person per year	0.1–1 (0.5)
S_module: soil fertility per field			
S_FertDepletion	Fraction by which soil fertility capital stock decreases by mineralization during 1 year of cropping	Dimensionless	0.1–1 (0.2)
S_FertilizUse?	Parameter determining use of fertilizer. 0, system not using fertilizer; 1, using fertilizer	Dimensionless	0 or 1 (0)
S_*F*inf_Avg	Soil fertility value to which the soil returns after an infinitely long fallow period	fertility units	–20 (10)
S_*F*inf_range	The range of S_*F*inf_Avg variation between fields	Dimensionless	0–2 (0.3)
S_InitRFH	Parameter defining a maximum multiplier for initial soil fertility units.		0.2–1 (0.95)
S_InitRFL	Parameter defining a minimum multiplier for initial soil fertility units. Initial soil fertility is varied, relative to F_infinity, within a range of (S_InitRFH-S_InitRFL)	Dimensionless	0.01–1 (0.7)
S_*K*fert_Avg	Half recovery time for soil fertility during fallow period. Suggested values: Natural fallow, 10–20; Improved fallow, 5–10; Cover crop, 2–5; Fertilizer, 0.5–2	Year	0–20 (15)
S_*K*fert_Range	The range of S_*K*fert variation between fields	Dimensionless	0–2 (0.3)
S_*K*fertfertil	Parameter influencing impact of fertilizer use on soil fertility	Dimensionless	0.1–10 (2)

2.3. Rice_store and consumption module

Mineralization of stored soil reserves forms the basis of soil fertility during a cropping year and the R_ConvEff parameter indicates the efficiency with which the actual loss of soil fertility is translated into a crop yield. This efficiency depends on the type of staple crop that is used (named ‘rice’ in the default example), and on the (arbitrary) units in which soil fertility is measured (here on a 0–10 scale). The impact of climatic variability on crop yields can be superimposed on the soil fertility based potential yield, by multiplication with a random variable [R_CropWorstW-1].

In the Rice_Store module, we keep track of the contents of the rice store, adding all yields and using it to feed people (R_PopDens × R_ProCapFoodReq), unless it is lost from the store (at a annual fraction of R_StoreLossFrac, by unspecified rats, mice or insects). The degree to which annual food demand could be met during a simulation run is accumulated and averaged in the food security module.

2.4. Household decision module

The cropping intensity (fraction of the land cropped in any given year) is a major control variable in the way the landscape evolved during the simulation. The model provides different routines for simulating household decisions on intensification of the crop-fallow rotation in response to the amount of food reserves in the store. If H_RegulMeth = 1 intensification decisions are based on the rice store only, in relation to a target value (H_RiceStocktarget); if H_RegulMeth = 2 the decision algorithm includes consumption and yield estimates, based on recent experience (the H_YieldMemory parameter gives weight to previous years and specifies the ‘learning style’: 0 =

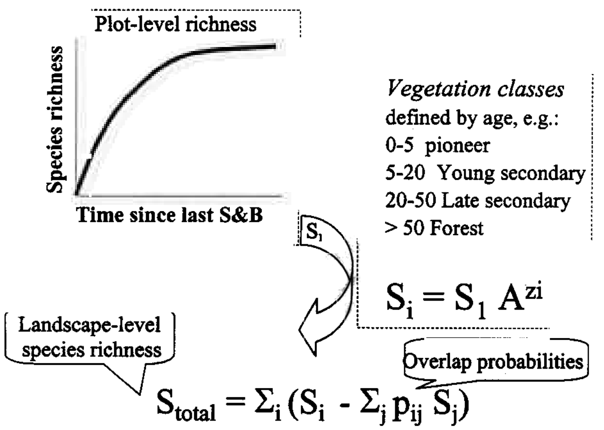

Fig. 2. Relations used for deriving total species richness of the landscape, S_{total}, on the basis of the species richness of each plot (related to its age since the last S&B event), and the allometric scaling rules for species richness within each land cover class (based on its area A and the scaling parameter z_l) and the overlap matrix p_{ij} between land cover types.

most recent experience replaces all past experience, 1 = initial values not modified, intermediate values provide a mix of past and recent experience). For either of these regulation methods, there is a maximum value (H_StepMax) to the change in cropping intensity deemed possible in a single (yearly) timestep.

Two methods are provided to implement decisions on cropping intensity. For H_Field_rule = 1 decisions on which fields to crop in the coming year are based on the average length of fallow for the given cropping intensity, and a length of each cropping cycle set by H_TimeCrop. The actual implementation to set the 0 or 1 value for H_Cropped? is 'if mod(time + H_NumbFields-H_FieldNumb[Field], (H_TimeCrop + H_Timefallow)) < H_TimeCrop then 1 else 0'.

For H_Fieldrule = 2 farmers are assumed to classify fields by soil fertility (in 'standardized normal' classes, based on the current average and S.D.) and distance to the village (H_DistWgtCropping), and choose the best fields currently available to crop. Via the H_ForestResFrac parameter a certain fraction of the landscape can be set aside as forest reserve, not available for growing food crops.

2.5. Carbon stock module

The sectors described so far generate the dynamics of the landscape mosaic and determine which fields will be cropped in which years, and over what length of time fallow vegetation will be allowed to grow in the non-cropped fields. The consequences of this dynamic for C stocks and Biodiversity are based on the length of the fallow period for each plot. The parameter C_AccumRateF determines the annual C stock increment (mg ha^{-1} $year^{-1}$) in fallow vegetation (Woomer et al., 2000), up to an endpoint of C_CStockAGMax. The C_CropY_Cstock parameter specifies the (time-averaged) aboveground C stock for cropping years. Belowground C stocks are assumed to be proportional to the soil fertility indicator and the C_stock BGmax parameter indicates the belowground C stock (in mg ha^{-1}) at maximum soil fertility.

2.6. Biodiversity module

The biodiversity module (Fig. 2) includes explicit scaling rules from plot/field to landscape level. First of all, the species richness of each fallow or forest plot is assumed to be a function of the time since the last field clearing ('slash and burn') event. This relation is characterized by two parameters: a maximum value B_SpecRichMax (number of species per unit field size) and a B_SpecRichK (year) parameter indicating the time after major disturbance [slash-and-burn (S&B) land clearing] required to reach half of the maximum richness. Data on (higher) plant richness for a range of tropical land cover types were indeed found to relate to time since disturbance in a similar way (Gillison, 1999). On the basis of the time since last clearing, we can thus derive the plot-level richness S of each plot.

The next step in the scaling process is to classify the vegetation into age-classes, such as pioneer, young secondary, late secondary or forest vegetation.; the parameter B_VegClassBound allows the model user to adapt the ages used for each transition. For each class an allometric relation between class-level richness and the number of fields is derived, driven by the parameters z in Fig. 2 (or

B_SpecRichPower in the model). This allometric scaling rule was introduced by Arrhenius (1921) and is the current default model based on island biogeography theory (Rosenzweig, 1995).

Finally, a total landscape level richness is derived by summation over the various vegetation classes, but correcting for the degree of overlap (the p_{ij} parameter in Fig. 2 or the B_SpecOverlap matrix in the model).

2.7. Default parameter values

Table 1 specifies the various default parameter values that were chosen to be representative of a situation in the humid tropics where shifting cultivation, o crop-fallow rotations, are still viable, at a relatively low population density of 10 persons per km^2. While the parameters do not refer to any particular site, their values were chosen on the basis of measurements in ASB benchmark sites (Gillison, 1999; Van Noordwijk et al., 1998; Woomer et al., 2000). Population density in the ASB benchmark areas varies from 3 (Acre, Brasil) to 60 (N. Lampung, Indonesia) persons per km^2.

2.8. Graphical output and spatial representation

The STELLA environment provides for options on graphical output of timeseries or bi-plots of all variables used in the model. A simple routine was developed in the form of an EXCEL workbook to link maps of input parameters to the model and to convert plot-level state variables into maps of soil fertility, C stock, vegetation type (Fig. 3) or plant species richness. This workbook is available at the same WWW site as the FALLOW model.

3. Results

3.1. Output for default parameter setting

With the default parameters land use intensifies in the initial years (Figs. 3 and 4), but approaches a steady state in which the relative areas of various successional land cover types remains constant, although individual plots in the mosaic keep changing. In this default run there is enough to eat in each year of the simulation (Fig. 4A), while soil fertility declines (Fig. 4B). Primary forest gets replaced by pioneer and young secondary forest-a fraction of the land is kept as ‘forest reserve’ (Fig. 4C). Initially, landscape level richness in—creases while plot—level richness declines (Fig. 4D). Landscape level richness is initially maintained (or shows a slight increase) while plot level richness decreases (Fig. 4E). Carbon stocks decrease while landscape level diversity initially increases (Fig. 4F).

3.2. Critical population density as function of fallow type and soil properties

When the population density is increased from the default value of 10 persons per km^2 to a value of 17, the default parametrization leads to a crash scenario (Fig. 5) after a certain transition time in which the soil resources are depleted. The decline of soil fertility is a non-linear function of human population density, as it involves a threshold process (Fig. 6B).

. Within the structure and limitations of the FALLOW model, we can define a critical human population density (‘carrying capacity’ for given technology and soil characteristics) as the highest population density for which food sufficiency can be sustained over a 100-year test period. As the model contains random weather impacts, a number of runs at each population density is required. The carrying capacity so defined depends on both the S_*K*fert (type of fallow) and inherent soil qualities (S_*F*inf) values (Table 2).

3.3. Model sensitivity to soil and crop parameters

Especially if a population density is chosen that (just) leads to a crash scenario, the influence of soil and crop parameters can be studied (Fig. 6C and D). If low-quality fallow vegetation (with a long half-recovery time for soil fertility, S_*K*fert) is replaced by an ‘improved’ fallow vegetation that leads to more rapid restoration of soil fertility, a crash scenario can be returned to a ‘stable’ domain (for constant population density). Under the current model structure an increase in the yield potential of the crop, reflected in a change in the R_Conveff parameter (Fig. 6D) has a direct impact on the 'intensification' decisions, as the model (implicitly) assumes a subsistence economy, growing rice only to supply for local demand. According to the model, higher yielding crops will reduce the need for reducing fallow lengths and thus contribute to the maintenance of higher soil fertility levels.

3.4. Landscape homogeneity

If the routines are used that explicitly select the fields with the highest current soil fertility (H_Fieldrule = 2; Fig. 6A; H_DistWgtCropping = 0), the returns on labor will be consistently higher than with the default (H_Fieldrule = 1). A change in this setting reflects a more complete local knowledge of the fertility status of all plots. and the absence of other constraints on access to plots (apart from the H_ForestResFrac rule). The setting of this H_Fieldrule parameter influences the spatial heterogeneity in the landscape and the variation in soil fertility (linked to soil C) as well as aboveground C stock (Fig. 7). As the homogenizing 'creaming off' of the landscape (H_Fieldrule = 2) leads to higher rice yields, but lower C

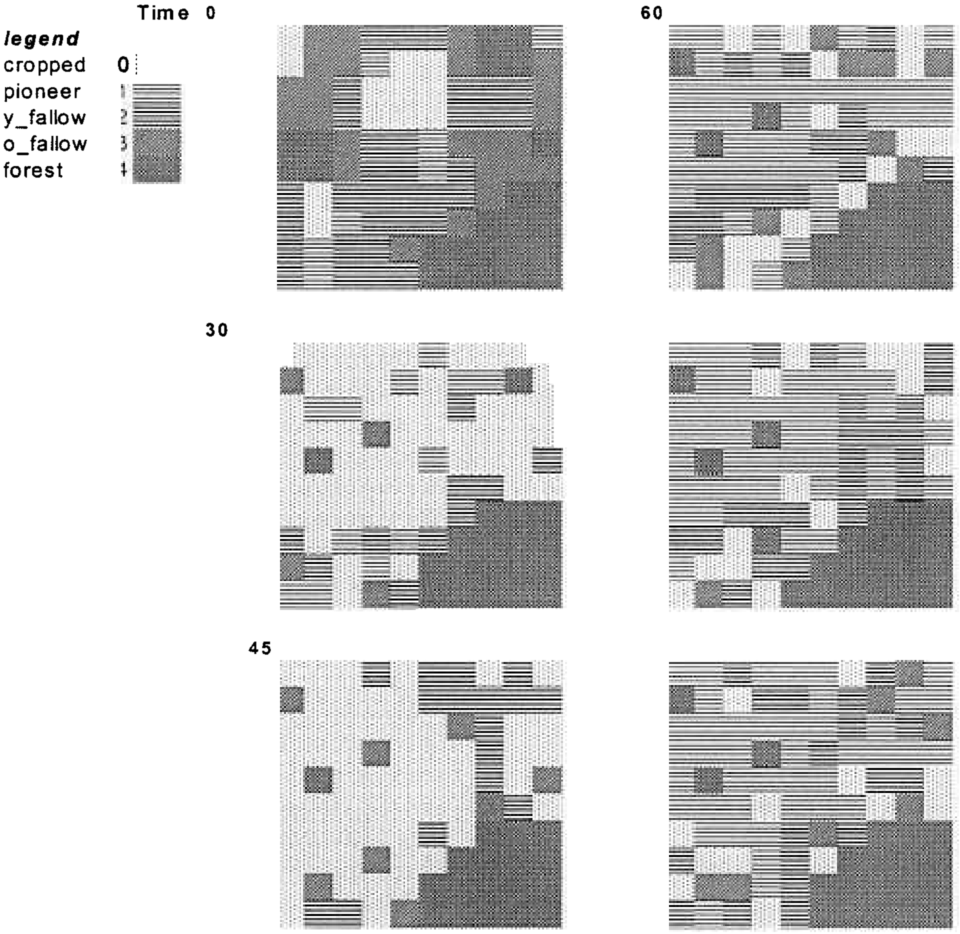

Fig. 3. Example of map (time series) showing land cover in a five-step classification (cropped land, pioneer vegetation, young fallow, old fallow and forest) for a 'default' run of the FALLOW model; the area in the lower right corner is indicated as 'forest reserve' and is not available for growing food crops.

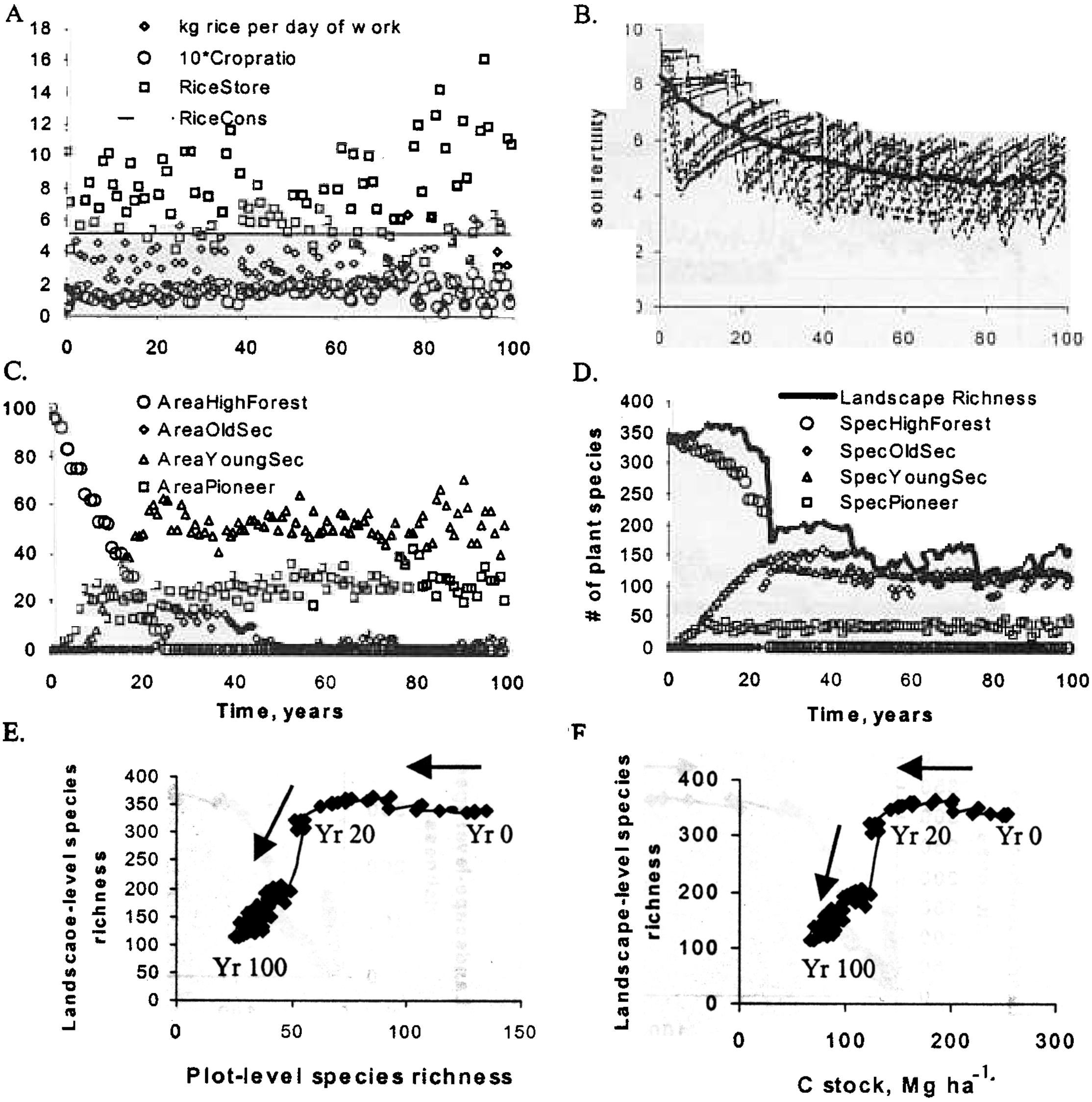

Fig. 4. Time series and some of the main trade-offs during a default run with a population density of 10 persons per km^2: A. Cropping intensity and food consumption; B. Soil fertility for a 5% sample of the individual plots plus the landscape level average; C. Land cover dynamics (percentage of the total area under various land cover types), D. Landscape level species richness and the richness in each of the vegetation classes per se (the total is less than the sum of the classes, because of species overlap), E. Trajectory of landscape level richness versus plot-level richness; F. trajectory of carbon stocks versus landscape level diversity.

stocks and biodiversity (results not shown, but similar to those for C stocks), the trade-off between local benefits (rice yields) and global benefits (C stock and biodiversity) does change by nearly a factor 2 in year 100.

3.5. Landscape-versus plot level model predictions

The potential impact of an ‘improved fallow’ versus a ‘natural fallow’, by reducing the S_*K*fert parameter, was explored on the relation between

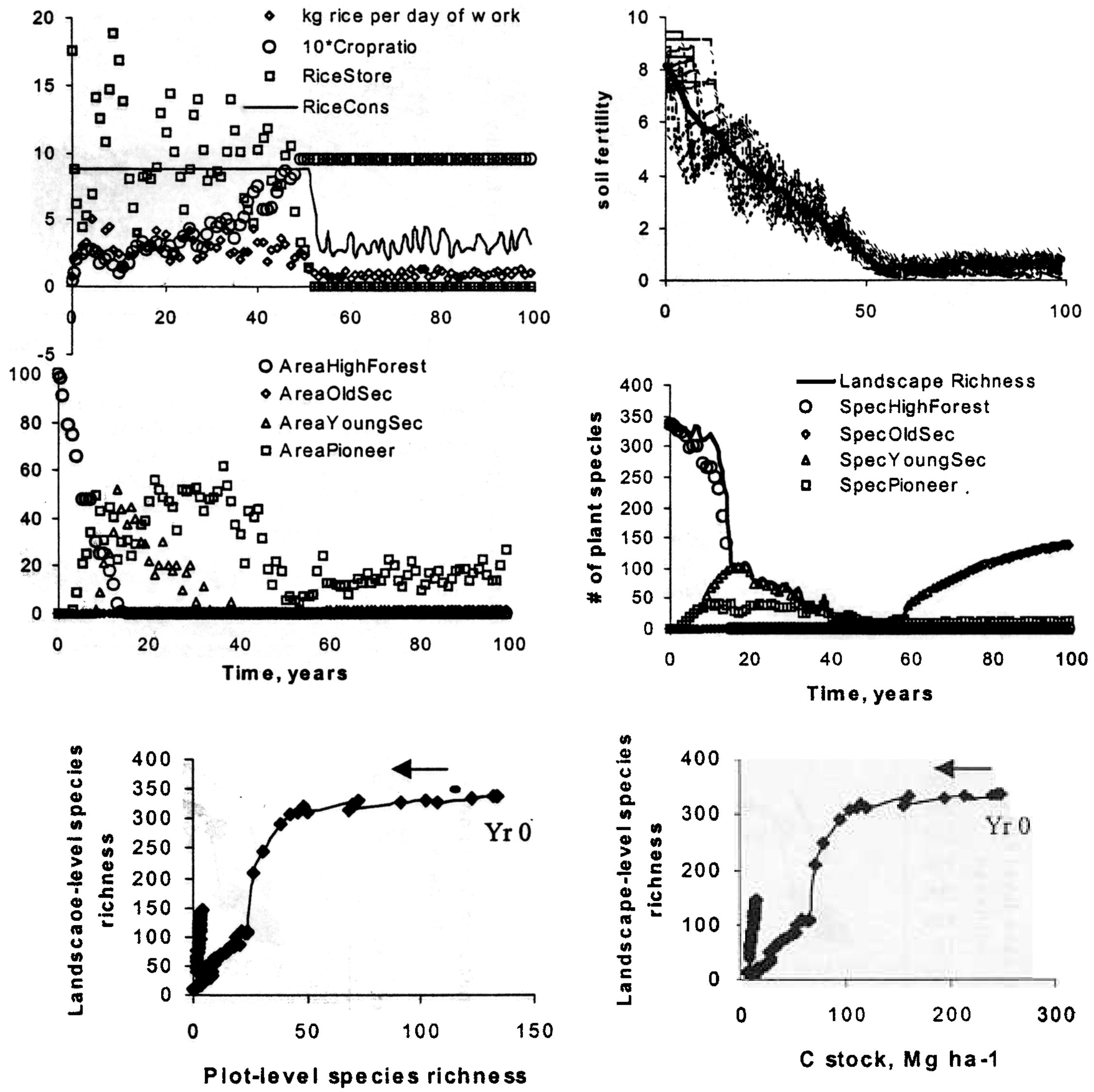

Fig. 5. Idem as Fig. 4, for a human population density of 17 persons per km^2; NB, the rice store in Fig. 5A represents the situation at the end of each year, after additions of the new harvest and subtraction of the annual consumption.

current soil fertility of the plots that are cropped with the returns on labor and the rice yields per total area (Fig. 8A and C, respectively). Both these relations, averaged over a landscape with its variability, are essentially the same as followed from the algebraic analysis of the Trenbath model (Van Noordwijk, 1999). The maximum yields per area are obtained when the relative soil fertility of newly opened fields is about 0.6, which is close to the value of about 0.55 found in the algebraic steady state solution. The current model, however, predicts that no simple relation can be found between preceding age of the fallow and the returns to labor or land, in contrast to steady state solutions where age of fallow would be directly linked to current fertility. At landscape level the

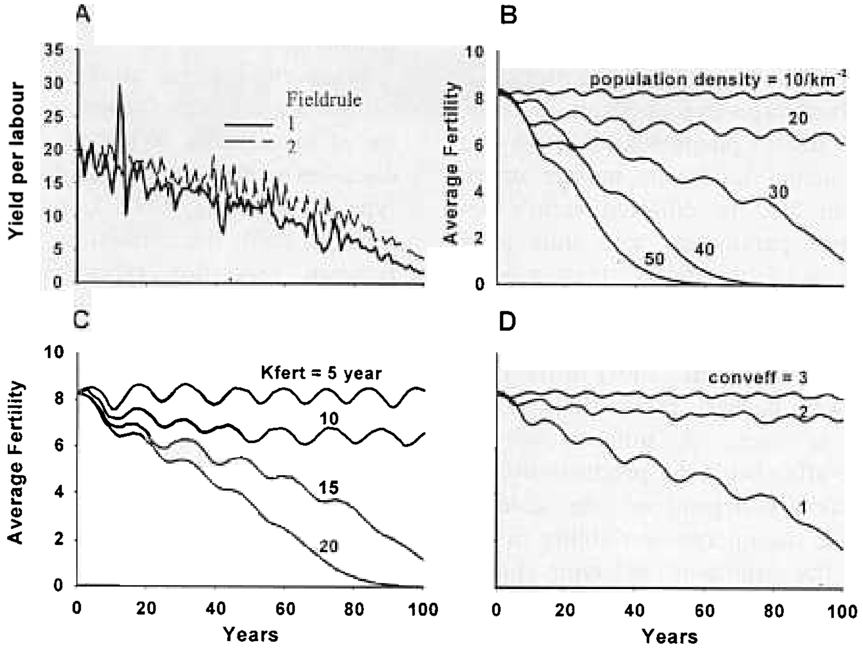

Fig. 6. Sensitivity analysis for a number of main parameters in the model; A. Yield per unit labor (kg rice per day) for application of FieldRule 1 (no plot-level knowledge of soil fertility) and FieldRule 2 (with good knowledge of plot level fertility); B. Changes in landscape level average soil fertility (arbitrary units) for human population densities in the range 10–50 persons per km^2); C. idem, for values of the S_*K*fert parameter in the range 5–20 year, representing different types of fallow vegetation; D. idem, for three values of the R_ConvEff parameter, that relates food crop (in rice equivalents) yields in mg ha^{-1} to each unit decrease in soil fertility.

Table 2

Sustainability thresholds for human population densities (number of persons per km^2) for shifting cultivation systems based on upland rice production during a 100-year test period according to the FALLOW model, depending on the type of fallow vegetation and its typical fertility restoration capacity *K*fert, and the inherent properties of the soil, determining the potential soil fertility F_{inf}; criteria for critical population density in at least five runs for each parameter setting were: food sufficiency > 90% and landscape-level soil fertility > 50% of initial value

Fallow vegetation	*K*fert (year)	Inherent soil quality		
		Poor = 5	Medium = 10	Good = 15
Degraded forest	15	3	9	11
Good forest	10	4.5	10.5	21
Improved fallow	5	7	19.5	22
Cover crop	3	10.5	24	36.5

trajectory of intensification, combined with the individual plot histories, causes a substantial change in the shape of the fallow-age-fertility relation (Fig. 8B and D), compared with the results for a sequence of steady states (as in the algebraic solution)

4. Discussion

The scaling up of the plot level Trenbath model to the current landscape-level account, demonstrated that the transient phenomena that may be expected in an actual landscape mosaic under intensification can lead to different ratio's between performance parameters, and thus to a different perception of 'trade-offs', than a comparison of steady state solutions. This conclusion emphasizes the need to interpret field-derived data (as presented by Tomich et al., 2001) in the context where they were derived, rather than as system properties as such. A number of the important trade-offs between productivity, C stock and biodiversity depend on the scale of model application, the internal variability in the landscape and the transient behavior under changes in land use intensity. In the real world, changes in human population density would add further complexity to the interpretation of these transients.

In developing this model we had to postulate explicit scaling rules for species richness as indicator of biodiversity. While an abundant literature discusses scaling rules within a single vegetation type (Rosenzweig, 1995; Loreau, 2000; May and Stumpf, 2000) the corrections we use for overlap between vegetation types are speculative and probably represent an area where further research is urgently needed.

Qualitatively, the model can reproduce initial increases in landscape level species richness as a consequence of 'disturbance' by low-intensity shifting cultivation, even though the average plot-level richness will decrease. This initially positive response to disturbance does not exist for the C stocks, and is in line with data collected for the ASB benchmark sites (Gillison, 1999). The model formulation we use implies that changes in plot-

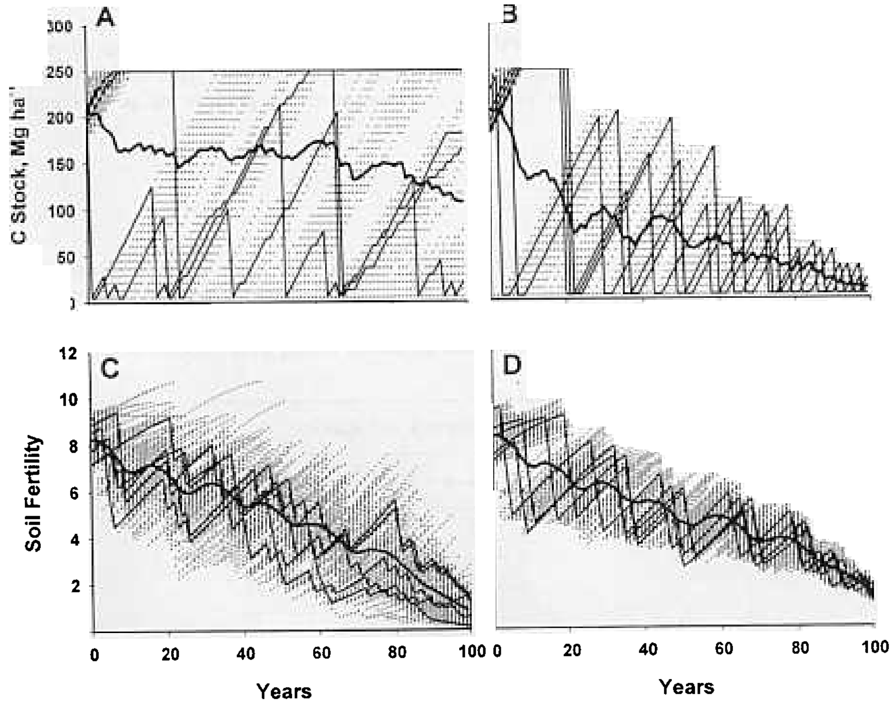

Fig. 7. Aboveground C stock (A and B) and soil fertility (C and D) for individual plots and for a landscape-level average (bold line) for simulations where decisions on the fields top be cropped are no direct reflection of plot-level fertility (A and C, H_FieldRule = 1) and for cases where near-perfect knowledge of soil fertility exists and no constraints in access to part of the landscape apples (B and D, H_FieldRule = 2).

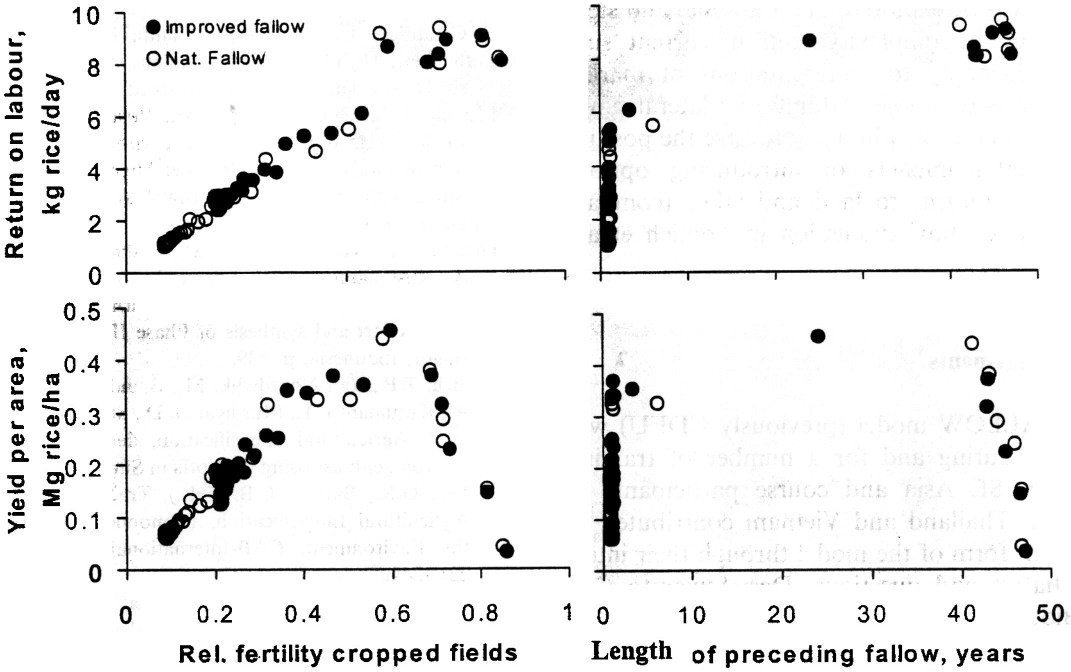

Fig. 8. Relationship between returns to labor and land and the relative soil fertility of cropped fields and the age of the pre-ceding fallow period, for simulations with *K*fert = 15 ('Nat. fallow') and 5 ('Improved fallow').

level species richness are fully reversible and that 'time can heal all wounds' from a biodiversity perspective, without irreversible changes in the pool from which recolonization is supposed to occur. Future versions of the model may have to more explicitly incorporate concepts of connectedness within the landscape mosaic and its impact on the lateral flow of organisms. We explored two ways of representing the linkage between overall, landscape-level decisions on intensification and the plot-level implementation in decisions of which plots to crop in what year. These different model formulations represent different degrees of perfection in local ecological knowledge, and are expected to have some impact on properties such as 'returns to labor'. The two versions, however, do not change the fundamentals of resource availability in the neighborhood of the 'carrying capacity'. Changes in agricultural technology (higher R_ConvEff parameter or fertilizer use) can have a much more drastic impact, according to the current model.

The current model requires further parametrization before quantitative 'validation' tests can be performed, but it appears to meet 'sensibility' criteria (predicted responses 'make sense') and is sensitive in its overall outcome to the main input parameters. The challenge is to keep the model simple enough to elucidate the main dynamics, but yet allow for scaling up. The versions of the model currently available on the web site includes options of farmers spending time to collect forest products (timber or non-timber) and trade these for rice equivalents. This version of the model also incorporates the option of using a S&B system to start 'agroforests' such as the rubber or fruit tree agroforests that replaced shifting cultivation in much of SE Asia (Van Noordwijk et al., 1998; Tomich et al., 1998a; Tomich et al., 2000a; Tomich et al., 2000b). A water balance module translates the landscape mosaic into predictions of total river flow and sediment load.

Human decision making based on explicit evaluation of options that arise during the simulation can be represented in the model and its ecological consequences be explored, but a gradual and stepwise increase in complexity from the current 'subsistence' economy to representations of market integration is desirable. Adding the 'lateral flow;' of human migration will likely reverse the positive environmental impacts of introducing options with higher returns to land and labor (compare the 'Pandora's box' discussion in Tomich et al., 1998a).

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