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Gullying in the southeastern Brazilian Plateau, Bananal, SP

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Abstract In the hilly lowlands of the southeastern Brazilian Plateau, the regional drainage network has been expanding into the tributary unchannelled basins ("rampa complexes") by gullying throughout the Holocene. Gully development is dominated by seepage erosion, in a manner similar to the conceptual model of channel headward growth proposed by Dunne (1970, 1980). The rate of removal of sediment stored in the gully floor by channelized runoff controls the rate of seepage erosion and for the period November 1982–January 1987 about 1076 m^3 $year^{-1}$ has been eroded at the study site. The dominance of subsurface flow in the present rangeland environment may be due to the construction by "Saúva" ants of tunnels in the soil through which overland flow enters the soil and generates pipe flow.

Formation de ravines sur le plateau de la région sud-est du Brésil

Résumé Durant le Holocène, le réseau de drainage des régions collinaires de basse altitude du plateau sud-est brésilien s'est étendu vers l'amont par effet de ravinement. La formation des ravines est provoquée surtout par les percolations selon un processus en accord avec le modèle d'expansion des têtes de ravine proposé par Dunne (1970,1980). Le taux de reprise par les écoulements superficiels du sédiment déposé sur le fond de la ravine, conditionne le taux d'érosion par percolation. De novembre 1982 à janvier 1987 près de 1076 m^3 par an ont été érodés sur le site étudié. La prédominance des processus d'écoulement hypodermique dans les terres à paturage est probablement due aux galeries creusées par les fourmis "Saúva", qui facilitent l'infiltration et provoquent des phénomènes de "renards".

INTRODUCTION

Gullies or incised channels have been reported from a number of locations ranging from arid to humid landscapes and are recognized as important sediment sources. Gully size is variable and may evolve a hierarchical network system. Dunne (1970, 1980) has proposed a conceptual model for the headwater development of channels in humid lands by the action of subsurface flows. Recent field investigations which support Dunne's model include Higgins (1982), Pillans (1985) and Howard (1986). To date, however, little attention has been given to the process oriented field studies and therefore channel erosion by subsurface flows is poorly documented.

In this paper we describe the process of gully and headward growth by subsurface flow processes; emphasis is given to the observation of mechanisms and controlling variable of erosion rates and directions of gully expansion. Field studies are being conducted in the Municipio de Bananal at 22°30'–22°45' S and 44°05'–44°28' W, from where water and sediments are drained toward to the Middle River Paraíba do Sul. Major drainage routes seem to be controlled by the structural trends of the Precambrian substratum which strikes roughly northeast-southwest and is constituted mainly by migmatites and a series of gneisses. Mean annual temperature is about 20°C; and average precipitation attains 1500 mm $year^{-1}$, being concentrated in the summer when monthly depths may exceed 200 mm. Until the mid-1700s the Atlantic tropical rainforest was present in the region and then was substituted by coffee plantations. Late in the nineteenth century, cattle grazing was introduced in the Paraíba Valley where it exists nowadays.

GULLYING HISTORY

In the Upper Pleistocene, some areas of the southeastern Brazilian Plateau experienced intense hillslope degradation which, together with stream aggradation, gave rise to thick alluvial fills and a poorly organized drainage network (Meis, 1977). The resulting wide, flat valleys with slightly inclined concave sides form a kind of drowned topography which extends into low-order unchannelled tributary basins called "rampa complexes" (Meis & Monteiro, 1979).

From the Pleistocene-Holocene boundary to the present, the regional drainage systems have had renewed valley dissection. River degradation has occurred throughout the Holocene, although at least two phases of aggradation led to well-developed fill terraces. Degradation of the main channel caused new channels to form in the tributaries and to extend progressively through the "rampa complexes" by gullying (Meis, 1977; Meis & Monteiro, 1979). The headwater progression of the incising channels has not been uniformly distributed over space and time and, therefore, the tributary basins operate at different stages; while some major valleys still aggrade, others have been trenched (Meis & Moura, 1984).

A recent field survey conducted in Bananal and its vicinity have shown that within an area of 262 km^2 most of the gullies (67%, n = 107) occur in the valley axis of the "rampa complexes" (concave or concave-straight in profile and plan view). Gullies in the "rampa" domain are in 42% of cases connected to the regional drainage network system, 20% are disconnected and associated with free faces of road cuts, and 38% occur in minor valleys disconnected from the main channel network (Oliveira & Meis, 1985). Most gullies connected to the main system develop deep channels through low gradient valleys and in 65% of the sites the gullyheads are extending into upper-slope segments where disconnected gullies usually develop. This fact led us to suppose that the two gully systems tend to connect with time.

STUDY SITE

Gully erosion studies are carried out at Fazenda Bela Vista, in a first order basin (0.15 km^2) adjacent to Piracema creek, a tributary of the River Bananal (see Fig. 1). The basin consists of a major hollow fed by a network of minor ones ("rampa complexes"). A series of clay-rich sandy colluvial layers, converging mostly from the tributary "rampas", interfinger and cover a thick stratified sandy alluvial fill in the main valley of the hollow.

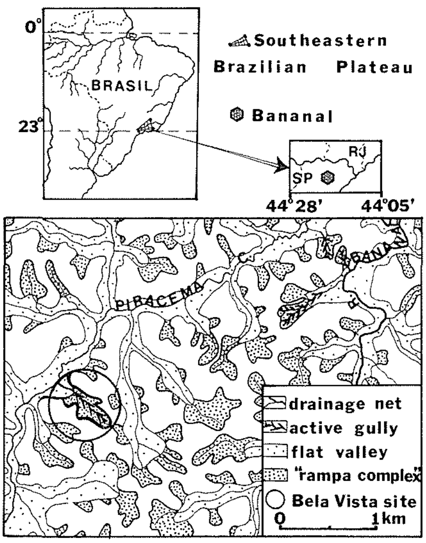

Fig. 1 *Location of the study site at Fazenda Bela Vista, in Bananal (São Paulo).*

The main valley of the basin contains about 272 000 m^3 of sediment which has been trenched in two major periods (Fig. 2). The first period (I) was probably associated with the dissection of the intermediate terrace level on the main river (T2) and the gully is already covered by vegetation. The current incision of the 210 m long active gully is part of period II. The middle-lower reach is dissecting the saprolite (IIa) and the upper one or headzone (IIb) is "suspended" by a local nickpoint given by an Upper Pleistocene colluvium, the so-called "Bom Retiro" regional layer (Moura & Meis, 1986). A narrow channel incision into the older gully (I) floor is the main route for water and sediment derived from gully II.

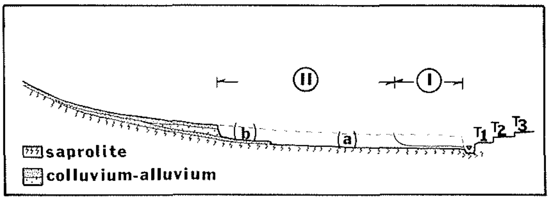

Fig. 2 Longitudinal profile along the main valley of the Bela Vista ampitheater and adjacent river valley terraces (T1, T2, T3); location of gully heads: head I, older vegetated gully and head II, active gully (sketch).

The dominant vegetation in the basin is grass (*Gramineae Paspalum)* which develops a dense root mat in the topsoil zone (about 20 cm). The intensive grazing by cattle seems to catalyse favourable "habitat" conditions for ants ("Saúva") as indicated by a number of anthills of different size (up to 3 m of diameter) on the surface. These hard-working insects are responsible for the construction of deep conduit systems (3–5 m deep) which are connected to the surface through holes of variable sizes. Recent surveys on the spatial distribution of the ant excavations have shown that anthills tend to predominate in the upper slope segments but the conduit system may extend for tens of metres downslope and laterally. Tests using smoke as a tracer indicates the connection between holes at the free face of the gully wall and anthills away from the gully edges. This suggests the ants may enhance water infiltration in this area.

HYDROLOGICAL PROCESSES

Cattle grazing which reduces plant cover and leads to local compaction of the soil is usually thought to increase Horton overland flow production. Sprinkler experiments at Bela Vista site, for example, have demonstrated that trampled sites produce overland flow for rains that on less disturbed sites produce no runoff (Coelho Netto *et al.*, in prep.). During heavy rains in the wet season, overland flow extends over much of the slopes. Despite a large production of overland flow, water may easily enter the soil through the conduit systems made by the "Saúva" ants, especially when soils are nearly saturated or saturated. In the peak rainy season of January 1987, we observed on the free face of the road cuts at Bela Vista a number of turbulent pipe-flows within a near-saturated soil matrix; we noted that such drains were receiving water from overland flow at the surface. We have also seen water exfiltrating from a dissected anthill after a rainstorm, perhaps due to a shallow perched saturated zone under high seepage pressures beneath the area of the anthill.

The shallow groundwater flow in the valley deposits upslope of the gully head appears to follow the subsurface palaeotopography. In the gully wall, springs tend to occur downstream of the surrounding tributary hollows. Exfiltration at spring may concentrate at the colluvium-alluvium

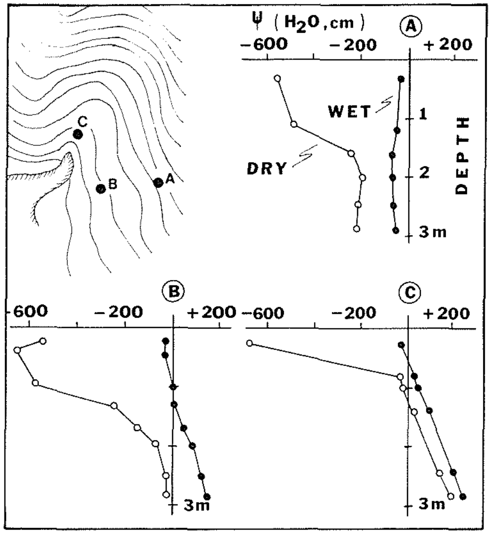

Fig. 3 Average values of matric tension (ϕ, in H_2O cm) for daily tensiometer readings during dry (June 1985) and wet (January 1986) periods in a small "rampa complex" unit at Fazenda São João.

boundary or may be distributed at different depths where clay-rich layers interfinger the highly permeable sandy body. The seepage face is also concentrated at the base of the root zone.

Tensiometer data from a single "rampa" unit near the Bela Visa site shows that topography may strongly control the convergence of subsurface flows toward the hollows following the model proposed by Dunne & Black (1970). Figure 3 illustrates the matric tension variations (ψ, in H_20 cm) within the soil profile for dry (July 1985) and wet (January 1986) periods at some stations. Higher negative pressures are observed at the base of the root zone in the dry period and tension values tend to decrease with depth and with distance downslope. Yet in the dry period positive pressure heads occur in the hollow axis at a depth about 1.3 m into the soil. The soil responds to the rainy season by a decrease in average tension near the surface and a rise of the water table. The subsurface saturated zone expands upslope during the rainy season and seepage pressure increases around the gully margin.

GULLY EROSION

During field observations in January 1987 we found that erosion and scarp retreat at Bela Vista site was clearly dominated by "seepage erosion" (according to Dunne's definition; Dunne, in press). The headward progression of narrow spring-sapping zones were seen to lead to failures of the overlying materials. These sapping zones were concentrated at the colluvium-alluvium boundary within the gully walls. The collapsed sediments tended to be deposited at the base of the vertical walls and functioned as a temporary barrier to basal erosion. Sapping mechanisms at the base of the root zone seem to operate at slower rates perhaps due to limited shallow subsurface storm flow generation or to the root strength added to the topsoil. The root zone tends to be undermined and to break into pieces due to the formation of cracks.

Sediments accumulated on the gully floor are removed by three kinds of runoff:

(a) Horton overland flow on the collapsed materials;
(b) waterfall impact particularly at the main gully head during intense storm periods, and
(c) water discharge from shallow subsurface and deeper groundwater flows.

The lateral migration of the channel flow, especially in the middle-lower reach, has also caused bank scour and the collapse of more sediments into the channel, contributing to the gully widening with time.

In Table 1 we show average erosion rates for different periods calculated on the basis of detailed topographic mapping (1:500) in November 1982 and January 1987. Stratigraphic evidence of colluvium deposited during the period of coffee plantation in the main valley indicates that gully II has developed after the introduction of cattle (in 1870). Local people provided

Table 1 *Gully erosion rates (Er) at Bela Vista site for different time periods and morphological variables of the contributing area upslope the considered gully head: drainage area (Da), average basin gradient (Gr) and hollow density (Hd).*

Period	*Site*	*Da* $(10^3\ m^2)$	*Gr* $(m\ m^{-1})$	*Hd* $(m\ m^{-2})$	*Er* $(m^3\ year^{-1})$
1870–1967	*IIa*	*160*	*0.14*	*0.01*	*803*
2/67–11/82	*IIb*	*88*	*0.20*	*0.01*	*813*
11/82–1/87	*IIb*	*88*	*0.20*	*0.01*	*681*
	A	*59*	*0.23*	*0.01*	*189*
	A'	*11*	*0.22*	*0.04*	*445*
11/82–1/87	*M*	*8*	*0.30*	*0.04*	*450*
	a (left)	-	-	-	*1604*
	a (right)	-	-	-	*1340*

information about the location of the gully head in 1967 (at the "Bom Retiro" nickpoint); after 1967 the retreat was reactivated apparently during heavy summer storms, after having been "stable" for at least a few decades.

Tabulated data show similar rates (about 800 m^3 $year^{-1}$) for the two longer periods despite a great variation in the respective drainage area. Since 1967 the gully head has divided in two major fingers: heads A and A' (in Fig. 4). Head A has advanced faster than head A'; the A contributing area is smaller but shows higher density of hollows than the

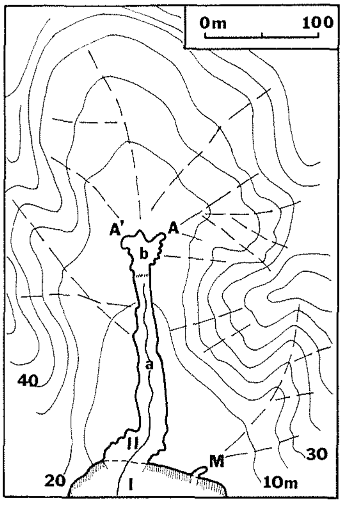

Fig. 4 *Detailed topographic map (base scale 1:500) of the Bela Vista amphitheatre; location of gully heads (A and A' at gully IIb, and M at gully I); hollow axes shown by dashed lines.*

A' area. Head M, connected to the older gully (I), shows similar rates of retreat to head A; it drains an area with the same hollow density of 0.04 (m m^{-2}), a steeper source area, but the drainage area is smaller. Sediment due to channel widening exceeded that due to gully head advance since 1982; faster retreat rates on the left bank could be related to the topographic configuration of the lateral hillslopes. The average erosion rate of local gully retreat increased in the last five years to about 1076 m^3 $year^{-1}$.

FINAL CONSIDERATIONS

The rate of gully head advance is not simply correlated with drainage area or hollow density upslope of the gully, but is partly due to the differing stratigraphy at the three gully heads (A, A' and M). In particular, at head A', clay-rich layers within the stratified sandy package spread the groundwater exfiltration laterally across the cut. No such intermediate layers occur at head A; thus, the concentration of flow discharge at the base of the sandy body favours seepage erosion. In all three cases incision depth and site springs in the head cut are controlled by the dense underlying "Bom Retiro" colluvium. Waterfalls at the gully heads of A and A' promote the relative rapid removal of the collapsed sediments, and consequently enhance the seepage erosion by exfiltration of the groundwater flows. At site M, the gully floor is dissected into the saprolite, causing a large exposure of the saturated zone and increasing the seepage forces. In case of head M, the effectiveness of seepage erosion at the base of the thick deposit can not be related to the action of waterfalls in controlling the removal of the collapsed sediments as the superficial water fluxes are diverted laterally by a road cut just above the gully head.

Besides the morphological and stratigraphic factors considered above, we can not exclude the role played by other variables in controlling gully erosion. Variations in rainfall will affect the supply of groundwater flows at a point; thus, erosion rate should correlate with rainfall. Because of the dominance of seepage erosion in gully retreat, the land use effects due to modifications of the soil surface must be of secondary importance. It is normal to attribute accelerated gullying to cattle grazing-induced runoff and erosion changes. In the Bela Vista the effect may be indirect. The grasslands planted to support the cattle also attract the "Saúva" ants. Tunneling by the ants promote piping and shallow subsurface flow. Perhaps it is the enhanced subsurface flow due to the ants that has led to accelerated gullying in this region of southeastern Brazil.

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REFERENCES

Dunne, T. (1970) Runoff production in a humid area. *US Department of Agricutlure Report ARS 41-160.*

Dunne, T. (1980) Formation and controls of channel networks. *Progr. Phys. Geogr.* **4**, 211-239.

Dunne, T. (in press) Hydrology, mechanics and geomorphic implications of erosion by subsurface flow. In: *Groundwater Geomorphology* (ed. by C. G. Higgins & D. R. Coates). Geol. Soc. Am. Spec. Pap.

Dunne, T. & Black, R. D. (1970) An experimental investigation of runoff production in permeable soils. *Wat. Resour. Res.* **6**, 478-490.

Higgins, C. G. (1982) Drainage systems developed by sapping on Earth and Mars. *Geology* **10**, 147-152.

Howard, A. D. (1986) Groundwater sapping on Mars and Earth. In: *Proceedings and Field Guide, NASA Groundwater Sapping Conference* (ed. by A. D. Howard, R. C. Kochel & H. E. Holt) (Flagstaff, Arizona, 1985), xi-xiv.

Jones, J. A. A. (1981) The naturo of soil piping: a review. *Brit. Geomorph. Res. Grp. Monography no. 3* geobooks, Norwich UK.

Meis, M. R. M. (1977) As unidades morfoestratigráficas neoquaternárias do Médio Vale do Rio Doce. *Anais da Academia Brasileira de Ciências* **49**, 443-459

Meis, M. R. M. & Monteiro, A. M. F. (1979) Upper Quaternary "rampas": Doce River Valley, SE Brazilian Plateau. *Z. Geomorph.* **23**, 132-151.

Meis, M. R. M. & Moura, J. R. S. (1984) Upper Quaternary sedimentaion and hillslope evolution: southeastern Brazilian Plateau. *Am. J. Sci.* **284**, 241-254.

Moura, J. R. S. & Meis, M. R. M. (1986) Contribuiçáo à estratifrafia do Quaternário Superior no Médio Vale do Rio Paraíba do Sul-Bananal, SP. *Anais da Academia Brasileira de Ciências* **58**, 89-102.

Oliveira, M. A. & Meis, M. R. M. (1985) Relações entre a geometria do relêvo e formas de erosão linear acelerada (Bananal, SP). *Geociências São Paulo,* , 87-99.

Pillans, B. (1985) Drainage initiation by subsurface flow in South Taranaki, New Zealand. *Geology* **13**, 262-265.