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Computer Simulation of High Mountain Terracettes as Interaction Between Vegetation Growth and Sediment Movement

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Summary

Terracettes are common features on steep slopes between 1700 and 2700 m a.s.l. in the central Pyrenees. These microforms can be understood as the result of the interaction between the growth of bunch grass (*Festuca eskia*) and geomorphic processes; the first element provides a discontinuity of the physical properties of the slope, and the second element modifies the growing pattern and affords the characteristic microprofile of the slope.

In order to analyse the former relationship, assuming that the sediment transport is only caused by a surface process, a computer simulation experiment has been performed. The first purpose of this model is the construction and verification of a set of hypotheses, and the production of a guide for field investigations. This model may then be used to investigate several questions concerning the geoecology of these features such as the role of geomorphic processes and vegetation behaviour, whether they represent a steady-state or an aggradation or degradation succession, and their efficiency as soil stabilisation features.

The first results, obtained during sensitivity analysis, show that it is easy to simulate the formation and evolution of individual forms although the biological model parameters for the generation of a continuous trend of terracettes are rather narrow, due to the risk of demographic instabilities or explosions. Once a parameter set is achieved, simulated terracettes are self reproducing in a dynamic equilibrium condition.

Simulated sediment transfer is lowered when a good terracette pattern is obtained, as a consequence not only of the vegetation cover but also of the topographical organisation.

The main questions posed are the role of reproduction from seeds and the fact that the model routes sediment but not water. The model is unable therefore to produce features related to concentrated runoff, indirectly simulating the role of montane processes which disturb the organisation of incipient channel forms.

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1 Introduction

Terracettes are micro-relief features common in above timberline slopes of mountains that belong to a family of periglacial forms like 'garland soils' and 'grassed stairs' (see Tricart 1967) which cover large surfaces where they are considered to be a significant system of sediment transport.

They show a convex downslope riser of bunch grasses retaining a tread of almost bare soil upslope. The riser is between 0.2 and 5 m wide and its average direction tends to be normal to the gradient, although they may be modified by the prevailing winds in which case they are oblique to the contours. The tread shows a plant cover which is less than 10% and its gradient is less steep than the general of the slope. In its lower section next to the riser, stone accumulations are often to be found. On occasions, these stones may pierce the riser forming stone threads.

In the Pyrenees, terracettes have been described by several authors (Gaussen 1971, Baudière & Serve 1971, Soutadé 1980). Their distribution (del Barrio & Puigdefábregas 1987) shows that they are restricted to an altitudinal range between 1700 and 2700 m. These limits correspond roughly with the winter (December – March) and whole year 0° degrees isotherm (del Barrio et al. 1990), suggesting that they are associated with a winter snowpack and a defined growing snowfree season in summer. In addition, terracettes tend to concentrate in convex and upslope situations, on steep gradients (25°–30°) and southern exposures.

The total plant cover of the terracette surfaces is often between 30 and 35%, and the main building species are bunch grasses such as *Festuca eskia, Festuca gautieri, Sesleria cerulea*, etc. Bunch grasses show a great density of tillers stemming from growing points at or just below the soil surface. The bunch habit results in a slow radial growth rate of the clump and therefore it reaches a high plant density in the clumps at the expense of leaving areas of bare soil among them.

Individual bunches show a definite life cycle with building and senescent phases such as those described in many plant species (*Festuca ovina* Watt 1947, *Carex bigelowii* Kershaw 1962). On flat or gentle slopes, this growth habit produces a mosaic of more or less circular random phases, including bare soil, building and senescent patches. Nevertheless, as the gradient becomes steeper, bunches become roughly semicircular and tend to connect among themselves, giving a pattern of continuous treads and risers following topographic contours. If the gradient is too steep or the sediment movement too rapid, terracettes become disrupted and in extreme cases they may cease to exist.

Terracettes were described by geomorphologists a long time ago (Odum 1922, Sharpe 1938, Meynier 1951, Rahm 1962, Tricart 1970, Anderson 1972) but their origin seems still controversial (Vincent & Clarke 1978). Several processes such as creep (Calyton 1966), solifluxion (Costin 1950), gelifluxion (Demangeot 1951), small scale soil failures (Vincent & Clarke 1982) have been cited together with a certain significance of surface wash (Soutadé 1980). Nevertheless, the interaction between plant growth and geomorphic processes seems to be a common feature in all cases.

In this work we attempt to explore such an interaction on the assumption that the sediment transport is only caused by a surface process like slopewash. A computer simulation experiment is used first to secure a set of working hypotheses, second, to test if these hypotheses ar able to produce forms similar to the ones observed, and third, to analyse feedbacks, testing on the field aspects shown by the model, and on the model testing some features observed in the field. The main questions to be analysed in the long run with this simulation experiment are:

a) Is simple interaction between vegetation growth and superficial sediment movement enough to organize a terracette pattern?

b) What are the main aspects of plant behaviour that are necessary to build such forms?

c) Why do they occur only in selected enviroments?

d) Are these forms a climactic self-reproducing pattern in a dynamic equilibrium, or the result of environmental aggradation/degradation?

e) Are these features efficient against soil erosion?

The present paper describes the working hypotheses and the organisation of a deterministic-stochastic computer program model, together with a sensitivity analysis performed during parameter optimisation by a trial and error process which has also been useful also to check its behaviour and to obtain early results. Validation and calibration of the model with field data have not been attempted to date.

2 Organization of the computer program

The simulation computer progam (Gallart 1989) was written in FORTRAN 77 language, with the help of the VPLOT package (DECUS), used for drawing with a dot line printer. This program is run in a DIGITAL VAX II/GPX minicomputer.

The simulation is performed on a grid of 80×160 points, with a set of distributed biological and geomorphic variables. This framework is handled as an element of a continuous slope, the first row and line being equal to the last ones. Sediment and vegetation (but not water) are therefore recirculated from the bottom to top and from the right rim to the left one and vice-versa.

Fig. 1 shows the main design of the program. After parameter input and initialisation of matrices, a stochastic biological iteration is performed for several deterministic geomorphic iterations. Several intermediate plots of the patterns and profiles of the results can be requested, and the program ends with a concluding plot of the evolution of plant cover along the entire simulation run. This model version handles much more information than it outputs.

3 Vegetation behaviour

The biological part of the model is based on a relatively intricate set of working hypothesis of the vegetation behaviour, the preliminary program versions having shown that management of the vegetation cannot easily be simplified without failure. This part of the model has a stochastic structure, and so these hypotheses are expressed in terms of probabilities or of functions which modify background probabilities (of birth, death, growth, etc.). Parameters and functions are conceptually defined and have been optimized by a trial and error procedure because they are difficult to obtain after field observations.

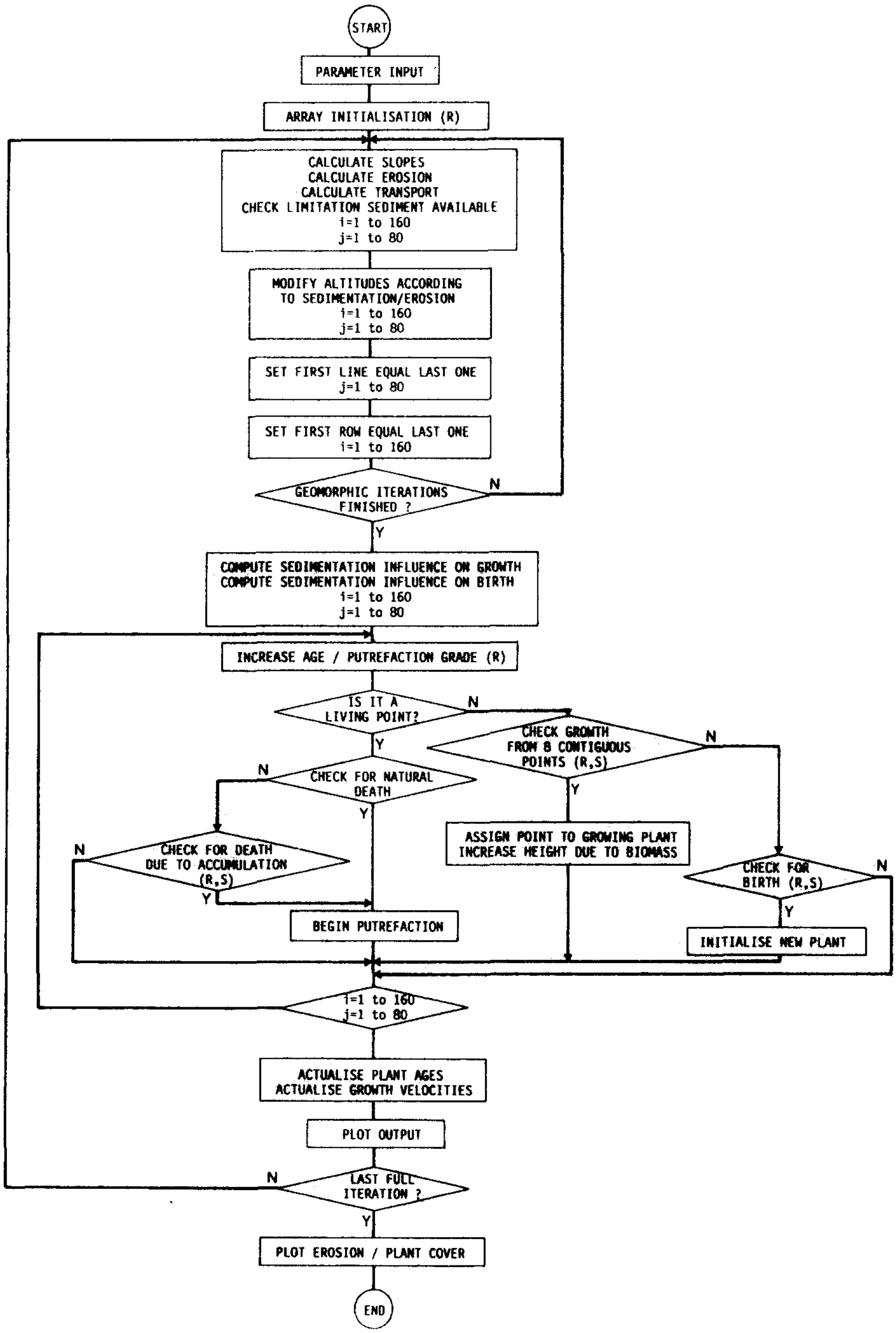

Fig. 1: *Abridged flow chart of the simulation program. (R) and (S) represent, respectively, the usage of random numbers and sediment transfer values in calculations or decisions. Recirculation of vegetation from left to right and from bottom to top was omitted in the figure. Sixteen geomorphic iterations are usually performed every biologic iteration.*

3.1 Birth: Every point has a preselected probability (PN) of birth from seed; this background probability is modified by erosion or sedimentation at this point, being maximal for a preselected sedimentation value (VSN), and being lowered linearly with increasing or decreasing sedimentation (negative values of sedimentation correspond to erosion values).

3.2 Age: Once a plant is born, it grows to be the neighbouring points with a basal velocity (probability of growth, RIQ) which decreases slightly with plant age and drops to zero when it reaches a preselected value (EM); age increments are no the unity but modified by a random value in order to obtain a stochastic variation in natural death ages.

3.3 Living points: Every plant is represented by a number of living points, all with the same basal growth probability. Points have a preselected death age (IM); when a point dies, a litter decay period starts while growth of the same plant towards this point is prevented and biomass thickness is progressively diminished. Point life or decay increments are also random numbers in order to obtain some variability. The probability of death of a living point increases with sedimentation if it exceeds a selected value (FM).

3.4 Growth: Vegetative growth of plants is radial from every point, but growth towards a point is disabled if sedimentation at the target point exceeds a selected value or is resticted (probability is decreased) by sediment transfer counter to the growing direction. The probability of growth from every point is increased by sedimentation in it. When a plant grows from a point to another, the height of the target point is increased with a value which represents the thickness of the biomass; this thickness is progressively lost after point death following the decay period.

4 Geomorphic processes

The geomorphic part of the model has a deterministic form with the result that the values of erosion, sedimentation and transport, measured in depths units, depend only on gradient, presence of vegetation and the behaviour of neighbouring points.

As previously stated, this simulation model was performed with the simplest geomorphic processes; onyl sediment detachment by splash and runoff, and transport by running water were considered. It should be pointed out that only sediment but not water is being routed and that this model cannot therefore simulate formation and evolution of features related to and transport by concentrated runoff. The limitations of this approach will be discussed later.

4.1 Sediment detachment

It is assumed that sediment is detached (eroded) by two processes:

First, a splash-like process is only active when the point considered lacks vegetation, taking then a uniform value (SE splash parameter).

Second, a runoff erosion process is represented by an equation based on Meyer & Wischmeier (1969). Water erosion is calculated as proportional to slope at an exponent of two-thirds. The vegetation effect is calculated by assuming that Manning's roughness is about 0.07 for bare stony soil and 0.33 for densely vegetated rims as water velocity is inversely proportional to roughness at an

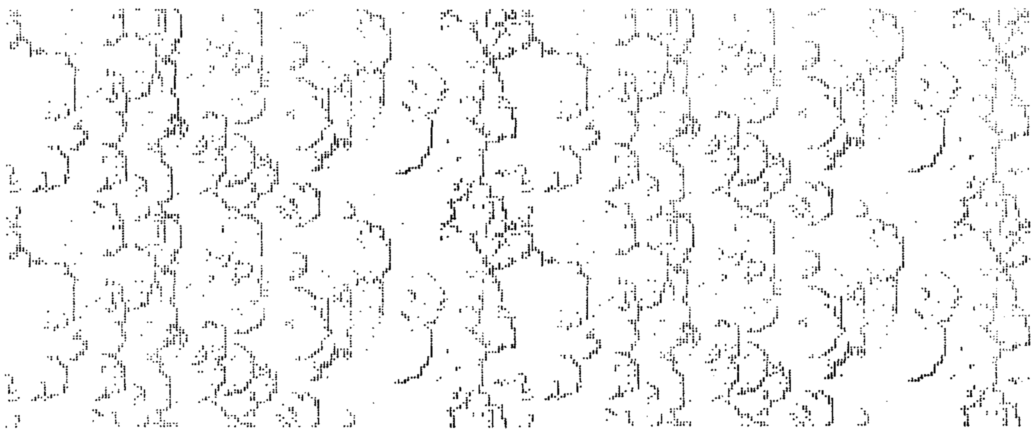

Fig. 2: *Full simulation pattern obtained by juxtaposition of four simulation cells handled by the program. Flow is from left to right, and black dots represent living vegetation points; this result was obtained after 560 geomorphic iterations, or 85 full iterations.*

exponent of 0.6, and detachment is proportional to the square of water velocity, runoff detachment has been taken therefore 6.5 times less in the areas densely vegetated in bare areas. Runoff erosion is then calculated by:

$$Ew = WE\ S^{2/3}\ VE \quad (1)$$

where
- Ew is erosion by runoff
- WE is a constant parameter
- S is slope gradient (sinus)
- VE is a vegetation factor which is the unity for non vegetated, and 1/6.5 for vegetated points.

4.2 Sediment transport

Following the same work (Meyer & Wischmeier 1969), running water transport was taken as proportional to the slope at an exponent of five thirds. As transport is related to the fifth exponent of velocity, the ratio between transport at vegetated and non vegetated points was taken as 108. Runoff transport is then computed by:

$$T = WT\ S^{5/3}\ VT \quad (2)$$

where
- T is transport by running water
- WT is a constant parameter
- S is slope gradient (sinus)
- VT is a vegetation factor for transport which is the unity for non vegetated and 1/108 for vegetated points

4.3 Topographic evolution

The amount of sediment available at every point provided by splash and runoff detachment and transport from contiguous points is checked for transport to the adjacent points at the subsequent iteration. If the sediment available exceeds transport capacity, the remainder is sed-

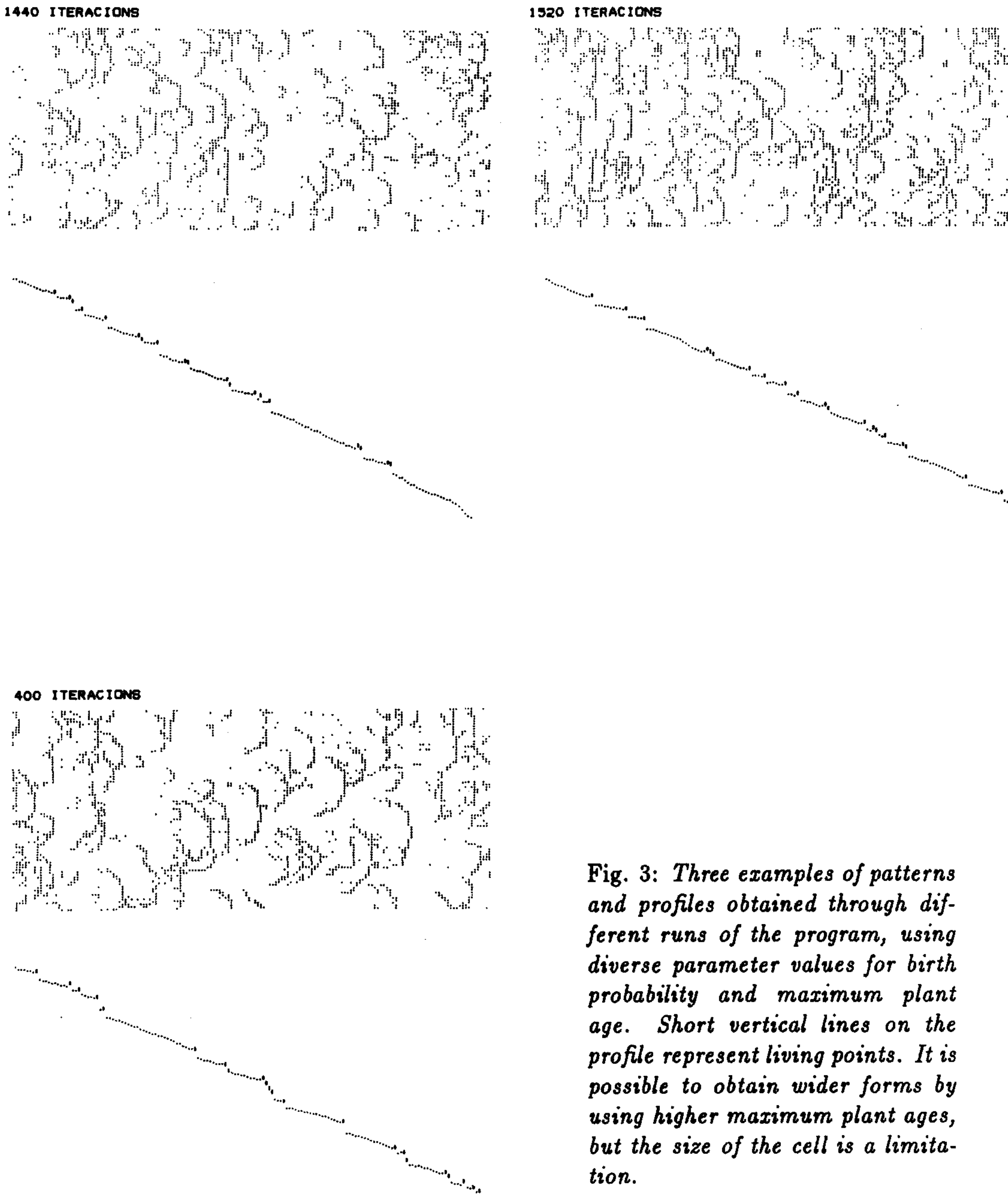

Fig. 3: *Three examples of patterns and profiles obtained through different runs of the program, using diverse parameter values for birth probability and maximum plant age. Short vertical lines on the profile represent living points. It is possible to obtain wider forms by using higher maximum plant ages, but the size of the cell is a limitation.*

Photo 1 + 2: *Different aspects of terracettes on the Izas basin, Central Pyrenees at 2200 m of a.s.l.; compare with figures 2 and 3.*

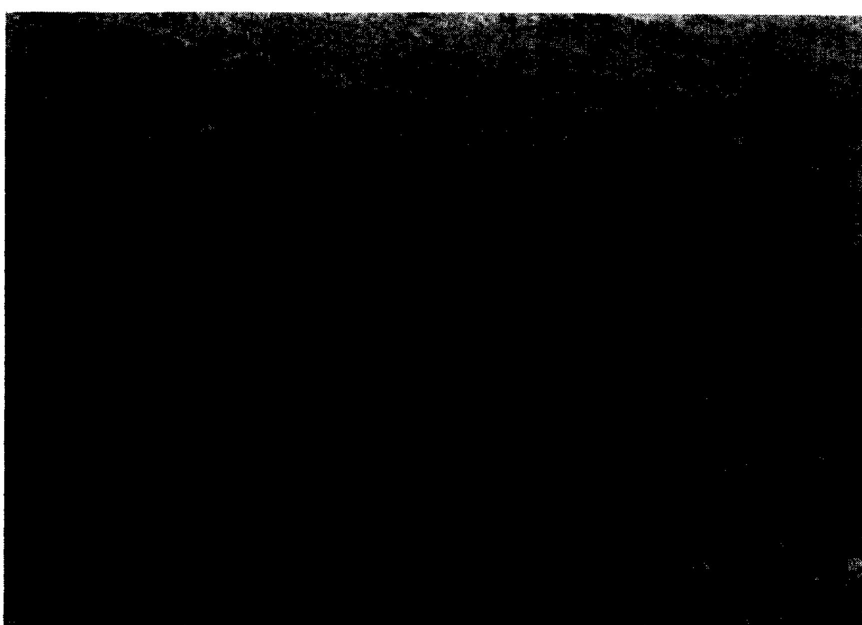

Photo 3 + 4: *Different aspects of terracettes on the Izas basin, Central Pyrenees at 2200 m a.s.l.; compare with figures 2 and 3.*

imented but if the transport capacity exceeds the available sediment, only this amount is conveyed to the other points.

When a geomorphic iteration has been performed on the entire piece, topographic elevations of the grid elements are modified according to the positive or negative values of sediment to be added.

5 Results

5.1 Generation and stability of terracette patterns

The simulation model is able to produce spare forms and generalised patterns of terracettes within a relatively wide range of parameter values. The sensitivity analysis has shown that the most selective parameters are those related to birth and growth; inadequate parameter values produce strong instabilities of the vegetation pattern with demographic explosion or oscillations as shown on fig. 5, a and b.

Once a set of adequate ranges of parameter values is obtained, terracette patterns are very stable along a significant number of iterations and are made up of forms which sprout, move downslope and die, being replaced by similar new forms within a system in a dynamic equilibrium condition. The long term evolution of vegetation covering shown in fig. 5c, is fully representative of most of the simulation runs and demonstrates that equilibrium is attained after a relatively short starting period.

Most of the patterns obtained with the simulation model are very comparable to those observed in actual field forms. Figures 2 and 3, and photos 1 to 4 provide some examples of the resemblances.

5.2 Erosion

The results obtained with the simulation runs show that sediment transfer decreases significantly when well shaped patterns of terracettes are obtained. The volumes of sediments transferred for different cover densities are shown in fig. 4. This figure suggests that transport capacity is the limiting factor of sediment transfer in low plant cover conditions (it is an infinite slope) whereas sediment transfer drops close to detachment values when cover becomes denser.

This can be accounted for by the distance washed by the flow before this is interrupted by vegetation. This distance is sufficient to meet the transport capacity provided by the slope gradient only in conditions of low vegetation density. The lower sediment transfer observed where good terracette patterns occur can be easily explained by the fact that these represent a good organisation of the microtopography, bare erodible areas being gentler, while steep rims become protected by vegetation; in these conditions, sediment movement is controlled by the growth rate of vegetation. This may account for the fact that the sediment transfer values are lower than sediment detachment ones obtained for well shaped terracettes in fig. 4.

6 Discussion and conclusion

This model can scarcely explain the geographical distribution of terracette patterns or any relationship with periglacial or frost-related processes. This limitation is due, on the one hand, to the fact that only sediment is routed; therefore, all forms related to concentrated water are disabled, indirectly simulating an en-

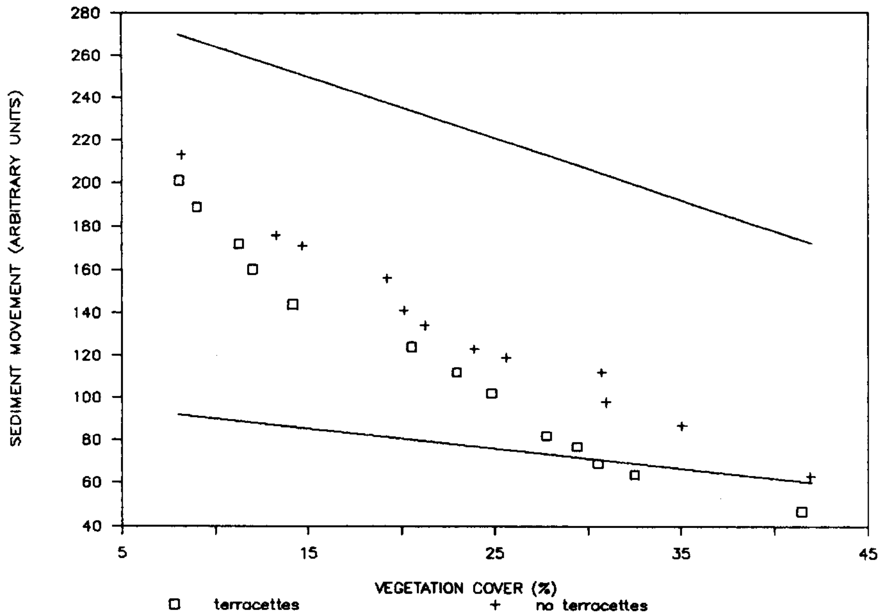

Fig. 4: *Sediment transfer values obtained by simulation for different vegetation covers. The upper line shows the sediment transport function, and the lower one represents sediment detachment, both calculated for a uniform slope of the same grade as the one used in the simulation. Note that sediment transfer is reduced when a good pattern is achieved, and can even be less than the predicted detachment because of microtopographic organisation (see text).*

vironment where frost heaving precludes rill formation because of high infiltration capacities and obliteration of incipient forms. On the other hand, most terracettes show coarse deposits which cannot be transported by runoff, but by other processes, mainly pipkrakes, frost creep and raindrop or hail impact. In fact, the equations used for erosion and transport, although they have been selected as representative of runoff processes, could be taken as a gross approximation of any surficial process influenced only by gradient and the presence of vegetation.

Routing of running water has not been attempted in this model to date, not only because of limitations of the continuous slope approach, but also because it could be very unrealistic if handled in a simplified manner. In fact, infiltration rates on the flat areas of terracettes are as high as 700 mm/h, and water very quickly exfiltrates at the feet of the vegetated rims during infiltration experiments. These huge permeabilities are the result of sedimentation over the vegetation biomass, and the effect of small ice lenses within the finer sediments during frost periods (Solé et al. 1989).

Sprout from seeds is a controversial topic among the authors because very

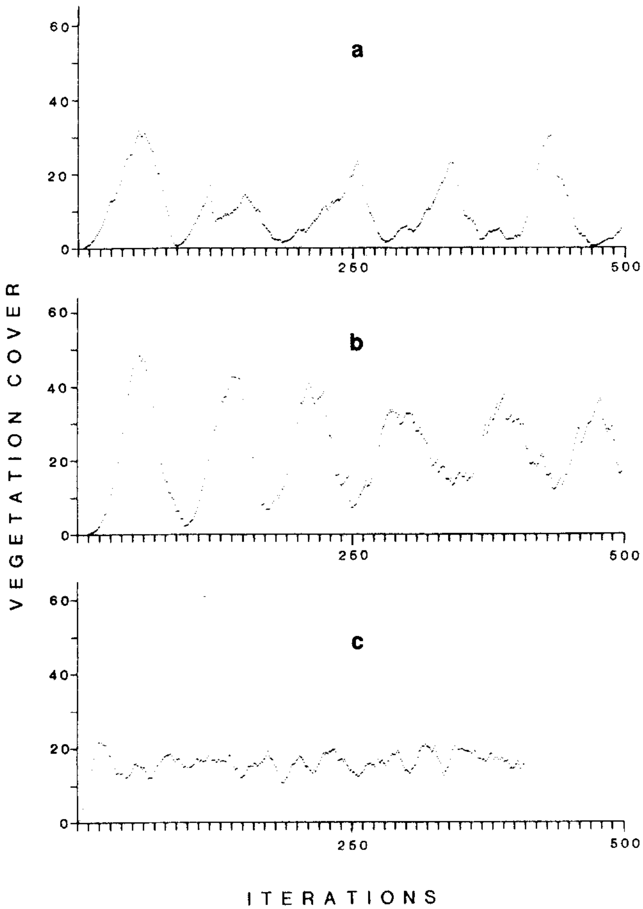

Fig. 5: *Evolution of vegetation cover during long-lasting simulation runs under three different conditions.*
a) represents an unstable condition where demographic explosions occur because randomly born plants grow too fast.
b) represents a nearly sinusoidal plot obtained as a consequence of a pendulum effect.
c) demonstrates a successful run where good stability is attained after few iterations.

young plants are very rare in the field. It is obvious that this kind of reproduction is necessary to explain the occurrence of plants on the divides. Moreover, terracette forms do not show a significant increase in width downslope. One explanation could be that sprout from seeds does not occur regularly over the years, but only during selected years because of especially favorable weather conditions. Mapping of different plants by DNA analysis could be very useful to assess the role of sexed reproduction.

Though somewhat unrealistic, the presented simulation model is being used to better understand and analyze the processes involved in terracette development, highlighting the fact that the interaction between surface sediment movement and plant growth is able to produce terracette forms. The results do not provide evidence, however, that runoff related processes are the only geomorphic processes capable of producing these forms.

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