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Gully erosion, land uses, water and soil dynamics: A case study of Nazareno (Minas Gerais, Brazil)

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Abstract
Gully erosion is a critical issue worldwide. To correctly understand the association that the environmental data (such as climate, vegetation cover, etc.) has with soil erosion susceptibility and land uses remains a challenge in land management. This paper evaluates land use interactions with macroscopic dynamics and microscopic soil properties in terms of soil's susceptibility to erosion. We examine the reactivation of a stabilized gully in Nazareno (Brazil) by comparing field assessments with laboratory experiments, using two types of soil (well-developed soil and granite-gneiss saprolite). Both of these showed that the macroscopic behavior of soils is connected with microscopic characteristics. Well-developed soil is more erosion resistant than granite-gneiss saprolite, but the surrounding land uses do not respect these differences. These analyses enable us to explain why this and other gullies in the municipality are apparently stabilized, but soil loss continues to occur. This paper demonstrates that urban and rural expansion played a major role in triggering gully and soil losses.

Keywords: soil loss; prevention; gullies; environmental planning.

Erosión, usos del suelo, la dinámica del agua y del suelo: Un estudio de caso de Nazareno (Minas Gerais, Brasil)

Resumen
Erosión es un problema crítico en todo el mundo. Este documento evalúa las interacciones de los usos del suelo con la dinámica macroscópica y propiedades microscópicas del suelo frente a la susceptibilidad su erosión. Examinamos la reativación de una cárcava recuperada en la ciudad de Nazareno (Brasil), comparando la evaluación de campo con experimentos de laboratorio utilizando dos tipos de suelo (suelo bien desenvuelto y granito-gneiss saprolito). Ambos demostraron que el comportamiento macroscópico de los suelos esta relacionado con las características microscópicas. Suelo bien desenvuelto es más resistente a la erosión que granito-gneiss saprolito, pero los usos de la tierra de los alrededores no respeta estas diferencias. Estos análisis han permitido explicar por qué este y otras cárcavas del municipio aparentemente se estabilizaron, pero las pierdas de suelo siguen ocurriendo. Se ha demostrado que la expansión urbana y rural desempeñó un papel importante en el desencadenamiento de estas erosiones y pierdas de suelo.

Palabras clave: pierda del suelo; prevención; cárcavas; planeamiento ambiental.

1. Introduction

1.1. Gully erosion: An environmental or social problem?

Soil erosion is a natural phenomenon; however, when accelerated, it causes social, environment and economic losses [1]. It affects not only the area itself, but there are also off-site impacts [2]. Several studies show the triggering, development and effects of gullies (complex soil erosion) and reclamation solutions [2-15].

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Over the past several decades, gullies have become a very important issue worldwide. The acceleration in the number of gullies is connected with human interference beginning in the 18th century, which has modified and intensified natural rates of soil removal and deposits [16].

In India, this problem is related to improper management of runoff, deforestation, overgrazing and incorrect agricultural activities [17]; the lack of rural conservative practices and the excess of mechanization are the causes seen in Latin America [18]; and in Europe, the USA, China and Africa, many studies have shown a high level of soil loss in gullies over years [19].

Although this type of erosion is associated with runoff and steep slopes, it mostly occurs by subterranean flow and in soils that are susceptible to crusting or piping [20]. Even activities that at first were considered unable to interfere in environmental dynamics (such as cattle trails or ditches to separate rural properties, whose origins are connected with human necessities) can initiate gully erosion [21]. Once developed, their natural recovery could take decades [22]. Therefore, reclamation projects may try to return the environment to its condition before erosion (restoration) or give a different function to the site (rehabilitation) [23]. However, in Brazil the choice of reclamation technique is likely to be based on the most commonly used one or the cheapest one. In those cases, the results are not satisfactory, and the process can even become worse [15].

There is a great quantity of water erosion processes (gullies) in Southern Minas Gerais' state (Brazil). These gullies affect productive areas and can be found on both public and private properties [27]. Approximately 1,700 gullies are located in the Alto Rio Grande watershed. This represents about 2,700 ha of soil loss [24-26]. Gully evolution is caused by deforestation and human land uses, such as old road building, mining and ditch openings as properties' divisions [14,27]. These gullies promote soil degradation and fertility loss [28].

Recovery measures have been taken in Nazareno city and region by the Projeto Maria de Barro (a Nazareno NGO) to reduce the impact of gullies [26]. However, some gullies show signs of destabilization due to reactivation and enlargement by processes such as landslides. A financially and technically viable project for gully reclamation in developing countries, like Brazil, is almost impossible. Even though studies and efforts have been made to mitigate the degradation, interactions between soil properties (macro and micro scales) and land uses remains necessary; studying these are the primary goal of this research. In conjunction with the Maria de Barro NGO, the next goal is to help provide assistance to land management practices (prevention activities) and gully reclamation projects (correction activities) to Nazareno. We observed that some gullies are in a similar situation, for example, in terms of the same environmental conditions (types of soil) and water flow concentration by roads. This paper presents the case study of Cravo Stream gully located at Nazareno city.

1.2. Study area

Nazareno is located in the Southeast of Brazil (Fig.1), in the Campos das Vertentes region (44°61'W, 21°21'S). The municipality covers an area of 324 km^2 and the mean level above sea level is 935 m [29]. The Nazareno region can be classified as an environment that is susceptible to soil erosion [29]. There are more than 60 erosion features in the area [27]. Over the last decade, several studies have been made to explain the region's soil erosion [13,25-27,30,31]. These studies showed that soil erosion is accelerated by the combination between environmental fragility and human activity (Table 1).

The region lies in the São Francisco Craton, which was predominantly formed by granite-gneiss territories of between the Archean and the Paleoproterozoic, Archean Greenstone Belts successions and Metasedimentary rocks [32,33]. The study area is located on the Barbacena Greestone Belt, which is limited by granite-gneiss terrains, presented discontinuously. The structures have NE-SW directions that follow regional patterns [34]. There is a shear zone (Lenheiro Shear Zone) near the study area [35].

In terms of soil description, [24,25,36-38] it is noted that well-developed soil (oxisol, or latosol, in Brazil) and granite-gneiss saprolites (Fig. 2) are predominant in the municipality. The well-developed soils in the study area have a granular structure and present gibbsite with high iron (Fe) levels. These characteristics induced an elevated porosity and permeability. On the other hand, granite-gneiss saprolites are predominantly caulinitic, presenting a block structure; these characteristics induced low

Figure 1. Located in Nazareno, Minas Gerais (Brazil): 69 gully areas in and near the municipality.
Source: The authors.

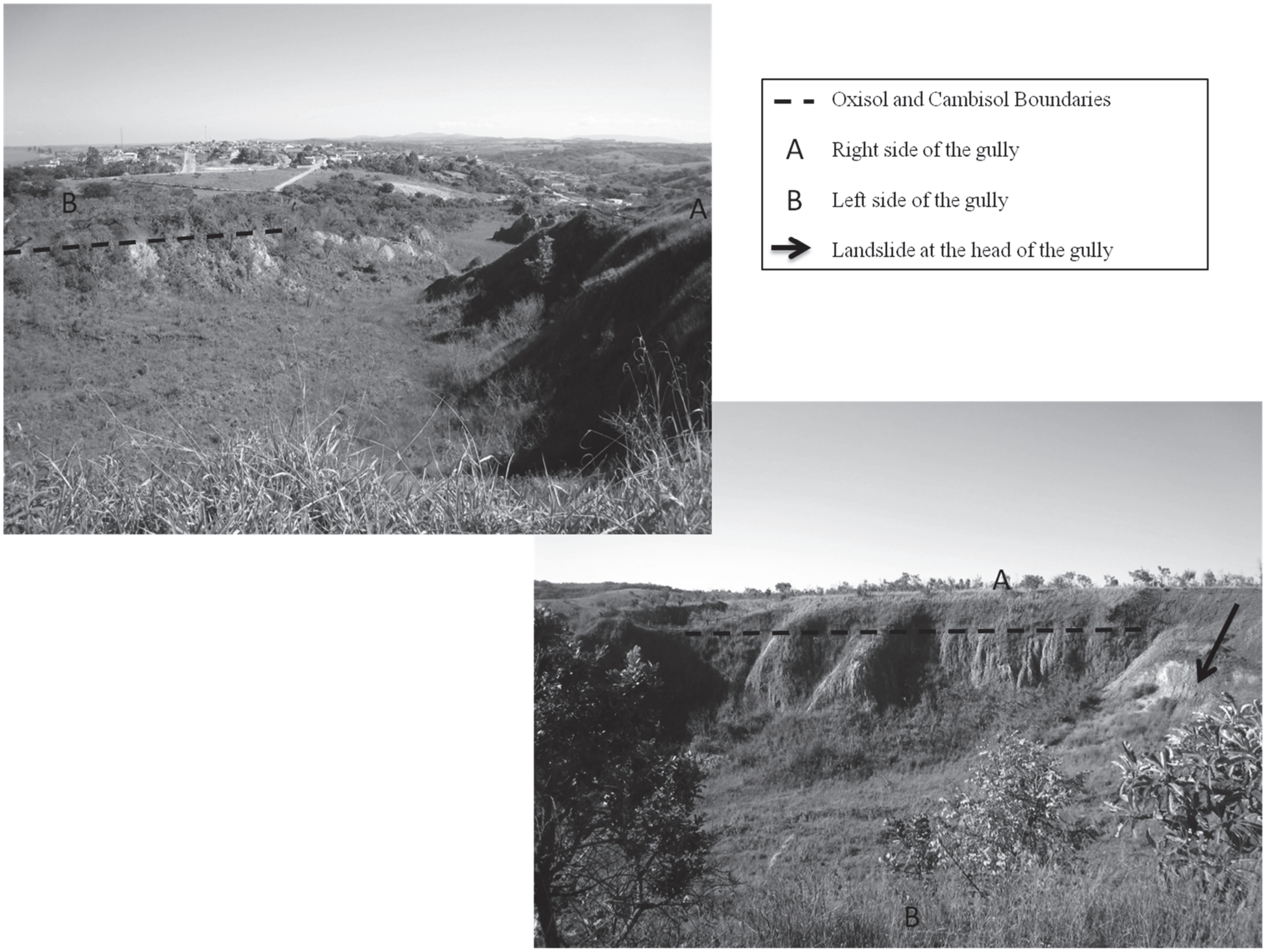


Figure 2. Soil boundaries and landslide inside the Cravo Stream Gully, Nazareno, Minas Gerais (Brazil).
Source: The authors.

porosity and permeability. Saprolites are derived from granite-gneiss, quartzite, micaschists and talc schists, granite-gneiss prevailing [39]. Therefore, there are more gullies in granite-gneiss saprolites (higher relation gully/square kilometer) in the study area [27].

The Nazareno region consists of hills with a convex-concave top and steep slopes, which lie at elevations of between 839 m and 1140 m above sea level. The steepest slopes and the higher elevations are situated in the northeast of the municipality [36-38].

Table 1.
Distribution of land uses areas in Nazareno, Minas Gerais (Brazil).

Description	Area (ha)
Municipality	32,895
Gullies	252
Semideciduous Forest	1563
Field	1814
Eucalyptus	77
Other Land Uses	28,506
Urban Area	118
Lakes and Rivers	803

Source: The authors.

The climate vary from Cwa and Cwb (Köppen classification), with average temperatures ranging from 18 to 22°C in the rainy season and from 15 to 19°C in the dry season. The average precipitation ranges from between 1200 mm and 1500 mm [38].

2. Materials and methods

We used the topographic map (Nazareno, SF-23-X-C-I-2 – 1:50,000) that dated back to 1975, from the Brazilian Geographic and Statistic Institute (IBGE) with GIS software (ArcGIS® - ArcMap), to assess the environmental information at the study area.

Land uses were analyzed at the gully perimeter. Both oxisol (O, well-developed soil) and granite-gneiss saprolite (S) were sampled and taken to the laboratory for physical (tropical soil characterization, soil particle size analyses and erodibility test, based on [40-46] standards) and chemical (pH, delta pH, electric conductivity, Eh, based on [47], organic matter – OM, based on [48], and Cation Exchange Capacity (CEC), based on [46]) experiments at the

Geotechnical Department of São Paulo University – (USP). Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) were also performed at USP´s Chemistry Institute – IQSC. This analysis was undertaken to compare the different behaviors of the two types of soil and to connect them to land uses. Some samples were not used in all experiments because it was not possible or easy to obtain them in the field.

3. Results and discussion

Fig. 3 shows the entrance to Cravo Stream gully. An improper drainage system along the compacted road can be seen. Due to this, the speed and the strength of the concentrated flow have been increased, and, the water flows down the road directly inside the gully removing soil particles. This runoff increases the rate of erosion in its end part. We can see, therefore, the importance of constructing a suitable superficial drainage system in terms of land management.

We observed a coffee plantation with a compacted unpaved road without a proper drainage system close to the gully´s limits (Fig. 4). The plantation itself, if managed with conservative practices, could even help to reduce erosion, by improving soil cover and infiltration. But, in this case, as Fig. 5 shows, there is another erosion feature inside the plantation area, indicating that conservative practices were not adequately performed. Besides, the unpaved road also contributes to the flow concentration towards the gully.

In 2012, landslides occurred inside the gully [49]. The top left of Fig. 4 shows one of them. We can see that, even with reclamation measures, there is still soil instability, which is associated with water flow.

Fig. 5 also shows two cross sections made with Cravo Stream watershed data. The granite-gneiss saprolite exposure was formed by deforestation, and its removal from subterranean water flow causes the gully slopes to become unstable, thus facilitating landslide processes. Whenever there is exposure of granite-gneiss saprolite and other parts of well-developed soil, runoff removes them, adding instability to the system. This removal process is slow, and may, therefore, deceive the population about gully's stability.

Figure 3. Cravo Stream Gully entrance, Nazareno, Minas Gerais (Brazil). The compacted road that does not have a proper drainage system can be seen.
Source: The authors.

We observed fluting and tunnel erosions (Fig. 6), which shows that the subterranean flow plays an important part as well as runoff on soil removal. The water table varies greatly with rain because it is already exposed. This, combined with the exposure of saprolite, creates instability within slope toes, causing piping and landslides. These complex subterranean water movements contribute to the enlargement of the gully towards its head. Houses were built at the end of the gully (nearby residences – Fig. 6) on erosion susceptible material. Thus, they might be affected by the soil that is removed from the gully and deposited there.

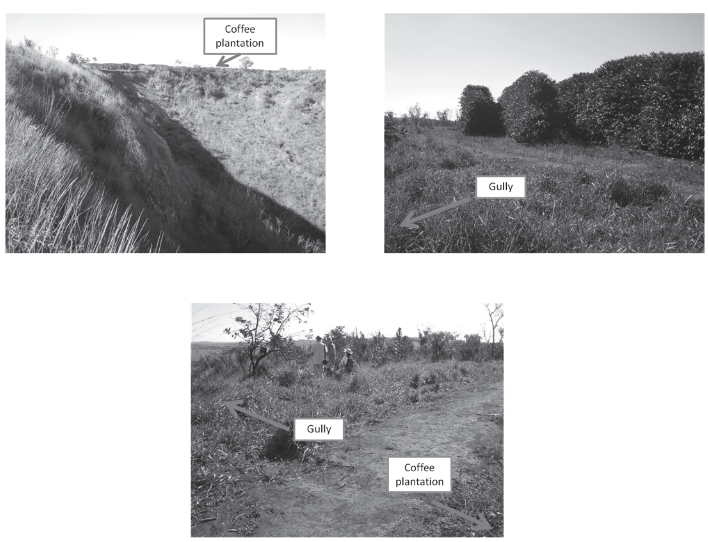


Figure 4. Top left: Coffee planted near the Cravo Stream Gully head and landslide. Top right: Zoom of the coffee plantation and the road surrounding it. Bottom: Unpaved and compacted road without a proper drainage system surrounding the gully and the plantation.
Source: a) and b): The authors; c) Adapted from [50].

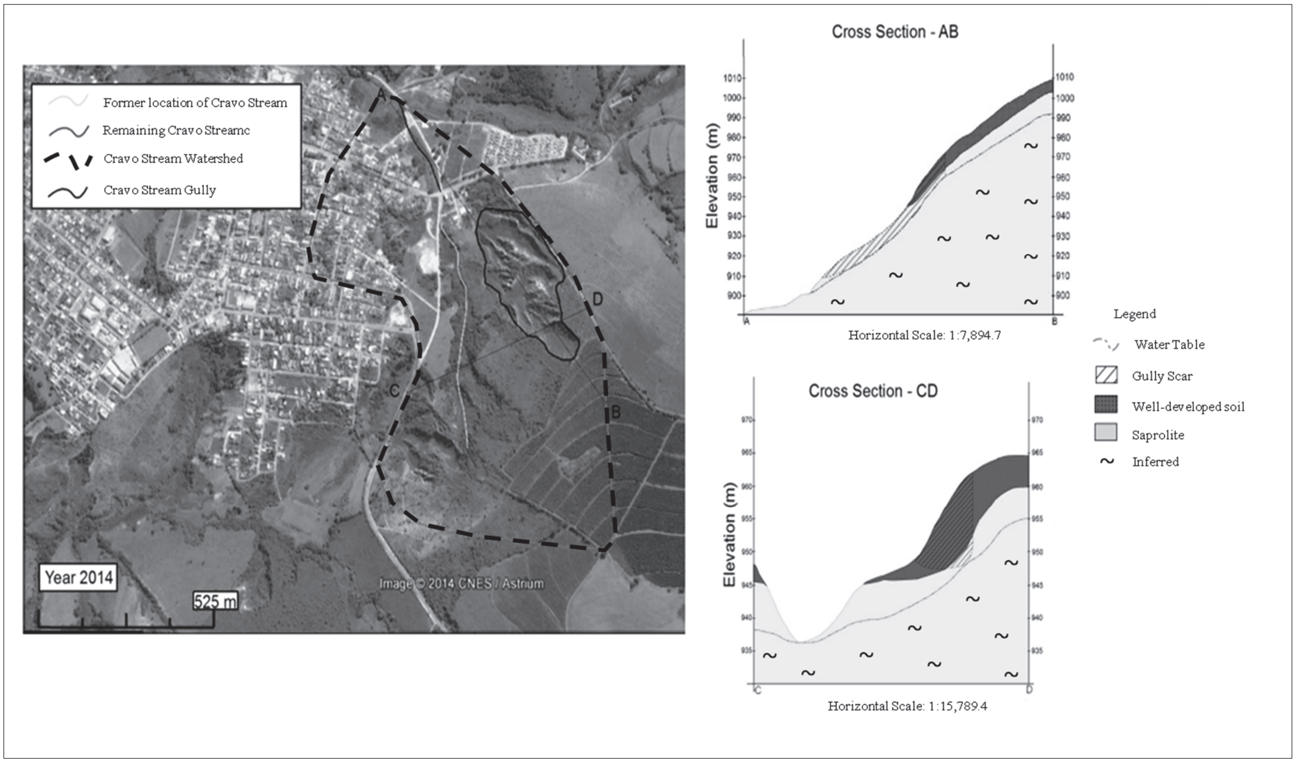


Figure 5. Cravo Stream watershed near the coffee plantation and the Nazareno urban area (Minas Gerais, Brazil); cross sections showing the approximate soil profile of the area and the soil loss caused by the gully.
Source: Adapted from [50].

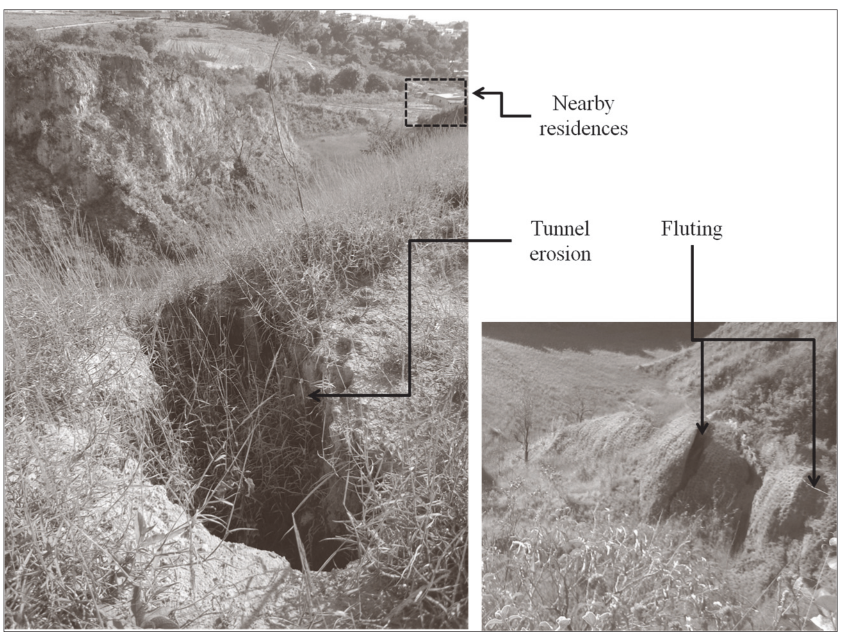


Figure 6. Tunnel erosion in the Cravo Stream Gully. Fluting inside and houses installed close to the end of it.
Source: The authors.

Land uses that do not consider soil properties and its susceptibility to erosion in this region, such as deforestation, mining, urban expansion and road construction without adequate drainage systems, as well as overgrazing exposes the soil. They also alter the drainage conditions of catchments and accelerate erosion creating gullies [29–31].

Currently, the Cravo Stream gully is surrounded by anthropogenic land uses and erosion features (Figures 5 and 6). This shows an absence of both urban and rural planning. Similar situations can be observed all over the region.

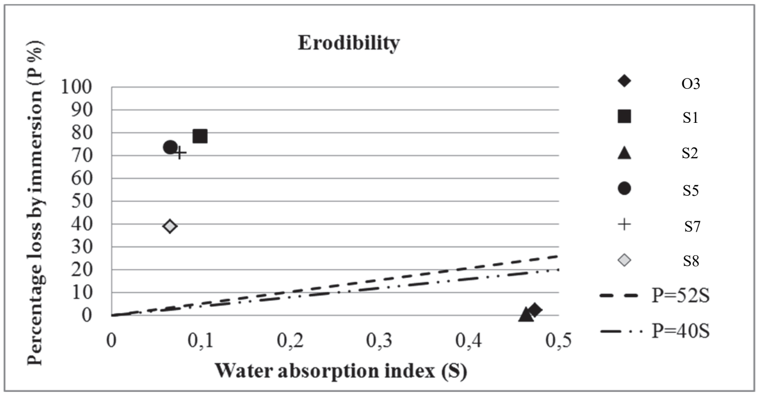
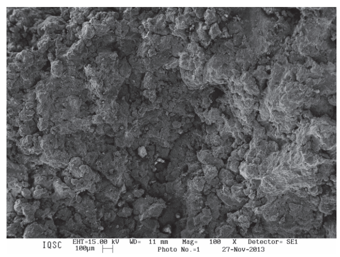
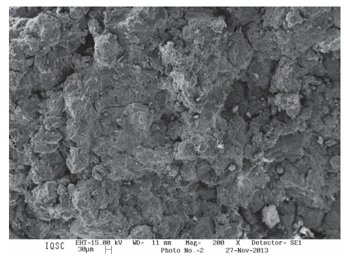
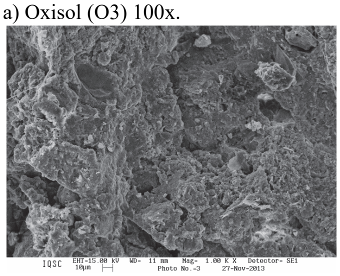


Figure 7. Erodibility experiment with oxisol and granite-gneiss saprolite from the Cravo Stream gully, Nazareno (Minas Gerais, Brazil).
Source: [50].


a) Oxisol (O3) 100x.


b) Oxisol (O3) 200x.


c) Oxisol (O3) 1000x.

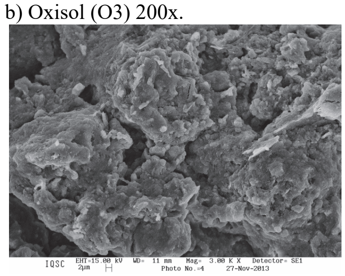

d) Oxisol (O3) 3000x.

Figure 8. Oxisol (O3) SEM from Cravo Stream gully, Nazareno (Minas Gerais, Brazil). Granular and homogeneous structure that may represent the presence of quartz or lateritic concretions.
Source: Adapted from [50].

The well-developed soil (O) and granite-gneiss saprolite (S) samples were analyzed, both in chemical and physical aspects (Table 2). The results show that well-developed soil has 78% fine particles, mostly clay. It may also have lateritic concretions. It has predominantly negative charges and a low electric conductivity (and, therefore, a lower salt concentration) with an oxidant behavior. These characteristics improve soil resistance to removal. The granite-gneiss saprolite shows a non-lateritic behavior of silty sands, which are less cohesive and more susceptible to soil removal than the oxisol. [29] assessed that granite-gneiss saprolite have fine sand and silt, which can promote crusting. As a result, infiltration is reduced and soil particles are removed within rainwater erosive forces. Soil moisture is influenced by texture: clay soils tend to retain water. The average granite-gneiss saprolite's moisture is about 11%, and oxisol's is about 26% [27].

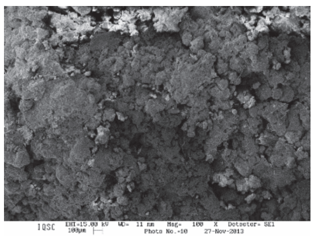
Above the two line criteria (P), we can observe that S1, S5, S7 and S8 are more erodible than the other samples (O3 and S2) (Fig. 7). [39] ascertained that soil losses were lower in oxisols than in granite-gneiss saprolites; this supports our findings.

Both well-developed soil (oxisol) and granite-gneiss saprolite present neutral to acid pH, low organic matter (O.M.) and low Cation Exchange Capacity (CEC) (Table 2). These characteristics are limited to vegetation growth on eroded lands [29].

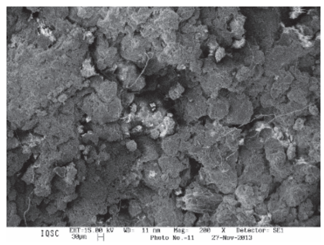
The results from the Scanning Electron Microscopy (SEM) are presented in Figures 8, 9 and 10. The well-developed soil sample (O3) is more homogeneous and its particles are uniformly connected with lateritic concretions. S2 sample, which is the transition of the two types of soil, showed a union of homogeneous particles with some rock weathered parts as S7 keeps weathered mineral structures and kaolinite. We associate the less cohesive structure in the microscopic scale to the susceptibility to erosive behavior of granite-gneiss saprolite. The homogeneous connection between oxisol particles makes them more resistant to soil removal. Fig. 10 shows distinct and sparse particles compared with the other samples that have mica and kaolinite, which can probably be related to soil removal.

The samples´ Energy Dispersive Spectroscopy (EDS) (Table 3) confirm the weathering evolution that was previously cited. Elements such as aluminum and iron oxides are associated with laterization. [43] noted that lateritic concretions may not be very easy to distinguish from clay clods, and could be linked to magnetite, ilmenite, hematite and quartz minerals.

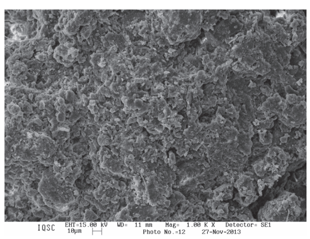
The results showed that certain land uses and the exposure of granite-gneiss saprolite can bring back soil erosion to an area, even if it seems to be stable or if the well-developed soil is above the granite-gneiss saprolite. Despite the fact that well-developed soil is resistant, it can be erodible in intense flow conditions. Soil loss is increased when the increase of runoff is combined with subterranean water flow dynamics. This results in degradation and expansion of the gully area. Under intense rains and when landslides occur inside the gully, this process is accelerated.



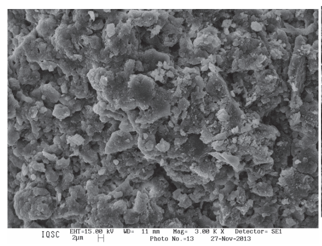
a) Granite-gneiss saprolite (S2) 100x.



b) Granite-gneiss saprolite (S2) 200x.

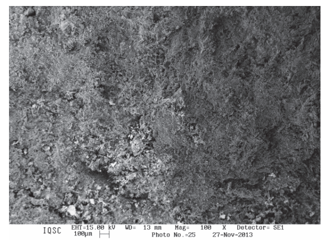


c) Granite-gneiss saprolite (S2) 1000x.

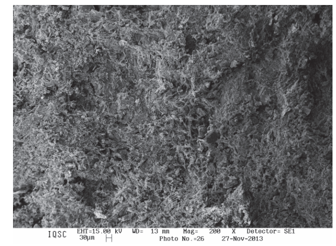


d) Granite-gneiss saprolite (S2) 3000x.

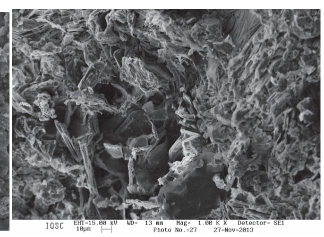
Figure 9. Granite-gneiss saprolite (S2) SEM from the Cravo Stream gully, Nazareno (Minas Gerais, Brazil). Sample from a transitional place (oxisol to granite-gneiss saprolite): granular and homogeneous structure with highly weathered minerals.
Source: Adapted from [50].



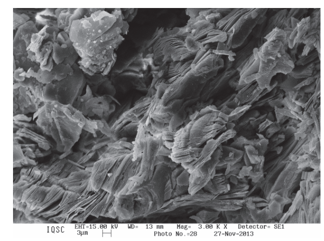
a) Granite-gneiss saprolite (S7) 100x.



b) Granite-gneiss saprolite (S7) 200x.



c) Granite-gneiss saprolite (S7) 1000x.



d) Granite-gneiss saprolite (S7) 3000x.

Figure 10. Granite-gneiss saprolite (S7) SEM from Cravo Stream gully, Nazareno (Minas Gerais, Brazil). Different and non-homogeneous structure with placoid (micas) and fanfold minerals (kaolinite). Sparse texture.
Source: Adapted from [50].

Table 2.
Experiments with two types of soil in the Cravo Stream gully, Nazareno (Minas Gerais, Brazil).

Sample	Physical Experiments			Chemical Experiments						
	Mini MCV-MCT	Particle Size Distribution	Dry Density[3] ($g.cm^{-3}$)	pH KCl	pH H_2O	ΔpH	Electric Conductivity ($\mu S.cm^{-1}$)	Eh (mV)	OM ($g.kg^{-1}$)	CEC ($cmol_c.100g^{-1}$)
Oxisol (O1)	*LG'* *[1]c': 2.20* *[2]e': 0.89*	Clay: 50% Silt: 28% Fine sand: 14% Medium sand: 7% Coarse sand: 1%	2.895	6.4	6.8	-0.4	5.70	+221.00	31.00	2.33
Granite-gneiss saprolite (S7)	*NA'* *c': 0.70* *e': 1.17*	Clay: 4% Silt: 61% Fine sand: 19% Medium sand: 15% Coarse sand: 1%	2.649	4.6	7.2	-2.6	19.60	+335.00	24.00	1.62

[1] *c'* – soil shaliness; [2] *e'*- degree of laterization; [3] Temperature: 20°C; [4] ΔpH = pH KCl – pH H_2O.
Source: Adapted from [50] and authors.

Table 3.
Semiquantitative EDS from samples of oxisol (O3) and granite-gneiss saprolite (S2 and S7), Nazareno (Minas Gerais, Brazil).

Elements	Percentages (%)		
	O3	S2	S7
O	53,59	54,55	53,58
Al	18,86	21,14	17,36
Fe	15,11	7,99	4,01
Si	11,57	15,35	21,15
Ti	0,86	0,62	0,32
K	-	0,35	3,31
Mg	-	-	0,27
Total	99,99	100,00	100,00

-: Not detected.
Source: [50].

4. Conclusions

The Cravo Stream gully in Nazareno (Minas Gerais, Brazil) shows an example of how microscopic structures and characteristics reflect macroscopic environmental behaviors as well as how land uses could influence and accelerate erosion processes in these soils. The results showed that the well-developed soil (oxisol) is more homogeneous, cohesive and well formed with lateritic behavior; these aspects can enhance soil resistance to erosion. The granite-gneiss saprolite structure has weathered minerals and other elements, such as kaolinite, which is associated with a different stage of formation. It is less cohesive, which may decrease its resistance to erosion. All of this can be connected to its distinct erodibility.

Land use, such as compact roads without a proper drainage system, and rural and urban expansion, are contributing to the acceleration of erosion features by directing runoff to the more erodible and fragile soil (saprolite) and, in some cases, removing resistant soil (oxisol) and exposing the susceptible one. Even if new gullies are not created now, the old ones (such as Cravo Stream gully) may gradually and slowly continue to remove material. Landslides (circular on oxisol and planar on saprolite) and subterranean instability (such as fluting and tunnel erosion) are proof that these features are not stable and are still negatively interacting with land uses.

An appropriate drainage system must be considered in every case (urban and rural areas); water flow should be diverted from the erodible soil. Besides, conservative practices may help to prevent and to mitigate gullies' problems in rural areas. This article can be used as a basis for reclamation projects and land use planning, not only for Nazareno itself, but for other areas in Minas Gerais state that have similar environmental conditions.

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