HYDROLOGICAL IMPACTS OF LAND USE CHANGE IN THE HILLSIDES OF COLOMBIA

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ABSTRACT

In this paper we examine the results of a series of numerical experiments based on field data obtained over a two-year period at the Tambito experimental cloud forest, in Cauca, Colombia. In these experiments we drive a GIS-based dynamic hydrological model offline with 52 separate iterations of a cellular automata-based land use change model that simulates the progressive deforestation of the catchment as a result of expansion of the agricultural frontier.

The hydrological model results are analysed to understand the changing sensitivity of catchment total hillslope runoff and erosion as deforestation occurs in different parts of the catchment. The sensitivity of these processes to deforestation shows non-linear behaviour as different parts of the catchment are deforested. In particular, an exponential increase in the sensitivity of these processes to deforestation is observed beyond 60% forest removal. These patterns of sensitivity are compared with landscape properties of the areas being deforested and of the areas remaining under forest in an attempt to understand the landscape factors responsible for these non-linearities in catchment response.

The patterns of sensitivity with deforestation observed reflect the spatial variability in landscape, soil and fluvial properties in the catchment. In particular, the sensitivity of runoff to land use change at a particular iteration of the cellular automata tends to reflect: (a) the landscape properties of the area remaining under

forest, (b) the soil properties of both forested and deforested areas, and (c) the location of the deforestation front relative to important lateral hydrological links in the catchment such as high order streams.

1. BACKGROUND

Land use change in tropical lowland forest is much discussed in the hydrological literature from the perspective of 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 are also being converted to pasture at an estimated rate of 1.1% per year - greater than that reported for lowland forests (FAO, 1993). As a result of heavy settlement of population in the Andean region between 1500 and 3000m, only 10% (Castaño, 1991) of the Colombia's TMCF remains. Though this accounts for only 3% of the area of the country, TMCF is rich in both hydrological and biological resources and therefore needs to be managed carefully. TMCFs are hydrologically unique and are one of the least hydrologically understood ecosystems of the humid tropics (Bruijnzeel and Proctor, 1995).

2. 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.). Slopes are extremely steep but vegetated. 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 minimum of 0° to a maximum of 68° at a spatial resolution of 25m.

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 sub-catchments 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, personal communication). 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. The forest is poorly vertically structured since, on these steep slopes, much of the light input is from the sides.

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.

3. 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 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 from pasture in this time. The area currently under pasture remains as pasture due to frequent cutting, and also 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 and bridges. The absence of large trees in the catchments reflects frequent landslides and treefall triggered by heavy rainfall or occult precipitation events followed by moderate winds. Treefall and standing death of trees is very common and leads to high rates of forest turnover which itself makes the concept of 'primary forest' difficult to apply.

4. MODELS FOR DEFORESTATION AND HYDROLOGICAL IMPACTS

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. Rather, we will examine the importance of the *pattern* of deforestation relative to landscape properties as a moderator of the sensitivity of catchment hydrology to deforestation.

In order to understand the hydrological significance of the pattern of deforestation, we produce a scenario for the pattern of deforestation in the catchments and then apply every iteration of this scenario as the vegetation cover for an integration of the 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. It simulates the conversion of forest to pasture only, and does not model regeneration of forest or more complex land use transitions. The automata 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 and 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. Iterations 1,4,8 and 12 of the land use change model are shown in Figure 2 - note that within 42 iterations the entire catchment is deforested.

For this paper a GIS-based dynamic hydrological model is applied to each of the land use transitions separately, offline and in a non-transient manner. The model will not be outlined here since it is fully described in Mulligan (1999). It is sufficient here to state that the model is a distributed GIS based hydrological process model, which is integrated at a spatial resolution of 25m and an hourly timestep across the whole catchment. The model is a non-riparian surface and shallow subsurface hydrological model, which also includes process equations for soil erosion and plant growth (Figure 3). The results of these model integrations are used to further understand how hydrological dynamics vary with progressive deforestation. The patterns of deforestation produced by the cellular automata are applicable only in tropical montane environments at the forest-agriculture frontier without complex patterns of land ownership.

This paper is not concerned with modelling the future of land use in Tambito, only with providing a plausible scenario for land use change with which to drive a hydrological model to further understand patterns of hydrological sensitivity. 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, as indicated by the cellular automata. The important property of the cellular automata in terms of understanding the impact of pattern on process is not the rate of deforestation but the location of deforestation with respect to hydrologically important landscape variables such as slope, altitude, topographic wetness index and the surface flow drainage network. Analysis of the patterns of deforestation show that the shallowest slopes are deforested first (in iterations 1-10) with steeper slopes being deforested later. The pattern is more complex for altitude: in the initial iterations the distribution of altitudes deforested is bimodal with a peak at 1450m and another at 2500m, reflecting the locations of the main cutting fronts (roads and existing pasture). As the cellular automata iterates, deforestation occurs more equally across the range of altitudes. Figure 4 shows the average slope angle and altitude of the deforested areas for every iteration of the cellular automata. In the first few iterations the lowest slopes are deforested with the average slope angle remaining less than 30° until iteration 5 before reaching an asymptote at 30° by iteration 12. The average altitude of deforested areas increases sharply from 2010-2060 masl between iteration 1 and iteration 5 and then decreases from iteration 5 to iteration 15 before increasing again from iteration 15 to iteration 42.

5. AN ANALYSIS OF THE IMPACT OF PATTERN ON PROCESS

The hydrological model was integrated once (for one month of meteorological data representing January 1998), for each iteration of the cellular automata land use model. Sensitivity was calculated for each output variable, for each integration of the hydrological model as the change in the value of the output relative to that for the previous integration of the model divided by the area of land deforested in the corresponding cellular automata iteration. In this way sensitivity provides a measure of the catchment hydrological response per unit of land use change and thus the importance of the pattern or location of change in terms of its impact at the catchment scale.

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5.1 Causes of the non-linear response of runoff and erosion to land use change.

The sensitivity of catchment outlet runoff to deforestation (Figure 5) shows that runoff is relatively insensitive until iteration 15 (58% of the catchment deforested) at which point sensitivity begins to rise sharply with further deforestation. This is true for model integrations where forest is replaced directly with pasture and where forest is replaced with bare soil, though the rise in sensitivity is steeper for the forest-pasture case. If one compares the patterns of change in sensitivity with those of average slope and altitude (Figure 4) of the areas deforested, these factors do not explain the exponential increase in sensitivity of runoff with deforestation.

Maybe cos after iteration 15 start the deforestation on steepest slopes

The pattern of change in sensitivity is very similar for catchment total soil erosion (Figure 6) since erosion is largely a function of runoff. Again the slope angles and altitudes of the areas deforested do not explain the pattern of sensitivity of this variable. One may, therefore, have to look at variables that represent connectivity of the flow network to explain this pattern of sensitivity. This seems reasonable since runoff and erosion are the only hydrological variables that:

Same as before.

(a) are directly affected by lateral connectivity or lateral accumulation along the drainage network and ,

(b) show an exponential increase in sensitivity with progressive deforestation (soil moisture, evapotranspiration and recharge show more complex patterns of change).

5.2 The role of flow connectivity

An examination of changes in flow connectivity as deforestation occurs (Table 1) indicates that the average stream order of the deforested area (following Strahler, 1964) increases perfectly linearly with the cells deforested (R^2=1.0), as does the average contributing area of the deforested segment. Neither shows a strongly non-linear change with deforestation so the non-linear response of runoff cannot be explained on this basis, in fact runoff and erosion sensitivity are non-linearly related with stream order and upslope area of the deforested part (Table 1).

5.3 Forcing by other hydrological variables

Since landscape variables such as slope, aspect, stream order and contributing area of the deforested area cannot be used to explain the non-linear response of runoff, it is possible that this response is the result of either :

(a) the non-linear response of another hydrological variable such as soil moisture which then forces the non-linear response of overland flow and erosion, or

(b) a response to the landscape characteristics of the area remaining under forest (as opposed to the deforested area), or

(c) a response to other properties of the forested or deforested areas as yet undefined.

Catchment average soil moisture (m^3water/m^3soil) changes linearly with the area of the catchment deforested ($\theta=5x10^{-6}+0.268A$, $R^2=0.99$). Though soil moisture sensitivity to land use change is non-linear, and runoff is related to soil moisture both functionally within the model and in the results ($Runoff=-31355\theta+11617$, $R^2=0.85$), soil moisture and runoff *sensitivity* are very poorly related. Runoff sensitivity shows a highly non-linear response to soil moisture sensitivity. Since soil moisture is the model variable most strongly linked with runoff, it is unlikely that other hydrological variables are responsible.

5.4 The contribution of forest and pasture.

If one looks at the average properties of the forested rather than the deforested areas for every iteration of the land use model (Figure 4) then some interesting patterns do emerge. Table 2 shows the relationships between runoff sensitivity and various landscape properties in the forested and deforested parts of the catchment for the full range of land use change iterations. Beyond iteration 30, high runoff sensitivity coincides with a steep increase in the average altitude of forested areas, an increase in the average slope of forested areas and a sharp decrease in the upslope contributing area of forested areas. By way of explanation, deforestation by the cellular automata leads a relatively stable mean altitude for deforested areas after the first few iterations which remove the lowest parts of the catchment. However, the mean altitude for forested areas continually increases as the agricultural frontier breaks up the forest cover leaving only high altitude remnants. Similarly the mean slope angle for the deforested areas is relatively stable after the first few iterations whereas the mean slope angle for the forested areas continually increases as the forest area is reduced until only small remnants of forest remain, producing strong fluctuations in the average slope angle. Whilst the upslope contributing area of the deforested areas increases most sharply in the early stages of deforestation because higher order flowpaths are 'captured' and contribute runoff to the deforested part. Further deforestation captures the flowpaths at lower orders and so the overall increase in the contributing area is less.

5.5 The contribution of soil properties

So, it is clear that patterns of change in the landscape properties of forest remnants as well as the deforested areas may contribute to the overall catchment runoff response to land use change. The catchment average soil properties of the forested and deforested segments may also contribute to the overall catchment runoff response as indicated by the relationships between runoff sensitivity and various of the model soil parameters for the deforested and forested areas across the range of land use change iterations. The soil parameters that vary spatially include the soil thickness, the hydraulic conductivity at the soil surface (Ks_{sfc}), the hydraulic conductivity at the soil-bedrock boundary ($Ks_{bedrock}$) and the gradient of the soil moisture-matric potential curve (the soil b-value). B-value is calculated as a function of soil texture following the method of Campbell (1985) and regionalised on the basis of field measurements (see Mulligan, 1999). If one analysis the patterns of change in these parameters as deforestation takes place (Figure 7), some interesting patterns emerge. Soil thickness of the forested area decreases as deforestation takes place since the remnant forests occur mainly in the upper slopes of the catchment. Since soil thickness is taken as *min*(soil thickness, rooting depth), the deforested part of the catchment tends to a constant soil thickness at the rooting depth for pasture (0.3m). Ks_{sfc} of the forested and deforested both increase slightly as deforestation occurs, $Ks_{bedrock}$ remains relatively stable for the deforested area but increases steeply after iteration 20 for the forested segment. These changes reflect changes in the soil thickness. The other major change beyond iteration 20 is in b-value, which increases significantly for the deforested section and decreases significantly for the forested section. So the major changes ion catchment average soil properties that take place as the catchment is deforested are in the hydraulic conductivities and the soil b-value. Changing soil bulk density distributions of the forested and deforested areas, which are a function of their soil thickness distributions, induces these changes.

Since hydraulic conductivity and b-value are major controls on the advance of the wetting front, infiltration and recharge in the model (Mulligan, 1999) it is likely that these changes control the hydrological impact of land use change in this catchment and the sensitivity of runoff to the same. This latter point is clear from Table 2, in which Ks_{sfc}, $Ks_{bedrock}$ and b-value of the deforested and forested parts of the catchment have clear but complex effects on the sensitivity of runoff to land use change.

6. CONCLUSIONS

The modelled sensitivity of runoff and soil erosion to land use change in the tambito experimental catchment is greatest in the latter stages of simulated deforestation where the upper parts (most inaccessible, higher altitudes, steeper slopes) of the forest are removed. The pattern of hydrological change and hydrological sensitivity with land use change is a complex function of the landscape and soil properties of the areas converted to pasture and of those remaining under forest in each land use iteration. In addition, non-linearities in the sensitivity of laterally connected processes such as runoff and erosion occur as the agricultural frontier crosses important hydrological links in the landscape, such as high order streams, which then contribute water derived from upslope to the deforested area.

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Figure 1 The location of the Tambito experimental catchments, Cauca, Colombia.

Figure 2 Patterns of modelled land use change for the Tambito catchments.

Figure 3 Basic outline of the TAMBITO hydrological model

Figure 4 Mean landscape properties of the forested and deforested area for 42 iterations of the land use change model.

Figure 5 Sensitivity of runoff to land use change for forest replaced by pasture and forest replaced by bare soil.

Figure 6 Sensitivity of soil erosion to land use change for forest replaced by pasture and forest replaced by bare soil.

Figure 7 Mean soil properties of the forested and deforested area for 42 iterations of the land use change model.

Variable (Y,X)	**Equation**	**R^2**
Streamorder *vs.* LUC	$Y=0.00006X+0.0359$	1.00
Upslope cells *vs.* LUC	$Y=0.0025X+38.546$	0.98
Runoff *vs.*upslope cells	$Y=0.002e^{0.1039x}$	0.89
Runoff *vs.* streamorder	$Y=0.0796e^{4.3254x}$	0.93

Table 1 Regression relationships between flow connectivity *vs.* area deforested and runoff sensitivity *vs.* measures of flow connectivity.

Variable	Equation	R^2
Forested area		
Mean altitude	$Y = 8.735X - 279.09$	0.86
Mean slope	$Y = 8.735X - 279.09$	0.86
Mean contributing area	$Y=50924e^{-0.2131X}$	0.86
Mean soil thickness	$Y = -1257.2X + 1694.3$	0.87
Mean Ks_{sfc}	N/A	-----
Mean $Ks_{bedrock}$	$Y = 215.26X - 152.95$	0.88
Mean soil B-value	$Y = -110.24X + 1381.4$	0.72
Deforested area		
Mean altitude	$Y = 5E\text{-}76^{e0.084X}$	0.59
Mean slope	N/A	-----
Mean contributing area	$Y = 0.002e^{0.1039X}$	0.89
Mean soil thickness	N/A	-----
Mean Ks_{sfc}	$Y = 1E\text{-}05e^{4083.7X}$	0.79
Mean $Ks_{bedrock}$	N/A	-----
Mean soil B-value	$Y = 9E\text{-}127e^{23.675X}$	0.75

Table 2 Relationships between properties of forested and deforested areas (X) and runoff sensitivity (Y) for the full range of land use change iterations.

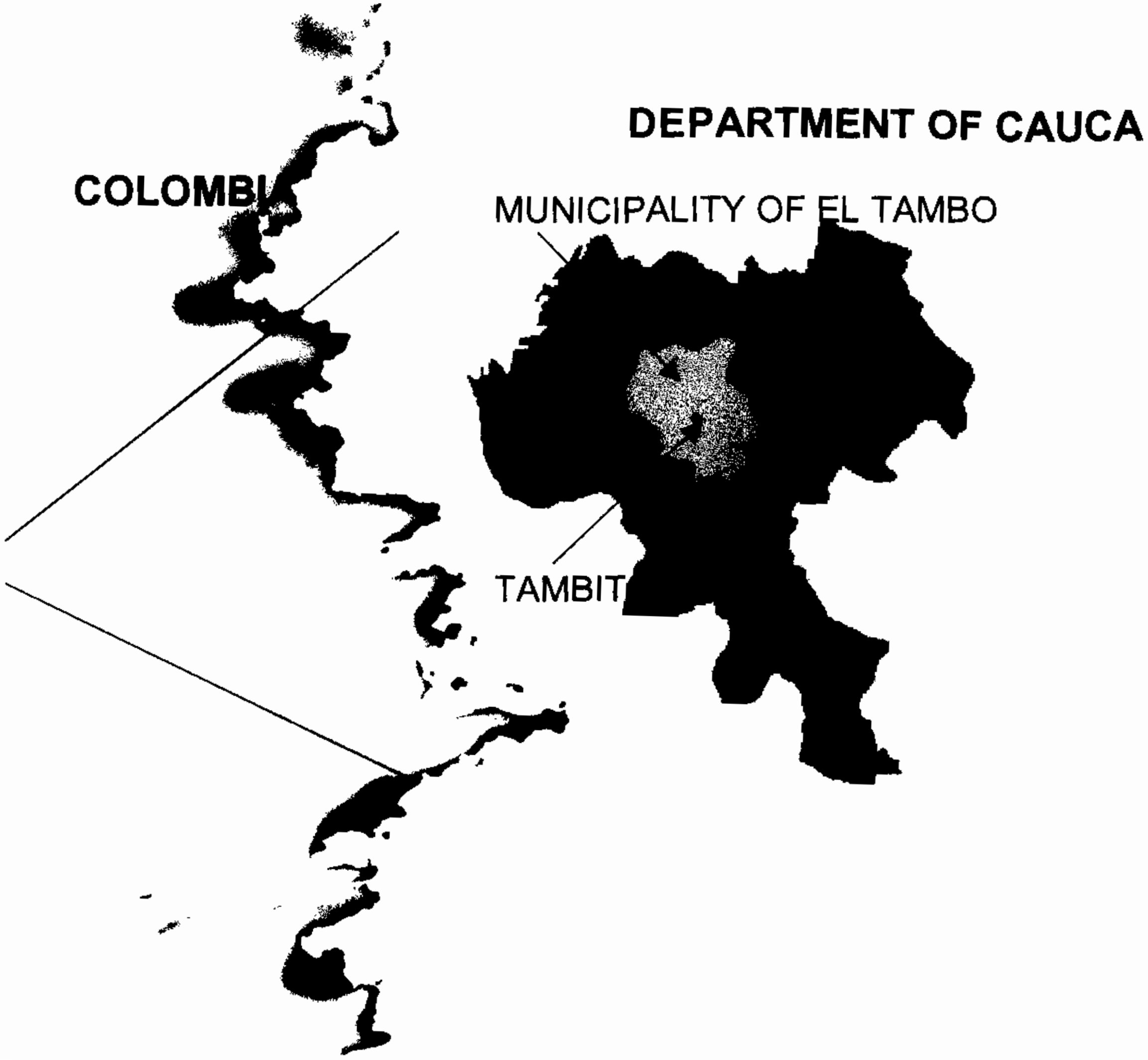
Iteration 1

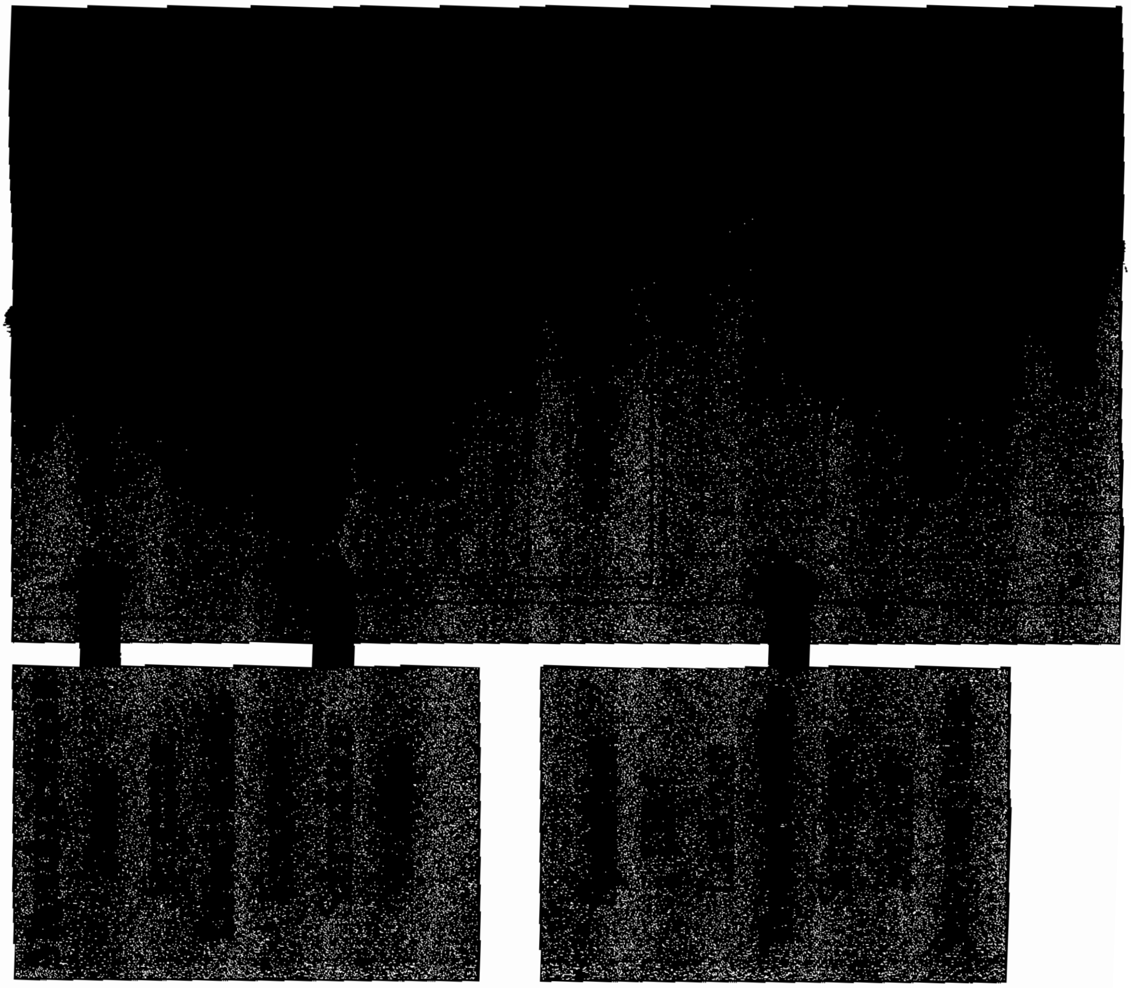
Iteration 4

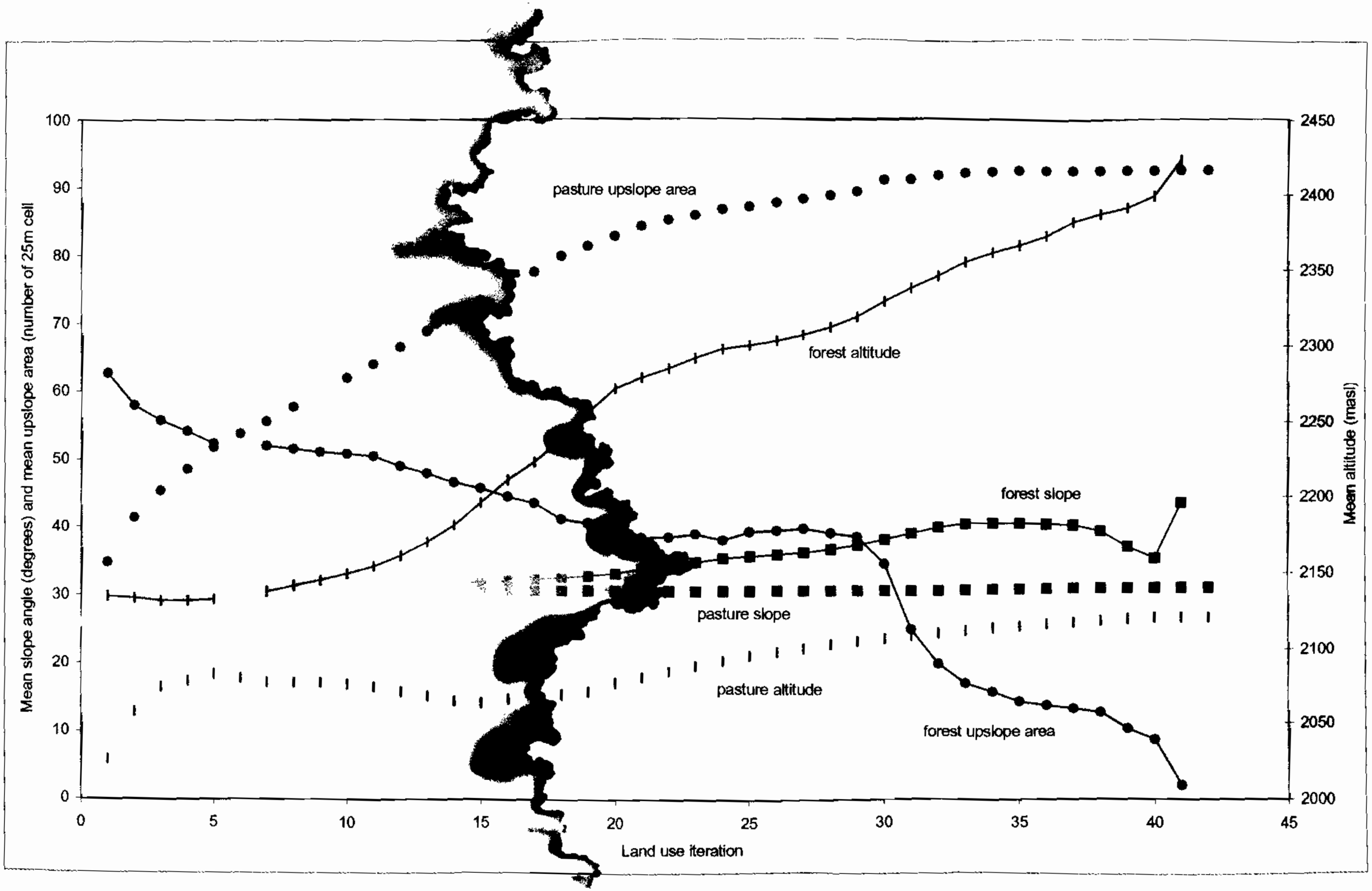
Iteration 8

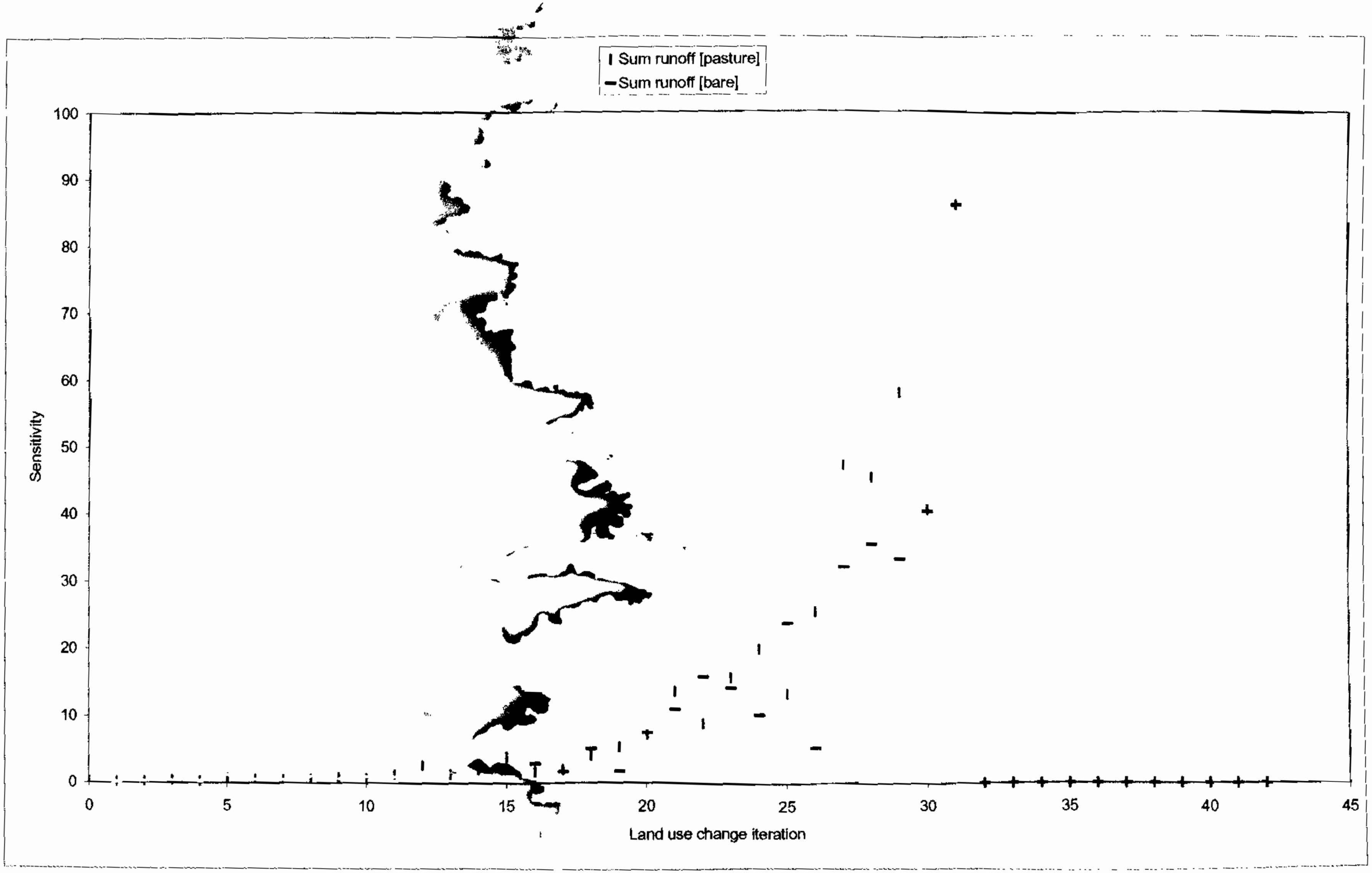
Iteration 12

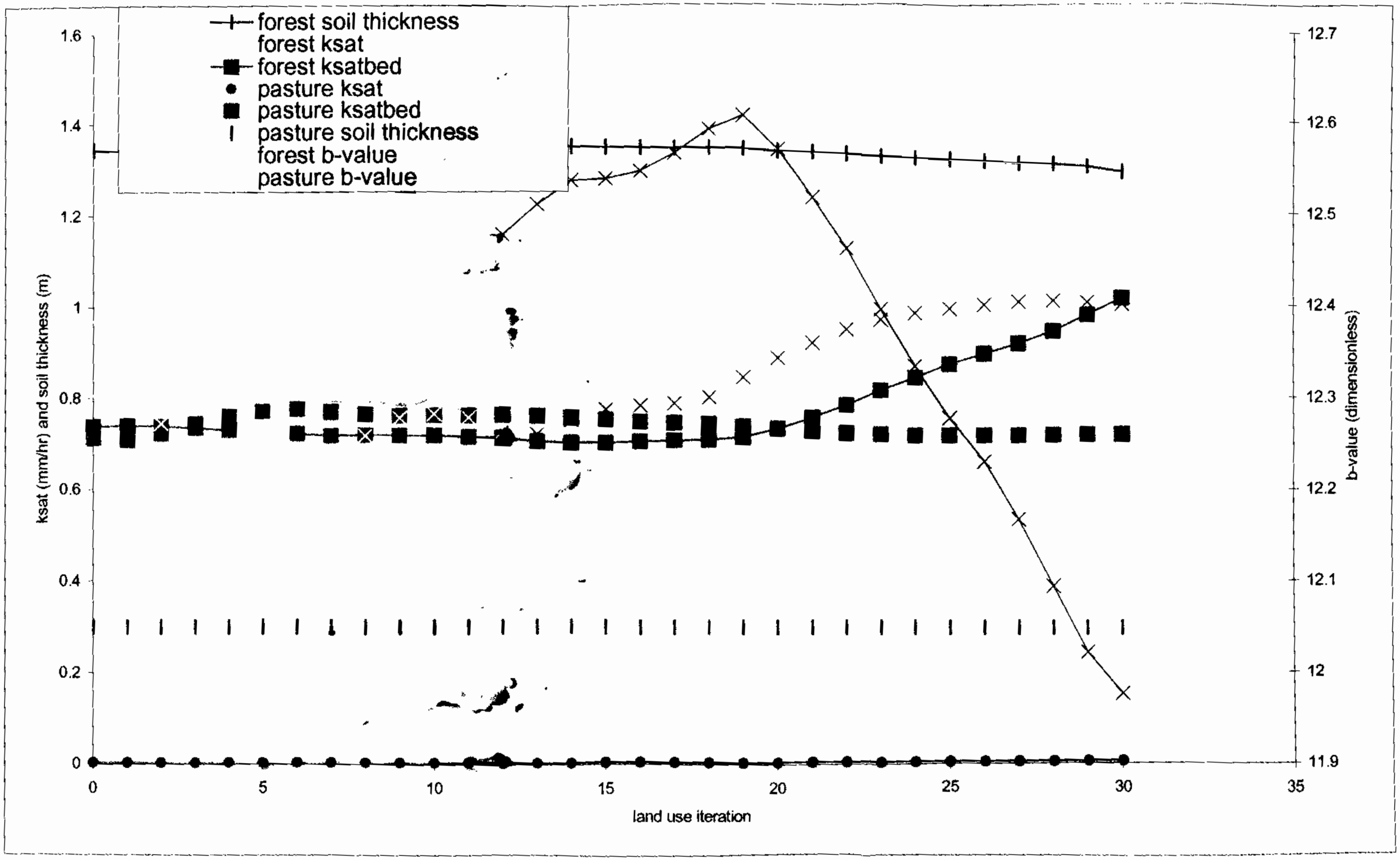
fig1


DEPARTMENT OF CAUCA
COLOMBI
MUNICIPALITY OF EL TAMBO
TAMBIT




pasture upslope area
forest altitude
forest slope
pasture slope
pasture altitude
forest upslope area
Mean slope angle (degrees) and mean upslope area (number of 25m cell
100
90
80
70
60
50
40
30
20
10
0
Mean altitude (masl)
2450
2400
2350
2300
2250
2200
2150
2100
2050
2000
Land use iteration
0
5
10
15
20
25
30
35
40
45


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


forest soil thickness
forest ksat
forest ksatbed
pasture ksat
pasture ksatbed
pasture soil thickness
forest b-value
pasture b-value
ksat (mm/hr) and soil thickness (m)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
b-value (dimensionless)
12.7
12.6
12.5
12.4
12.3
12.2
12.1
12
11.9
land use iteration
0
5
10
15
20
25
30
35