HYDROLOGICAL SENSITIVITY TO PROGRESSIVE DEFORESTATION IN A TROPICAL MONTANE ENVIRONMENT

M. Mulligan[1], J. Rubiano[2] and M. Rincon-Romero[1]
[1]Department of Geography, Kings College London, Strand, London, WC2R 2LS, UK. mark.mulligan@kcl.ac.uk
[2]Hillsides Programme, International Centre for Tropical Agriculture (CIAT), A.A. 2713, Cali, Colombia.

Tropical mountainous environments (TMEs) are one of the most rapidly changing environments on earth. With increasing population pressure in many countries, the agricultural frontier is moving rapidly into TMEs. By virtue of their topography TMEs are extremely spatially variable environments climatically, geologically and biologically. This variability means that the hydrological and other impacts of deforestation in these environments will also be highly spatially variable. Steep slopes and high density drainage networks mean that impacts are likely to be higher in magnitude and greater, though more variable, in areal extent than the lowland equivalent.

This paper uses a simple cellular model for deforestation at the agricultural frontier in TMEs to examine potential patterns of land use change in areas where there are large influxes of population. Experiments are carried out with an advanced GIS-based dynamic hydrological model to understand the impact of a simulated advancing agricultural frontier in the Tambito experimental catchments in south west Colombia.

The distributed hydrological model is integrated twice for 50 separate iterations of the land use change model. As the agricultural frontier replaces forest with pasture or bare soil in the Tambito catchment, the sensitivity of the hydrological system shows a non-linear response to each unit of land use change. This indicates that the *pattern* of change, in terms of the location of the deforested areas, is important as well as the *magnitude* of land use change. Some hydrological variables show an increasing sensitivity as more of the catchment is deforested whilst other show more complex patterns. Runoff and erosion are particularly sensitive to land use change though this sensitivity is only exhibited beyond a critical threshold of 75% deforestation. Below 75% deforestation the impacts on runoff and erosion are small but beyond 75% deforestation, even the smallest additional land use change can have serious hydrological consequences. This indicates that, even small areas of forest play an important role in catchment hydrology in TMEs, especially for variables, which accumulate along lines of drainage direction like runoff and erosion.

BACKGROUND : LAND USE CHANGE IN TMEs

Land use change in the tropical lowland forest is much discussed in the hydrological literature from the perspective of climate change (Shuttleworth et al., 1990; Shukla et al., 1990), water yield (Bosch and Hewlett, 1982), flooding (Hsia, 1987), sediment yield (Wiersum, 1984), and nutrient budgets (Bruijnzeel and Wiersum, 1985). Much less impacts research has been carried out in tropical montane cloud forest (TMCF) though these ecosystems too are being converted to pasture at an estimated rate of 1.1% per year - greater than that reported for lowland forests (FAO, 1993). Only 10% (Castaño, 1991) of the Colombia's TMCF remains as a result of heavy settlement of population in the Andean region between 1500 and 3000m. Though this accounts for only 3% of the area of the country, TMCF is rich in both hydrological and biological resources. They are one of the least hydrologically understood ecosystems of the humid tropics (Bruijnzeel and Proctor, 1995).

Though deforestation in the tropical lowlands will have important implications for lowland hydrology and soil erosion, other impacts, for example, loss of biodiversity and mesoscale climatic effects are likely to be much more significant in these systems. In the tropical mountains as a result of steeper slopes and higher rainfall inputs, along with their locations at the hydrological source for the lowlands there are likely to be much greater hydrological impacts resulting from land use change. A simple analysis of the widely used erosion equation of Thornes (1990); Thornes and Brandt (1993) indicates the potential significance of the tropical hillsides as areas of extreme soil erosion and as source areas for sediment. According to this model, erosion increases as a power function of slope with an exponent of 1.66. Where vegetation cover is less than 30% erosion will increase dramatically as a function of slope. This notion is widely supported by field and experimental studies (Morgan, 1978; Quine and Walling, 1993;).

On this basis alone one may expect much greater impacts of deforestation on soil erosion in the tropical hillsides than in the tropical lowlands. Slope angles in TMEs can be very steep. Even with the smoothing of land surface contours which occurs as a result of the production of digital elevation models (DEMs), at 25m resolution, slopes of >40° are not uncommon in parts of the Pacific slopes of the Colombian Andes. The distribution function for slope angles in the Tambito experimental catchments is normally distributed around a mean of 30.7° with a standard deviation of 8.5°. Slopes range from a minium of 0° to a maximum of 68°.

THE TAMBITO EXPERIMENTAL CATCHMENTS

The Tambito experimental catchments are located close to the agricultural frontier on the Pacific slopes of the Western (Occidental) Cordillera of the Colombian Andes in the Department of Cauca, Colombia (2°30.4'N 76° 59.9' W, see Figure 1). The catchments vary between, 1374 and 2894 masl, in an area covering only 5.5 by 4.1 Km (1424 Ha.). The catchments include two sub-catchments, the Palo Verde, which is largely primary forest and the Tambito which is a mixture of primary forest, secondary forest and pasture. The subcatchments have similar slopes, geologies, soils and aspects. A manual floristic survey of the catchments in 1996 indicated a cover of 861 Ha. of primary forest, 527 Ha. of secondary forest and 36 Ha. of pasture in the two catchments (Cortes, 1996). The forest is classified as sub-Andean tropical montane cloud forest, which differs from lowland forest in structure as well as composition. TMCF has low stature, an abundance of epiphytes and high standing dead biomass. Xerophytic features are sometimes present and may reflect the high levels of UV radiation received at these altitudes.

Since 1997 the Tambito catchments have been the subject of an intensive hydrological monitoring, experimentation and modelling effort which has included the installation of automatic monitoring stations, the development of a GIS database and various catchment-wide studies to quantify the spatial variability of soil and vegetation properties.

HISTORICAL LAND USE AND LAND USE CHANGE IN TAMBITO

The historical land use of the Tambito catchments is complex. Tambito means 'small market' and the site was almost certainly a stopover on the route from the Pacific lowlands to the markets of El Tambo and Popayan throughout this century. The pasture and secondary forest areas of the catchments are a relic of this legacy. There is also evidence of small-scale timber removal by Carton de Colombia at the head of the Palo Verde catchments but the very steep terrain and poor communications ensured that this was a very small-scale exercise. For 20 years the area has been a reserve of the University of Cauca and Fundacion Proselva and parts of the secondary forest have developed in this time. The area currently under pasture remains as pasture due to frequent cutting and grazing by horses used to transport food and materials into and out of the reserve.

Apart from these small scale impacts it is likely that much of the remainder of the catchments are primary forest that have undergone only very light selective logging near to the main rivers for timber to produce paths, houses and bridges. The absence of large trees in the catchments reflects frequent treefall triggered by heavy rainfall or occult precipitation events followed by moderate winds. Treefall is common, with an increased frequency of treefall for steeper slopes and older trees that tend, not only to be larger, but also to contain a heavy dressing of epiphytic vegetation and greater mass of standing dead biomass. The forest is poorly vertically structured since much of the light input is from the sides as well as the top.

A SIMPLE CELLULAR MODEL FOR LAND USE CHANGE AT THE AGRICULTURAL FRONTIER

A number of researchers have examined the impact of land use change on hydrological processes in the tropics through field monitoring (Richardson, 1982), field experimentation (Roche, 1981; Hewlett and Fortson, 1983) and numerical modelling (Vugts and Bruijnzeel, 1988, Shuttleworth, 1990). Though the detail is complex the general conclusions of this research indicate that 'removal of forest leads to higher streamflows' (Bruijnzeel, 1990). Because of the level of instrumentation necessary very little research has been carried out to look at impacts on stores and fluxes other than streamflow, for example soil moisture, runoff and recharge. As a result the exact mechanism (*i.e.* higher baseflow, higher runoff, or both) that produces higher streamflows in deforested areas is unclear. The intention of this paper is not to add to the debate of the wide ranging hydrological impacts of land use change in the humid tropics but rather to examine the importance of the *pattern* of deforestation as a moderator of hydrological impact. As used here pattern refers both to:

(a) the spatial location of deforestation relative to varying catchment properties such as rainfall, temperature and position in the drainage network,
(b) the spatial form of deforestation for example clustered, corridor, frontier, trellised, dendritic -see Lambin (1994,1997).

In order to understand the hydrological significance of the pattern of deforestation, we produce a scenario for the pattern of deforestation and then apply every iteration of this scenario as the vegetation cover for integration of a distributed hydrological model. The model for land use change used here is a cellular automata designed specifically for the purpose. The cellular automata model uses only a DEM, an initial land use map and maps of the network of rivers and roads. The cellular automata simulates the conversion of forest to pasture only, it does not model regeneration of forest or more complex land use transitions. It assumes that deforestation spreads in an epidemiological fashion from roads and agricultural frontiers. In this way an agricultural frontier moves through the landscape from all access points, the resistance to the spread of this frontier is assumed proportional to **sin (slope)**. The cellular automata are not intended to model the *rate* of deforestation, just the *form*. No parameters of the model are temporally dependent. Any notion of the rate of deforestation is solely a function of the total length of the advancing frontier and the availability of low slopes at the frontier. Since the hydrological model is applied to each of the land use transitions separately, offline and in a non-transient manner, no specification for the rate of advance of the agricultural frontier is necessary.

The patterns of deforestation produced by this automaton are applicable only in tropical montane environments at the forest-agriculture frontier without complex patterns of land ownership. The model replicates but simplifies the observed pattern of change (as far as is indicated by the agreement with the pattern of secondary forest in the catchment). Four iterations of the cellular automata deforestation model are shown in Figure 2 and the trajectories of vegetation cover are shown in Figure 3. Note that within 32 iterations the whole catchment is deforested. The important properties in terms of understanding the impact of pattern on process are not the rates of deforestation but the location of deforestation with respect to hydrologically important landscape variables such as slope and altitude. Figure 4 shows frequency distributions of the slope angles deforested in iterations 1,10,20,30,40 and 50 of the cellular automata. It is clear that the shallowest slopes are deforested first (in iterations 1-10) with steeper slopes being deforested later. If one looks at altitude (Figure 5) the pattern is more complex and is driven essentially by the location of the cutting fronts in the first timestep (the road at the head of the Palo Verde catchment, and the deforested area at the confluence of Tambito and Palo Verde). In the initial iterations, the distribution of altitudes deforested is bimodal with a peak at 1450m and another at 2500m. As the cellular automata iterates, deforestation occurs more equally across the range of altitudes.

This paper is not concerned with predictions of land use change nor its impacts rather the models are used in order to understand the emergent complexity of distributed but connected hydrological processes and their sensitivity to plausible patterns of land use change. It is clear from an examination of surrounding areas in Cauca that it is entirely plausible that Tambito could be fully converted from forest to pasture with the shallowest slopes and those nearest the road converted first.

MODELLING THE HYDROLOGICAL IMPACT

The cellular automata land use iterations form the basis upon which we may use a hydrological model to analyse the catchment-wide implications of deforestation in a particular form. The experiment performed here is as follows. Each of the land use change iterations is used as the land cover for a different one-month long integration of the TAMBITO hydrological model using measured meteorological data for January 1998. In each integration primary, secondary, pasture and bare are parameterised according to field measured values for each land use. In this parameterisation, deforestation only effects the vegetation cover and leaf area index, which have impacts on plant growth, evapotranspiration and interception. There are no direct impacts of deforestation on soil or other properties within the model. Hence, any impacts of deforestation are impacts only of canopy removal. In each case the hydrological model is applied twice: first with the immediate replacement of forest with pasture (in order to examine longer-term sensitivity) and second with the replacement of forest with bare soil, which is more representative of the short-term situation.

The TAMBITO hydrological model is summarised in Figure 6. The model is a distributed process model of hydrology, vegetation dynamics and soil erosion applied at a 25m resolution to the Tambito catchments. The model is integrated within a GIS and is dynamic with a timestep of one hour and requires hourly meteorological input data, which are distributed according to field measurements. These data are used to calculate hydrological fluxes, along with plant growth dynamics and soil erosion. Results are written as time series of two-dimensional maps, time series of values for particular grid cells, and catchment totals or integrals.

A summary of the basic functions of the model is given here, for more detail see Mulligan (1999). The TAMBITO model simulates hydrological fluxes in all cells according to the inputs and properties of the cell. Evapotranspiration is calculated as the sum of soil evaporation, transpiration, and interception loss, all of which are driven by the available energy and water availability. Rainfall is intercepted by the vegetation according to its leaf area index, vegetation cover and measured leaf surface water storage capacity. Non intercepted rainfall falls direct as canopy throughfall and is combined with interrupted throughfall (canopy drainage) to produce net precipitation. Infiltration occurs at the rate of advance of the wetting front (that is at the saturated hydraulic conductivity at the wetting front). The potential for overland flow generation is proportional to the instantaneous difference between the rate of advance of the wetting front and the precipitation intensity plus the input of water from upslope. Recharge is calculated following the method of Campbell (1985).

Canopy storage is updated on an hourly basis as:

$$Cst=Cst\text{-}1+Rt\text{-}Eit\text{-}Dt \quad \text{[Equation 1]}$$

where,
Cs = canopy storage,
T = time,
R = rainfall input (mm),
Ei = interception loss (mm),
D = canopy drainage (mm).

Soil moisture is updated on an hourly basis as:

$$\theta_t=\theta_{t-1}+I_t-Es_t-E_t-R_t \quad \text{[Equation 2]}$$

where,
θ = soil moisture(m^3water/m^3soil),
t=time,
I = infiltration (mm),
Es = soil evaporation (mm),
Et = evapo-transpiration (mm),
R = recharge (mm),

and surface water fluxes are updated on an hourly basis as :

$$Wt=W_{t-1}+Pn_t+Ron_t-Roff_t-I_t \quad \text{[Equation 3]}$$

Where
W = surface water depth (mm),
Pn = net precipitation (mm),
Ron = runon (mm),
Roff = runoff (mm).

Runoff is routed downslope using a uni-directional scheme which assigns all runoff from a particular cell to the downstream cell with the steepest drop in altitude. The TAMBITO model is a hillslope model, it does not model the dynamics of river flow or groundwater and is not intended to provide information on fluvial dynamics.

Soil erosion is calculated using the equation of Thornes (1990) and is a function of slope, runoff volume and vegetation cover. Vegetation growth is modelled using a production efficiency model (Monteith, 1997; Monteith, 1983; Prince, 1991; Prince *et al.*, 1994) forced by photosynthetically active radiation (PAR) and limited by water availability and respiration (Mitchell *et al.*, 1993). Partitioning of assimilate occurs in response to water availability. To date nutrients are not incorporated into the model though they are recognised as an important factor in the growth dynamics of TMCF (Edmisten, 1970,Vitousek and Sanford, 1986; Marrs et al, 1988).

THE COMPLEX SPATIAL PATTERNS OF MOUNTAIN HYDROLOGY

The Tambito catchments show complex spatial variability in meteorological conditions, soil and vegetation types. Rainfall in the catchments varies from 4602 mm/annum at 1450 masl to 7681 mm/annum at 2200 masl (average for 1995 and 1996). Since the main control on rainfall in this area is altitude rainfall may vary between 2830 mm/annum and 10674 mm/annum at the altitudinal limits of the catchments. Mean annual temperatures vary from 22.5°C at 1374m to 12.6°C at 2894m. In addition cloud cover dynamics in the catchment are complex leading to complex patterns of solar radiation receipt and of occult precipitation. Occult precipitation is a significant input of water to the catchment but is not included here for simplicity. Research is in progress to quantify the role of occult precipitation. The distribution of soil properties within the catchments shows no systematic variation with land cover, slope, aspect or various topographic indices (Mauricio Rincon-Romero, personal communication).

THE NUMERICAL EXPERIMENTS

The TAMBITO hydrological model is used here as a tool for representing the complexity of the hydrological processes operating throughout the catchments and understanding the impact of simple land use changes when filtered through this complex system. For each of the 32 land use iterations from the current land use to complete deforestation of the catchment, the TAMBITO hydrological model was integrated for one month of meteorological data (January 1998). Hourly rainfall was distributed with altitude according to the measured altitudinal relationship between the long term Tambito (1450 masl) and 20 de Julio (2200 masl) sites (0.0116 mm/m). Temperature was distributed with altitude according to a relationship derived from data for 350 Colombian stations (0.006 °C/m) and consistent with the altitudinal temperature lapse rate reported by Holdridge (1947,1967) and others. Solar radiation is calculated using the equations of Iqbal (1983). It is a function of latitude, longitude, slope, aspect, julian day and hour and is corrected for cloud cover using a stochastic atmospheric transmissivity model based on the difference between modelled and measured solar radiation receipt for the Tambito meteorological station (Mulligan, 1999). Net solar radiation is calculated using a linear regression between incoming and net solar radiation for the forest surface produced from hourly data between June and December 1997. Net solar radiation is 84% of the incoming radiation so that the vegetated surface has an albedo of 16%.

The model was only integrated for one month for each land use iteration because of the prohibitive computational expense of integrating for a longer period for each of the 52 land use iterations. The period chosen, January 1998, showed typical meteorological conditions for the area. Although this short period integration would exclude some of the higher magnitude, lower frequency events one would expect to see for a longer term analysis, it is adequate for the purpose of understanding the sensitivity of the hydrological system to land use change. Meteorological conditions for the period 1^{st}-31^{st} January, 1998 are summarised in Table 1.

CATCHMENT SENSITIVITY TO DEFORESTATION : THE IMPACT OF PATTERNS ON PROCESS

The following model outputs were written as hourly catchment-wide integrals for use in the analysis: total evapotranspiration, total recharge, average soil moisture, total runoff and total erosion. These variables were chosen as (a) indicators of the model behaviour and (b) important hydrological variables for understanding the impact of deforestation. In order to understand the impact of pattern on process the sensitivity of each variable, expressed as the change in the value of the output variable between land use iterations per unit change in the deforested area between the same iterations. In other words, the sensitivity measures the response of the output variable *per unit* of deforestation and thus reflects the importance of the location and pattern of deforestation on the hydrological behaviour of the catchment.

Table 2 summarises the impact of deforestation on the key hydrological variables for the integrations where forest is replaced directly by pasture. As one might expect, as deforestation occurs, evapotranspiration decreases due to the lower leaf area index and canopy storage capacity of pasture compared with primary forest (0.03 mm compared with 0.25 mm). At the same time the shallower rooting depth of pasture compared with forest (30 cm compared with 300 cm) means that evapotranspiration from pasture becomes water limited much sooner than evapotranspiration from forest. Recharge shows a complex pattern of change as deforestation occurs. Recharge decreases during the initial stages of deforestation, possibly as a result of greater limitation of recharge imposed by soil moisture where the soil moisture storage capacity is low because the root zone (at the base of which recharge occurs) is only 30cm deep. As deforestation continues the decreased evapotranspiration and increased soil moisture leads to an increase in recharge. Since recharge has a strong power relationship with soil moisture recharge is very sensitive to change in soil moisture. The complex pattern of change in recharge is also a function of the location of deforestation with respect to the variability in soil texture within the catchment (Ksat varies from 43.2 mm/hr to 277 mm/hr). Soil moisture fraction increases as deforestation occurs, due to reduced evapotranspiration but also because the lower soil moisture capacity of shallow rooted pasture means that, though the total volume soil water can be lower, the soil moisture concentration will be higher. In other words, soils with a shallow coupling with the atmosphere are much more dynamic than soils with deeper coupling. A small input or output of water from a shallow coupled soil can have a large effect of the soil moisture concentration.

Rather unusually deforestation leads, in this model, to a decrease in runoff volumes and thus a decrease in erosion. The reason for this is clear. In the transition from forest to pasture or bare soil, the volume of soil coupled to the atmosphere for evapotranspiration changes dramatically. When forest is replaced by pasture the soil moisture budget is calculated over a much smaller volume of soil (a rooting depth of 30cm instead of 3m). This means that the soil hydrological budget becomes much more dynamic as a smaller volume of water input or output can cause a greater change in the soil moisture concentration which, itself acts as a driver for the soil hydrological fluxes.

As deforestation continues more and more of the catchment becomes more tightly coupled with the atmosphere in this way. This limits the depth of the wetting front before it is considered as recharge and so increases the hydraulic conductivity at the wetting front thereby increasing the infiltration and reducing overland flow over the catchment as a whole. Where this occurs along the main flowpaths, overland flow from upslope is soon re-infiltrated. Despite the reduction in the protective vegetation cover (particularly in the bare soil case, Table 3) the reduction in overland flow volume produces a very large reduction in soil erosion. Although overland flow decreases, this does not mean that the catchment yield increases. It is clear from Table 2 and Table 3 that recharge increases significantly with deforestation. These effects together may mean that catchment water yields are not greatly affected in volume by deforestation but are affected in timing and dynamics.

The pattern of change is qualitatively similar for all variables in the forest to bare soil experiments as for the forest to pasture integrations, though the change in flux per unit land cover is different. It is not, however, the purpose of this paper to examine in detail the change in hydrological fluxes with deforestation. Here we are more interested in the non-linearities that exist because of the spatial complexity and connectedness of the system. These are expressed in the system sensitivity per unit land use change as deforestation continues. Sensitivity is expressed as the percent change in the output variable between two land use integrations divided by the percent change in the deforested area between the same integrations. The sensitivity of evapotranspiration to land use change (Figure 7) is greatest in the initial stages of deforestation because deforestation is concentrated in the lowest parts of the catchment (the highest orders in the flow network) which are very wet because of input of water from upslope. As land use change continues evapotranspiration becomes less sensitive for the pasture and the bare soil integrations though there is some non-linear behaviour beyond iteration 25, particularly for the bare soil integration.

Recharge (Figure 8) shows much more erratic behaviour but with a generally increasing sensitivity of recharge to deforestation as it proceeds. This reflects the increasing soil moisture availability in the catchment as deforestation proceeds. The bare soil and pasture integrations are similar and sensitivity is, on the whole, 50% lower than for evapotranspiration. Soil moisture (Figure 9) is not particularly sensitive to the pattern of land use change but shows a complex pattern of sensitivity, which increases initially and then stabilises before increasing again. Although runoff decreases as deforestation proceeds, the sensitivity of runoff (Figure 10) to a unit deforestation increases exponentially as the area is deforested until total deforestation is reached at iteration 32, at which point the runoff stabilises and sensitivity drops to zero. Runoff is a very sensitive variable with changes of up to 100% in a single land use iteration. There are small differences between the pasture and bare soil integrations. Soil erosion (Figure 11) shows a similar pattern of sensitivity to deforestation with a sharp increase in sensitivity as the final patches of forest are removed.

CONCLUSIONS

The response of evapotranspiration, recharge and soil moisture to deforestation as indicated by the TAMBITO model are as would be expected, evapotranspiration decreases, soil moisture increases and recharge shows a complex pattern of change which depends upon the spatial patterns of soil moisture in the catchment. Overland flow and erosion show a rather surprising response since both decrease with deforestation. If we compare this to the generally accepted ideas on impacts of deforestation on the water yield in tropical catchments, the results are clearly in contradiction. In support of this discrepancy one may argue that (a) the reduction in erosion is solely a function of the reduced runoff, (b) runoff does not equate with catchment water yield since baseflow and throughflow contributes significantly to river flow regimes in tropical landscapes and these are not considered in this simple analysis. Most importantly, the reduction in runoff with deforestation exhibited by this model is solely a function of the reduced depth of soil coupled to the atmosphere when deeply rooted forest is replaced by shallow rooted pasture or bare soil. This change in coupling has not been considered in previous models and is likely to be of great significance.

An examination of the hydrological sensitivity of the Tambito catchments shows clear non-linearities in the sensitivity of key hydrological variables to progressive deforestation in the Tambito catchments. These non-linearities arise as a result of the hydrological connectedness of the catchment and the importance of the spatial pattern of the remaining forest for the integrated hydrological behaviour of the catchment. Of particular interest are threshold-type activity exhibited by some variables such as evapotranspiration, where deforestation in a particular part of the catchment causes a sharp increase in the overall catchment response. Overland flow and erosion are the main hydrological processes that connect landscapes laterally. Since they represent the integration of active hydrological processes over the network of local drainage directions, they show strong sensitivity to deforestation. Both runoff and soil erosion show an exponential increase in sensitivity (change in runoff or erosion per unit change in land cover) as deforestation proceeds. This indicates that partial deforestation of this catchment (up to 75%) could take place with relatively little impact on overland flow and erosion but beyond this the sensitivity of the system increases dramatically and further deforestation would have very serious hydrological consequences. Research is in progress to examine how these patterns of sensitivity reflect the properties of particular parcels of land undergoing deforestation in each iteration.

ACKNOWLEDGEMENT

This research was funded by grants from The Royal Society (MM), The British Council (MM,JR) Colciencias and the University of London Central Research Fund (MR) whose support is gratefully acknowledged. The authors would like to express their gratitude to the late Alvaro Jose Negret, Fundacion Proselva and the University of Cauca, Popayan for the use of the Tambito field site and its facilities. We are also grateful to other Colombian organisations that provided logistic support, in particular the International centre of Tropical Agriculture (CIAT) and the Regional Corporation for Cauca (CRC). Thanks also go to those who provided assistance in the field, particularly Andrew Jarvis, Koulla Pallaris, Quintin and Olga.

BIBLIOGRAPHY

Bosch, J.M. and Hewlett, J.D. (1982) A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology 55:3-23.

Bruijnzeel, L.A. (1990) Hydrology of moist tropical forests and effects of conversion : a state of knowledge review. Unesco IHP, Paris.

Bruijnzeel, L.A. and Wiersum,K.F. (1985) A nutrient balance sheet for *Agathis dammara* Warb. Plantation forest under various management conditions in central Java, Indonesia. Forest Ecology and Management 10:195-208

Brunijnzeel, L.A. and Proctor, J. (1995) Hydrology and biochemistry o tropical montane cloud forests : what do we really know? In Hamilton, J.S., Juvik, J.O., Scatena,F.I.V. Tropical Montane Cloud Forests, Springer Verlag.

Campbell, G.S. (1985) *Soil Physics with BASIC :Transport Models for Soil - Plant Systems* Dept of Agron. and Soils, Washington State University. Elsevier.

Castaño, C. (1991). Bosque de niebla y hombre tradicional. Cap 7. Pages 151-170 in Bosques de Niebla de Colombia. Banco de Occidente. Bogotá.

Cortes, A. (1996) **

Edmisten J.A. (1970) Preliminary studies of the nitrogen budget of a tropical rain forest pp. H-211 - H-215 in Odum, H.T. and Pigeon, R.F. (eds.) A tropical rainforest. US Atomic Energy Commission, Oak Ridge, Tennessee.

FAO (1993) Forest resources assessment 1990, tropical countries. Forestry paper 112, Rome. Food and Agriculture Organisation of the United Nations.

Hewlett, J.D. and Fortson, J.C. (1983) The paired catchment experiment. Pp.11-14 in J.D. Hewlett (ed.) Forest Water Quality. School of Forest Resources, University of Georgia, Athens, GA, USA.

Holdridge, L. R. (1967) *Life zone ecology*. San José, Costa Rica: Tropical Science Center.

Holdridge, L.R. (1947) Determination of World Plant Formations from Simple Climatic Data. *Science*, 105: pp. 367-368.

Hsia,Y.J. (1987) Changes in storm hydrographs after clearcutting a small hardwood basin in central Taiwan. Forest Ecology and Management 20:117-134.

Iqbal, M. (1983) *An Introduction to Solar Radiation*. Academic Press, Toronto.

Lambin, E. 1994. Modelling Deforestation Processes: A Review. TREES Series B/11. European Commission DG XIII, Luxembourg.

Lambin,E.F. (1997) Modelling and monitoring land-cover change processes in tropical regions. *Progress In Physical Geography*, Vol.21, No.3, pp.375-393.

Marrs, R.H., Proctor, J., Heaney, A. and Mountford, M.D. (1988) Changes in soil nitrogen-mineralization and nitrification along an altitudinal transect in tropical rainforest in Costa Rica. Journal of Ecology 76:466-482.

Mitchell, P.L., Sheehy, J.E., Diamond, S.M. and Woodward, F.I. (1993) *Notes on the Shrub Model for MEDALUS*. MEDALUS project internal publication. University of Sheffield.

Monteith, J.L. (1977) Climate and the Efficiency of Crop Production in Britain. *Philosophical Transactions of the Royal Society of London Series B*. 281:277-294.

Monteith, J.L. (1983) *Using Tube Solarimeters to Measure Radiation Intercepted by Crop Canopies and to Analyse Stand Growth*. Applications note TSL-AN-4-1. Delta T Devices, Burwell, Cambridge.

Morgan,R.P.C. (1978) Field studies of rainsplash erosion. Earth Surface Processes and Landforms 3:295-299. (missing)

Mulligan (1999) A simple hydrological model for tropical montane cloud forests. Department of Geography, King's College London, Occasional Paper No. 48. ISSN 0309 2178 www.kcl.ac.uk/geography

Prince, S.D. (1991) A Model of Regional Primary Production for Use With Coarse Resolution Satellite Data. *International Journal of Remote Sensing*. 12, 1313-1330

Prince, S.D., C.O. Justice and B. Moore III (1994) Monitoring and modelling of terrestrial net primary production. IGBP-DIS Working Paper : 8. IGBP.

Quine,T.A. and Walling,D.E. (1993) The use of Caesium-137 Measurements to Investigate Relationships between Erosion Rates and Topography in Thomas,D.S.G. and Allison,R.J. (1993) Landscape Sensitivity. BGRG Symposia Series. John Wiley and Sons, Chichester.

Richardson, J.H. (1982) Some implications of tropical forest replacement in Jamaica. Zeitschrift fur Geomorfologie neue Folge Suppl. Band 44:107-118.

Roche,M.A. (1981) Watershed investigations for development of forest resources of the Amazon region in French Guyana pp. 75-82 in Lal,R. and E.W. Russell (eds.) tropical Agricultural Hydrology. J. Wiley, New York.

Shukla, J., Nobre,C. and Sellers, P.J. (1990) Amazonian deforestation and climatic change. Science 247:1322-1325

Shuttleworth, W.J., Gash,J.H.C.,Lloyd,C.R.,Moore,C.J., Roberts,J.,Marques Filho,A., Fisch,G., De paula Silva Filho, V., De Nazara Goes Ribeiro,M., Molion,L.C.B., De Abreu SA, L.D., Nobre,J.C.A., Cabral,O.M.R., Patel, S.R. and Carvalo de Moraes, J. (1985) Daily variations of temperature and humidity within and above an Amazonian forest. Weather 40:102-108.

Thornes, J.B. (1990) The Interaction of Erosional and Vegetational Dynamics in Land Degradation : Spatial Outcomes in Thornes, J.B. (ed.) *Vegetation and Erosion*. John Wiley and Sons.

Thornes, J.B. and Brandt, C.J. (1993) Erosion-Vegetation Competition in a Stochastic Environment Undergoing Climatic Change Stochastic Rainfall Variations. in Millington, A.C. and Pye, K.J., *Environmental Change in the Drylands: Biogeographical and Geomorphological Responses*, Wiley.

Vitousek P.M. and Sanford, R.L. (1986) Nutrient cycling in moist tropical forest. Annual Review of Ecology and Systematics 17:137-167.

Vugts, H.F. and Bruijnzeel, L.A. (1988) Water and nutrient dynamics of plantations of *Pinus caribaea* on degraded grassland soils in south western Viti Levu, Fiji. Research proposal for the Netherlands Foundation for the advancement of tropical research (WOTRO), Free University, Amsterdam, 11pp.

Wiersum, K.F. (1984) Surface erosion under various tropical agroforestry ecosystems pp. 231-239 in C.L. O'Loughlin and A.J. Pearce (eds.) Proceedings of the Symposium on the effects of forest land use on erosion and slope stability IUFRO, Vienna and East-West Centre, Honolulu, Hawaii.

List of figures

Total rainfall (@ 1450masl)	191.8 mm
Maximum hourly rainfall (@ 1450masl)	13 mm/hr
Average hourly solar radiation (catchment average)	174 W/m^2
Maximum hourly solar radiation (catchment average)	533 W/m^2
Average cloud cover (@1450 masl)	50%
Average hourly temperature (@ 1450masl)	19.0 °C
Minimum hourly temperature (@ 1450masl)	14.5 °C
Maximum hourly temperature (@ 1450masl)	26.4 °C

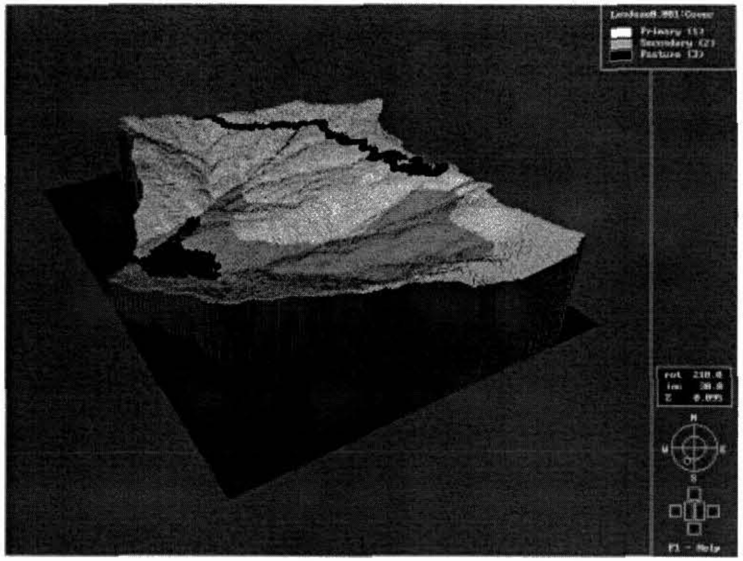
Table 1 General meteorological conditions for th Tambito catchments, 1st-31st January 1998.

Iteration	% of catchment deforested	Catchment mean evapotranspiration (mm/month)	Catchment total recharge (mm/month)	Catchment mean soil moisture (m^3water/m^3soil)	Catchment total runoff (mm/month)	Catchment total erosion (mm/month)
1	7.7	93.4	128523	0.27	3521	75927213
5	21.7	87.4	72956	0.29	2235	56363609
10	39.4	77.9	63128	0.31	1493	44806488
15	57.6	65.0	113287	0.33	582	28495805
20	75.1	52.5	106092	0.35	187	15014043
25	86.0	47.9	100211	0.37	15	3464119
30	92.8	46.5	95218	0.37	0.04	186426
35	97.1	46.0	96908	0.38	0.00	7554
40	99.7	45.9	70794	0.38	---	14
45	100.0	45.9	---	0.38	---	---

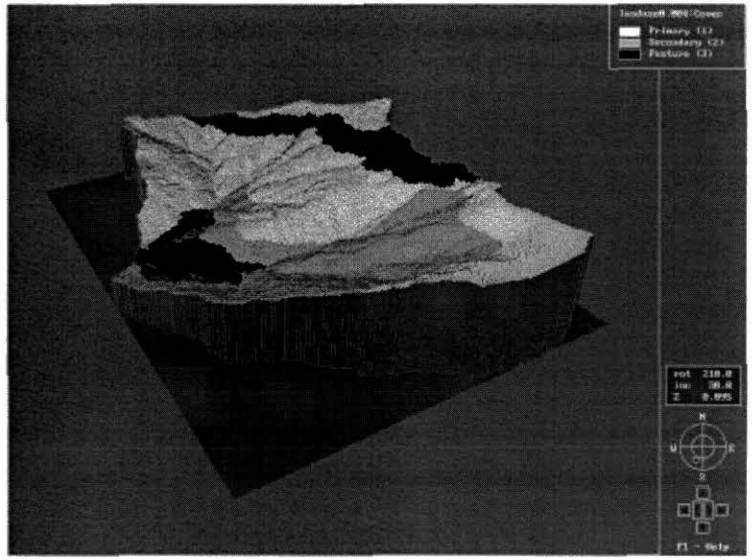
Table 2 Change in hydrological fluxes as forest is replaced by pasture.

Iteration	% of catchment deforested	Catchment mean evapotranspiration (mm/month)	Catchment total recharge (mm/month)	Catchment mean soil moisture (m^3water/m^3soil)	Catchment total runoff (mm/month)	Catchment total erosion (mm/month)
1	7.7	94.3	136293	0.28	3819.47	78514825
5	21.7	87.4	72956	0.29	2234.67	56363609
10	39.4	82.0	69329	0.32	1679.44	47064435
15	57.6	71.0	124534	0.34	850.05	29536927
20	75.1	60.8	115364	0.36	285.72	15488448
25	86.0	58	107936	0.38	21.85	3208093
30	92.8	58	100207	0.38	1.01	201262
35	97.1	58.5	105980	0.39	0	8064
40	99.7	58.9	77083	0.39	0	14.33
45	100.0	58.9	---	---	---	---

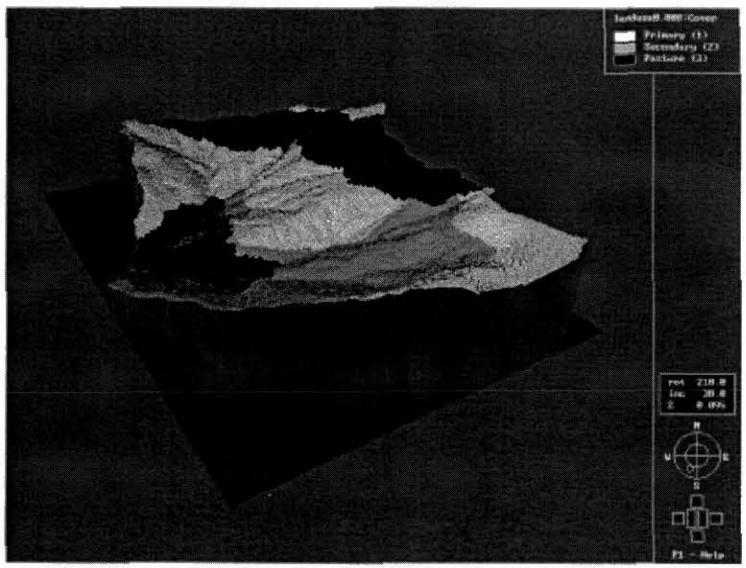
Table 3 Change in hydrological fluxes as forest is replaced by bare ground



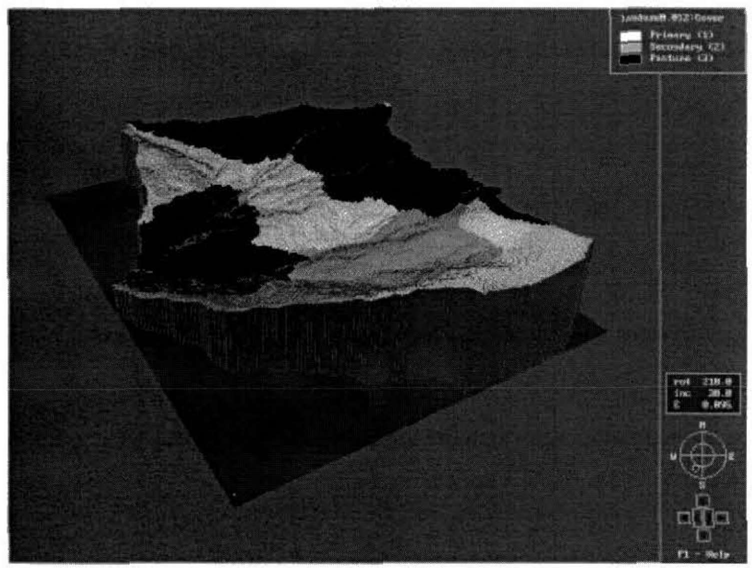
Iteration 1



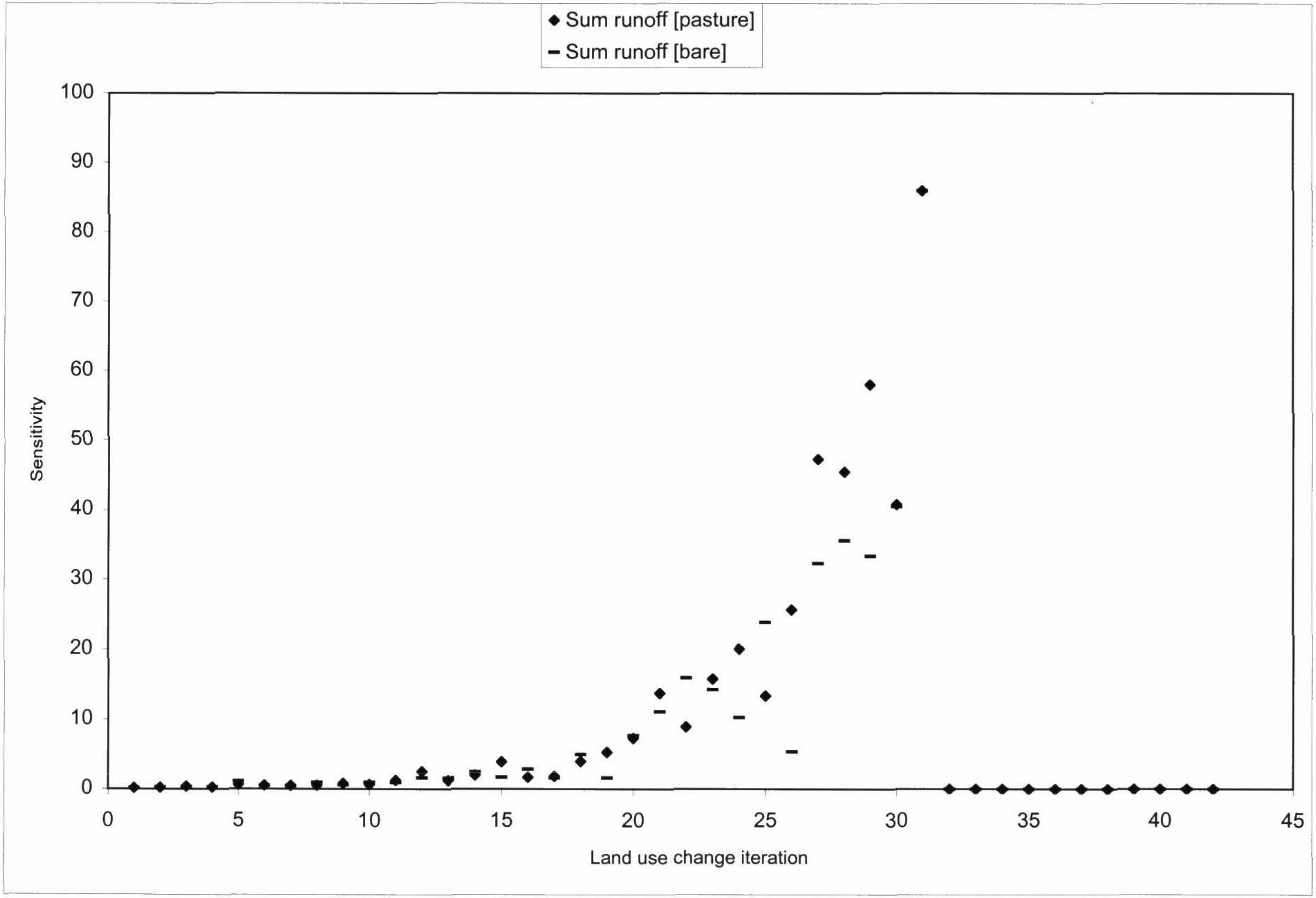
Iteration 4



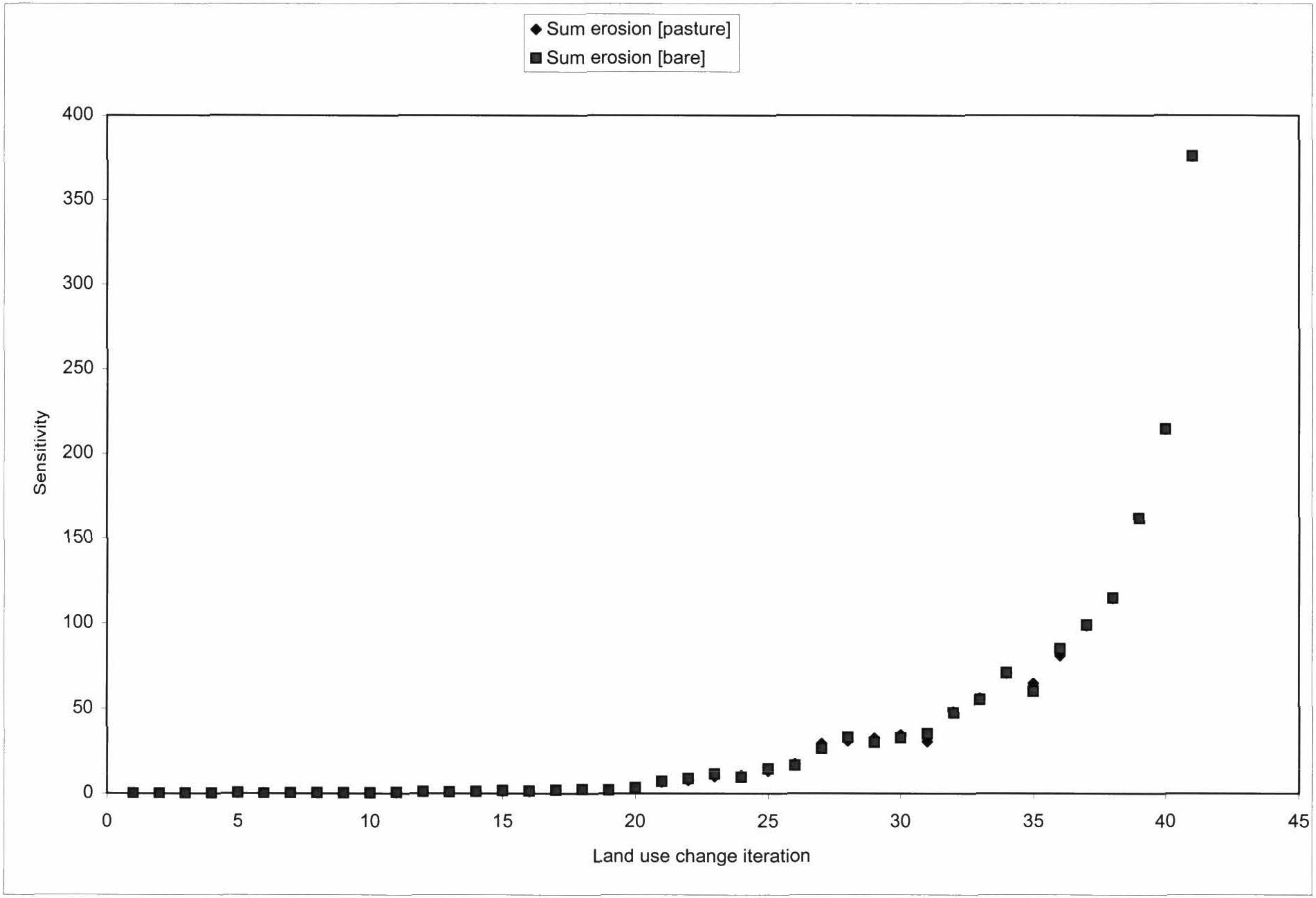
Iteration 8



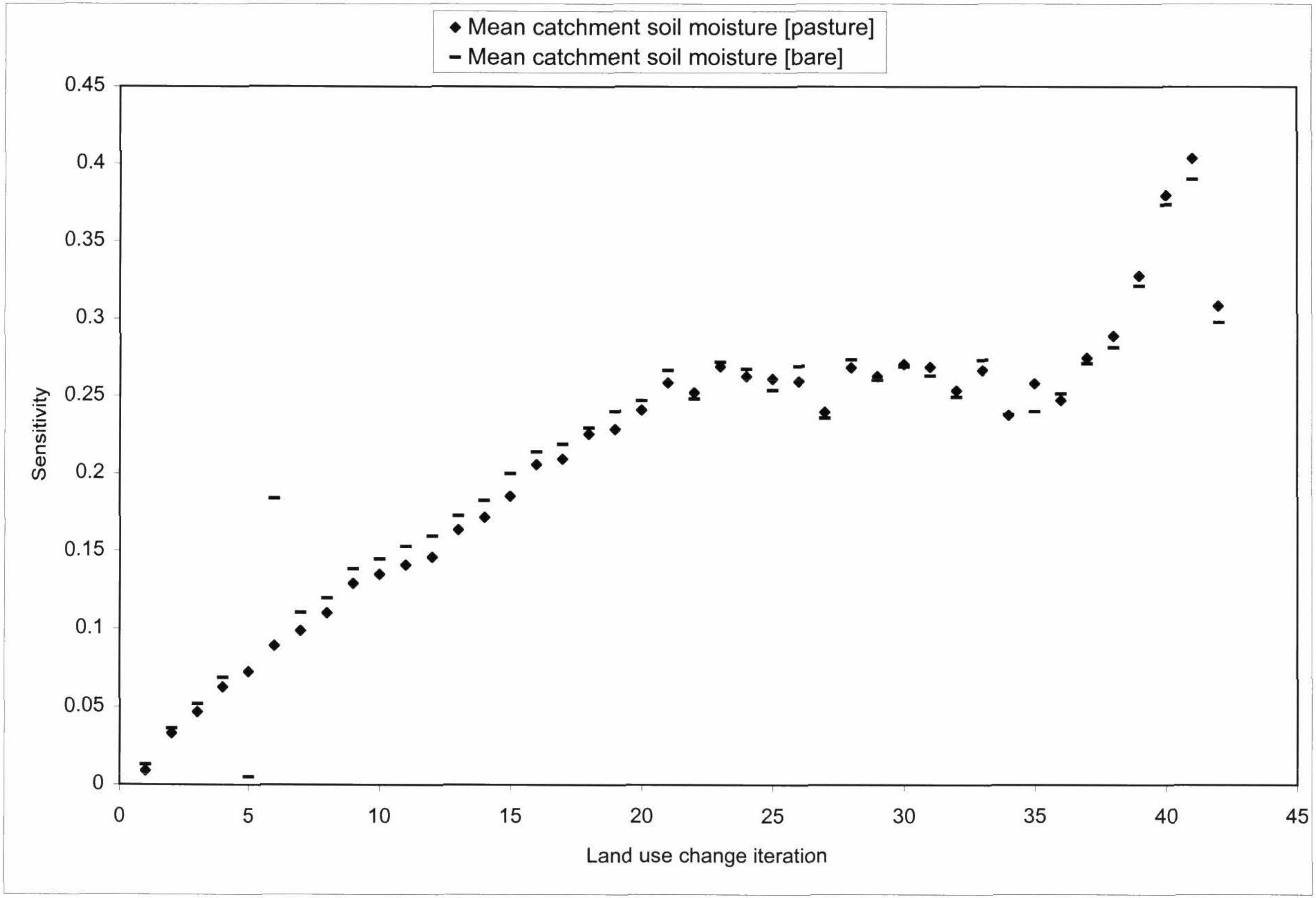
Iteration 12



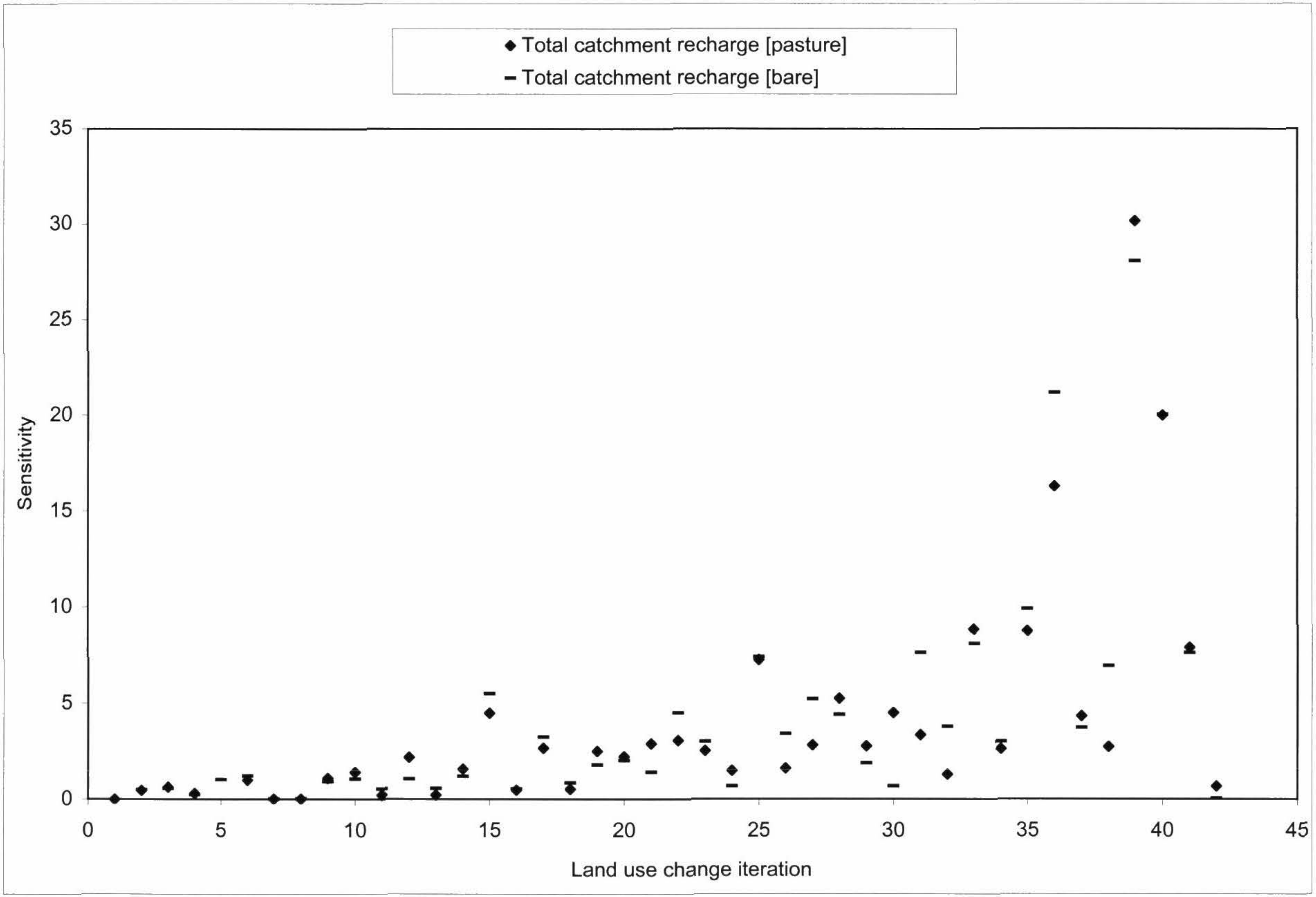
Sum runoff [pasture]
Sum runoff [bare]
Sensitivity
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
45
Land use change iteration



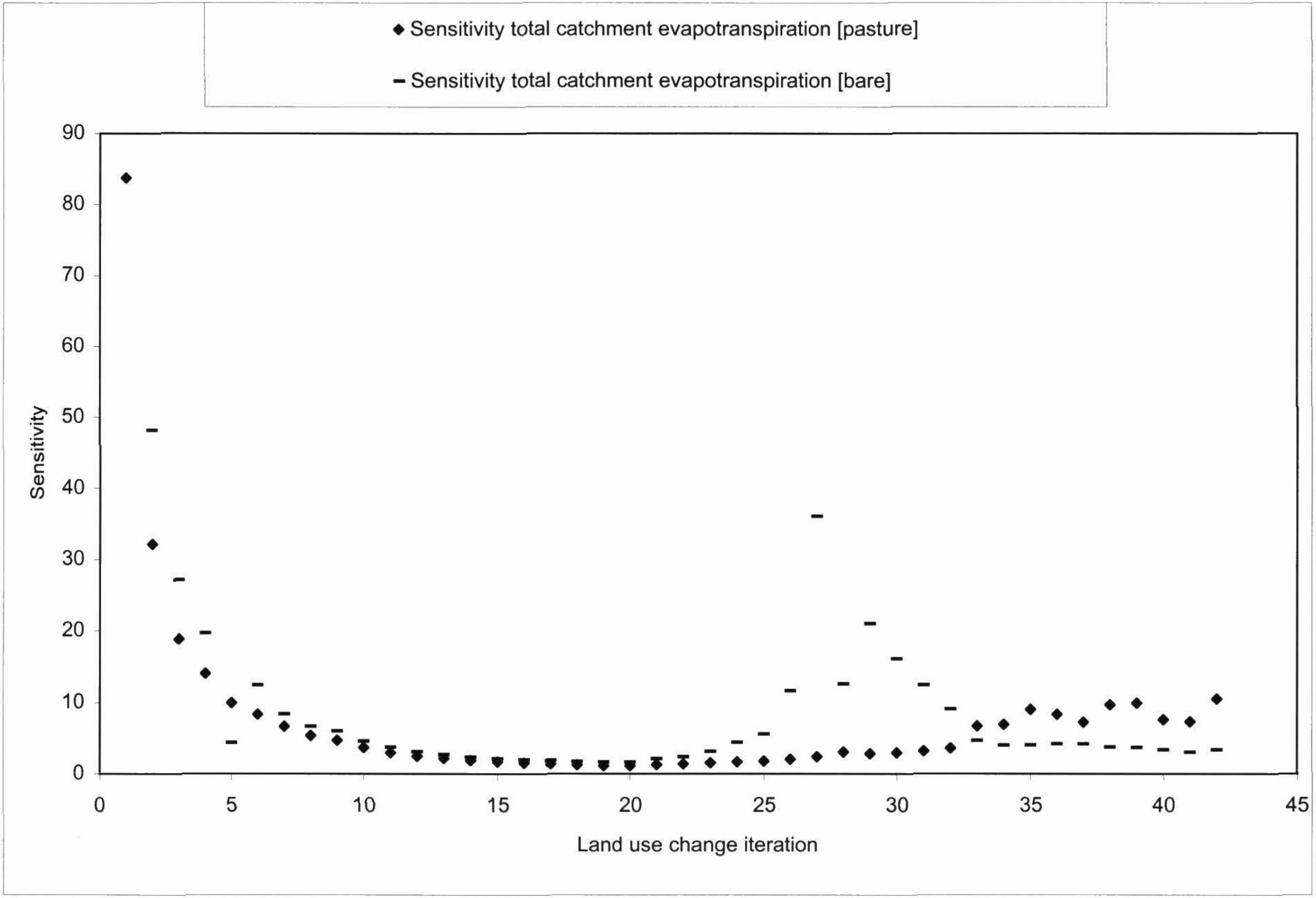
Sum erosion [pasture]
Sum erosion [bare]
Sensitivity
400
350
300
250
200
150
100
50
0
0
5
10
15
20
25
30
35
40
45
Land use change iteration

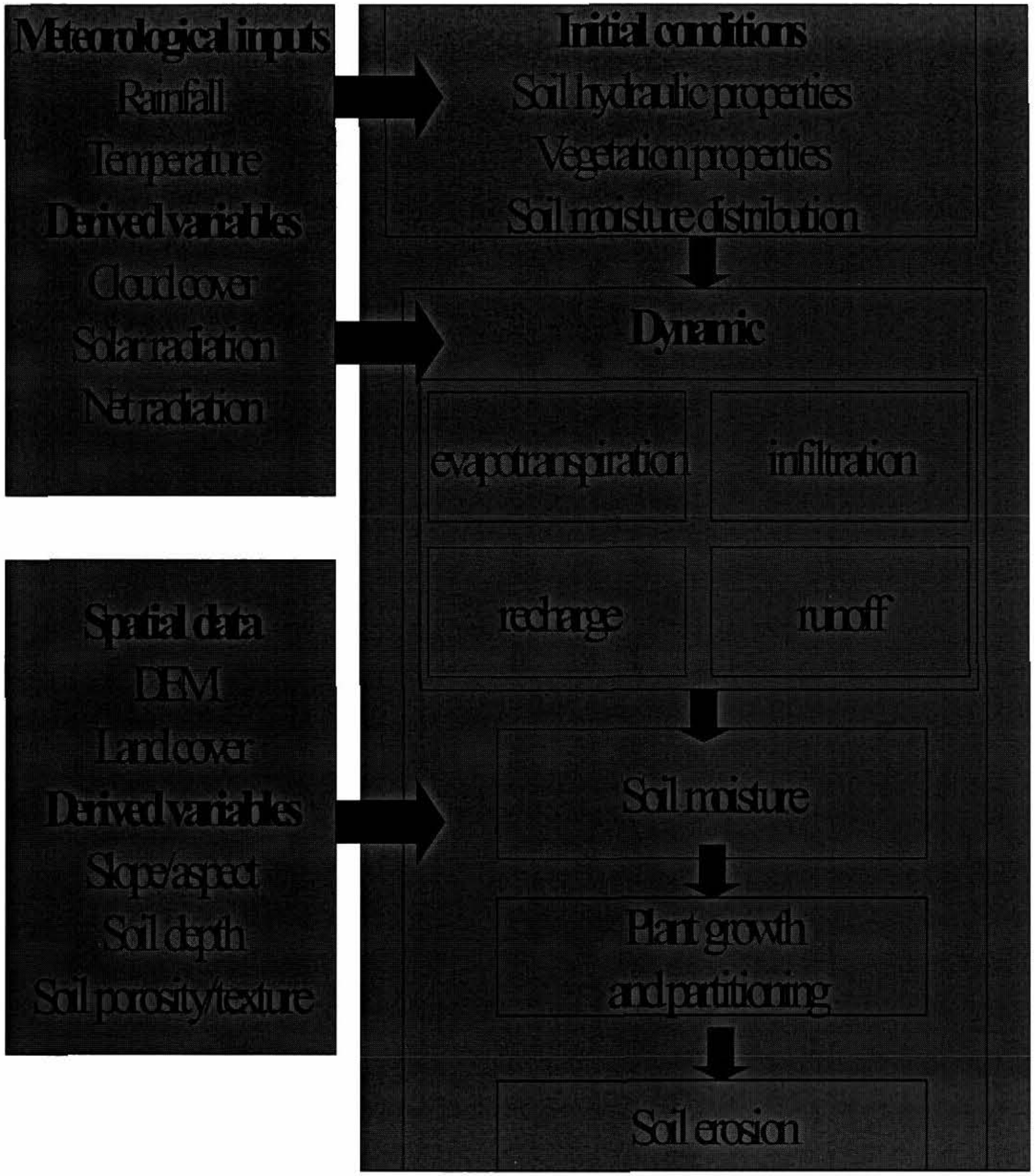


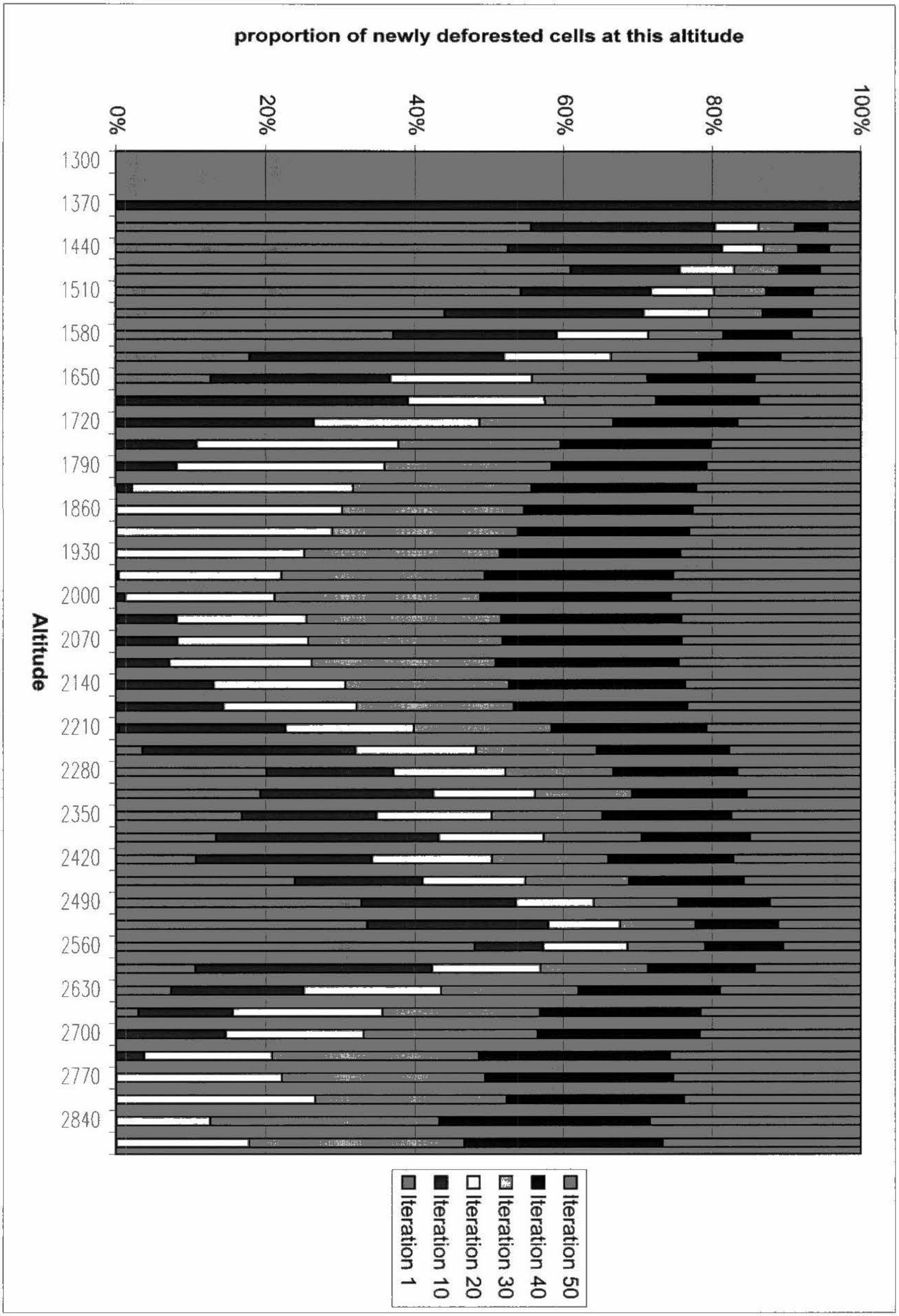
Mean catchment soil moisture [pasture]
Mean catchment soil moisture [bare]
Sensitivity
Land use change iteration
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0
5
10
15
20
25
30
35
40
45



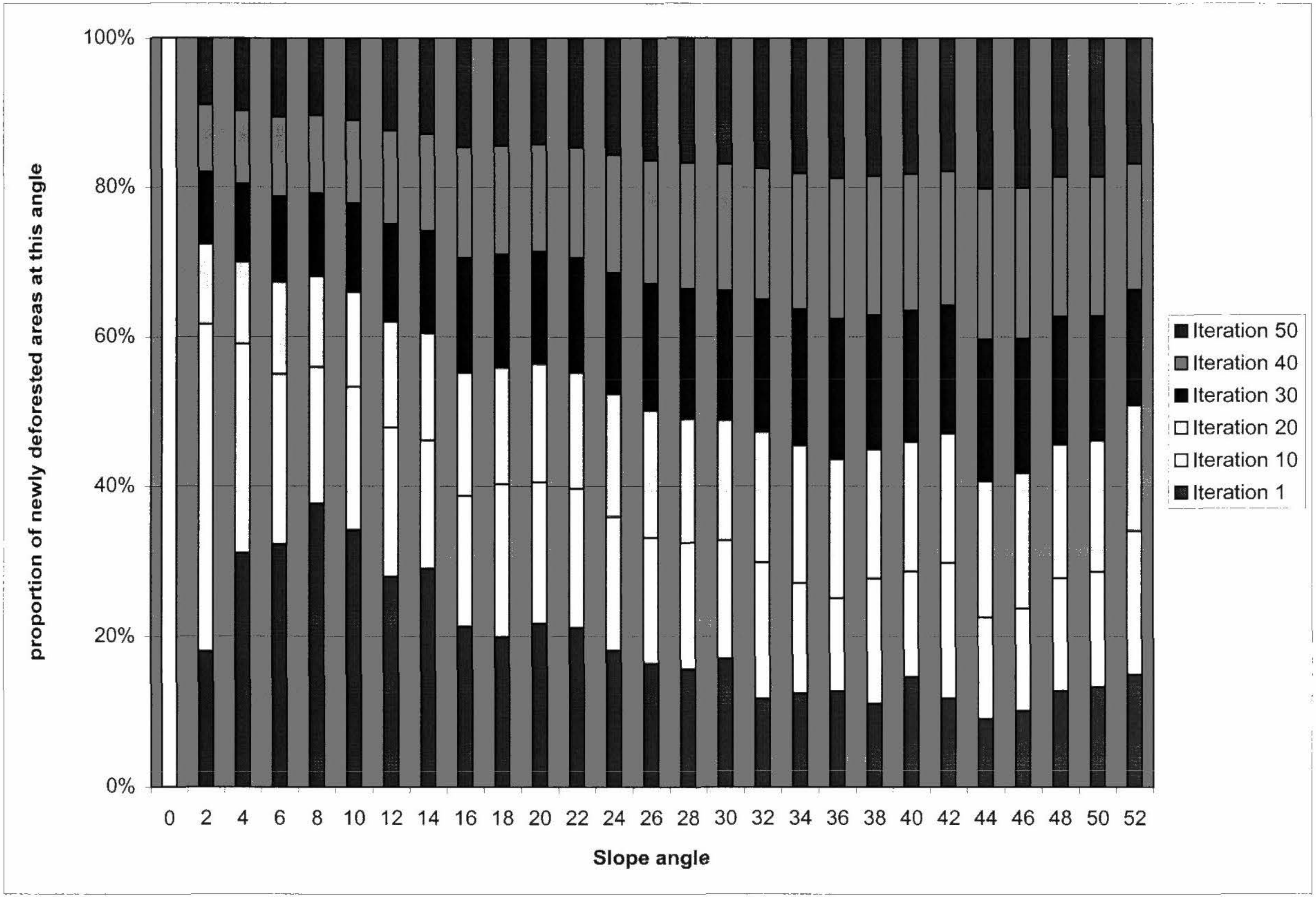
Total catchment recharge [pasture]
Total catchment recharge [bare]
35
30
25
20
15
10
5
0
Sensitivity
0
5
10
15
20
25
30
35
40
45
Land use change iteration


Sensitivity total catchment evapotranspiration [pasture]
Sensitivity total catchment evapotranspiration [bare]
Sensitivity
Land use change iteration
0
10
20
30
40
50
60
70
80
90
0
5
10
15
20
25
30
35
40
45

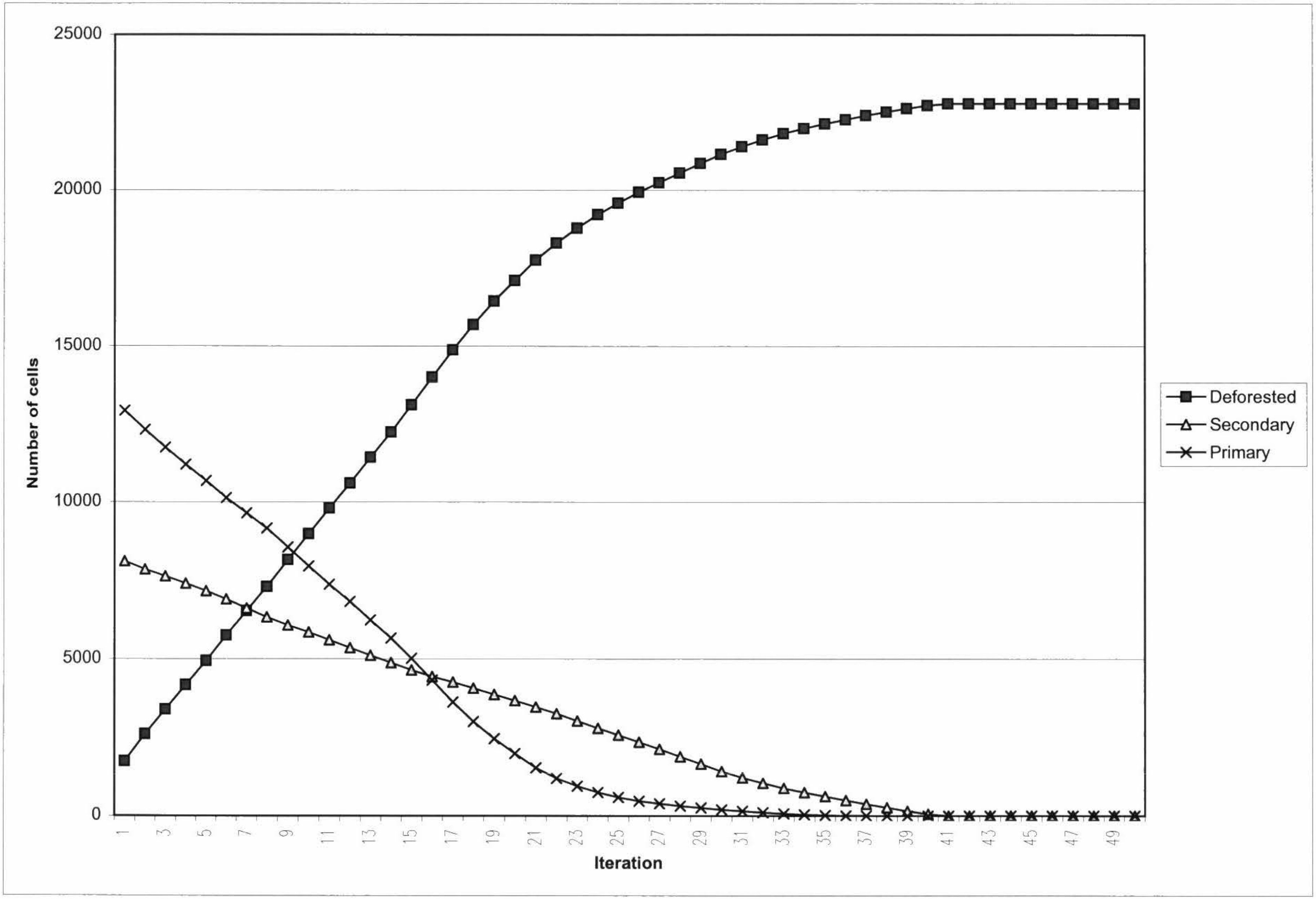

Meteorological inputs
Rainfall
Temperature
Derived variables
Cloud cover
Solar radiation
Net radiation
Spatial data
DEM
Land cover
Derived variables
Slope/aspect
Soil depth
Soil porosity/texture
Initial conditions
Soil hydraulic properties
Vegetation properties
Soil moisture distribution
Dynamic
evapotranspiration
infiltration
recharge
runoff
Soil moisture
Plant growth
and partitioning
Soil erosion

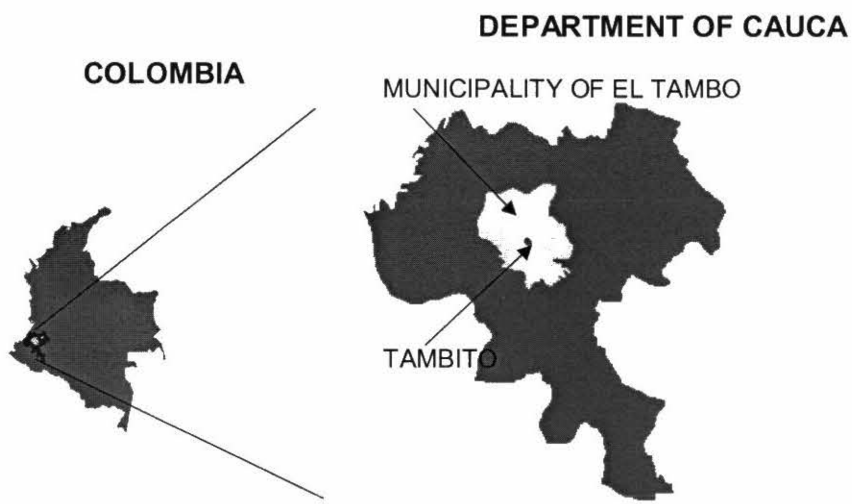


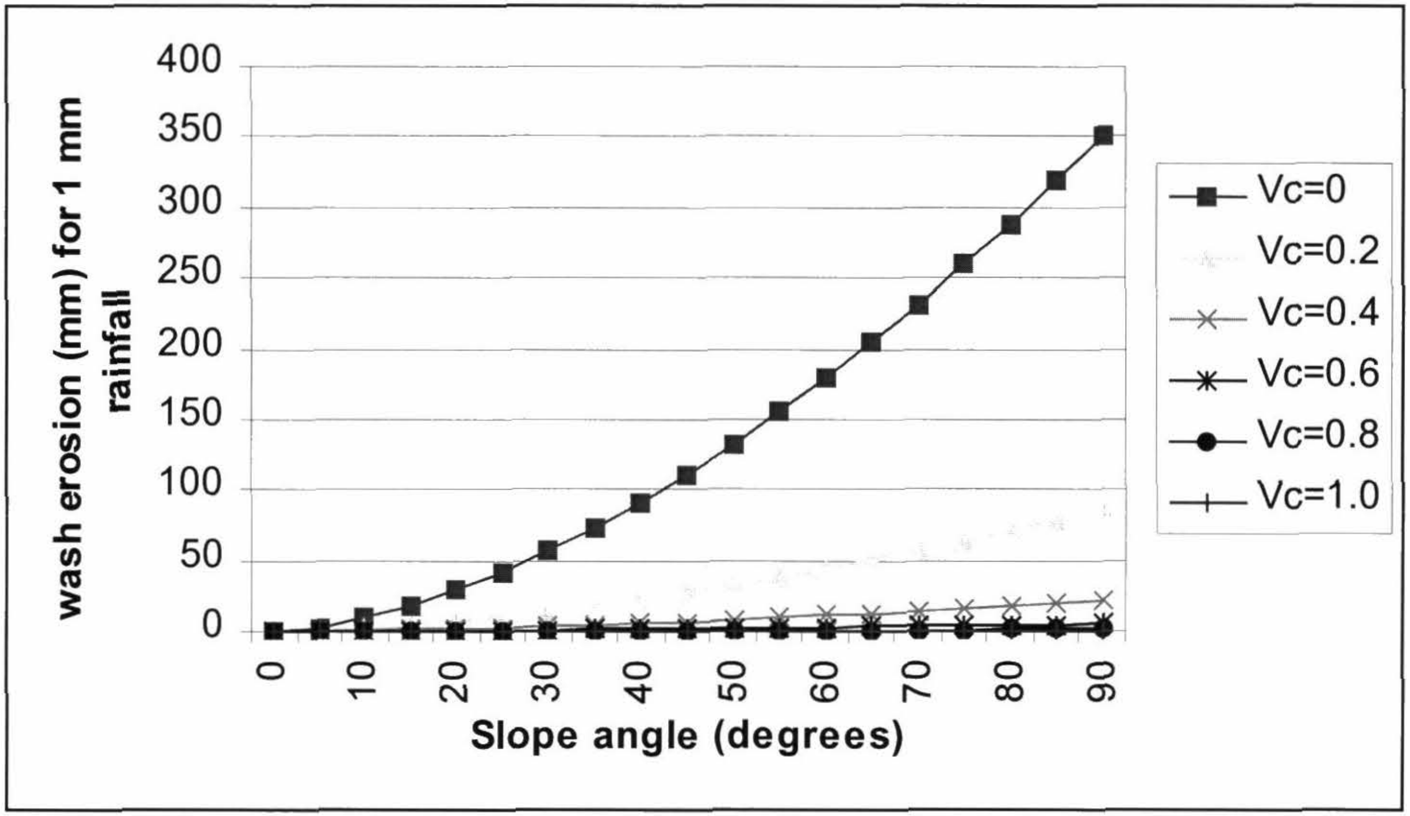
proportion of newly deforested cells at this altitude
0%
20%
40%
60%
80%
100%
Altitude
1300
1370
1440
1510
1580
1650
1720
1790
1860
1930
2000
2070
2140
2210
2280
2350
2420
2490
2560
2630
2700
2770
2840
Iteration 50
Iteration 40
Iteration 30
Iteration 20
Iteration 10
Iteration 1



100%
80%
60%
40%
20%
0%
proportion of newly deforested areas at this angle
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
52
Slope angle
Iteration 50
Iteration 40
Iteration 30
Iteration 20
Iteration 10
Iteration 1


25000
20000
15000
10000
5000
0
Number of cells
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
41
43
45
47
49
Iteration
Deforested
Secondary
Primary


DEPARTMENT OF CAUCA
COLOMBIA
MUNICIPALITY OF EL TAMBO
TAMBITO


wash erosion (mm) for 1 mm rainfall
400
350
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
Slope angle (degrees)
Vc=0
Vc=0.2
Vc=0.4
Vc=0.6
Vc=0.8
Vc=1.0