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Coupling agent-based models of subsistence farming with individual-based forest models and dynamic models of water distribution

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ABSTRACT

Subsistence farming communities are dependent on the landscape to provide the resource base upon which their societies can be built. A key component of this is the role of climate and the feedback between rainfall, crop growth, land clearance and their coupling to the hydrological cycle. Temporal fluctuations in rainfall alter the spatial distribution of water availability, which in turn is mediated by soil-type, slope and landcover. This pattern ultimately determines the locations within the landscape that can support agriculture and controls sustainability of farming practices. The representation of such a system requires us to couple together the dynamics of human and ecological systems and landscape change, each of which constitutes a significant modelling challenge on its own. Here we present a prototype coupled modelling system to simulate land-use change by bringing together three simple process models: (a) an agent-based model of subsistence farming; (b) an individual-based model of forest dynamics; and (c) a spatially explicit hydrological model which predicts distributed soil moisture and basin scale water fluxes. Using this modelling system we investigate how demographic changes influence deforestation and assess its impact on forest ecology, stream hydrology and changes in water availability.

1. Introduction

This paper addresses the issue of land-use changes induced by human societies and their interaction with ecological and hydrological systems. These three (society, ecology, hydrology) are multi-component non-linear systems with their own complex dynamics, but their internal processes cannot in general be de-coupled from the changes that are induced by the interactions between the systems. A modelling scheme needs to allow us to determine where the important interactions lie and to understand the timescales on which the various processes operate, in a way that is appropriate to the scale of system under consideration. This is particularly the case where the issue of sustainability is concerned, as this may involve timescales much longer than that of individual people, and may require long-lived institutional mechanisms in order to become practicable (see e.g. Matthews and Selman, 2006). Only by developing a fully coupled approach that includes aspects of all systems under consideration are we likely to be able to appreciate the actions required, given that direct experimentation with landscape-scale systems is not feasible. Unfortunately we lack the kind of large scale systems-level understanding of physical, ecological and social processes that would allow us to directly deduce the best sustainable management practices. In view of this, an approach that may be fruitful is to develop models at small scales, where we may have access to direct measurement, and to hope to build models in which the large scale behaviour will emerge from the small scale via interaction between the system components.

In recent years individual-based and multi-agent (Gilbert, 2007; Wooldridge, 2001) approaches to land-use change modelling have begun to be adopted, as they allow a more flexible approach to the representation of people's interaction with the environment: spatial heterogeneity can be more easily included, and the effects of decision making disaggregated (Barthel et al., 2008; Monticino et al., 2007; Matthews et al., 2007; Richards et al., 2004a,b; Parker et al., 2003). The potential for using agent models in ecosystem management has been described by Doran (2001) and has also been reviewed more recently by Bousquet and Le Page (2003). Agent-based models of farming communities have existed for a number of years (see e.g. references in Matthews, 2006), but as Matthews points out, many of these models, including the well known study of the Anasazi (e.g. Axtell et al., 2002), tend not to have dynamic environments (although the environments do change over time), or else treat the environment as prescribed (see e.g. Ziervogel et al., 2005; Bharwani et al., 2005). Studies that incorporate dynamic agent-based changes in land use may only have statistical models of forest cover (Linderman et al., 2005;

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Evans and Kelley, 2004). On the other hand previous forest modelling studies have tended to treat disturbances as generated internally to the forest system (Chave, 1999), prescribed (Pacala et al., 1996; Deutschman et al., 1997) or scenario based (Kammesheidt et al., 2001; Gustafson et al., 2000), so that clearance of land for agriculture, for example, is not directly connected to forest dynamics. Conversely, where distributed modelling of the physical environment is included, the effects of human and ecological systems may not be dynamic – for example Vanacker et al. (2003) study the effects of deforestation on soil wetness and thus on the probability of land-sliding, but the forest cover is changed using historical data, or else extrapolated statistically into the future assuming the character of deforestation will be unchanged. More recent models have begun to address the problem more comprehensively (Matthews, 2006; Christiansen and Altaweel, 2006) by including soil water availability modelling for crops, but the soil water behaviour may not be spatially coupled, so they do not have the ability to assess how the changes in land use affect the catchment scale water availability or the potential for flooding. Matthews (2006) incorporates a dynamic forest component also, but does not comment on its interaction with land clearance for farming at the catchment scale.

Our aim here is to begin the process of coupling together individual-based dynamical models of both human and ecological systems with distributed models of the hydrology, and explore some of the ways in which their spatial distributions and spatial interactions may be important. We will briefly describe the model system in Section 2, reserving a complete description to an Appendix. Section 3 discusses model experiments and results are discussed in Section 4. Section 5 discusses some issues with coupling models in general and the application to the current case, and we conclude in Section 6.

2. Model description

We will simulate catchment-scale processes over timescales of a few hundred to a few thousand years, where the land surface cover is changing from year to year, but giving rise to changes in the hydrology. This work extends and improves on that outlined briefly in Bithell et al. (2006). We will show how the effect of forest removal by a growing farmer population, both for fuel, fodder and for agricultural land, leads to changes in the forest structure, both spatially and in terms of relative numbers of species, and how this forest removal affects the catchment hydrology. The hydrological model is spatially distributed over a regular grid of cells within which the land-cover type determines the hydrological characteristics. The forest model is based primarily on competition for light between trees selected from one of two functional types. Trees can take any location on the landscape, but interact with the hydrological model only at the scale of the cells into which the hydrology is discretized. Households clear forest both to gather fodder and fuel, and to make space for fields. Soil compaction within field boundaries affects hydraulic conductivity, and the reduced canopy layer affects the rate at which rainfall can reach the soil.

2.1. Landscape characteristics

Because our hydrological model is largely forced by topography we will focus on a small mountainous catchment. The population is envisaged to be rural in character and heavily dependent on forest for both animal fodder and fuel. We have a topography, and a hydrological parameterization and dataset, as well as some social data on type and distribution of households and usage of forest for fodder and fuel from a previous study. These data have previously been published in a series of papers describing the hydrological and erosional consequences of land-use change and environmental modelling strategies (see Brasington, 1997; Brasington et al., 1998; Brasington and Richards, 1998, 2000). These also outline the development, calibration and robust validation of the rainfall-runoff model used in our current research (e.g., Brasington et al., 1998). Further data from that project also provide an insight into socio-economic conditions, including estimates of the use of forest products and an indication of the forest cover, type and degradation history (Gardner et al., 1995; see also Shah et al., 1991). Although these data are gathered from a real-world case, we do not claim that the results here should be applied to a particular location – the state of the model is not sufficiently mature to give results that we would anticipate as directly applicable for catchment management. For example, we do not have a local forest parameterization available, so will use a pre-existing model from a different location, and look at the ends of the parameter range in order to give an indication of the possible dynamical effects. However, in order to get realistic results from the hydrology, which is heavily calibration dependent, we will use the topographic, rainfall and soil characteristics from the previous study (as described below). Our results are therefore more aimed at the types of effects that we might anticipate in this kind of small steep catchment, rather than predictions of the actual behaviour that occurs in a particular location. In this sense we are nearer to the exploratory/explanatory approach of Parker et al. (2003), than to the descriptive approach that attempts to make a simulation of a particular real-world system.

The catchment has an area of 4.1 km^2, small enough to facilitate the computational demands of individual-based ecological modelling (see below). Rainfall and discharge data are available for the catchment discretized at hourly intervals derived from four year monitoring campaign organized as a collaborative UK Universities research project between 1991 and 1995 (see Gardner et al., 1995). As part of that study, 1:10,000 topographic mapping of the catchment was undertaken and a digital elevation model (DEM) interpolated at 20 m resolution with 1 m RMSE in the vertical (also see Fig. 1). This reveals the steep, deeply incised nature of the catchment and an altitudinal range of 1200 m over just 4 km.

The pattern of the rainfall and runoff for a single hydrological year (May–April, 1992–1993) is shown in Fig. 2. The monsoonal character of the rainfall is clearly evident, with 90% of the annual precipitation (typically 2200–2600 mm) falling between July and September followed by nine months of drought. This strongly seasonal climate results in the development of a deep soil moisture deficit during the winter months thus leaving little “memory” of the previous monsoon season preserved in the soil. As demonstrated in remainder of the paper, the rainfall-runoff dynamics of such headwater catchments are strongly related to the pattern of land-use and forest cover. The latter were mapped from aerial surveys 1991 and the resulting distribution is plotted in Fig. 3. This shows that in the lower reaches of the catchment, where irrigation supplies are plentiful, the dominant land-cover is rice terracing, while the intensity of cultivation declines with altitude leaving only scattered areas of unirrigated maize terracing interspersed with dense secondary forest in the steep headwaters.

2.2. Hydrology

We attempt to predict the spatial distribution of soil moisture using a finite volume solver in which the system is broken down into cells between which the fluxes of moisture are explicitly calculated. In a catchment where subsurface flow pathways are dominated by the topography a simple kinematic approximation has been shown to be good first order predictor of water fluxes in steep catchments (see Beven, 2001) and provides a simple platform to for coupling hydrology to other processes. We adopt this type of approach here using a finite volume model that includes saturated-

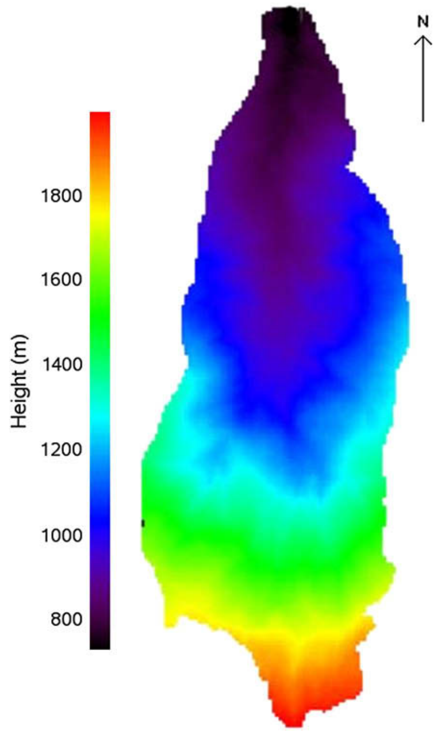

Fig. 1. Twenty-metre resolution digital elevation model derived by interpolation from 1:10,000 topographic mapping.

zone horizontal fluxes between cells, driven by the local hydraulic gradient, and includes four layers in each cell representing canopy, root zone, unsaturated and saturated zones. Absorption into the soil surface and exfiltration from fully saturated cells are explicitly represented. Surface and canopy evaporation is included, although in the current version of the model the effect of forest transpiration on the soil moisture is not incorporated into the parameterization directly. Leakage from the base of the saturated layer to deep ground water will be assumed to be negligible in all runs of the hydrology unless the soil moisture deficit is lower than 30 cm. We assume that the rainfall is uniformly distributed and that any variations in the hydrological processes arise from land-use alone – i.e. that the soil properties are initially uniform throughout.

2.3. Forest

For the ecological component we use an individual-based modelling technique, where we directly represent every tree in the catchment. The dynamical evolution of the forest gives a distribution of available wood resources, both spatially and in terms of tree size, that can be accessed by farmers, who fell individual trees and return them to their household. The advantage of the individual based approach, apart from the fact that the evolution of forest structure is coupled to the farming activity, is that we can directly specify the gathering process for wood in terms of movements of individual people targeting individual trees, rather than needing to make extra assumptions about where trees might be within a grid cell, for example.

We will make use of the SORTIE model for which code is available (Deutschman et al., 1997) and for which there is a full description in Pacala et al. (1996). The model uses empirically derived allometric relations between tree growth parameters and shading to give a dynamical model of forest in which competition between trees is directly related to their relative positions in the landscape. However, as already mentioned, we do not have immediately available a parameterization of individual tree species that apply to the catchment for which we have a hydrological parameterization. We therefore choose to model only two extreme members of the SORTIE set of trees, a narrow-dispersing shade tolerant variety (American beech) and a very broad-dispersing shade intolerant species (yellow birch) regarding them as fiducial functional types that will represent the broad kind of behaviour expected.

However, we will include one aspect of the mountainous context not included in the original model, namely that the relief in the catchment in question is very pronounced. This gives rise to

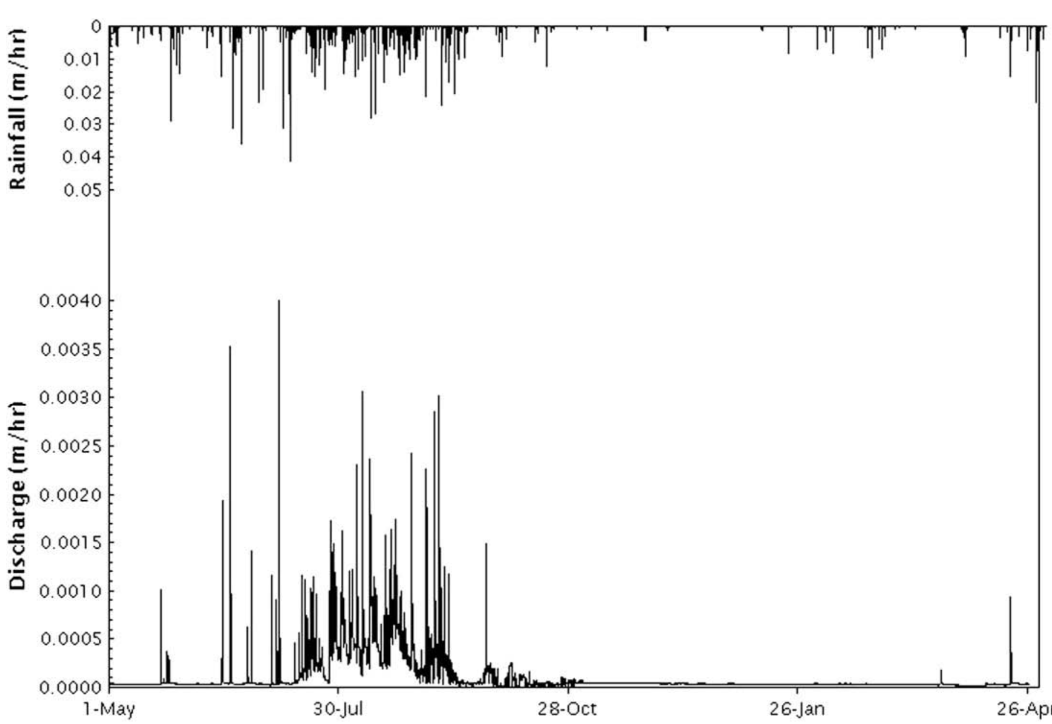

Fig. 2. Rainfall-runoff dynamics for a single hydrological year, May–April 1992–1993. Over 90% of the total annual rainfall (2488 mm) occurs in the three months of July–September.

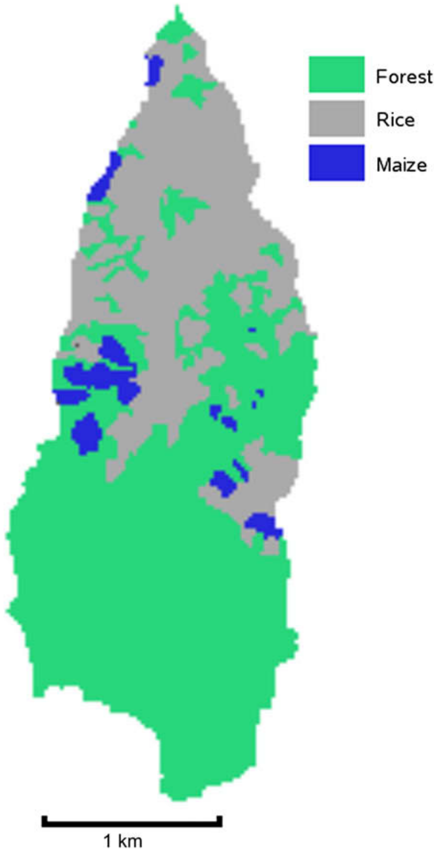

Fig. 3. Observed land use distribution as of 1995. Grey areas are farmland under rice cultivation, blue under maize and green areas represent forest. See Brasington et al. (1998).

strong self-shading and also means that relative heights of trees are distorted by the slope of the landscape. We therefore modify the shading algorithm to include the effect of extra local shade induced by elevation differences between the locations of the trees (we do not include the global self-shading of distant parts of the catchment, as this takes place at low solar angles that are probably not important in competition between the trees (see Pacala et al., 1996)). Since the shade cast on one tree by another tree depends on relative heights of the two trees, we achieve this by temporarily adding their difference in DEM elevation to the height of the tree casting shade for the duration of each shading calculation. As we show below, for this catchment this leads to differences in resource distribution available to the farming community.

2.4. Households

As with the ecological model, we will model the human component of the system by simulating individuals. We represent each household within the catchment and within each household we represent each individual person. Such models are often referred to as agent-based (Gilbert, 2007), and they may have quite complex sets of rules designed to simulate various aspects of human behaviour. In this study, we do not aim to develop very computationally elaborate reasoning agents. Rather we adopt a simple resource-gathering approach that allows interaction most directly with the tree model. Households settle in the landscape, clear a set of DEM grid cells for use as a field, allocating a land-use type dependent on location (rice or maize), and keep the fields clear of trees. The household then consumes wood and sends out people into the forest to replenish the wood store. These agents have no global view of the system but are limited to detecting local properties within each grid-cell of the DEM as they move randomly about the landscape. This mimics the difficulty of gaining a global view of the system owing to obscuration by the local tree cover. Households and people do not communicate with other agents and have no memory of past events. A more detailed model might include these effects, but we omit them in this first investigation. Interaction between agents will be limited to indirect effects – in this case competition for land and for wood. We remark on this further in the discussion below as it bears upon the process of searching for resources. Effects on the hydrology also occur indirectly through modification of the hydraulic conductivity and canopy changes that results from use of the land for fields and for wood gathering.

2.5. Timing

We assume throughout that the surface topography is completely stable. This is of course somewhat unrealistic: the landscape shows evidence of prior landslips, even in the forested regions, and a more comprehensive model would include surface evolution. However, in order to illustrate the relative timescales on which hydrological, forest and human processes take place, the assumption of a fixed landform is not unreasonable. Although the detail of the surface form will be changing, the macro-scale properties of the catchment are likely to remain relatively stable on centennial to millennial timescales. We also keep the same annual rainfall time-series throughout, simply reproducing the same pattern from year to year. While this clearly lacks realism it allows us to isolate the changes that take place as a result of land-use variations without the added complication of inter-annual climatic variability. In the current case the catchment dries completely between monsoons. As a result we do not miss any hydrological coupling between years, except where this might reflected in the linkage of hydrological processes to longer timescale changes in forest dynamics, or to anticipation of future yield by the farmers. However, we can make direct comparison from year to year of the impact of human occupation without the complication of inter-annual rainfall variability. The latter may, of course, be important, but the current methodology gives us a control case against which such variations could be measured.

As we show below, although the evolution of forest and land-use takes place on decadal timescales, their effects are felt dramatically in the course of a single flood event. The relevant hydrological timescales required to represent the storm water dynamics which ultimately determine the annual moisture balance are extremely fast compared with the slower moving social and ecological processes. Because the catchment is steep, flows through the system vary on a timescale of a few hours, requiring hydrological model implementation with a timestep of 1 h to fully capture storm period dynamics. On the other hand, we will keep the original timestep of the SORTIE model for the forest and update the tree structure once every five years. Household steps are intermediate between these timescales – wood is gathered on a daily basis when the household store needs replenishing, until there is at least a year's worth of wood in storage. Fields are cleared of trees once each year.

These timings allow us to track changes in the catchment discharge within monsoon storms, but means that the catchment-scale farm and tree structure are essentially static as far as the hydrology is concerned. Although we could track the removal of individual trees at the same timescale as the hydrology (and indeed this might give some information about the ease with which certain areas of forest might be harvested during monsoon storms) we instead follow the overall catchment changes in forest and farm cover on an annual basis and then route the rainfall timeseries through the hydrological model with the forest and farm structure fixed.

More detail on model structure and timing is given in the Appendix, following the ODD structure of Grimm et al. (2006).

3. Experiments

In order to examine some of the characteristics of our model system we perform a set of experiments, gradually increasing the number of components involved. Because of the long integration times required, particularly for the forest model, we will not attempt an exhaustive exploration of the full system, but will look at three illustrative examples: the effect of environmental heterogeneity on a single household in a static forest, the effect of competition between households in the same static forest environment, and the effect of a growing population on a dynamical forest, and the resulting impact on the hydrological system.

We begin the modelling process by integrating the forest model for several thousand years initialized with a random initial condition in which the two types of tree are scattered across the catchment with an initial density of 175 stems per hectare each and an initial stem size of 1 cm. This is the slowest evolving component of the system, so we are able to check the timescale on which changes to the forest occur when human and hydrological processes can be ignored. The forest model proves to have an initial transient (c.f. Pacala et al., 1996; Chave, 1999), with a peak basal area near year 300. However, the relative number of tree species continues to evolve for at least 1000 years, consisting largely of replacement of the shade intolerant functional type by the shade tolerant (see below). It is likely that regional forest cover will have existed for much longer than such a transient (in the absence of major natural disasters that might deforest the whole catchment), however, natural disturbances can disrupt this apparent smooth evolution and give shade intolerant trees the chance to persist (see, e.g. Deutschman et al., 1997).

Once we have the baseline forest established we introduce sets of households. One of the advantages of the individual/agent approach is that we can investigate the effect of environmental heterogeneity on the experiences of individual households. In order to focus on the way in which the dynamics of gathering takes place without other complications, we initially keep the forest static and neglect the hydrological component. We integrate the forest forward in time for 200 years until the peak stem density of the shade intolerant species so as to allow a realistic spatial distribution of trees to develop with a realistic distribution of stem sizes. We then freeze the forest model except for tree removal by resource gathering farmers. The effect is that the density of trees is slowly depleted around any household, necessitating a progressively longer-distance search each year in order to be sure of having adequate supplies in store. To begin with we introduce a single household that persists for several thousand years. Clearly this is not realistic, but the effect of a single household on a system of such a size is very small, so we allow for long-time persistence in order to be able to get a good measure of the effect. Once the household is in place, each household member (except for the household head) wanders at random through the landscape, stepping from cell to cell of the DEM, until enough wood has been discovered to supply the house at least for a year (whole trees are removed with dbh between 10 cm and 1 m), or until the trip length reaches between 20 and 30 km (1000 steps across the 20 m grid), at which point we assume that a whole day has been used and another household member must take over. This allows us to examine how the distribution of household labour involved in the search for resources is affected by resource depletion over time. We run the model up to 100 times in order to allow for stochastic variability in the random walk through the non-uniform pattern of tree-cover. We then examine how the heterogeneity of the environment affects households occupying different positions. We repeat the above single-household experiment progressively moving the fixed household location from 250 m into Northern end of the system up to 250 m from the Southern end in steps of 250 or 500 m.

Having established the single-house case, we can look at how the characteristics of the gathering process are affected by including several households. Again, the household population is kept static, and the forest is frozen at year 200. We examine the cases of between 2 and 40 households, with the houses placed randomly in the lower half of the catchment (consistent with the land-use pattern of Fig. 3), but with a preference for being closer to the Northern end (where the land is flatter and thus it is easier to establish fields). Competition for resources now affects the average gathering distance and labour required, but the spatial position of a household is also important in determining access to the forest resource. We are also able to examine the rate at which the resource is consumed and to compare this with the expected forest evolution timescale.

As a final experiment, we allow both the forest dynamics and the household population to vary, and feed the changing land-cover into the hydrological model. We introduce the households at three different times so as be able to check whether the evolutionary stage of the forest model affects the hydrological system. New agent

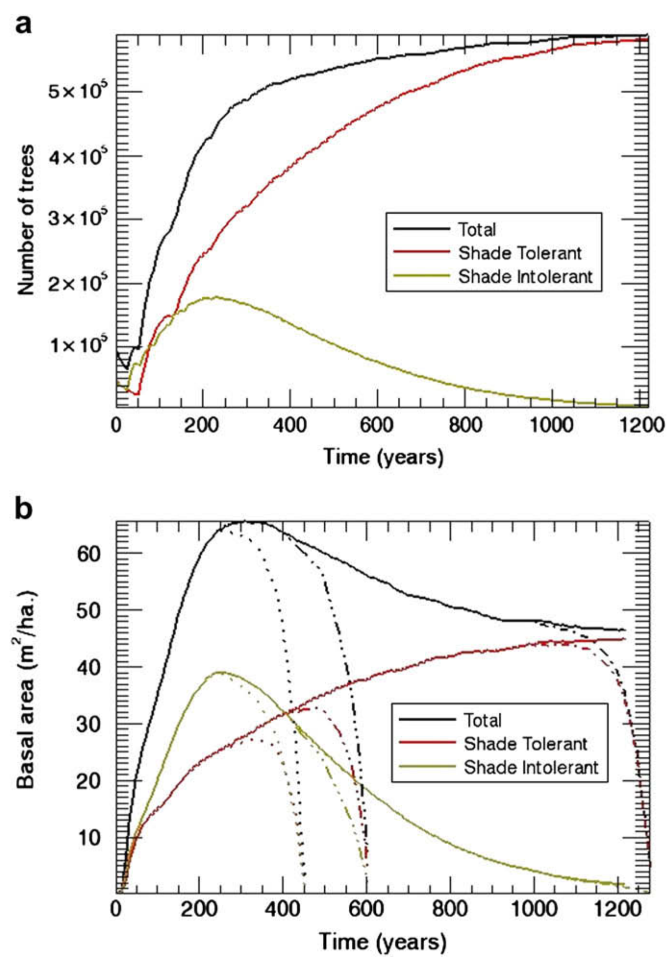

Fig. 4. (a) Tree numbers as a function of time. Note that the total number of trees eventually exceeds 500,000 even in this small catchment (approximate area 413 ha.). (b)Tree basal area per hectare. Solid lines show the case with no farming activity. After a peak of over 65 m^2/ha, the total declines to less than 47 m^2/ha even though the total number of trees continues to rise. Although shade intolerant trees are always less numerous after year 125, they continue to dominate the basal area (and thus the total available wood) until year 400. Dotted lines show the effect of including farming activity, with population size doubling every 30 years, introduced at year 250, dot triple-dash at year 400 and dot-dash at year 1000. In each case the catchment is cleared after 200 years as this is the timescale for all land to become entirely in use as fields.

households are created at a constant rate set to give a doubling of the household population every 30 years (equivalent to a growth rate of 2.3% per year) consistent with recent population increases in developing countries (e.g. Ives and Messerli, 1989; FAO, 1999). Each year a uniform *pseudo*-random number is generated in the range 0 to 1 for each existing household, and a new household is created if the value exceeds 0.023. This rate was chosen to give rise to a net exponential population increase but with some degree of variation. The rate of household increase is kept constant for 200 years, at which point virtually the entire valley is deforested (see below). We repeat the experiment with households introduced at year 200 a further eight times to look for any effects stochastic variability of the population increase on the destruction of the forest cover, and its hydrological effects.

4. Results

We begin by looking at the catchment when it is completely forested, assuming there to be no people present. Fig. 4 shows the timeseries of tree numbers and tree basal area density (area of the diameter at breast height, dbh, summed over all trees per hectare) for each of the two functional types and for all trees. These results are consistent with previous studies (Pacala et al., 1996; Chave, 1999), and indicate an initial rapid rise in the basal area reaching a peak near 65 $m^2\,ha^{-1}$ which then declines to an almost constant value or $\sim$46 $m^2\,ha^{-1}$. Notice, however, that the different functional types have very different long-term behaviour, with the shade intolerant pioneer species initially dominating the basal area (although not the number of stems), but gradually being replaced by the shade tolerant but more slowly dispersing trees. The qualitative form of this result is largely unaffected by initial conditions or the form of the allometric rules used to represent the forest (although the exact values may be affected both by this and by the initial conditions – see e.g. Pacala et al., 1996). The principal difference from Pacala et al. is that with only two types of tree, the shade intolerant species peak is at around 250 years, whereas this peak may be delayed to about 500 years when there is competition with other species. However, the peak in basal area occurs at much the same point, around year 300. Fig. 5 shows the time evolution of the spatial distribution of the trees as three snapshots separated by 200 years. Here we can again see the gradual replacement of shade intolerant by shade tolerant trees, as well as the tendency for functional types to be spatially correlated, with trees of similar type occurring together in stands. A further effect not included in Pacala et al. is the difference in shade that arises as a result of the high relief in the catchment. In Fig. 6 we show basal area, smoothed with a box-car average over 5 $\times$ 5 pixels (100 $\times$ 100 m) together with the North–South component of the catchment slope. As described in Section 2.3, we allow for local variations in elevation between cells to affect the shading of trees by their neighbours. The global effects of this can be seen in the spatial structure of tree density which follows the catchment slope, with higher density in the shallow-sloping lower reaches of the catchment. This effect, would be expected to make the lower altitude areas more favourable for farming, providing a better wood supply on less steeply sloping ground.

Now that we have a forest baseline, we can introduce the single household experiment. In the current case, the basal area gives a measure of the total fuel and fodder available to the farmers, so we delay the introduction of humans until the rapid rise in basal area is over. In Fig. 7a, b we show, for one model, run the total number of steps travelled by all the members of a single household as a function of time, and the number of household members involved in gathering, for a household 250 m from the Northern end of the catchment, introduced into the forest near year 200. We note that the fluctuations in trip length are very large, partly because many of the larger trees are able to supply the household wood requirement for an extended period, but also as a result of the inefficiency of random search – many journeys may involve wandering through areas where the useful trees have already been removed. In Fig. 7c we show the average of 100 runs of the model with a single household in the same location, with the 50-year running mean superimposed. Although the fluctuations are still large it can be seen that the increase in the mean number of steps with time is entirely linear (after a transient of about 1000 years, which occurs only this close to the Northern end of the catchment), as would be expected for a random walk (the distance that can be

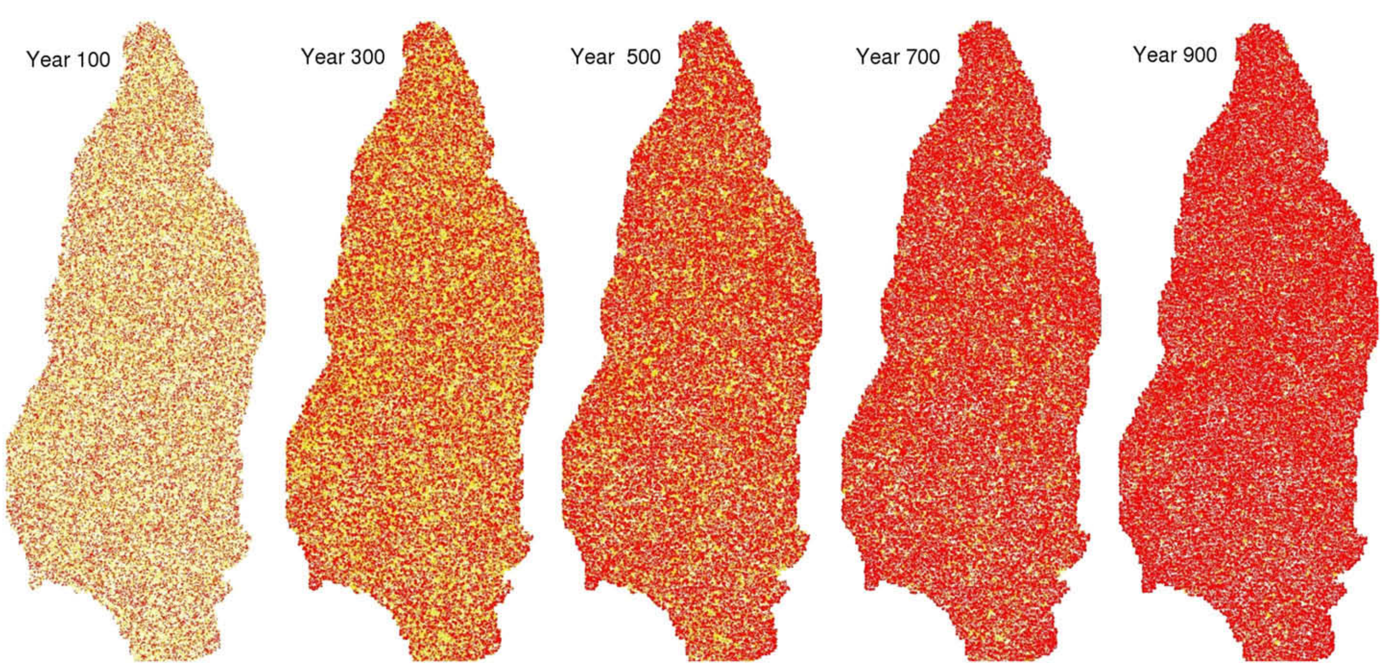

Fig. 5. Distribution of trees over time at 200 year intervals. Tree canopies have been drawn as filled circles with size equal to the tree canopy diameter, except where the diameter is less than 0.5 m. Shade tolerant trees are shown in red and shade intolerant in yellow. The general increase in tree basal area (since trunk diameter is proportional to canopy diameter) is visible, particularly between 100 and 300 years. Replacement of shade intolerant by tolerant trees is also clearly evident.

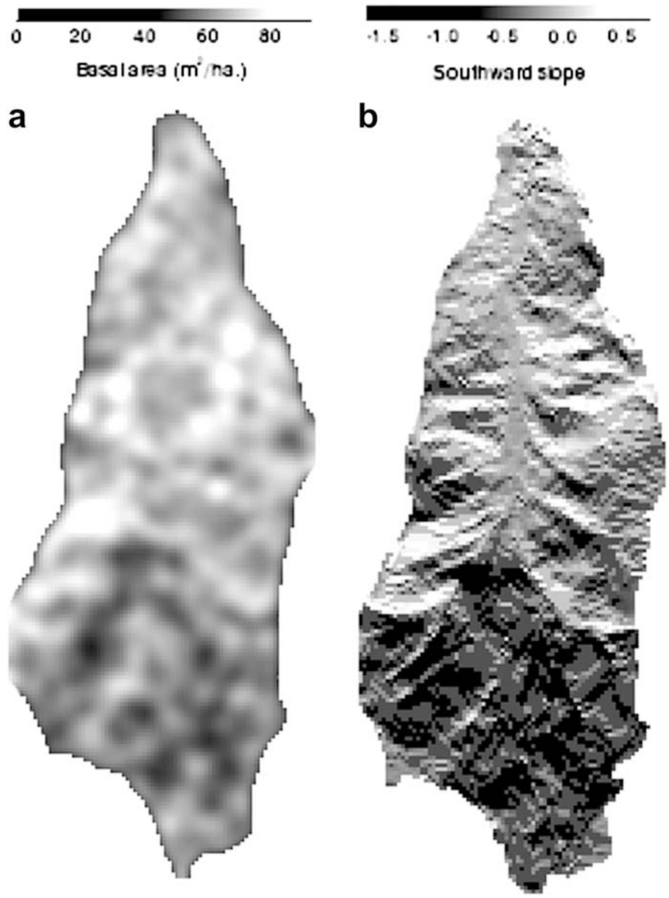

Fig. 6. (a) Tree basal area at year 300 smoothed over five pixels to eliminate small scale variations in tree density (b) North–South component of the catchment slope. Areas with negative values (dark) are north facing, and those with positive values south facing (light). The lower light levels in the southern part of the catchment where the slopes are more north facing, on average, leads to a lower mean tree density on scale of 100 m and larger.

reached from home increases as the square root of number of steps, so the *possible* area of search increases linearly with step number: however, the *required* search area increases linearly with time, as the region near the household gets depleted, but is still examined for the possible presence of useful trees). The mean number of household members involved in the search increases from 20% to nearly 60% over the time period (Fig. 7d). However, as Fig. 7b shows this involves years when the entire household is needed, as the depletion of trees near the household increases the difficulty of the search to the point where insufficient gathering is achieved until all household members have made long journeys through the landscape.

Now that the time dependence of gathering is known we can look at the effects of catchment shape and forest heterogeneity. In Fig. 8 we show the linear rate of increase of search distance with time as a function of position along the length of the catchment. Close to the Northern end of the system the constriction of the catchment leads to a rapidly increasing search distance with time, but this rate of increase drops as the household is moved up into the wider part of the system Thereafter the rate of search increases slowly as the tree density decreases in the higher part of the system (c.f. Fig. 6), until the effect the upper edge of the system begins to be felt at 250 m from the Southern end. However, although the position of the household within the landscape affects the individual households, the effect on the rate of forest consumption is negligible, with households removing an average of about five stems per year from the system.

Following on from the single household experiments, we can examine the effect of competition between households by again running the model with fixed forest, and a fixed number of households. In each case we now run the model 10 times for 300 years (this restriction being imposed by the increased run-time required as the number of households increases), with numbers of households from 2 to 40. The linear relationship obtained for a single household is progressively destroyed. By the time we have 30 households, the increase in search distance with time instead is exponential (Fig. 9a) – households have to search regions that have already been exploited by other farmers, but their ignorance of the area searched by others makes the process progressively more inefficient as the resource base is destroyed. Furthermore, the search distances also increase exponentially rapidly with the number of households (Fig. 9b). The heterogeneity of effects on households is even more severe than in the single household case – since the households tend to cluster in the lower part of the catchment, the houses near the narrowest part of the system experience much larger search distances than those adjacent to forest in the upper parts (by about a factor of 30 in the 30 household case). However, despite these non-linearities, since each household has a fixed requirement for wood per year, and the search process is ultimately successful, the number of stems removed per household per year remains fixed and close to five. On the other hand each household clears of order 1200 stems in order to create a field for planting crops. We assume that this first clearance only provides resource for a few years and cannot be stored long term (or else is used up in initial building projects to create the household). Given this very low rate of resource use, and that there are nearly half a million trees in the catchment, even 50 households would take over 1500 years to completely remove a static forest (including initial field clearances). For this reason we now turn to a case where the population is relatively rapidly increasing over time, but also allow the forest dynamics to operate in order to see whether tree seeding will compensate for a rapid population increase. We will also investigate the effect of the changes in land-cover on the hydrological properties of the system.

Since the forest model and hydrology are fairly expensive to run, we are now limited to relatively few repeats of the model runs. Three runs of the agent model were made introducing people at the peak of the shade intolerant tree basal area (at 250 years), at the cross over between the two types (at 400 years) and once the dominance shade tolerant trees was established (at 1000 years). The resulting rapid decline in both kinds of tree type is illustrated in Fig. 4b. Most of this effect is caused by the clearance of land for fields by the exponentially growing household population. The ratio between tree types is thus little affected by the presence of people as they clear land for farming irrespective of the type of tree and maintain the land cleared for the future. The gap filling shade intolerant species therefore have no opportunity to colonize cleared land and raise their numbers relative to the shade tolerant type (contrasting with Deutschman et al., 1997). Fig. 10 includes the effects of tree cutting by the growing population, showing the rapid stripping of the lower part of the catchment over a timescale of just over a hundred years. Eight repeat runs of the model with households introduced near year 200 gave a variability of this timescale between 175 and 250 years (not shown). Once the population reaches 80 households or so (equivalent to the 1995 population), most of the trees in the lower part of the catchment have been felled, reflecting the fact that a hectare of land is required to support each household. By year 200 there are few trees remaining except in the highest regions of the catchment, with the upper slopes being almost entirely converted to maize. This highlights an area of the model that requires development, namely the feedback between landscape processes and the social model – by the time the catchment became denuded, the cost of farming in the upper

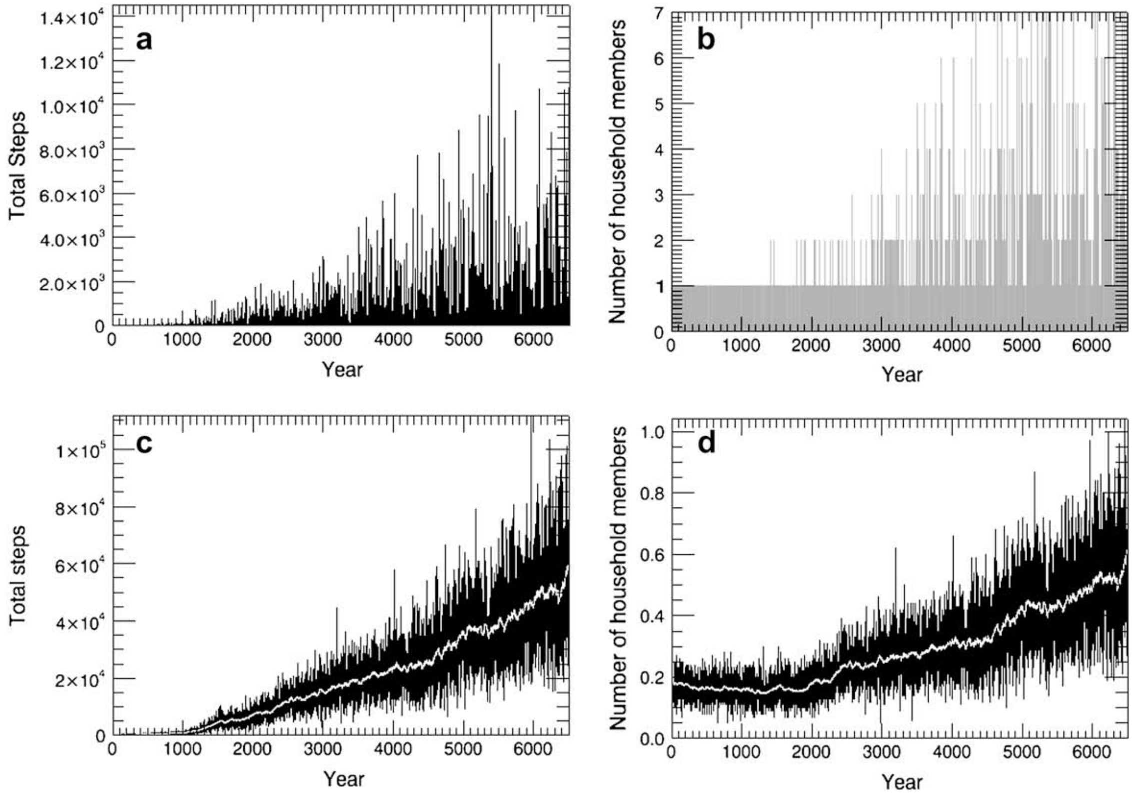

Fig. 7. (a) Total number of steps required each year required by one household to find sufficient wood in a static forest. The household is located 250 m from the northern end of the catchment and introduced after 200 years of forest evolution. Step lengths are between 20 and 30 m (depending on whether they are diagonal across the DEM grid). The integration is carried out for 6000 years in order to establish the long-time dependence of gathering, but this is of course well beyond the likely survival time of a single household in one location. (b) Number of household members involved in the gathering activity. (c) Total steps as a function of time averaged of 100 runs of the single house model, with the house in the same location. The initial transient up to year 1000 is a result of the very northernly position of the household and is not seen for other locations (which are linear from time zero). The 50-year running mean is superimposed in white to emphasize the late-time linear behaviour. (d) Time average number of household members involved in wood gathering over the 100 runs. Clearly only 20% of one person's time is required early on, rising to about 50–60% at late times, although Fig. 7b shows that on occasion all household members may be needed. The white line again shows the 50-year running mean.

regions and the lack of wood would most likely drive outmigration from the area in search of more suitable land, or at least force occupants of the region to search for resources beyond the boundaries of the catchment itself.

The hydrological model was run for a period of 200 years coincident with the introduction of the farmer agents. Simulations were undertaken for each of the farmer introductions (at 250, 400 and 1000 years), and for the eight repeat runs near year 200 mentioned above, although only small differences in the resulting hydrological dynamics were discernable – largely timing differences of up to 20% in the response of the annual water balance (Fig. 13). For the initial condition with no human populations, the spatial pattern of soil moisture during the monsoon period is closely tied to the topographic structure of the catchment as shown in Fig. 11a. This shows high soil moisture deficit (dry areas) on the interfluves and convex slopes where upslope area is low and hydraulic gradient is high with wetter areas downslope in the concave riparian zones. As the farmers are introduced, rice cultivation in the lower reaches of the catchment reduces the vertical hydraulic conductivity (due to hydraulic sealing) and the soil moisture distribution mirrors the growth of agriculture as shown in Fig. 11a (second map, after 100 years and fourth map, after 200 hundred years), with the soil moisture deficit highest under forest, lower under maize, and lowest of all under rice. This has direct consequences for the pattern of storm runoff, as shown in Fig. 11b which plots the predicted rainfall-runoff dynamics for a two-week period in August. As the population grows (from three households at $t = 0$, through 38 at 100 years to 337 at 200 years) the predicted storm period response becomes progressively more flashy. This reflects the changing balance of the simulated runoff components, with a greater proportion of surface runoff generated from the expanding cultivated areas (Fig. 12). These effects are manifest in the annual water balance, shown graphically in Fig. 13. The partitioning of the water balance (runoff and evapotranspiration) is strongly sensitive to the expansion of agriculture, with the loss of forest predicted to contribute to a 4% increase in total evaporative

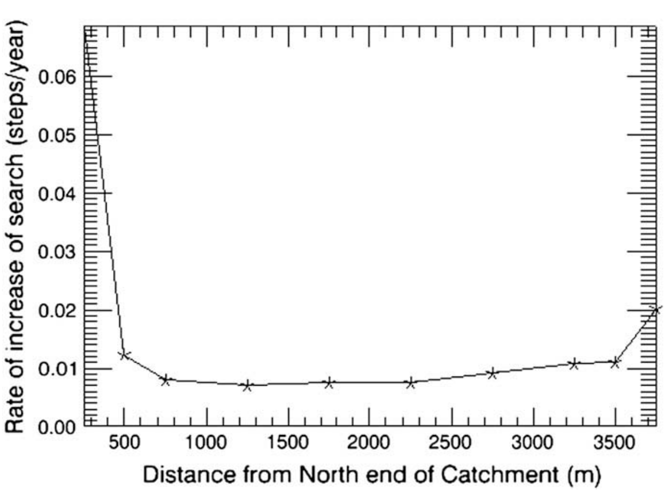

Fig. 8. Change in number of steps per year required by a single household to gather adequate resources from static forest as the position of the household is changed North to South along the catchment (with fixed near-central east–west position).

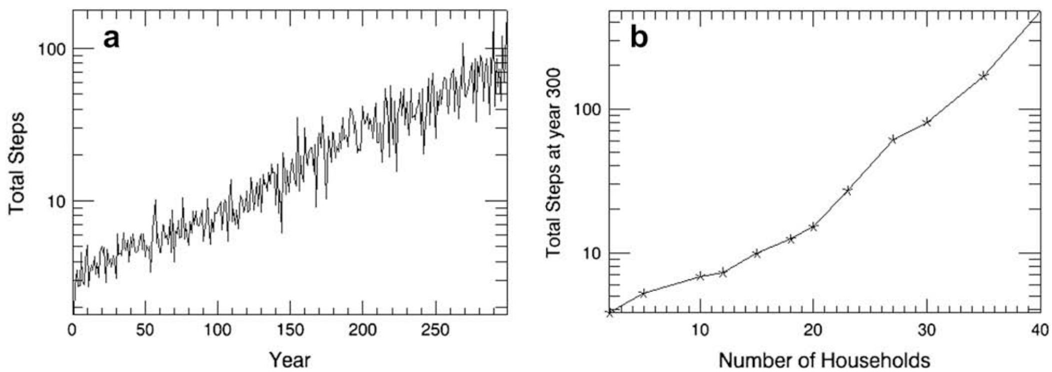

Fig. 9. (a) Log-linear plot of the total number of steps against time averaged over 10 model runs and then averaged over 30 households for fixed household locations in static forest. (b) Log-linear plot of the number of steps required to discover forest resources at year 300 against the number of households in the catchment.

losses, a 22% decrease in annual discharge and an 18% increase in the internal storage of water and loss to deep ground water. Evaporation (Fig. 13c) is closely linked to the pattern of rice cultivation, the extent of which peaks at 150 years. This land-use provides a large reservoir of water storage from which evaporation is drawn at the potential rate. However, at 150 years, all land below 1000 m is cultivated and the continuing growth of agriculture is accommodated by more water efficient maize production at higher elevations, offsetting the increase in evaporation.

5. Discussion

5.1. Model coupling

A number of authors have discussed the issues that arise when coupling together model from different disciplines: A short review of this can be found in Matthews et al. (2005). Various categorizations have been made of the degree to which the models are bound together, from simple file sharing between independently running programs, through a stage where there is some sharing of functionality, perhaps through a set of shared libraries, to full integration of code in which the various sub-models are combined into a single system (Antle et al., 2001; Westervelt, 2001; Hartkamp et al., 1999 and references therein). Here we will adopt the Antle et al. (2001) terminology of "loose-coupling" "tight coupling" and "integrated" for these three types of approach. Westervelt (2001) in particular gives a good summary of the trade-offs in terms of execution and integration speed, concurrency of sub-model operation, required programmer expertise, ownership/support of code and debugging issues that are likely to arise in each case.

On the other hand, Hartkamp et al. (1999) and Lau et al. (1999) discuss issues of data conformity and the need to make spatial representations (e.g. raster versus vector data types) and co-ordinate systems (such as differences in geographical projection) agree, and to match model spatial and temporal scales, if necessary through an appropriate interpolation method. We might call this a model *compatibility* issue – this is one which cuts across the three categories of loose, tight and integrated coupling, and has more

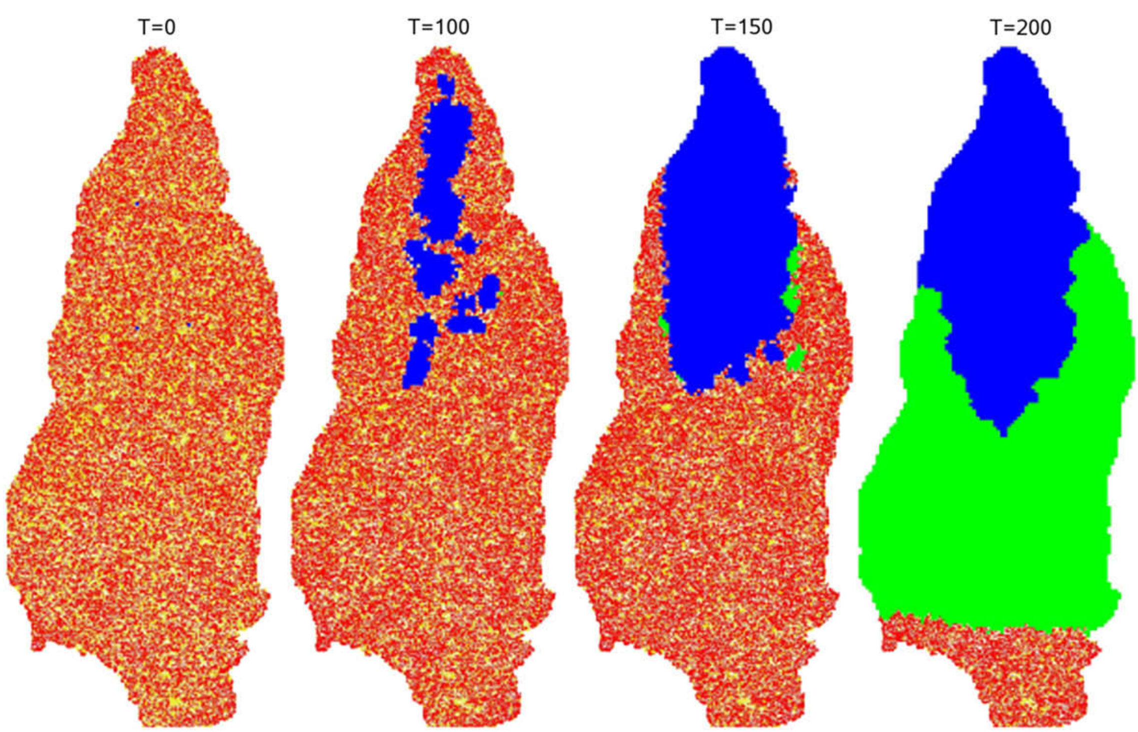

Fig. 10. Snapshots of land-use over time as the farmers begin to remove forest, in the case where removal begins at year 400. We show the initial state (three households), 38 households (after approx. 100 years), 122 households (after approx. 150 years) and 337 (after approx. 200 years). Note that the last of the four shows much more extensive cultivation of land than is the case in the observed catchment state (Fig. 3). Rice farms are coloured blue and maize farms bright green. Trees' colours as for Fig. 5.

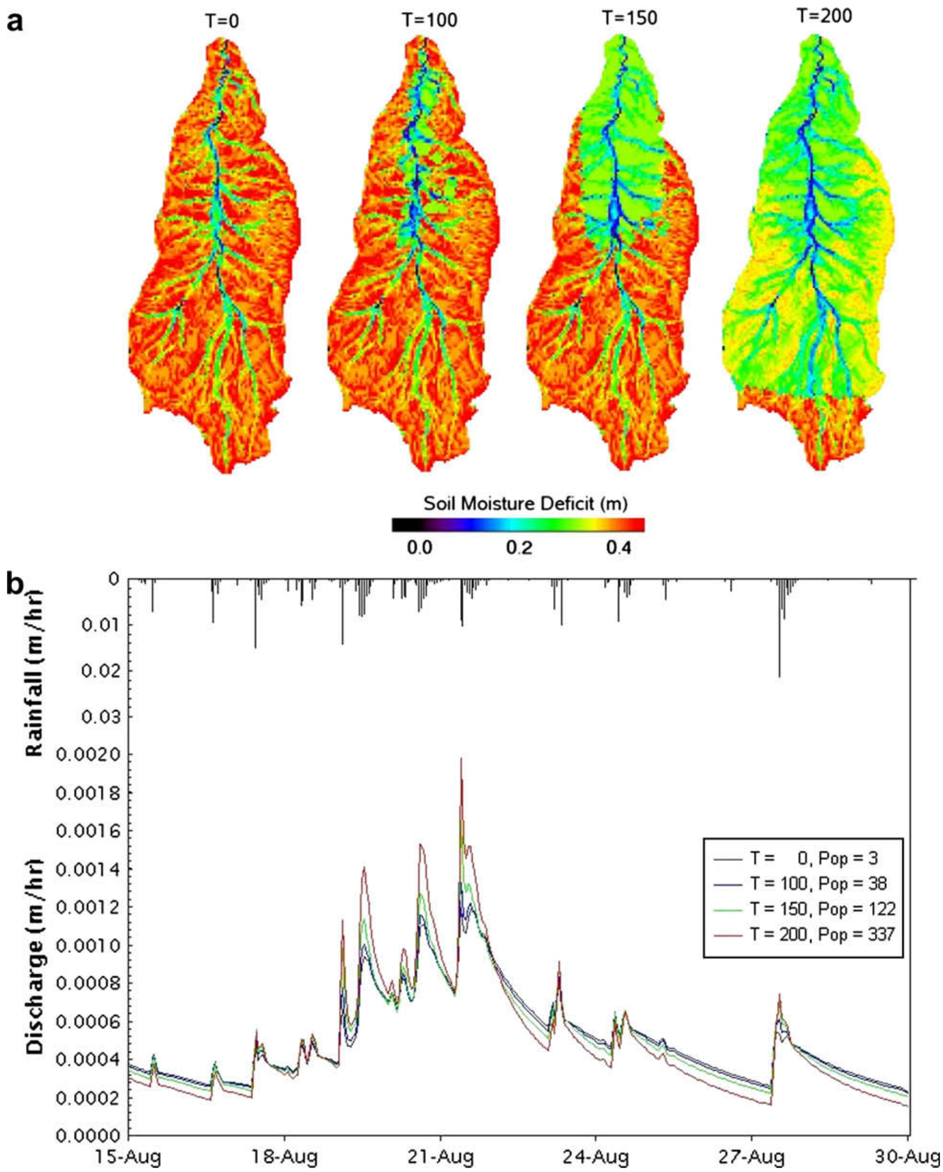

Fig. 11. (a) Soil moisture deficit maps (m) corresponding to the above land-use distributions at the peak of the monsoon period (hour 2872). (b) Modelled discharge for land-use distributions at $t = 0$, 100, 150 and 200 years for a central two-week period during the height of the monsoon.

ramifications than just the need to interpolate data sets from one system to another. Numerical stability is not only heavily algorithm dependent, but also depends on the space and time scales of at which the model is discrete, which is further coupled to the order of the numerical scheme and the implied accuracy of interpolation. If models with different stepping algorithms are naively combined, then serious stability issues might result. This is still a problem with techniques that seek to abstract the coupling between models to a shared or translatable ontology in an attempt to make it more independent of implementation language and internal details (Matthews et al., 2005; Mentges, 1999) – arbitrary perturbations of one model set of state variables by another with different order of time and space resolution and different time stepping may lead to unexpected problems. The implication is that even loose-coupled codes might need serious internal re-organization in order to work together properly. This view is re-inforced when one considers that many models may have been calibrated to work well at a particular spatial and temporal scale – interpolations to other scales may destroy the structures on which these models rely for validation and render coupling to another model useless (Antle et al., 2001; Lau et al., 1999). In the current case we are able to ensure compatibility between our different sub-models because we have access to the complete source code for each. In addition, the flexibility of agent or individual-based approaches minimizes the need to worry about spatial scales. Issues of time stepping and the appropriate temporal scales are still an issue however (see below).

In addition to the compatibility issue we should include as an extra refinement the *directionality* of coupling – in many cases it may be that the output from one sub-model serves as input to another, but that there is no feedback in the opposite direction. This may be entirely appropriate in process terms, or else may simply be expedient (in terms, for example of computational time), or necessary because there is insufficient data or knowledge about the feedback process to allow it to be incorporated. In the case of climate models, global-scale general circulation models are often used to provide boundary conditions for higher resolution regional models that may include more detailed physical processes or surface features. In principle this should produce feedbacks into the global scale model, but this is not done precisely because the processes running at the regional scale would be too expensive to

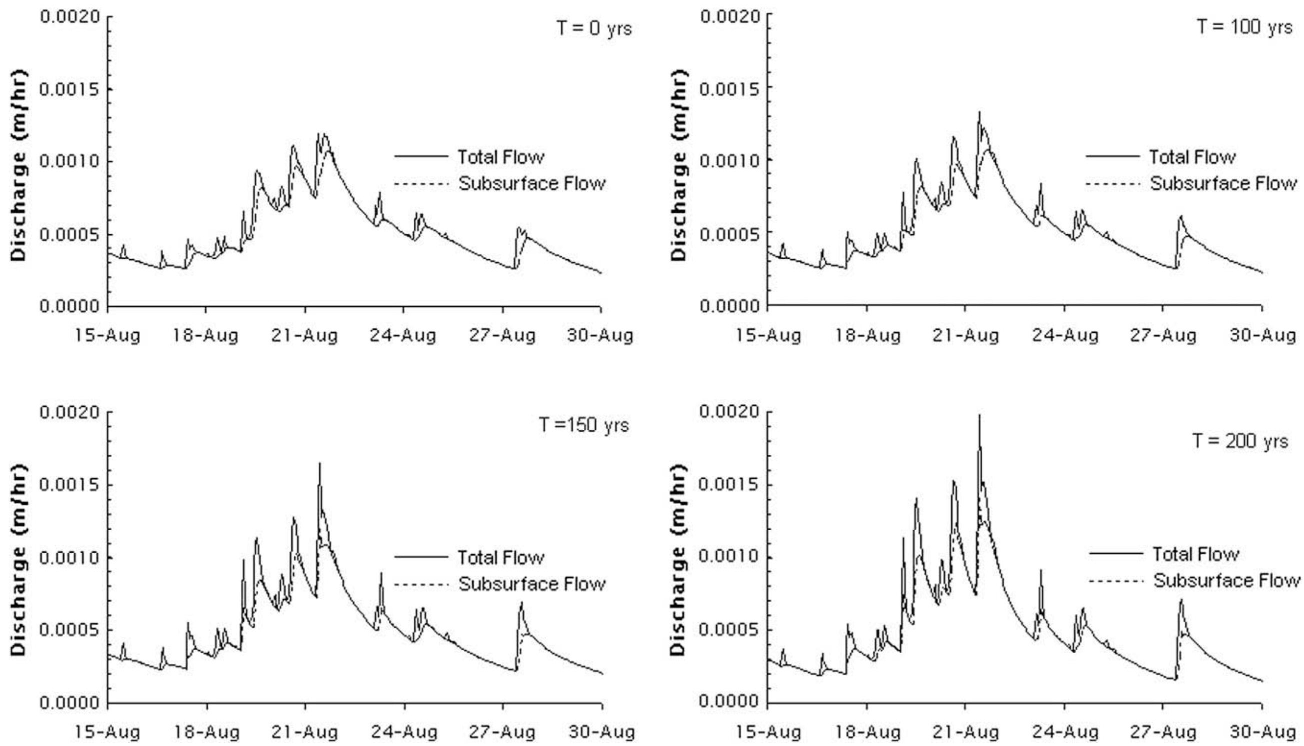

Fig. 12. Predicted surface and subsurface runoff contributions modelled for each of the runoff timeseries shown in Fig. 11.

model globally (see, e.g. Lau et al., 1999). This kind of one-way coupling may also be appropriate if there is significant scale separation temporally or spatially between the sub-models, such that feedback to larger scales, for example, take place on timescales that are very long compared to simulation scales of interest.

Where multiple sub-models are being joined, it may not be possible to apply the terms loose, tight or integrated across the full range of models. Spatially models might be fully integrated, but temporally loosely coupled. The join between two model components may incorporate full or partial feedback, even where they are integrated into a single code, but be uni-directional between another two. The model we present here is one that must be described as "mixed mode" coupling. Spatially, our agent-based farmers and individual-based trees are nearly fully integrated. Trees and people occupy the same landscape and are positioned using the same co-ordinate system, with the same spatial resolution (i.e. horizontal positions are arbitrary up to the accuracy of floating point numbers). People must travel across the landscape in order to access trees as individual entities, and this allows us to get a good representation of spatial search patterns. At the same time they interact directly with the trees, rather than with some derived quantity such as stem or wood-volume density. Temporally and physically, however, the coupling is loose. Wood gathering by farmers takes place daily and annually, whereas the trees have a 5-year timestep. The latter is partly to respect the timestep with which the original SORTIE forest model was designed, but also because the forest competition calculation is very expensive, and is the major bottleneck in running the code. However, it seems reasonable to suppose that there is a temporal scale separation here, in that trees develop sufficiently slowly that the behaviour of humans is effectively instantaneous, whereas the humans must wait for a long time before any trees develop to a state where they can perform a useful function. Physically the farmers do not navigate around the locations of the tree positions when moving across the landscape. Again this seems reasonable given that the tree density does not reach more than a few thousand stems per hectare (much less than one per square metre), at which level they will not form a serious obstacle to movement. Our inclusion of the hydrology must be referred to as unidirectional loose-coupling, although in one sense the coupling is close in that precisely the same DEM is used in the hydrological code as in the farmer and tree models. This ensures a compatibility between the sub-models. We

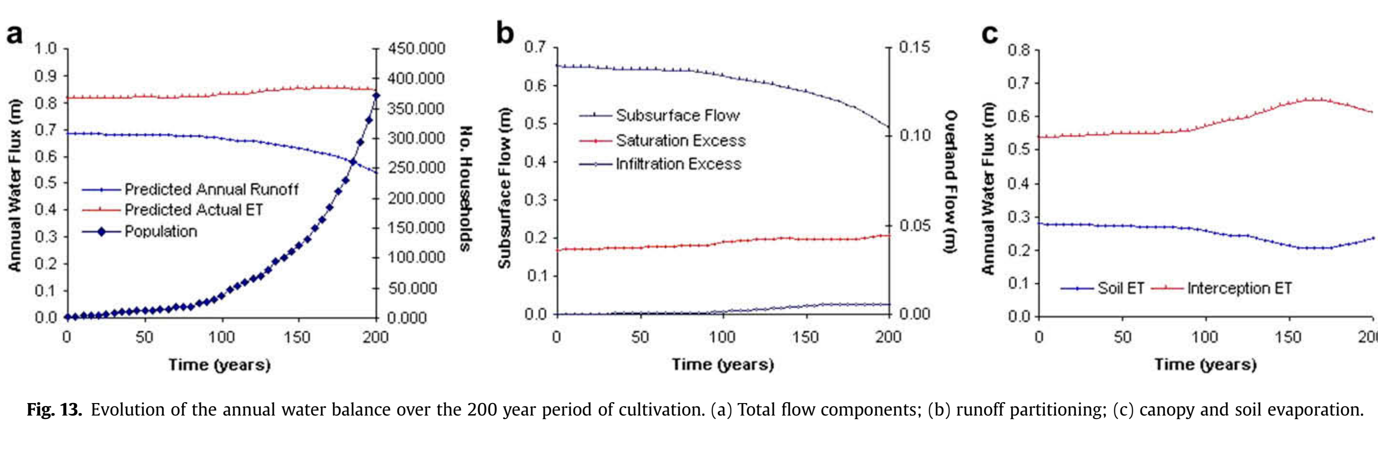

Fig. 13. Evolution of the annual water balance over the 200 year period of cultivation. (a) Total flow components; (b) runoff partitioning; (c) canopy and soil evaporation.

use the same 20 m raster grid for the DEM, to organize the spatial search with which farmers find trees, and to determine the height of the landscape when calculating tree shading (interpolated linearly to individual tree positions). In terms of resource gathering, we assume that the tree density prevents farmers from seeing further than 20 m on average through the forest, so that they must search one 20 m cell at a time in order to find resources. However, for coupling to the hydrology model we output a land-use in each cell (forest, rice or maize) to a land-use file and use this to drive the hydrology for a full year independently of the other sub-models. Again, we argue that temporal scale separation makes this reasonable. The hydrological time-step must be 1 h for numerical stability. Significant changes to the landscape are unlikely to take place at this kind of frequency, and indeed are much more likely to make a difference on a multi-year timescale. The slow and smooth annual rates of change of the results (Fig. 13) bear this out. On the other hand, flood events take place on a very short timescale and we need a short timestep to resolve them.

5.2. Further developments

In the process of making this model, we have elided a great deal of detail in order to set up a workable initial system. A number of improvements could be made straighforwardly to give a more realistic representation of a real situation.

In the first case we miss a significant feedback effect from the hydrology both to the trees and to the farmers. On the one hand increased intensity of discharge may make the catchment less tolerable place to live. On the other hand, the changes in soil moisture most likely should feed back into the forest model – however, using SORTIE we have no model mechanism via which this can take place. Trees are potentially sensitive to soil moisture, but on the other hand transpiration by trees can affect the soil moisture levels. A simple way to model the former would be to incorporate the soil moisture sensitivity into the tree death rate (e.g. Caspersen et al., 1999), but incorporation of transpiration would require some additional parameterization of tree physiology in order to estimate the rate of uptake from the soil under a range of climate conditions.

This last point underlines a further shortcoming, which is a lack of heterogeneity in catchment properties, either in terms of the rainfall distribution or the soil characteristics. Over such a small area, however, the spatial variabilities may not be very large. The lack of temporal variability is more of a worry. Changes from year to year in rainfall are a critical component for agricultural production (c.f. Ziervogel et al., 2005). This is further compounded by the fact that long term landscape changes may be experienced by householders in the form of short term flood events, with little predictability in their frequency of occurrence. Although the changes in the distribution of farming and forest are rather slow, taking place over years, the effects of this are felt in changes in the river discharge on timescales of hours – so the effects of slow changes would actually be experienced by residents of the area as sudden catastrophies. The likelihood of such extreme discharge events is dependent on global changes in the landscape – although the individual farmers are only clearing their own fields and gathering wood for their families, and some of the change in soil moisture is due to local soil compaction, the flow of water through the whole landscape is affected. This applies also to the nature of the land use – decisions by individuals to grow different crop types (here driven purely by the landscape itself) affect the way in soil moisture and discharge behave downstream. An analysis of the way on which climate fluctuations coupled to the hydrology could affect farm productivity (including probability of land instability and landsliding), and how this might interact with farmers anticipation of future climate would be informative (see, e.g. Bithell et al., 2006; Ziervogel et al., 2005 for a dryland case).

However, this emphasizes the further point that we do not have a true householder model. The inclusion of crop modelling, animal husbandry and a more detailed assessment of the use of forest products (in terms of heating, cooking, provision of shelter, and animal fodder) would be helpful here (see. e.g Matthews, 2006), as would a more realistic population dynamics, with an age structure for households, reflected in an appropriate division of labour. This would also allow us to study more carefully the effects of social preferences on choice of crop-type or of other activities that might be further coupled to the availability of local markets, both for the selling of surpluses or for the acquiring of materials that would otherwise have to be obtained from the landscape. The way in which these off-farm activities could affect the hydrological response of a catchment is not one that is routinely considered (but see Becu et al., 2001). This further brings to the fore the fact that we have no sociality in our model as it stands. Households do not exchange information, provide each other with help or support, or organize any joint processes at the catchment scale. We therefore have no possibility that social capital may contribute to the overall distribution of water resources within the system (see e.g. Lansing, 1999). At a simpler level, we have a very primitive representation of householders (our rules are purely abstract and only loosely based on notions of actual human behaviour). The very rapid and highly non-linear increase in competition for resources, for example, arises largely because of the inefficiency of blind random walk, without any reference to whether an area has been searched before, or whether a given direction of travel looks promising. The simple expedient of remembering the location at which a previous successful find was made, and travelling directly to this point from the house location before beginning a random walk has a dramatic effect on the search distance – compare Fig. 14, in which this simple addition of memory has been made, with Fig. 7a. Other adaptive strategies, such as co-operative search among household members, switching to different tree sizes, and cutting trees of a particular species could easily be added. However, we have also neglected the effects of the topography on the search process – in practice it is likely that in such a steep and highly dissected terrain the process of searching for resources would depend very strongly on direction of travel. This would also likely lead to the creation of a network of pathways through the forest that would facilitate the collection and retrieval of wood. As an extra component in this process we could also include not just the cost of the search process, but of the handling and transport of resources back to the household, which we have currently neglected.

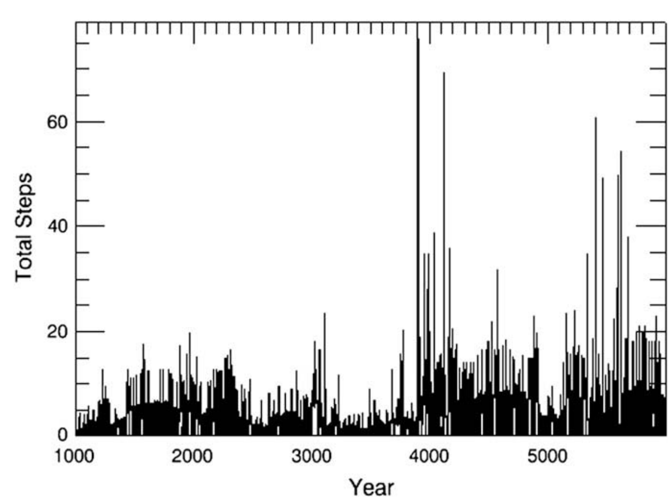

Fig. 14. Resource gathering including memory of the last location in which trees were successfully discovered. Single household in static forest 250 m from the north catchment end (c.f. Fig. 7a).

An extension of this would be to give the farmers awareness of, and sensitivity to, the effects of their resource collection on the forest. With the addition of in/out migration from the valley, we would have the potential to assess whether population pressure would really lead to complete destruction of the catchment forest cover – it is more likely that the difficulty of harvest and poorer tree availability in the higher part of the catchment would actually limit the local population growth unless the necessary forest products could be imported from outside the sub-catchment. Similarly while we have included the direct effects of land-use change on the hydrology in terms of the soil moisture deficit and can show quantitatively how the long term process of conversion from forest to field affects the flood frequency and magnitude at hourly timescales, the effects of land abandonment on landsliding and sediment delivery where soil moisture is enhanced (c.f. Vanacker et al., 2003) could be included. Also, although we have here only looked at the processes within a single sub-catchment, the changes in discharge (and by implication changes in sediment flux) may feed into a larger river system and possibly affect the livelihoods of other communities. Again, this is a dynamic process, involving co-operation between farmers, the economics of land maintenance and the structure of irrigation and drainage required for different crop types: effects which could be directly incorporated into the farm model (see, e.g. Becu et al., 2003).

Finally, we have given little consideration to the forest dynamics. Although the rate of landscape change is slow compared to the hydrological timescale for this catchment, when the population is increasing it is rapid compared to the dynamical timescale of forest evolution. We would expect the distribution of tree numbers and sizes to be affected by the pattern of resource gathering (see, e.g. Linderman et al., 2005), but in the current case the rapid increase in population does not give time for any dynamical processes in the forest to have an effect. So, the relative abundance of tree functional types is not influenced by the forest clearance process, with both types decreasing rapidly in abundance as the population rises. This effect is really one of population *density* increase, so we would expect similar kinds of effect on a larger scale where the population per unit area of forest is rapidly changing. The timescale on which the forest removal can take place implies either that this sub-catchment has not experienced rapid population increase, or has not been occupied for more than 100 years or so, or else that other processes not included here are operating to limit the rate of forest removal. In the latter case we would expect that the limitation of population would allow for long term evolution of the relative abundance of tree species, mediated by the rate of land use change or abandonment.

6. Conclusions

We set out in this paper to make a coupled model that would bring together three aspects of land-use change, namely hydrology, ecology and people. In particular we have looked at how the spatial patterns of forest clearance and accompanying land-use changes affect the way in which the flow of water takes place through steep topography. In doing so we have met with a number of challenges. In particular, as the number of model components increases, the difficulty of performing a comprehensive sensitivity study of the coupled system becomes prohibitive, not just simply because the computational time becomes long, but also because the parameter space to be explored becomes significantly larger, and the non-linearities of the coupled system may be different from those expressed by each model individually. In the current case, for example, the exponential increase in foraging time caused by interaction between the households, although likely an artifact of our simplistic agent search strategy, made model runs rapidly slower as the number of households was increased. The only way to deal with this particular case is to make a change to the model structure, rather than to further explore it in its current form. A further challenge that needs to be met is in the area of model validation when there are a number of coupled components that may change only on very long timescales. Most likely this can only be dealt with by making an ergodic hypothesis, in which a number of different cases are studied that are hopefully at different evolutionary stages, and can thus be used as a proxy for studying time evolution. However, the evolution of independent systems may be path dependent, so that the particulars of a given situation cannot be applied elsewhere, and systems may be sensitive to boundary conditions, which can clearly vary from place to place. The validation of model time variation is thus a particular problem, except for components such as stream discharge that vary relatively rapidly, and can be directly measured where the catchment under study is suitably accessible. These issues will continue to be a formidable barrier to the development of coupled land use models to a level where they become suitable for informing policy on issues of environmental management.

Acknowledgements

The anonymous referees are thanked for helpful and constructive comments on the paper.

Appendix

Model description following the ODD outline of Grimm et al. (2006).

Overview

Purpose

The purpose of the models is to understand how dynamical models of farmers, trees and hydrology interact.

State variables and scales

The model has three components – a grid-based hydrological model, an individual-based forest model and an agent-based farmer model. A uniform grid is used both for the elevation of the landscape and as a spatial search tool (similar to Bithell and Macmillan, 2006). The current model operates with a grid-scale of 20 m over a landscape of a few square kilometres. Individual trees and agents can take arbitrary locations, but use the grid to determine topography. In addition the farmers use the grid cells as the base units for allocating fields. Cells are given a feature class which is used by the hydrological model to determine parameters such as soil hydraulic conductivity and vegetation canopy capacity.

Fig. A1 gives a class diagram for the model (which is written in C++). The main state variables and methods are given for each class. In the case of the SORTIE model we refer the reader to Pacala et al. (1996) for the Allometric Parameters, and to Brasington et al. (1998) for the details of the hydrological model. In general x and y refer to the horizontal position co-ordinates of individual trees or people, which are independent of the digital elevation model (DEM) grid. The latter is rectangular and contains a cell object at each location where there is data, otherwise it is denoted as missing. Cells are containers that have a list of trees and a Boolean flag to indicate whether they are part of a farm (occupied). Lists of occupied cells are maintained by each household and denoted as fields. Each tree keeps track of its current cell, and each person keeps a pointer to the cell in which their household is located, as well as maintaining their current position, which may be anywhere on the terrain (other than inside "missing" cells). Trees are given a name to store which species they belong to, and a Boolean variable to denote whether they are alive (in principle this could be used to keep track of "dead wood", but here is simply used to allow

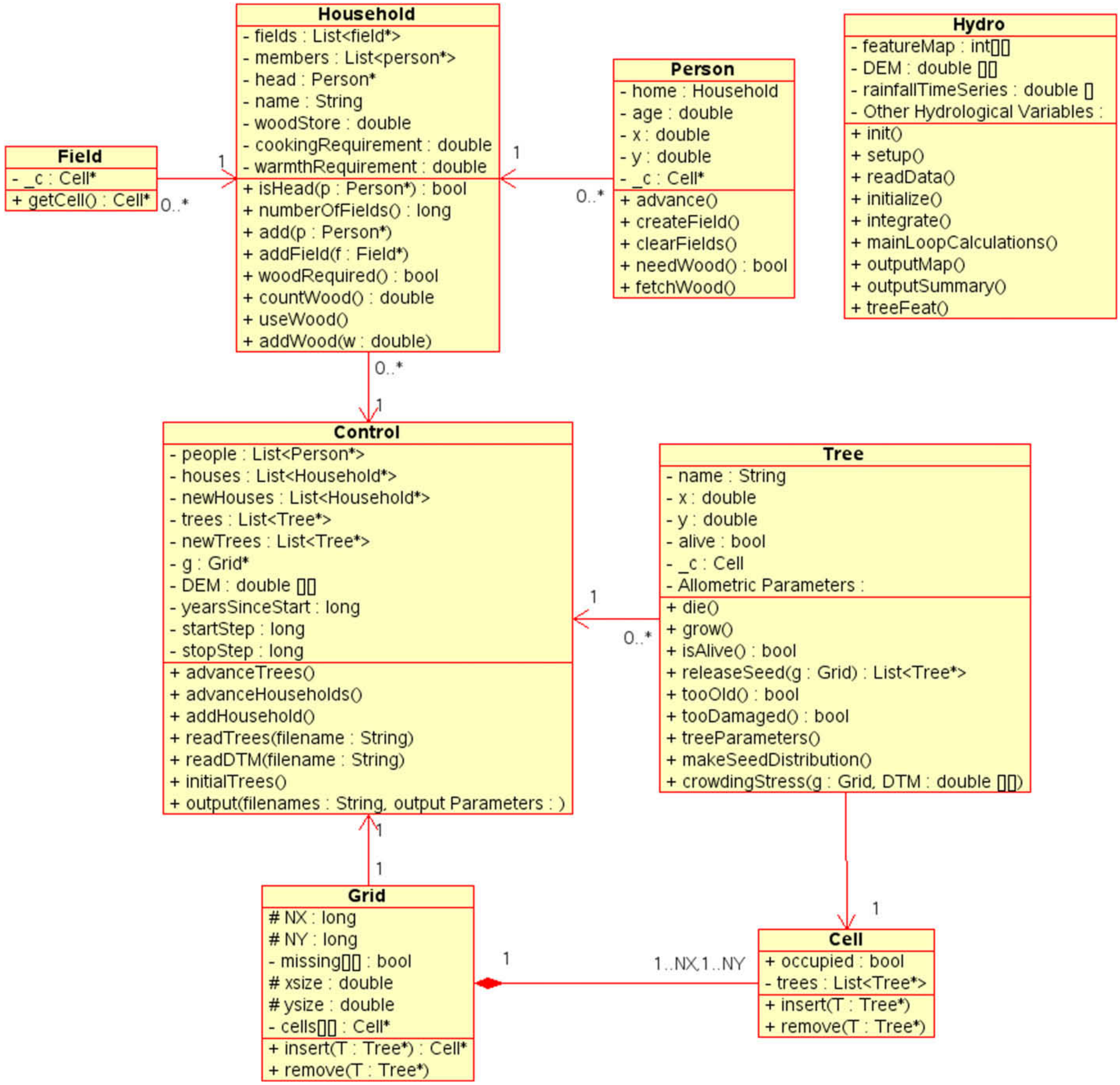

Fig. A1. Model class diagram.

trees either to die from natural causes, or to be killed by farmers, either to clear fields or during resource gathering). Each household has one person denoted as the household head, plus a wood-store and a set of requirements for the use of forest products. Each person keeps track of their own household and whether they are the head of household or not. The control class maintains a list of all trees houses and people in the model at any time, along with scheduling parameters, a pointer to the grid and DEM, and lists to store newly generated trees of households.

Process overview and scheduling

The model progress is entirely driven by the control class, of which only one instance is created at model start. The control class advances each of the households individually, to consume resources annually, and then each person is required to find new fields or clear those already occupied (household head) or else to make repeated trips in to the forest to gather resources (with trips of up to 20 km, up to one per day per person each year). Once every 5 years the forest model is updated. Land-use maps are generated at the end of each year and fed to the hydrological model, which then runs independently, with its own one hour timestep, for the entire year. Fig. A2 give an overview of the procedure as an approximate UML sequence diagram.

Design concepts

Agent and individual-based models

Historical, models that make computational simulations by directly representing each discrete entity in a population have been referred to as individual-based models in ecology, but as agent-based

Fig. A2. Model sequence diagram.

models in the social sciences. In principle there is little difference between the two. In both cases the properties at population level emerge as a consequence of interaction between the discrete entities in the model, both with each other, and with their environment. An agent model may have a sophisticated reasoning engine, cognitive and perceptual apparatus built in, allowing for adaptation of behaviour to a changing environment, but this is not a requirement, nor is it specifically ruled out in an individual-based model. However, it may be stretching a point to refer to trees as agents when most of their behaviour (at least in this model) is passive (there seems to be no real sense of "agency"), whereas the farmers actively clear fields and harvest trees, although they have in this case no real reasoning mechanisms and make little in the way of adaptation. Interaction is largely mediated by changes to the fields and forest indirectly affecting the access to resources that are available.

Heterogeneity

Although the agents and trees in the model are nominally identical when created, the differences in their local environments lead to variability – in the case of trees to changes in growth and death rates and thence to seeding, and in the case of farmers to resource access, and hence to required levels of labour input. Resulting differences in land-cover then feed into the soil moisture distribution and ultimately to differences in flooding and discharge.

Stochasticity

Locations of trees and houses, generation of new individuals, and search processes for field locations and for trees all vary randomly throughout. We select random numbers from a uniform random distribution where required. One point to note is that we do not, in the current paper, vary the numbers, sex or ages of household members – this might lead to significant further variability in the real-world case.

Details

Initialization

The first trees are located at random *x*,*y* positions within the landscape to give an average initial density of 175 stems per hectare, and alternately selected from each of the two species. The tree model is integrated forward in time for 2000 years on its own to give a baseline forest. Households are introduced at random locations into the lower half of the catchment and then random walk until they find an empty grid cell in which to establish a field. The first set of households may be introduced at any time into the baseline forest integration: thereafter the household number is held static, or else new households are generated from the existing population. The hydrological model soil moisture is initialized to give a plausible discharge before the rainfall data is added.

Input

Hydrology requires a rainfall time-series and a landcover map. The latter is derived from the land use categories of the agent model (forest, maize or rice).

Submodels

Hydrology. The simulation of rainfall-runoff dynamics can be undertaken through a wide range of modelling strategies (Beven, 2001). Here, with our focus on exploring the interrelationships between land-use, hydrological response and forest ecology we use the terrain based rainfall-runoff model of Brasington et al. (1998). We employ a three-dimensional cell model based on the regular grid discretization of the digital elevation model (DEM). Lateral subsurface flows are then represented using a simplified kinematic scheme, similar to that used in TOPMODEL (see Beven, 2001), while vertical soil moisture fluxes are determined using Philip's equation, parameterized according to land-use. Full details of the model are presented in Brasington et al. (1998) and only a brief review of the model structure is provided here.

Soil moisture accounting is performed for each grid-cell using a four layer model structure (Fig. A3). The upper layer represents water stored as interception on the vegetation canopy. Water can evaporate from this reservoir to satisfy the potential atmospheric demand or, if its capacity is exceeded, fall to surface where it is partitioned into surface runoff or infiltration into a near-surface root zone store, determined by the soil suction as represented by Philip's equation. Moisture in the root zone is subject to transpiration or percolation through the unsaturated zone to a shallow (saturated) ground water zone below. Within the saturated zone, lateral flows between adjacent cells are solved using a kinematic finite difference scheme, driven by the local hydraulic gradient. The elevation of saturated zone is then determined by solving the continuity equation for the vertical and lateral fluxes. If the saturated layer reaches the surface, exfiltration may take place. Surface water is then routed to the catchment exit using a distance-velocity based algorithm, in which flow pathways are derived from the DEM. Provision is made for leakage from the bottom of the saturated zone to deep ground water (i.e. a loss from the model at the base of the cell). Brasington et al. (1998) describe the calibration and validation of this model. In total the model has eight free parameters which can be lumped at the catchment scale, or varied spatially according to soil type or landuse. Calibration and testing of the model was undertaken with both lumped and land-use based parameterizations, the latter based on a relative scaling of soil hydraulic parameters based on field experimental data. The model was shown to be able to explain 68% of the variance in stream runoff during the complex monsoon period of 1992 and predict behavioural patterns of soil moisture consistent with the tensiometric records.

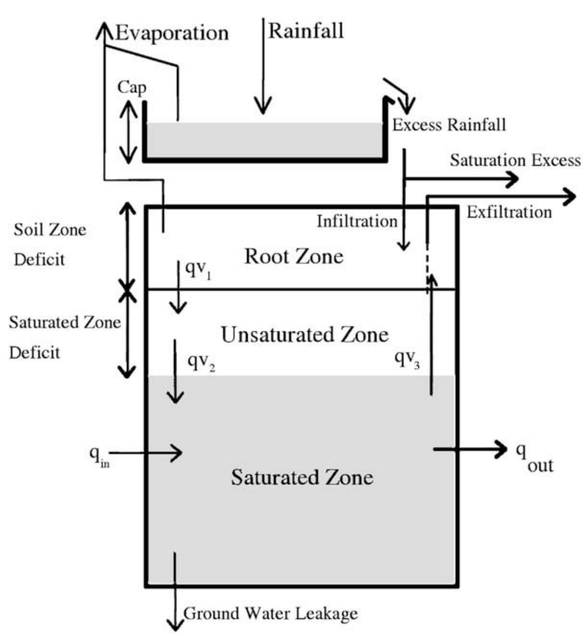

Fig. A3. Schematic representation of a single cell in the hydrological model. See Brasington et al. (1998) for a detailed description.

Forest. As mentioned previously, we represent every tree in the catchment and allow them to grow under a dynamic model of competition. We want to use a model that includes the spatial positions of trees explicitly so that farmer agents can find and harvest them. For this reason we will not use a gap model (see e.g. Kammesheidt et al., 2001), which does not keep track of the spatial position of trees, nor a model that places trees on a grid (such as TROLL – Chave (1999) – the relative merits of gridded versus free positioning of trees are discussed in Bithell and Macmillan (2006)). As a compromise we will make use of the SORTIE model for which code is available (Deutschman et al., 1997 – this has been re-cast into C++ from the original C) and for which there is a full description in Pacala et al. (1996). The model is one in which neighbouring trees reduce each other's growth and chances of survival by reducing access to light. The effect of moisture on tree growth, although potentially important, will not be included in the present work. The SORTIE model is set in the Great Mountain Forest of North America, and includes a parameterization of nine different species of tree. Tree growth is represented by the diameter at breast height (dbh), which is linearly related to the canopy diameter and is used to determine all other tree properties. Tree height (linearly related to canopy depth) is rapidly increasing with dbh for trees with small dbh, but saturates at some asymptotic height, depending on species or functional type. Trees produce seed proportionally to basal area, which disperses randomly away from the parent with a probability declining exponentially with the cube of distance. New trees can be placed freely (down to the resolution imposed by numerical truncation). Some canopy gaps are created by random death of trees at 1% death rate per year. Most importantly the growth rate decreases and death rate of saplings increases according to shading by other trees. Empirical extinction coefficients represent the optical depth to radiation of each tree, and the sum of optical depth of all canopies along the line of sight is used to compute the overall extinction in each solid angle of sky. This calculation of the shading is the most expensive part of the modelling process, but this is somewhat ameliorated by the long model timestep, which is set to 5 years.

Households. Households come into being fully populated with eight members able to forage immediately for food. One agent is designated as the head of the household. This person identifies an initial field and keeps it clear of trees. This discovery is limited initially to a random point in the lower half of the valley. The household head then moves up the valley randomly examining the cells in the DEM. When one is found to be free of occupation, the cell is marked as occupied and the agent searches for contiguous cells that are also unoccupied until the total cell area comes to one hectare. These cells are then marked as occupied and are thus not available for use by other agents. The effect of searching from the lower half of the valley is that the more desirable land (lower elevation, flatter terrain, better communications with regions outside the sub-catchment, higher tree density – see below) is occupied first, as seems to be the case in practice from the current land-use pattern (Fig. 3). Once a field is occupied it is assumed to produce enough food to feed a household of up to eight people in every year. In practice climate fluctuations from year to year are likely to render this improbable (see e.g. Ziervogel et al., 2005), but we do not consider this here. Fields below 1000 m elevation are assumed to be cultivated as rice paddy, and those above this level cultivated for maize, consistent with the observed pattern of land-use shown in Fig. 3. The hydrological parameter values for the different land-use types (forest, rice, maize) are given in Brasington et al. (1998).

Other agents in the household forage in the forest for fodder and fuel. Wood is kept in storage and used at a constant rate by the household equivalent to 1 m^3 of wood per capita per year. In a timestep, each agent in the household queries the wood storage and proceeds into the forest to gather wood if the amount in store is below the requirement for the household for the year, moving randomly from cell to cell until a tree of suitable size is located. Note that this is somewhat inefficient as the agents do not communicate their intention to gather wood to each other. Foraging agents wander randomly through the model domain, examining the trees in each cell as they go. Those trees that are between 0.1 and 1 m in diameter are considered useable and felled to be transported back to the household. In practice, trees may in fact be coppiced although this practice does lead to much reduced tree size (Stainton, 1972). The physical cost of search and transport is not currently included in the model (c.f. Vanacker et al., 2003; Linderman et al., 2005): in practice the desirability of the lower lying fields may be somewhat offset by the distance required to gather wood once much of the catchment is occupied. The coupling of agent activity to the hydrology is handled via changes in the canopy capacity and hydraulic conductivity as mentioned above.

References

Antle, J.M., Capalbo, S.M., Elliott, E.T., Hunt, H.W., Mooney, S., Paustian, K.H., 2001. Research needs for understanding and predicting the behaviour of managed ecosystems: lessons from the study of agroecosystems. Ecosystems, 4723–4735.

Axtell, R.L., Epstein, J.M., Dean, J.S., Gumerman, G.J., Swedlund, A.C., Harburger, J., Chakravarty, S., Hammond, R., Parker, J., Parker, M., 2002. Population growth and collapse in a multi-agent model of the Kayenta Anasazi in Long House Valley. Proceedings of the National Academy of Sciences U.S.A. 99, 7275–7279.

Barthel, R., Janisch, S., Schwarz, N., Trifkovic, A., Nickel, D., Schulz, C., Mauser, W., 2008. An integrated framework for simulating regional-scale actor responses to global change in the water domain. Environmental Modelling and Software 23, 1095–1121.

Becu, N., Perez, P., Barreteau, O., Walker, A., 2001. How bad isn't the agent-based model CATCHSCAPE. In: Rizzoli, A.E., Jakeman, A.J. (Eds.), Proceedings of the First Biennial Meeting of the International Environmental Modelling and Software Society. www.iemss.org.

Becu, N., Perez, P., Walker, A., Barreteau, O., Le Page, C., 2003. Agent based simulation of a small catchment water management in northern Thailand description of the CATCHSCAPE model. Ecological Modelling 170, 319–331.

Beven, K.J., 2001. Rainfall-Runoff Modelling: The Primer. Wiley.

Bithell, M., Macmillan, W., 2006. Escape from the cell: spatially explicit modelling with and without grids. Ecological Modelling 200, 59–78.

Bithell, M., Brasington, J., Richards, K., 2006. Discrete-element, individual-based and agent-based models :tools for interdisciplinary enquiry in geography? Geoforum, doi:10.1016/j.geoforum.2006.10.014.

Bharwani, S., Bithell, M., Downing, T.E., New, M., Washington, R., Ziervogel, G., 2005. Multi-agent modelling of climate outlooks and food security on a community garden scheme in Limpopo, South Africa. Philosophical Transactions of Royal Society of London Series B 360, 2183–2194.

Bousquet, F., Le Page, C., 2003. Multi-agent simulations and ecosystem management: a review. Ecological Modelling 176, 313–332.

Brasington, J., 1997. Monitoring and modelling hydrological response and sediment delivery in heterogeneous highland catchments. Unpublished Ph.D. Thesis, University of Cambridge, 478 pp.

Brasington, J., El-Hames, A., Richards, K., 1998. Hydrological modelling in humid tropical catchments. In: Harper, D., Brown, A. (Eds.), The Sustainable Management of Tropical Catchments. John Wiley & Sons Limited, Chichester, pp. 313–336.

Brasington, J., Richards, K., 1998. Interactions between DTM scales and parameters for TOPMODEL. Computers and Geosciences 24, 299–314.

Brasington, J., Richards, K., 2000. Turbidity and suspended sediment dynamics in the Nepal Middle Hills. Hydrological Processes 14, 2259–2274.

Caspersen, J.P., Silander Jr., J.A., Canham, C.D., Pacala, S.W., 1999. Modelling the competitive dynamics and distribution of tree species along moisture gradients. In: Mladenoff, D.J., Baker, W.L. (Eds.), Spatial Modelling of Forest Landscape Change: Approaches and Applications. CUP.

Chave, J., 1999. Study of structural, successional and spatial patterns in tropical rain forests using TROLL, a spatially explicit forest model. Ecological Modelling 124, 233–254.

Christiansen, H.J., Altaweel, M., 2006. Simulation of natural and social process interactions. Social Science Computer Review 24, 209–226.

Doran, 2001. Intervening to achieve co-operative ecosystem management: towards an agent-based model. Journal of Artificial Societies and Social Simulation 4 (2). http://www.soc.surrey.ac.uk/JASSS/4/2/4.html.

Deutschman, D.H., Levin, S.A., Devine, C., Buttel, L.A., 1997. Scaling from trees to forest: analysis of a complex simulation model. Science 277, 1684.

Evans, T.P., Kelley, H., 2004. Multi-scale analysis of a household-level agent-based model of landcover change. Journal of Environmental Management 72, 57–72.

FAO, 1999. FRA2000 Forest Resources of Nepal, Country Report Forest Resources Assessment WP 016, Rome 1999. Forestry Department, Food and Agriculture Organization of the United Nations.

Gardner, R., Jenkins, A., Ormerod, S., 1995. Land-use, Soil Conservation and Water Resource Management in the Nepal Middle Hills. Royal Geographical Society, London. Report No 2.1–2.9.

Gilbert, N., 2007. Agent-based Models. In: Series: Quantitative Applications in the Social Sciences, vol. 153. Sage Publications.

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S.K., Huse, G., Huth, A., Jepsen, J.U., Jørgensen, C., Mooij, W.M., Muller, B., Pe'er, G., Piou, C., Railsback, S.F., Robbins, A.M., Robbins, M.M., Rossmanith, E., Ruger, N., Strand, E., Souissi, S., Stillman, R.A., Vabø, R., Visser, U., DeAngelis, D.L., 2006. A standard protocol for describing individual-based and agent-based models. Ecological Modelling 198, 115–126.

Gustafson, E.J., Shifley, S.R., Mladenoff, D.J., Nimerfro, K.K., He, H.S., 2000. Spatial simulation of forest sucession and timber harvesting using LANDIS. Canadian Journal of Forest Research 30, 32–43.

Hartkamp, A.D., White, J.W., Hoogenboom, G., 1999. Interfacing geographic information systems with agronomic modeling: a review. Agronomy Journal 91, 761–772.

Ives, J.D., Messerli, B., 1989. The Himalyan Dilemma: Reconciling Development and Conservation. United Nations University Press, The United Nations University, Tokyo, Japan.

Kammesheidt, L., Kohler, P., Huth, A., 2001. Sustainable timber harvesting in Venezuela: a modelling approach. Journal of Applied Ecology 38, 756–770.

Lansing, S.J., 1999. Anti-chaos, common property and the emergence of co-operation. In: Kohler, T., Gumerman, G. (Eds.), Dynamics in Human and Primate Societies. OUP.

Lau, L., Young, R.A., MvKeon, G., Syktus, J., Duncalfe, F., Graham, N., McGregor, J., 1999. Downscaling global information for regional benefit: coupling spatial models at varying space and time scales. Environmental Modelling and Software 14, 519–529.

Linderman, M.A., An, L., Bearer, S., He, G., Ouyang, Z., Liu, J., 2005. Modelling the spatio-temporal dynamics and interactions of households, landscapes and giant panda habitat. Ecological Modelling 183, 47–65.

Matthews, R., 2006. The People and Landscape Model (PALM): towards full integration of human decision-making in biophysical simulation models. Ecological Modelling 194, 329–343.

Matthews, R.B., Polhill, J.G., Gilbert, N., Roach, A., 9–12 December 2005. Integrating agent-based social models and biophysical models. In: Proceedings, MODSIM Conference, Melbourne, Australia.

Matthews, R., Selman, P., 2006. Landscape as a focus for integrating human and environmental processes. Journal of Agricultural Economics 57, 199–212.

Matthews, R.B., Gilbert, N.G., Roach, A., Polhill, J.G., Gotts, N.M., 2007. Agent-based land-use models: a review of applications. Landscape Ecology 22, 1447–1459.

Mentges, E., 1999. Concepts for an agent-based framework for interdisciplinary social science simulation. Journal of Artificial Societies and Social Simulation vol. 2 (2). http://www.soc.surrey.ac.uk/JASSS/2/2/4.html.

Monticino, M., Acevedo, M., Callicot, B., Cogdill, T., Lindquist, C., 2007. Coupled human and natural systems: a multi-agent-based approach. Environmental Modelling and Software 22, 656–663.

Richards, K., Bithell, M., Dove, M., Hodge, R., 2004a. Discrete element modelling: methods and applications in the environmental sciences. Philosophical Transactions of Royal Society of London A 362, 1797–1816.

Richards, K., Bithell, M., Bravo, M., 2004b. Space, time and science: individuals, emergence and geographies of space and place. In: Matthews, J.A., Herbert, D.T. (Eds.), Unifying Geography: Common Heritage, Shared Future. Routledge, London, pp. 327–352.

Pacala, S.W., Canham, C.D., Saponara, J., Silander, J.A., Kobe, R.K., Ribbens, E., 1996. Forest models defined by field measurements: estimation, error analysis and dynamics. Ecological Monographs 66, 1–43.

Parker, D.C., Manson, S.M., Janssen, M.A., Hoffmann, M.J., Deadman, P., 2003. Multi-agent systems for the simulation of land-use and land-cover change: a review. Annals of the Association of American Geographers 93, 314–337.

Shah, P.B., Schreier, H., Brown, S.J., Riley, K.W., 1991. Workshop on Issues in Soil Fertility and Erosion in the Middle Mountains of Nepal. Integrated Survey Section, Topographical Survey Branch, Kathmandu, Nepal.

Stainton, J.D.A., 1972. Forests of Nepal. John Murray Ltd., London.

Vanacker, V., Vanderschaeghe, M., Govers, G., Willems, E., Poesen, J., Deckers, J., De Bievre, B., 2003. Linking hydological, infinite slope stability and land-use

change models through GIS for assessing the impact of deforestation on slope stability in high Andean watersheds. Geomorphology 52, 299–315.
Westervelt, J.D., 2001. Geographic information systems and agent-based modelling. In: Gimblett, H.R. (Ed.), Integrating Geographic Information Systems and Agent-based Modeling Techniques. OUP, pp. 83–104.
Wooldridge, M.J., 2001. Introduction to Multi-agent Systems. John Wiley & Sons Limited, New York, 376 pp.
Ziervogel, G., Bithell, M., Washington, R., Downing, T., 2005. Agent-based social simulation: a method for assessing the impact of seasonal climate forecast applications among small-holder farmers. Agricultural Systems 83, 1–26.