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ORIGINAL PAPER

The effects of biological geotextiles on gully stabilization in São Luís, Brazil

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Abstract This paper analyses the contribution of biological geotextiles to gully stabilization in the urban area of São Luis City (Sacavém District). Biological geotextile mats were constructed from palm leaves. At Sacavém, gully rehabilitation included the following techniques: (1) installation of Buriti geotextiles, in association with barriers of wooden stakes and the construction of contoured terraces; (2) analysis of sediment particle size and (3) photograph comparison of the development of vegetal cover. Rehabilitation used $\sim$30 kg of grass seeds (*Brachiaria decumbens*) on slopes, in combination with geotextiles. Besides recuperating a degraded area, income has been generated to poor people, who live around Sacavém gully, either by producing the geotextiles or by applying them on the soil, together with grass seeds, lime and NPK to improve soil properties.

Keywords Biological geotextile · *Buriti* mats · Gully · Rehabilitation

1 Introduction

Soil degradation by erosion is one of the world's most serious environmental problems, causing extensive loss of cultivated and potentially productive soil and decreased crop

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yields (Fullen and Catt 2004; Morgan 2006; Goudie and Boardman 2010). It has been estimated that some 4,000 million tonnes of soil per year have been eroded from the continental USA since the 1930s (Fullen and Catt 2004). Major causes of water and wind erosion include deforestation, overgrazing and arable land mismanagement. By removing vegetation cover, the erosion-resisting capacity of the soil becomes disturbed. These sites include both agricultural and non-agricultural lands. Most rehabilitation efforts on degraded lands involve different techniques, which could include traditional engineering or soil bioengineering.

Soil bioengineering has been recognized as a technique to provide slope stabilization and erosion control, taking into account both traditional engineering and biological principles, using living and dead vegetation, associated with construction materials. Normally, bioengineering projects are less costly than conventional engineering, and they have been applied in different environments, including stream bank stabilization, roadside slopes, river restoration, hillslopes, mine tailings and gully slopes (Descheemaeker et al. 2006; Smets et al. 2009; Fatahia et al. 2010; Rodrigues and Bezerra 2010).

Land degradation is attributed to both environmental and socio-economic conditions, including unauthorized and/or inefficient urban development and planning (Sobreira 1989; Goudie 1994; Fullen 2003; Downs and Booth 2011; Guerra et al. 2014). Soil erosion in urban areas is generally associated with irregular population settlement. Consequently, inappropriate land management, including poor maintenance of vegetal cover, is the principal cause of water erosion (Casal et al. 1999; Valentin et al. 2008; Munro et al. 2008). Vegetation cover is often undervalued in terms of its control over landscape incision (Howard 1997; Poesen et al. 2003).

São Luís, like many other Brazilian cities, has experienced rapid population growth in recent decades, which has created a series of socio-economic and environmental problems, including accelerated soil erosion. Sacavém is one of these communities, where natural and human factors contribute to severe gully erosion (Sathler et al. 2005; Guerra et al. 2005; Bezerra et al. 2010). Rapid population and urban growth have intensified problems, compounded by poor planning and improper land use.

Biological geotextiles are potentially excellent biodegradable and environmentally friendly materials useful for soil conservation. The application of biological geotextiles, constructed from the palm leaves of *Mauritia flexuosa* (Buriti), has been investigated at the 'Laboratory of Environmental Geomorphology and Land Degradation' (LAGESOLOS) of the Federal University of Rio de Janeiro.

2 Study area

The settlement of São Luís was established in 1612 and has evolved in distinct phases. Rapid urban growth was associated with industrialization in the late eighteenth century. The local lithology belongs to the *Barreiras* Formation, consisting mainly of Tertiary sandstones with intercalations of shales, argillites and siltstones (Guerra et al. 2004, 2005). Weathering of these rocks produces erodible soils, including lithosols, oxisols, concretionary red/yellow clay soils and concretionary plinthosols (Maranhão 1998). Thus, erodible soils and regolith are subject to high erosion rates, especially on steep slopes subject to additional human interventions. Furthermore, although regional slopes are quite gentle, there is localized high relative relief. Secondary mixed forest and brushwood are the dominant vegetal covers adjacent to urban gullies. The climate is humid tropical, with average annual temperatures of 26 °C, reaching higher values in October–December and lower from April to June (Fonseca 2001). Rainfall distribution is irregular, marked by two very distinct seasons (rainy and dry). The highly seasonal erosive rains incise a complex series of soil erosion landforms, mainly gullies.

3 Materials and methods

In order to investigate the role of geotextiles, studies were undertaken at a specific site to determine the effects of rehabilitation in an urban environment.

3.1 Sacavém gully rehabilitation

Soil bioengineering techniques have been applied in Sacavém gully using biological geotextiles constructed from *Buriti* palm (Fig. 1). The aim was to minimize soil erosion, by intercepting rainfall, retarding run-off velocity and sediment loss (Smets et al. 2008; Guerra et al. 2009; Smets and Poesen 2009; Bhattacharyya et al. 2009, 2010). These techniques included the following: 1. Buriti geotextiles in association with barriers of wooden stakes (Fig. 2) and the construction of contoured terraces; 2. analysis of sediment particle size and 3. photograph comparison of the development of vegetation cover.

The rehabilitation work used ~30 kg of grass seeds (*Brachiaria decumbens*) on the slopes, in combination with geotextiles. To protect the topsoil, the shrub Sabiá (*Mimosa caesalpiniae folia*) was used on the higher parts of the gully. The rehabilitated area was fertilized with 500 kg ha^{-1} of NPK (4-14-8), and decomposing palm was added to the topsoil, as a source of organic matter. The project employed ten local men for 6 days, who conducted the work using hand-held tools (Fig. 3). A tractor (type backhoe loader) was used for 2 days to construct the terraces.

The rehabilitation work in Sacavém was divided into three areas, because of local relief characteristics. Areas 1–3 (Fig. 4) were constructed by men and the tractor; the upper parts of areas 4–8 (Fig. 4) were constructed using the tractor and areas E, M and D (Fig. 2) were reshaped exclusively by manual labour.

In Part 1 (Fig. 4: areas 1–3), the team used biological geotextiles and organic matter from decomposing palms, seeds and inserted barriers of wooden stakes along contours. This area had formed due the concentration of run-off from the street above the gully (Fig. 5).

Area 2 was mostly made by the tractor, which constructed the terraces by reshaping the gullies. This part was formed by water flows collected from the street and was totally modified by tractor work. Here, there was evidence of active rill erosion. After tractor work, the reshaping of slopes and the application of biological geotextiles were achieved manually.

Area 3 was made by men, using Buriti biological geotextiles, organic matter from decomposing organic material (palm trees and leaves), wooden stakes and the planting of shrubs, as the area was inaccessible to the tractor. To reshape the internal part of the gully, we used techniques to minimize water flow energy, using barriers of wooden stakes (Fig. 2) and the application of biological geotextiles, grass seeds and organic matter from decomposing palm leaves. On the barriers, Sabiá bushes were planted to stabilize the topsoil. The rehabilitated area in Sacavém is ~2,000, and ~800 m^2 is covered with Buriti biological geotextiles (Fig. 5).

The particle-size distribution of soil samples from Sacavém gully walls and the gully floor was determined, using EMBRAPA (1997) protocols. Vegetation cover index was

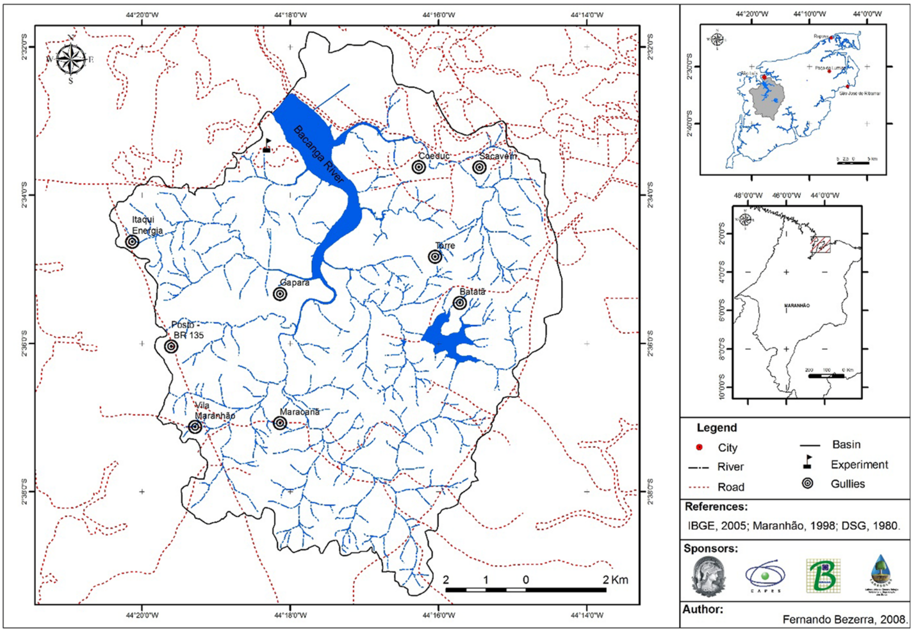

Fig. 1 Location of gullies and rehabilitated site at Sacavém gully, São Luís City, Brazil

Fig. 2 Area 3 of the rehabilitated gully, with work in progress. *E*, *M* and *D* were reshaped exclusively by manual labour, São Luís, Brazil (LAGESOLOS 2008)

Fig. 3 Men working with hand-held tools, São Luís (LAGESOLOS 2008)

monitored at Sacavém, using photographs and supervised classification tools (Arcgis 9.3), which can perform pixel-based classification. Vegetation cover development was monitored weekly from March to May 2008, using photographs taken from fixed points.

4 Results

4.1 Gully rehabilitation

Due to difficulties in diverting flows, which would require more extensive engineering works, the channel was maintained, and the basal slope was strengthened to support the flows (Fig. 5: arrow). In the upper part of this area (slope angle ~8°), contours were surveyed and barriers of wooden stakes were used to brake run-off velocity from adjacent vegetated slopes. Some slope segments had slope angles of ~45° (Fig. 4: part 3). However, this was considered too steep for the effective application of biological geotextiles.

In area 2, work was completed to reshape the gullies and construct the ~12-m-high terraces using the gully material. Tractor work was impeded, because on the second terrace, the tractor had difficulty in working, because the high sand content made the slope unstable. These terraces are crossed by a flow convergence area, which was formed by the workers inserting sand bags, decomposing palm leaves and grass seeds, to form a vegetated channel after grass growth.

Most erodible materials tended to be silts and sands, which are non-cohesive and sufficiently small to be transported by the flow rates characteristic of rills (Fullen and Catt 2004;

Fig. 4 Rehabilitated areas with cover of Buriti geotextiles, Sacavém, São Luís (areas *1–3* were constructed with men and tractors; upper areas *4–8* were constructed using a tractor) (LAGESOLOS 2008)

Goudie and Boardman 2010). In the study area, soil textural analysis confirms the coarse texture (Table 1). The samples had high sand (68.5–96.7 %), fine sand (1.1–10.5 %), variable silt (1.1–23.0 %) and clay (5.0–27.0 %) contents. Soil organic matter contents are low (~1 % by weight) and are even less in the subsoil. These soil properties indicate high erodibility. Clay lenses were present at ~2.5 m depth (Fig. 4: areas 4–8). Because of this, the tractor worked better than on the second sandier terrace. According to photograph comparison data, in 1 month, complete vegetation cover had developed (Figs. 6, 7). Continued success requires continued high-quality maintenance, which is being achieved by local people, under project supervision.

One month after the rehabilitation work, São Luís experienced intense and prolonged rains (Table 2), which presented attendant on minor site problems. However, local people were re-employed to work on site maintenance. This shows that we can prove that the entire rehabilitation process was successful, especially in an erosive tropical climate. The monthly precipitation (10/03/08–09/04/08) of 753.7 mm had a recurrence interval of ~60 years, and there was only some minor damage and erosion, especially where water convergence occurred, but this damage was easily rectified. This evidence indicates that the work was successful. The gully stabilization project was carefully costed. Financial returns from fruits from planted trees and shrubs are also being evaluated, as part of an ongoing cost-benefit analysis. These evaluations will enable both cost-benefit analysis of reclamation and identifying the time horizon to project profitability. The ongoing site development can be monitored via the LAGESOLOS website: http://www.lagesolos.ufrj.br.

Fig. 5 *Continuous lines* areas rehabilitated with Buriti palm mats. *Hatched lines* the rehabilitated area in Sacavém (LAGESOLOS 2008)

Table 1 Texture of soil samples from Sacavém gully

Samples	Sand (%)	Silt (%)	Clay (%)
1	96.67	2.23	1.10
2	68.46	23.04	8.50
3	83.25	9.25	7.50
4	92.85	2.75	4.40
5	94.76	2.14	3.10
6	96.60	1.60	1.80
7	94.15	1.05	1.80
8	78.97	10.53	10.50
9	94.12	3.38	2.50

Sand = 2,000–50 µm, silt = 50–2 µm and clay ≤2 µm

Textural data show that the main component material of the slopes at Sacavém gully is sand, with many samples being >90 % sand (Table 1). Thus, the soils are highly erodible, and so the use of biological geotextiles is very important to arrest the erosion process.

5 Discussion

Soil bioengineering techniques have been used at Sacavém gully. Biological geotextiles constructed from Buriti mat were placed on the soil surface, in order to decrease run-off velocities, trap sediments and protect planted grass seeds from erosion. Comparative studies have been extensively reported. For instance, Stokes et al. (2010) reviewed the

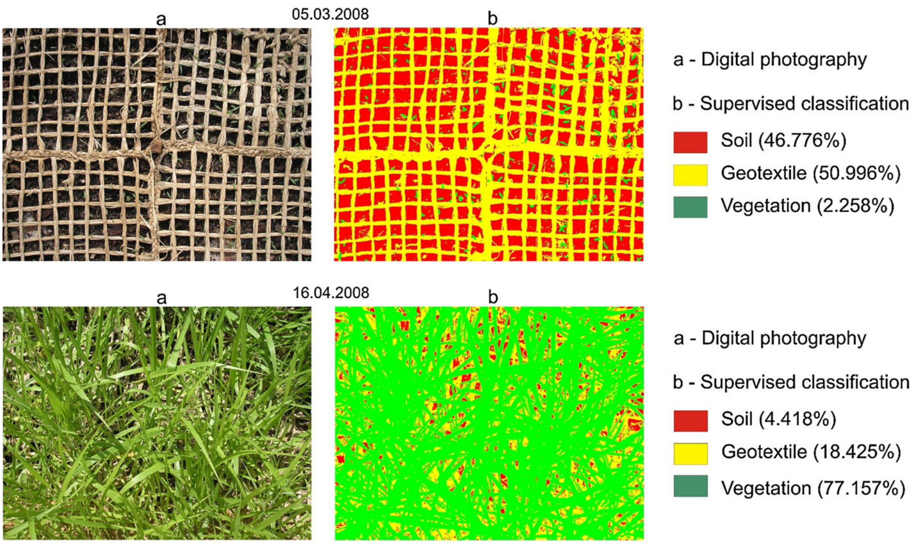

Fig. 6 Photograph comparison of vegetation cover development at Sacavém gully

Fig. 7 Grass development, one month after rehabilitation (16/04/08), at Sacavém gully (LAGESOLOS 2008)

performance of soil bioengineering techniques in different countries, including the 'Office National des Forêts' (France). Since the mid-nineteenth century, this Office has maintained a department 'Restauration des Terrains en Montagne' which restores degraded forests in

Table 2 Daily meteorological data from São Luís City (10/03/08-09/04/08)

Min. temp. (°C)	Max. temp. (°C)	Relative humidity (%)	Rain (mm)	Date
23.3	30.8	76.0	5.0	10/03/2008
24.4	31.5	78.0	0.0	11/03/2008
24.2	30.4	78.0	0.0	12/03/2008
22.8	29.8	80.0	22.0	13/03/2008
23.2	26.4	91.0	8.6	14/03/2008
22.8	29.4	85.0	8.6	15/03/2008
22.9	28.4	70.0	83.0	16/03/2008
23.8	29.4	75.0	10.6	17/03/2008
23.0	26.3	82.0	28.6	18/03/2008
23.3	28.0	81.0	27.1	19/03/2008
22.9	30.3	71.0	0.4	20/03/2008
23.0	29.6	73.0	37.3	21/03/2008
23.2	29.2	77.0	0.0	22/03/2008
23.9	30.0	74.0	2.3	23/03/2008
23.9	27.6	80.0	37.6	24/03/2008
24.0	30.0	78.0	1.8	25/03/2008
23.4	29.4	84.0	34.6	26/03/2008
23.6	27.4	89.0	24.2	27/03/2008
23.2	30.0	74.0	38.6	28/03/2008
24.3	29.0	77.0	0.4	29/03/2008
23.4	27.6	95.0	10.6	30/03/2008
23.8	28.9	86.0	28.6	31/03/2008
23.6	28.7	87.0	102.2	01/04/2008
23.0	29.5	67.0	97.8	02/04/2008
22.7	29.4	74.0	29.6	03/04/2008
24.3	30.4	70.0	3.1	04/04/2008
24.2	26.2	90.0	0.0	05/04/2008
22.0	27.0	81.0	71.8	06/04/2008
23.3	31.2	68.0	3.7	07/04/2008
23.8	29.7	83.0	35.6	08/04/2008
23.8	31.2	77.0	0.0	09/04/2008
–	–	**Σ**	**753.7**	–

Bold values indicate the total amount of rain during one month

mountainous areas of France. In North America, soil bioengineering was performed on stream, river, lake and levee systems for flood control as well as cut-and-fill slopes in the 1920s and 1930s. Much of this initial work was ignored until the 1970s, when it was revived in western Canada in the restoration of coal mine sites. In the southern hemisphere, soil bioengineering is widely used in Australia and New Zealand. In both countries, much of the indigenous vegetation has been cleared since European settlement in the 1800s (Stokes et al. 2010).

Soil bioengineering has achieved important results at Sacavém gully. These techniques have shown the effects of geotextiles plus vegetation cover in reducing run-off and erosion and promoting water circulation in the soil profile. This can be confirmed by the rapid vegetation growth, in 1 month (Figs. 6, 7), due to tropical rains, together with the techniques applied on the reshaped gully. Li et al. (2006) found similar results in Shanghai (China) and demonstrated the advantages of soil bioengineering for riverbank stabilization. These include the following: (a) the establishment of a soil–root matrix which provides progressively increasing strength and structural stability, (b) the ecological integrity and biodiversity of aquatic system are restored and protected, (c) plants have the ability to be self-healing and self-reinforcing and (d) the landscape is dramatically improved by re-vegetation.

It was not feasible to analyse all biophysical processes associated with reclamation at São Luís. However, several studies highlight the probable processes activated by the bioengineering work (Bhattacharyya et al. 2010). Ahn et al. (2002) analysed soil erosion, plant growth, rainfall, run-off and sediments from the experimental studies in Korea. They concluded that mulch mat-treated slopes had many more plants than untreated slopes and more rapid growth rates, some 3–5 times those of untreated slopes. Treated slopes had much less run-off, and 100–500 times lower suspended sediment concentrations. When herbaceous plants and woody plants were planted together, sediment levels in run-off water decreased by a factor of 100–1,000. Mulch mat-treated slopes had ~100 times less soil erosion under most rainfall conditions. For the slope treated with these mats containing woody plant seeds, the amount of soil erosion was only ~0.1 % to that of untreated slopes after heavy rain.

Photograph analysis during gully rehabilitation monitoring in São Luís showed that vegetation cover protected soil surfaces (Fig. 6). Fatahia et al.(2010) estimated the influences of vegetation on ground in South Australia. Tree roots provide three stabilizing functions: (a) soil reinforcement, (b) dissipation of excess pore pressures and (c) the establishment of sufficient matric suction to increase soil shear strength. Li and Eddleman (2002) demonstrated the influence of foliage and stems of shrubs and trees on stream banks. They concluded that the bioengineering properties of vegetation reduce surface erosion by the following: (a) intercepting raindrops, preventing soil compaction and maintaining high infiltration rates, (b) braking surface run-off velocity, (c) restraining soil particle detachment via shallow, dense root systems, consequently reducing sediment transport and (d) delaying soil saturation through transpiration.

Fullen (1998) suggested that erosion rates progressively decrease through time, as the ley grass cover matured at Hilton Experimental Site, Shropshire (UK). He concluded that erosion rate and slope angle were poorly correlated, suggesting that grass leys are highly effective for soil conservation, even on steep slopes, as this has also happened on the recuperated gully in Sacavém.

De Baets et al. (2006) investigated the impact of grass root density on topsoil erodibility and compared the effects of vegetation cover on sheet and rill erosion rates with the effects of the root area ratio of grass roots on relative soil detachment rates. The data suggest that grass roots are very effective in reducing soil detachment rates.

Smets et al. (2009) investigated the effectiveness of three biological geotextiles in reducing soil losses during laboratory-simulated concentrated flow. Treatments included three biological geotextiles (Borassus, Buriti and bamboo) and were compared with bare soil surfaces. The results obtained by Smets et al. (2009) confirm the effectiveness of the three fibre mats, in particular Buriti, which has been used for this case study, in Brazil.

Regarding geotextile mats constructed from *Borassus aethiopum* (Borassus) and *M. flexuosa* (Buriti), Bhattacharyya et al.(2009) concluded that Borassus mat cover on bare soil significantly ($P < 0.05$) reduced total soil splash erosion by ~90 % compared with bare plots (24.81 kg m^{-2}). Plots with Borassus mats had 51 % less mean splash height than bare plots ($n = 21$ sets of measurements). However, Buriti mat cover on bare soils had no significant ($P < 0.05$) effect on soil splash height or splash erosion.

6 Conclusions

This study assessed the effects of biological geotextiles on the stability of a gully environment, using several techniques. Accelerated erosion in Sacavém gully (São Luís) is enhanced by intense rains, acting in combination with vegetation clearance and the erodible sandy soil texture. Intense human action, with inappropriate soil use and irregular settlement, also plays a very important role in promoting gully erosion. The gully was stabilized using a combination of land sculpturing, planting and the application of geotextiles. Only 1 month after the rehabilitation work was completed, the area was exposed to intense erosive rains (one-month total 753.7 mm, with a recurrence interval of ~60 years). Vegetation resisted erosion and the Buriti geotextiles seemed to have achieved the main objective of arresting erosion and rehabilitating the gullied area.

Integrating the results indicates positive effects of using biological geotextiles, as they offer potential for sustainable development and soil conservation. Furthermore, they can also be used for economic development, creating jobs and reducing poverty in poor urban areas. Long-term monitoring at Sacavém will enable thorough evaluation of the effectiveness of an integrated soil conservation programme on both erosion rates and processes and sustainable economic development.

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