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

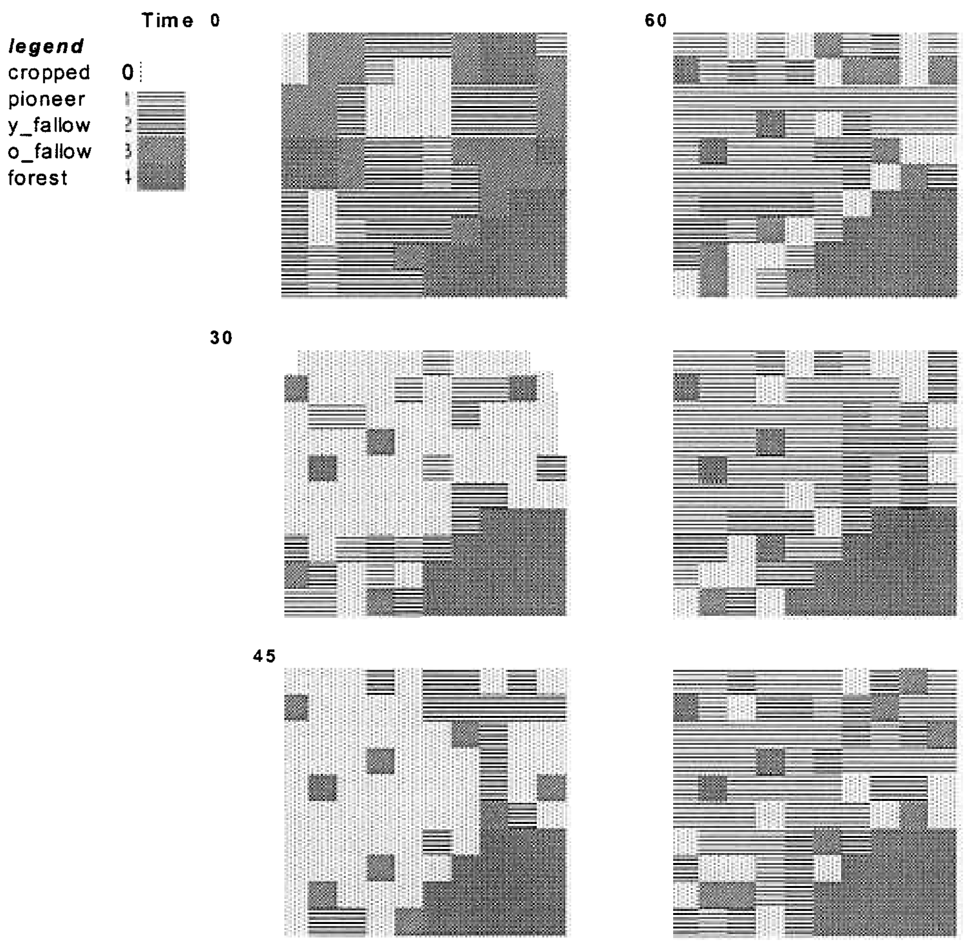

Fig. 3. Example of map (time series) showing land cover in a five-step classification (cropped land, pioneer vegetation, young fallow, old fallow and forest) for a 'default' run of the FALLOW model; the area in the lower right corner is indicated as 'forest reserve' and is not available for growing food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

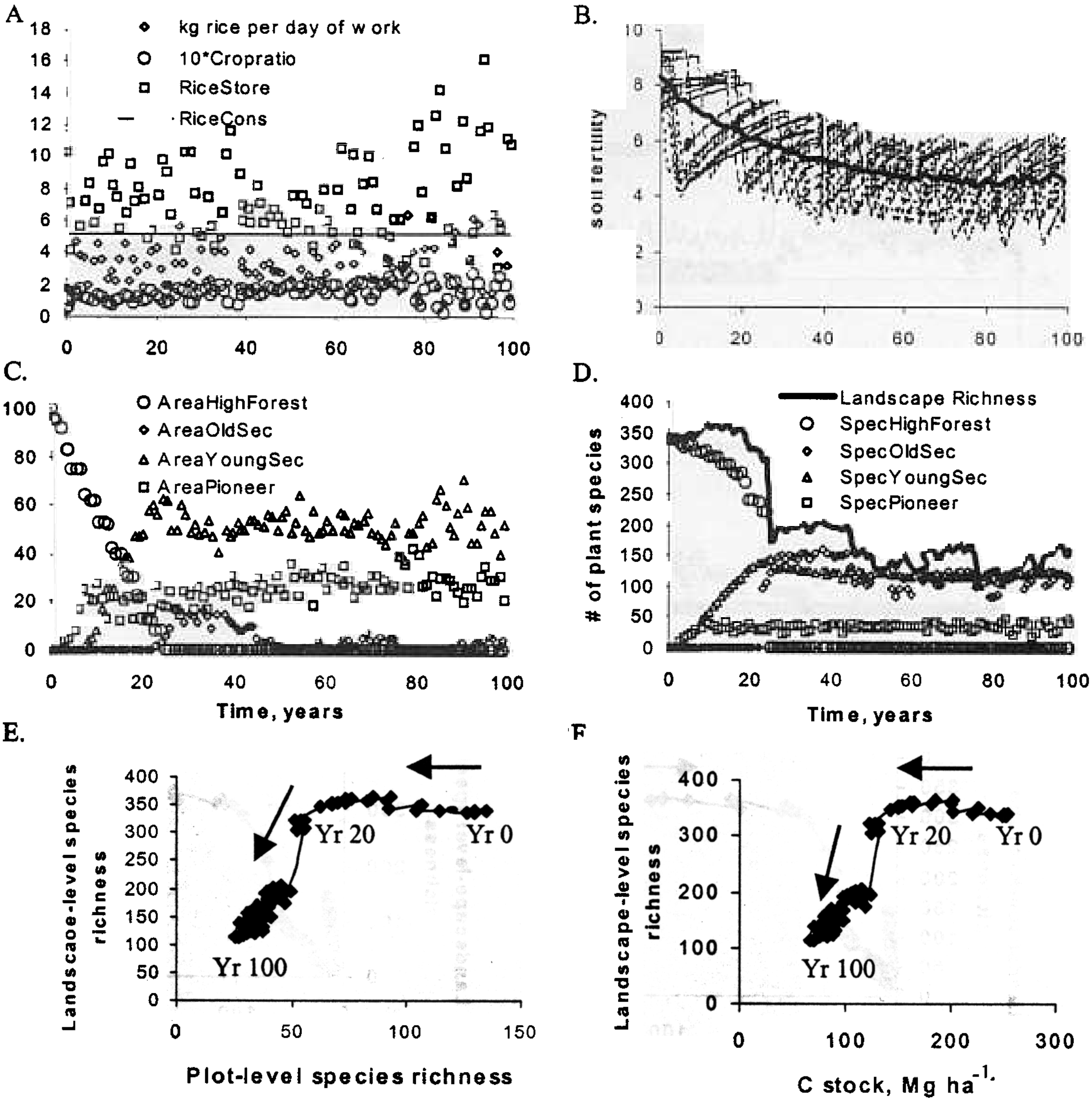

Fig. 4. Time series and some of the main trade-offs during a default run with a population density of 10 persons per km^2: A. Cropping intensity and food consumption; B. Soil fertility for a 5% sample of the individual plots plus the landscape level average; C. Land cover dynamics (percentage of the 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

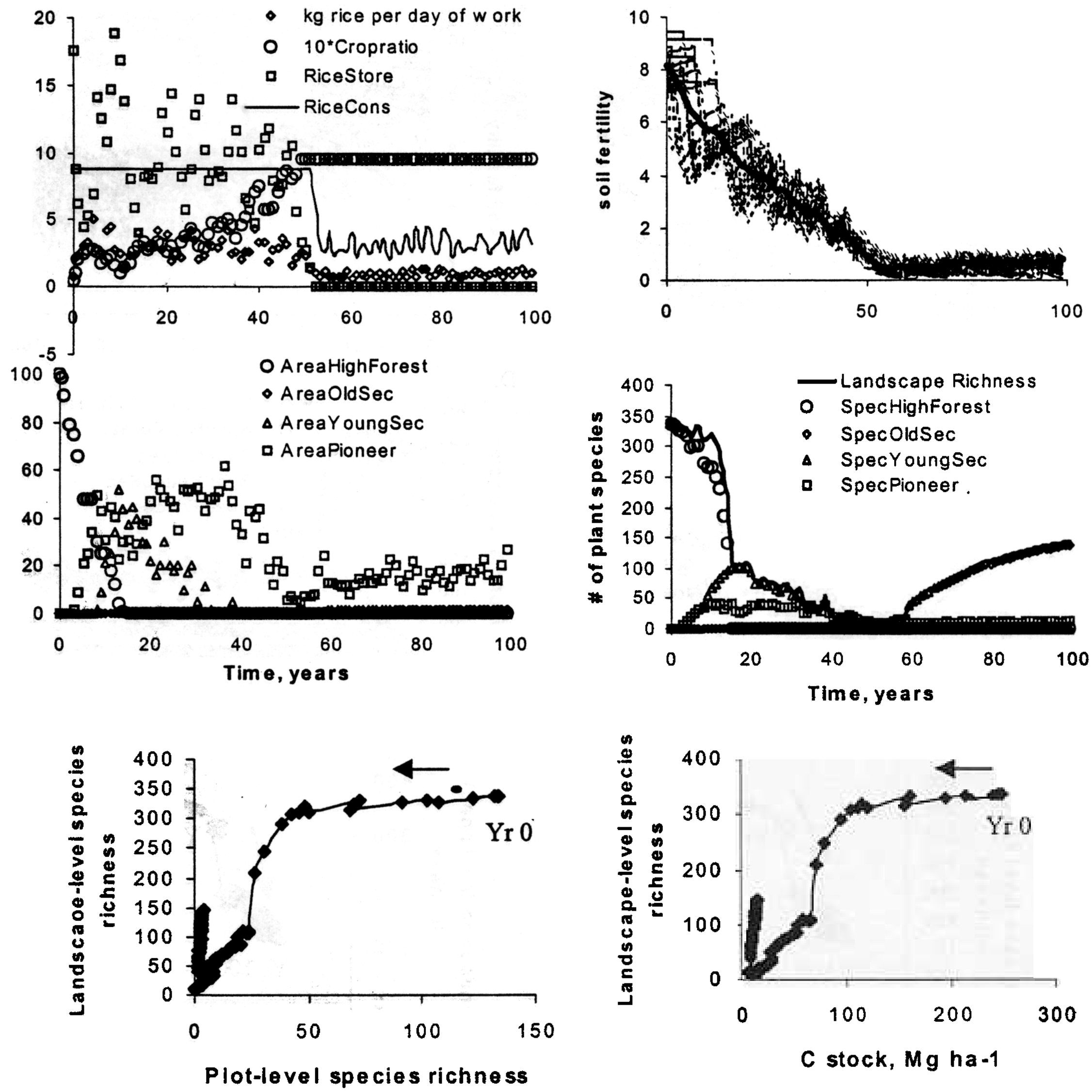

Fig. 5. Idem as Fig. 4, for a human population density of 17 persons per km^2; NB, the rice store in Fig. 5A represents the situation at the end of each year, after additions of the new harvest and subtraction of the annual consumption.

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

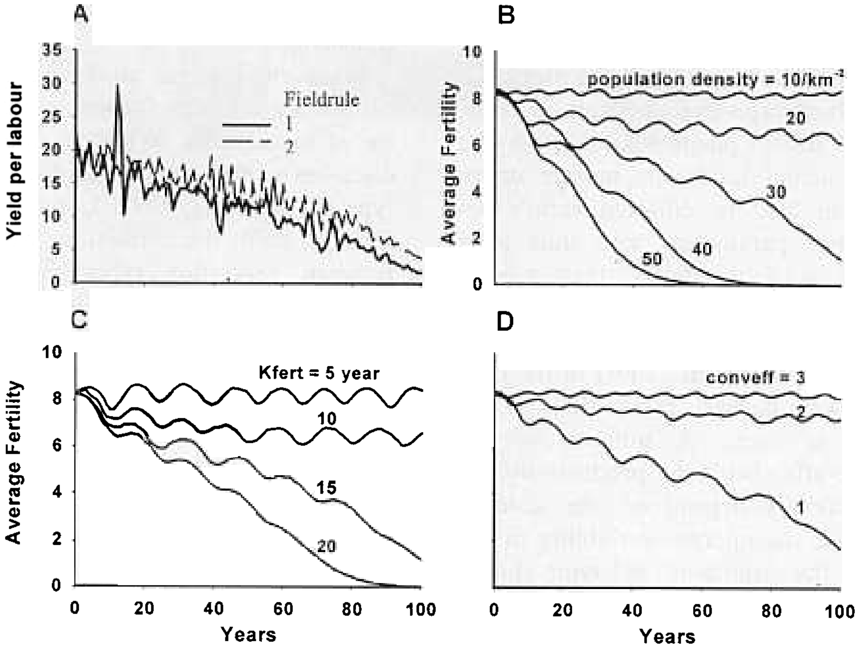

Fig. 6. Sensitivity analysis for a number of main parameters in the model; A. Yield per unit labor (kg rice per day) for application of FieldRule 1 (no plot-level knowledge of soil fertility) and FieldRule 2 (with good knowledge of plot level fertility); B. Changes in landscape level average soil fertility (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-

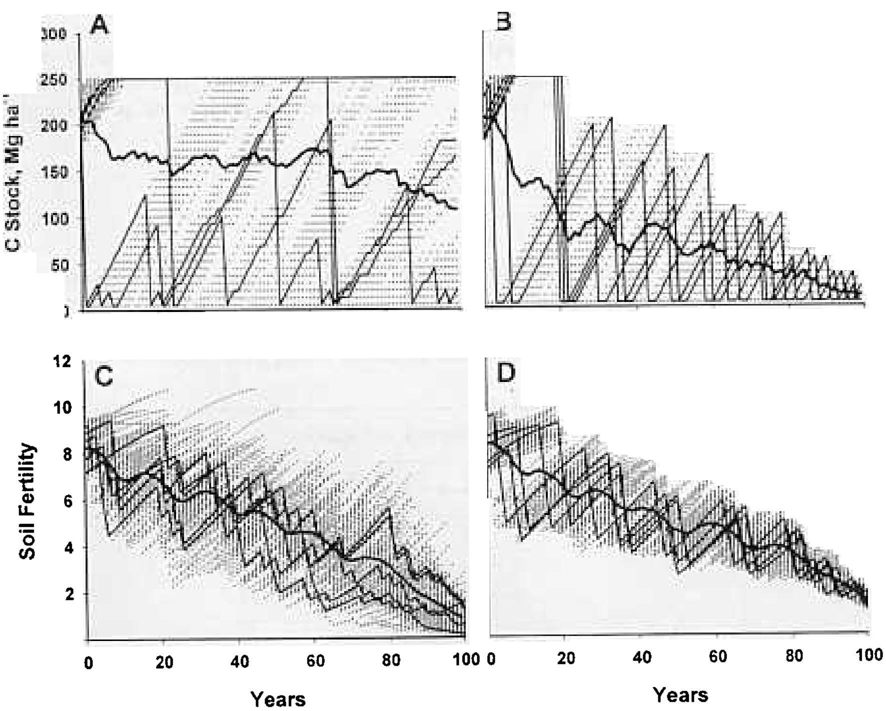

Fig. 7. Aboveground C stock (A and B) and soil fertility (C and D) for individual plots and for a landscape-level average (bold line) for simulations where decisions on the fields top be cropped are no direct reflection of plot-level fertility (A and C, H_FieldRule = 1) and for cases where near-perfect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

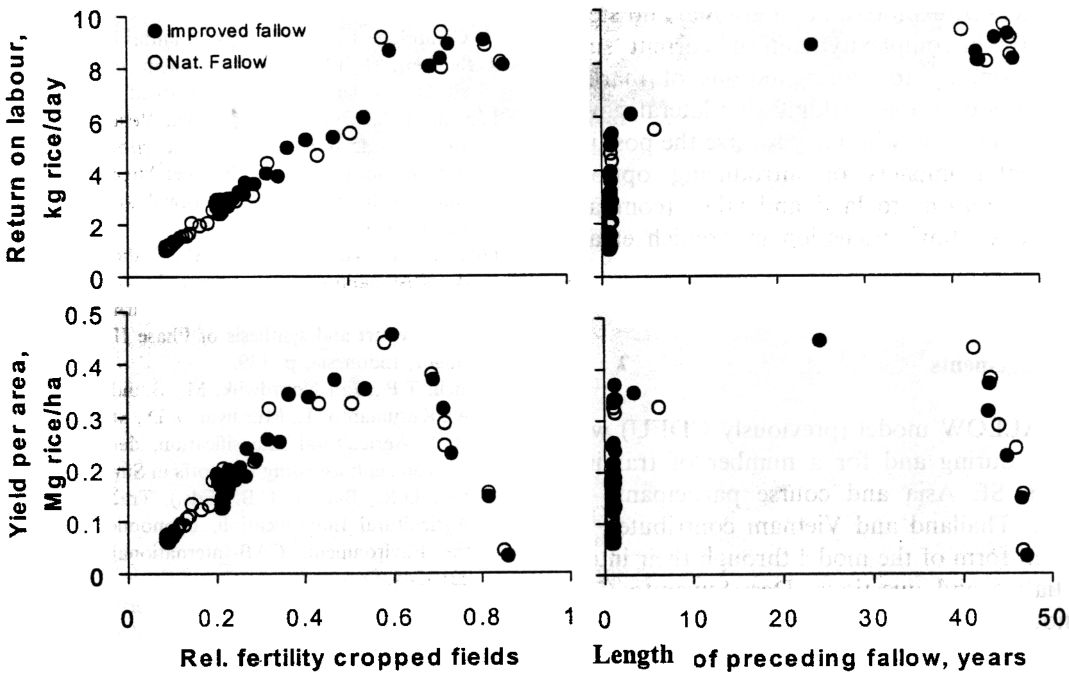

Fig. 8. Relationship between returns to labor and land and the relative soil fertility of cropped fields and the age of the pre-ceding fallow period, for simulations with *K*fert = 15 ('Nat. fallow') and 5 ('Improved fallow').

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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