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Research Article

Sandy soil spots in northwestern Paraná: approaches for identification and quantification

Abordagens para identificação e quantificação de manchas arenosas no noroeste do Paraná

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Abstract: The predominance of sandy soils in the Northwest region of the state of Paraná, associated with the removal of natural vegetation, favored the development of patches of white sand on the surface without any aggregation. These spots are associated with the different types of land use existing in the region and the process of lateral soil transformation. As they constitute material without aggregation, they can be easily transported by wind and water and deposited in water bodies, causing severe environmental impacts. Thus, using thermal infrared satellite images, the objective of the present study was to map, determine the formation process of the spots and estimate the predominant particle size fractions. The model used and validated with field and laboratory information, allowed the identification of surfaces with patches of white sand present in the study region and estimating their percentage in different classes. After filtering the samples with vegetation cover during the product calculation period, an R^2 of 0.78 was obtained. The removal of natural vegetation has contributed to the formation and expansion of sandy patches and erosion in the northwest region of Paraná.

Keywords: Sandification; Sandy Patches, Pedogenic Processes, Satellite Images, Erosion.

Resumo: O predomínio de solos de textura média na região Noroeste do estado do Paraná, associada a retirada da vegetação natural, favoreceu o desenvolvimento na superfície de manchas de areia branca sem agregação. Essas manchas se encontram associadas aos diferentes tipos de uso da terra existentes na região e ao processo de transformação lateral dos solos. Por constituírem material sem agregação, podem ser facilmente transportados pelo vento e pela água e depositados nos corpos hídricos, causando severos impactos ambientais. Assim, o objetivo do presente trabalho foi mapear e caracterizar as áreas com a ocorrência de manchas arenosas na região noroeste do Paraná. O modelo utilizado e validado com informações de campo e laboratório, permitiu identificar as superfícies com manchas de areia branca presentes na região de estudo e estimar o seu percentual em distintas classes. Após a filtragem das amostras com cobertura vegetal no período de cálculo do produto, foi obtido um R^2 de 0,78. A retirada da vegetação natural contribuiu para o surgimento e desenvolvimento das manchas arenosas e das erosões na região noroeste do Paraná.

Palavras-chave: Arenização; Manchas Arenosas, Processos pedogenéticos, Imagens de satélite, Erosão.

1. Introduction

In northwestern Paraná, the soils are predominantly of medium and sandy texture (FIDALSKI; HELBEL JUNIOR, 2020), characterized by low natural fertility and high susceptibility to erosion processes due to both concentrated and diffuse surface water runoff (EMBRAPA, 2018; NÓBREGA et al., 2023). Soil and water losses in this region are increasing, particularly in areas with pasture, sugarcane, and cassava cultivation, with annual losses estimated at 2.2 t ha^{-1} and 27 mm; 6.5 t ha^{-1} and 70 mm; and 37.0 t ha^{-1} and 196 mm, respectively (MERTEN; ARAÚJO; BARBOSA, 2016). Consequently, the occurrence of sand patches on the surface is common, especially in low-slope areas and drainage headwaters (hollows). These patches are also found in other landscape positions and are related to different land uses. Although they are easily identified in the field, they are not individually represented on the available soil maps for the region.

Deforestation of the natural vegetation (Semideciduous Seasonal Forest) followed the land use process, affecting spring areas and riparian forests (MAACK, 1968). This deforestation opened new areas for coffee plantations, which were later replaced by pasture (FIDALSKI, 1997a) and more recently by sugarcane cultivation for ethanol production, as well as cassava cultivation (PAIVA; NÓBREGA, 2010). Over time, the effect of these land uses and management practices have significantly impacted the physical and chemical properties of the soils, including reduced water retention and availability (FIDALSKI; HELBEL JUNIOR, 2020). Additionally, these changes have contributed to an increase in the occurrence of linear erosion processes. Mangueira (2014) identified approximately 918 erosion features throughout the northwestern region. According to the author, the morphological characteristics of the soils, particularly their texture, play a key role in the development of erosion, along with the ways in which the land is managed and utilized.

The replacement of natural vegetation for agriculture has negatively impacted the accumulation of organic matter on the soil surface (FIDALSKI, 1997b). As a result, it has damaged soil aggregation in the surface horizons (FIDALSKI et al., 2021), leading to the breakdown of soil structure and turning them into patches of unaggregated sand.

Sand patches are associated with different types of land use and management in the northwest region of Paraná, being common in degraded pasture areas, with heavy cattle trampling and agricultural areas with soil disturbance for planting, among other forms of use, leading to the loss of organic matter and fine particles (silt and clay) from horizon A (OLIVEIRA; SANTOS; CALEGARI, 2020; SANTOS; OLIVEIRA, 2020).

Studies in the region have shown that the formation and thickening of sandy horizons can occur naturally along slopes, resulting from a lateral transformation process of the Bw horizon in Ferralsols (Latossolos) into the Bt horizon in Acrisols (Argissolos), associated with mechanisms of clay loss and transfer (CUNHA; NÓBREGA; CASTRO, 2008). Since these materials can be transported by wind and water, the deposition of sand may negatively impact watercourses and downstream areas on slopes. Therefore, it is crucial to correctly identify these horizons to implement appropriate soil management and conservation practices, aiming to mitigate environmental impacts and enhance the land's productive capacity (NANNI; DEMATTÊ; FIORIO, 2004).

Pedological surveys are the primary method for obtaining information about soil attributes, which is why there is a continuous effort to develop procedures that can accurately identify and map soil classes (NANNI; DEMATTÊ; FIORIO, 2004; NANNI; DEMATTÊ, 2006). Given the environmental fragility of sandy soils, understanding their spatial distribution in the landscape is crucial. Detection methods that complement traditional techniques can include remote sensing, using reflectance spectra and satellite imagery (DEMATTÊ et al., 2018). However, a key challenge lies in distinguishing high-reflectance targets in the optical spectrum (e.g., visible, near-infrared, and short-wave). While sand patches are easily identifiable in satellite images, their high brightness and saturation can cause confusion with other features, such as dry vegetation (non-photosynthetically active – NFA, e.g., straw and residues). Alternatively, thermal infrared imagery can help reduce this spectral confusion and better identify areas prone to sandy soils (SALISBURY; D'ARIA, 1992; CHEN et al., 2021).

Considering the widespread adoption of no-till farming techniques in Brazilian agriculture, along with the use of cover crops in the off-season and post-harvest straw, the identification of sandy soils requires alternative spectral bands due to their high similarity with non-photosynthetically active (NFA) vegetation (DAUGHTRY; HUNT; MCMURTREY, 2004; BREUNIG; GALVÃO; FORMAGGIO, 2008). Sandy soils can be detected and characterized by their low emissivity in thermal infrared spectral regions, known as reststrahlen features (SALISBURY; D'ARIA, 1992; SALISBURY et al., 1992). Several indices have been proposed to model the sand fraction of soils, using inputs such as thermal infrared band ratios (BREUNIG; GALVÃO; FORMAGGIO, 2008; BREUNIG et al., 2009) or the Sand Differential Emissivity Index (SDEI) (CHEN et al., 2021). The availability of emissivity products from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) further enhances the ability to explore these spectral features. The ASTER Global Emissivity Database (GED) product, derived from average pixel emissivity data between 2000 and 2008 (HULLEY et al., 2015; HULLEY; HOOK, 2015), provides a valuable resource for identifying areas of sandy soils through their reststrahlen features. However, due to the scale of analysis in remote sensing products, fieldwork and detailed ground inspections are essential for complementing and validating remote sensing data.

The objective of this study was to map and characterize areas with the occurrence of sandy patches in the northwestern region of Paraná, using a combination of thermal remote sensing, soil micromorphology, and field activities. Satellite imagery, sample collection, and field analysis of soil profiles were employed as key strategies for evaluating soil parameters, while micromorphological analysis provided insights into the processes of clay removal.

2. Regional Setting

The study area (Figure 1) is in the northwestern region of Paraná, covering approximately 24,488 km² and comprising 61 municipalities. It is in the southern portion of the Paraná sedimentary basin, within the Bauru Supersequence (FERNANDEZ; TCACENCO-MANZANO, 2023), which spans parts of São Paulo, Paraná, Mato Grosso do Sul, Mato Grosso, Minas Gerais, Goiás, and northeastern Paraguay, encompassing an area of approximately 370,000 km². The lithology of the region consists of sedimentary rocks from the Bauru basin, specifically the Caiuá Group (FERNANDES; COUTO; SANTOS, 2012). This group is further subdivided into the Goio-Erê (peripheral aeolian deposit zone), Rio Paraná (central sand sea zone), and Santo Anastácio Formations (sand sheet plains) (FERNANDES; COIMBRA, 1994).

Located in the Third Paraná Plateau, the study area has a mostly gently undulating relief (MAACK, 1968). The regional relief is uniform and monotonous, with the existence of plateaus inclined towards the Paraná River valley. The altitude varies from 600 meters, near the contact with the Serra Geral formation, to 300 meters on the banks of the Paranapanema and Paraná rivers (NAKASHIMA, 1999). The following morpho-sculptural units are visible (SANTOS et al. 2006): Maringá Plateau; Campo Mourão Plateau; Paranavaí Plateau; Umuarama Plateau and River Plains.

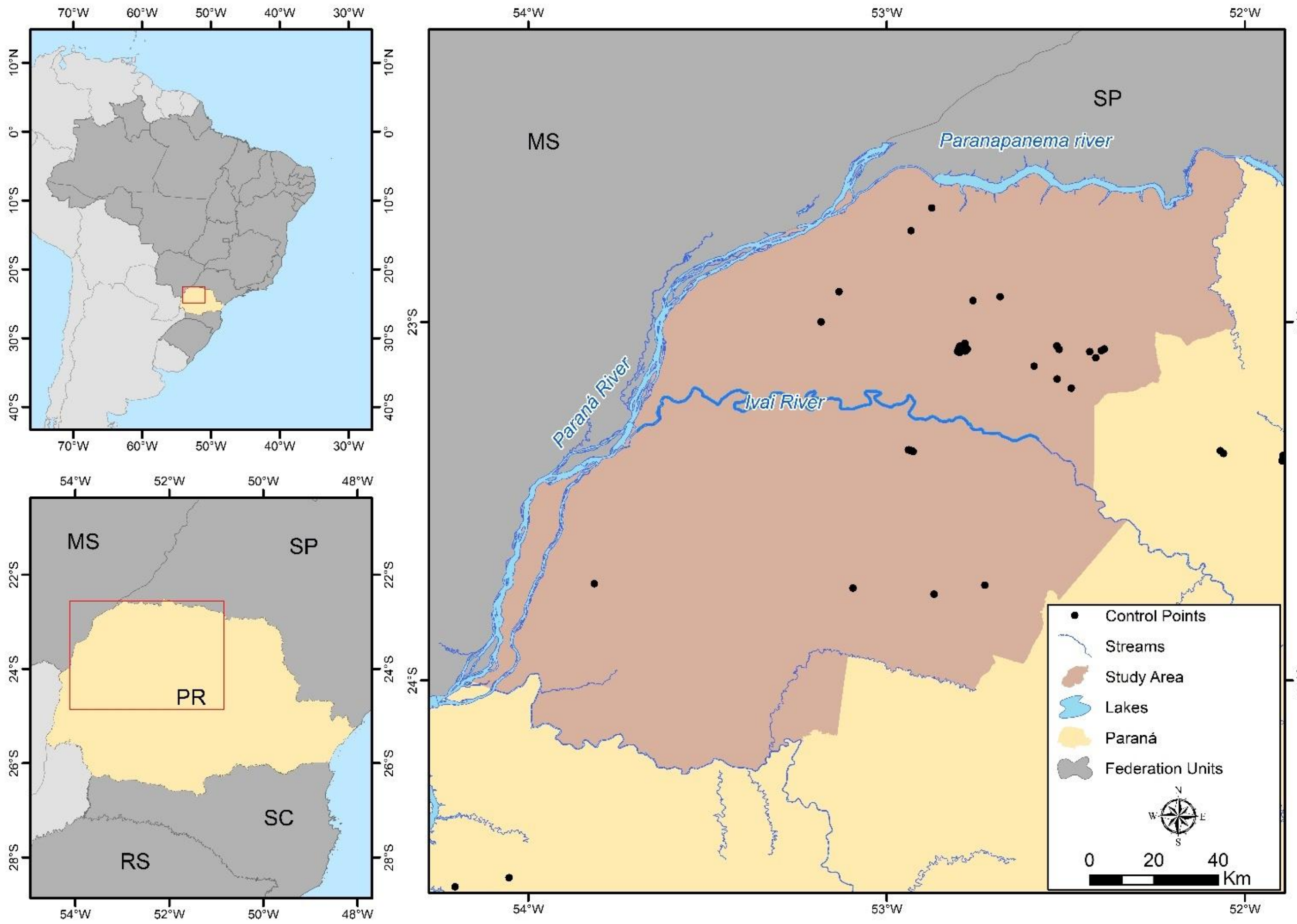

Figure 1. Location map of the study area, northwest of the state of Paraná (PR), southern Brazil. Shapefiles adapted from IBGE (2022).

The pedological systems are composed mainly by Ferralsol (Latossolo Vermelho) and Acrilsols (Argissolo Vemelho e Vermelho Amarelo) with medium texture in top and mid-slope segments and Arenosols (Neossolo Quartzarênico), sandy texture, in low slope segments and valley bottoms (CALEGARI, 2000; CUNHA; CASTRO; SALOMÃO, 1999). Due to their morphological characteristics, Arenosols typically have limitations for use, requiring substantial amounts of correctives and fertilizers to become productive, which often renders them economically unviable (MAIA; MARMOS, 2010). These soils are inherently susceptible to linear erosion processes, frequently resulting in large gullies in rural and peri-urban areas. Intensive use of these soils should be avoided, and when necessary, management practices should account for their high level of intrinsic fragility (NETO et al. 2023).

The climate is humid temperate with hot summers, Cfa according to the Köppen and Geiger classification (KÖPPEN, 1936; GEIGER, 1954; ALVARES et al., 2013). It presents annual rainfall averages between 1250 and 1800 mm with higher concentrations in the summer months (NITSCHE et al. 2019). Average annual temperatures vary between 18 and 25 °C (MANGUEIRA, 2017; KOTTEK et al., 2006; ALVARES et al., 2013).

The predominant natural vegetation was the Semideciduous Seasonal Forest (RODERJAN et al., 2002). However, according to these same authors these original forest formations underwent significant transformation, gradually being converted into land for agricultural use.

The northwestern region of Paraná experienced intense occupation starting in the 1950's, driven primarily by coffee farming, which replaced nearly all forests with coffee plantations (RODERJAN et al., 2002; PAIVA; NÓBREGA, 2010; KOHLHEPP, 2014). Over time, coffee farming was replaced by pasture (FIDALSKI, 1997a), and more recently, sugarcane cultivation for alcohol production and cassava farming have come to dominate land use in the region (PAIVA; NÓBREGA, 2010). Specifically, within the time range of the remote sensing data utilized, according to the MAPBIOMAS platform, pasture area decreased from 18,445.17 km² in 2000 to 13,833.68 km² in

2008, while the sugarcane area increased from 609.21 km² in 2000 to 3,359.29 km² in 2008 (SOUZA et al., 2020). Today, the remaining forested areas are confined to a few conservation units and the Paraná River floodplain.

3. Materials and methods

The research was structured into several stages based on the proposed objectives.

3.1 Mapping of sand patches and estimation of the sand fraction using Remote Sensing

Thermal infrared (TIR) data were extracted from the emissivity product generated under the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Emissivity Dataset (GED) program (AG100: ASTER Global Emissivity Dataset 100-meter V003). The emissivity data were derived using the Temperature Emissivity Separation (TES) algorithm, combined with atmospheric Water Vapor Scaling (WVS) correction, which incorporates atmospheric profile information from the MODIS MOD07 product within the MODTRAN 5.2 radiative transfer model (HULLEY; HOOK, 2011; HULLEY et al., 2015). This product represents a composite of cloud-free pixel values averaged over all available ASTER data (2000-2008) (HULLEY; HOOK, 2011), integrating multiple scenes to generate an average emissivity for various targets over time. It is important to note that no recent data are available for this product due to the failure of the shortwave infrared (SWIR) bands, which are essential for cloud masking (HULLEY; HOOK, 2015). However, there are ongoing initiatives to launch new satellites in the future, which will include thermal infrared bands (GUO et al., 2023).

In this study, the TIR bands were used to detect characteristic features associated with soils dominated by the sand fraction, known as quartz reststrahlen features (SALISBURY et al., 1992). To identify areas with a higher likelihood of sandy soils, the Normalized Thermal Sandy Index (NTSI) was calculated. The NTSI is derived from the normalization of ASTER bands 10 and 14 (centered at 8.3 μm and 11.3 μm, respectively), as defined by Eq. (1) (BREUNIG et al., 2008; BREUNIG et al., 2009).

$$NTSI = \frac{(\varepsilon 11{,}3\mu m - \varepsilon 8{,}3\mu m)}{(\varepsilon 11{,}3\mu m + \varepsilon 8{,}3\mu m)} \tag{1}$$

3.2 Estimation of the soil sand fraction - Field and laboratory data

The data from the normalized index were compared with granulometric information on the total sand fraction of the soil surface horizon (to a depth of 20 cm) from 72 soil profiles published in various scientific journals, dissertations, theses, and technical reports (Figure 1 and Supplementary Table – see Supplementary Material available at DOI: 10.5281/zenodo.13929537). An empirical regression model was then developed for the study area using the logistic sigmoid function. Classical statistical parameters such as R^2, adjusted R^2, root mean square error, and model confidence levels were calculated.

Given the limitations associated with the ASTER GED product (which represents an average of several dates and has a spatial resolution of 100 meters) and the field data, samples where the NTSI showed low values (e.g., negative) and high sand fraction content were excluded from the analysis, as these were likely associated with vegetation. Areas with high vegetation cover exhibit very low NTSI values regardless of the surface layer's soil characteristics. Even if a soil has a high sand fraction, the presence of vegetation tends to increase emissivity and lower the NTSI. This effect arises from the high emissivity of vegetation across the thermal infrared spectrum due to water content in the canopy components, effectively masking the sandy soil beneath.

Out of 147 identified soil profiles, 75 were in vegetated environments, leaving 72 profiles available for analysis (see supplementary material available at DOI: 10.5281/zenodo.13929537). Due to the nature of the ASTER GED data, it was not possible to obtain optical images from the period 2000-2008 to classify land use, as the product calculates an average of all high-quality images during the analyzed period. Notably, the samples included soils with both low (basalt) and high sand fractions (sandstone), allowing the model to estimate sand fraction in the surface layer for soils derived from different lithologies.

After estimating the areas with the highest sand concentrations using both methods, the data were cross-checked to assess their agreement with field information. The final validation, or ground truthing, involved several field visits to the study area between 2010 and 2024, which facilitated a thorough understanding of the landscape. Concurrently, morphological descriptions from the publications that provided granulometric data were consulted. To streamline the analysis, three occurrence classes were established based on the sand content of the soil surface: ≤ 50%, 50-80%, and ≥ 80% total sand.

3.3 Micromorphological interpretation

The micromorphological analysis was conducted based on the interpretation of thin sections collected from the surface horizons of a Acrisol (Argissolo Vermelho-Amarelo) profile at the experimental farm of the Universidade Estadual de Maringá in the municipality of Cidade Gaúcha/PR (CUNHA, NOBREGA; CASTRO, 2008). The description and collection of micromorphological information were carried out following the guidelines of Stoops; Marcelino and Mees (2010). Specific fields within the thin sections were selected for the characterization of the microorganisms present, and photographs were taken using a Zeiss Axioscope 5 petrographic microscope, which facilitated the development of an evolutionary model for the microorganisms.

This methodology enabled a comprehensive understanding and characterization of the different scales at which soils are organized, ranging from micromorphological structures to broader landscape features, while also detecting their interrelationships.

4. Results

4.1. Spatial Distribution of Sand Patches in the Northwestern Paraná Landscape.

The modeling and filtering of samples from areas with vegetation cover during the ASTER GED product calculation period (2000 to 2008) yielded an R^2 of 0.78 (± 15.13) (Figure 2). The excluded samples are highlighted in gray (as indicated by the ellipse in Figure 2) and likely correspond to points that contained vegetation throughout the ASTER GED composition (2000-2008). The blue dotted line represents an empirical threshold established to identify areas where the NTSI is associated with clayey soils, slightly clayey soils, or even vegetation (gray area on the map in Figure 3). The model exhibits saturation at approximately 80% sand content. In this range, the model's confidence band indicates a greater error in the estimates (Figure 2).

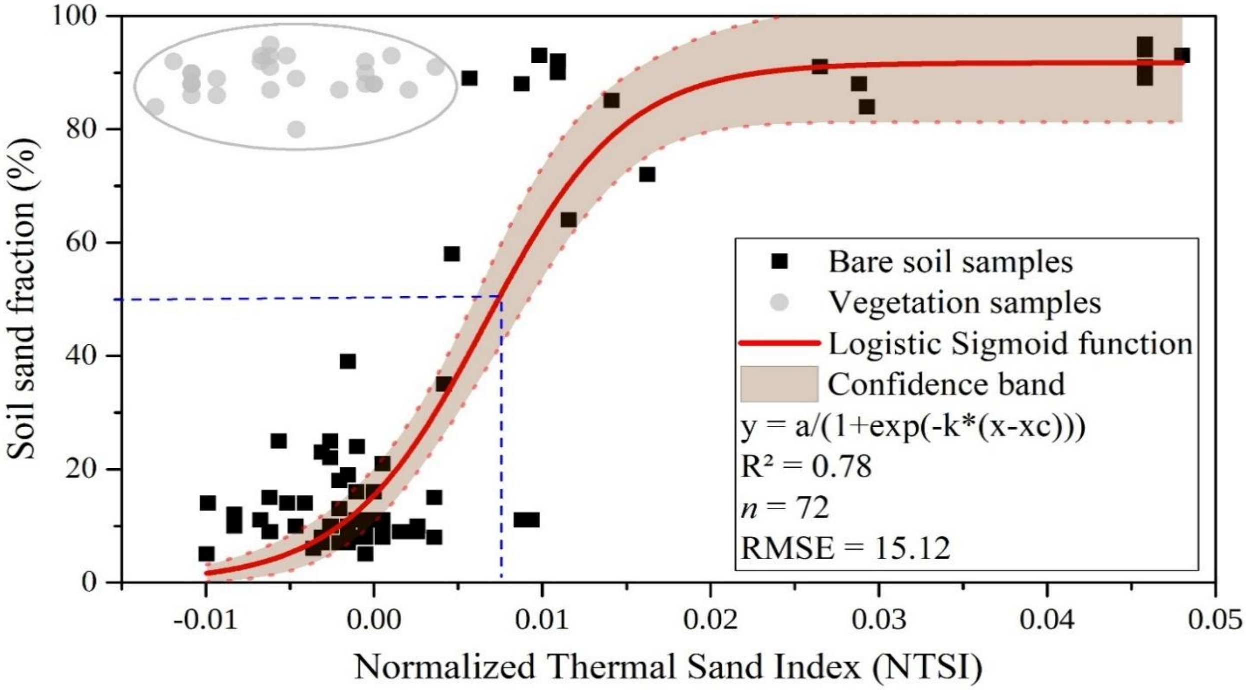

Figure 2. Sand Fraction Estimation Model for the Surface Based on the Normalized Index Derived from the GED-ASTER Product and Field Data.The model was developed using seventy-two field samples, with those typically associated with vegetation filtered out. RMSE refers to the Root Mean Square Error, while n denotes the number of samples.

With the spatialization of the logistic sigmoidal model (Figure 2), it was possible to map the distribution of sand patches in the study area based to the variation of total sand (Figure 3).

Areas with vegetation cover or lower sand concentration accounted for approximately 90% of the total area. The 50-80% sand class represented 7%, while the class with over 80% sand comprised approximately 3%. Overall, a higher concentration of sand patches was observed in the central-northern region of the study area.

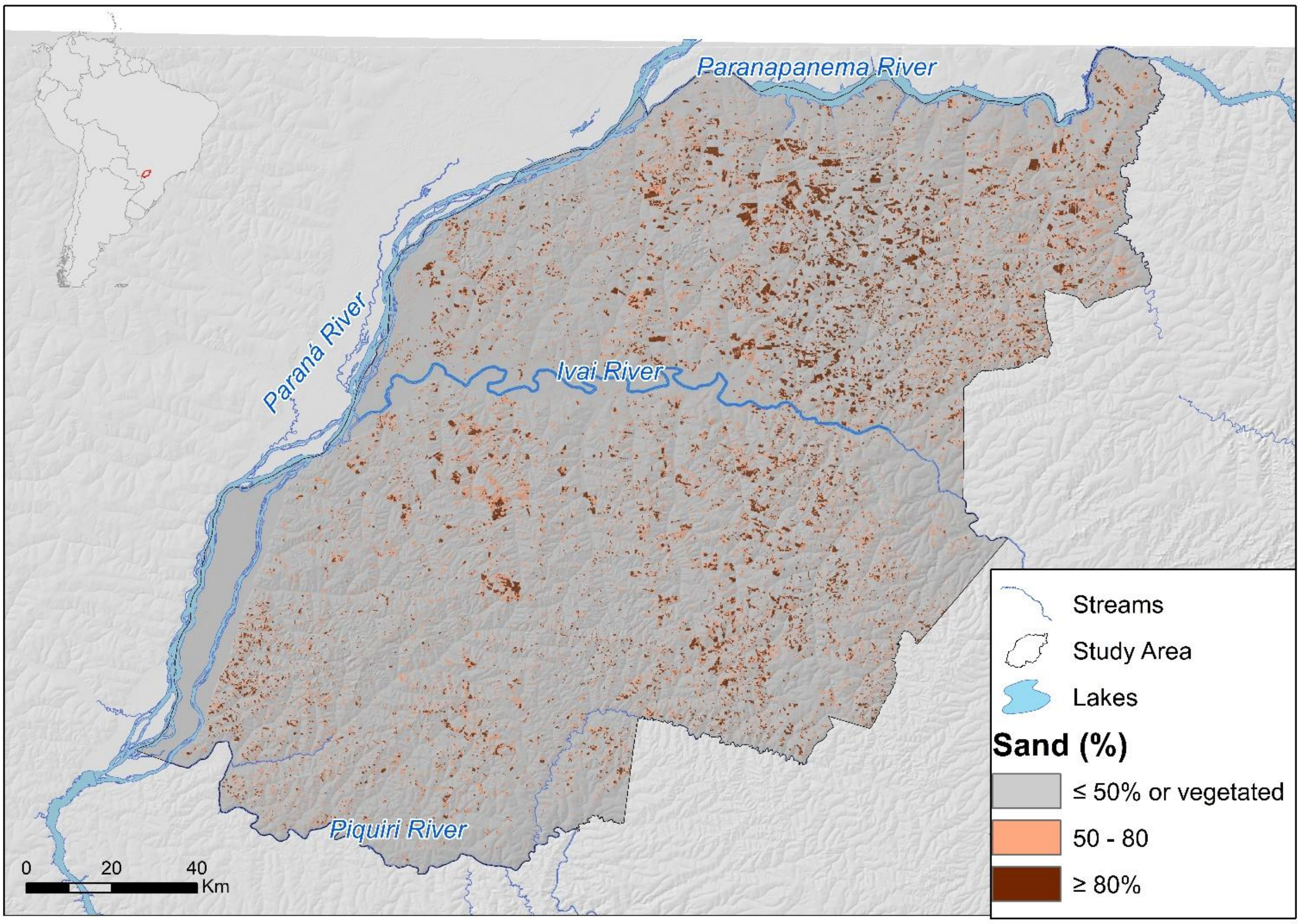

Figure 3. Map of Sand Patches Based on Estimated Surface Sand Fraction Percentages.

Upon detailed evaluation of the classes, it was found that areas estimated to have lower sand concentrations (≤ 50%) do not necessarily correspond to low actual sand values. Instead, these areas are often associated with a high degree of soil coverage by green vegetation, particularly from agricultural practices that cover the soil. The high emissivity of green vegetation, which contains a higher water content in the leaves, results in low NTSI values that mask the presence of soils with higher sand concentrations. According to Salisbury et al. (1992) and Breunig et al. (2008), the spectral response of clayey soils is quite similar to that of vegetation and soil cover in the thermal infrared spectrum due to the high emissivity of water across this range. This specificity of the method accounts for the predominance of areas with lower estimated percentages of sand fraction in regions covered by vegetation.

The classes with sand concentrations of ≥ 80% and 50-80% are predominantly found in areas where sand patches are exposed. In these locations, the mineral composition of the sand fraction exhibits low emissivity in ASTER band 10 and high emissivity in band 14, resulting in elevated NDSI values. These classes are associated with various land uses and covers in the region, such as degraded pastures, sugarcane fields, fallow land, preparation for planting, and cattle trampling. These activities have contributed to the removal of vegetation and, consequently, facilitated the elutriation process, leading to the relative accumulation of the sand fraction on the surface (OLIVEIRA; SANTOS; CALEGARI, 2020). The ASTER GED products represent an average emissivity over several years, which complicates the association of specific land uses and covers for each pixel. Nonetheless, the model provides valuable insights into regional trends.

In relation to fallow areas or those prepared for planting, the patches in these classes exhibit regular geometric shapes that align with the boundaries of rural properties (Figure 4A). When combined with trails and trampling from cattle, the patches take on relatively linear forms (Figure 4B). Due to the limitations associated with using a composited product, many sand patches reflect the pattern of the plots, which may be linked to the average land use patterns in the region.

At the bottom of valleys, the patches are associated with relief features, including embankments, and often exhibit signs of piping and hydromorphism (CUNHA; CASTRO; SALOMÃO, 1999). These patches represent areas where clay loss and removal processes occur from both the surface and subsurface horizons (lateral transformation systems), frequent in the study area (CUNHA; CASTRO; SALOMÃO, 1999; CALEGARI, 2000; OLIVEIRA; SANTOS; CALEGARI, 2020).

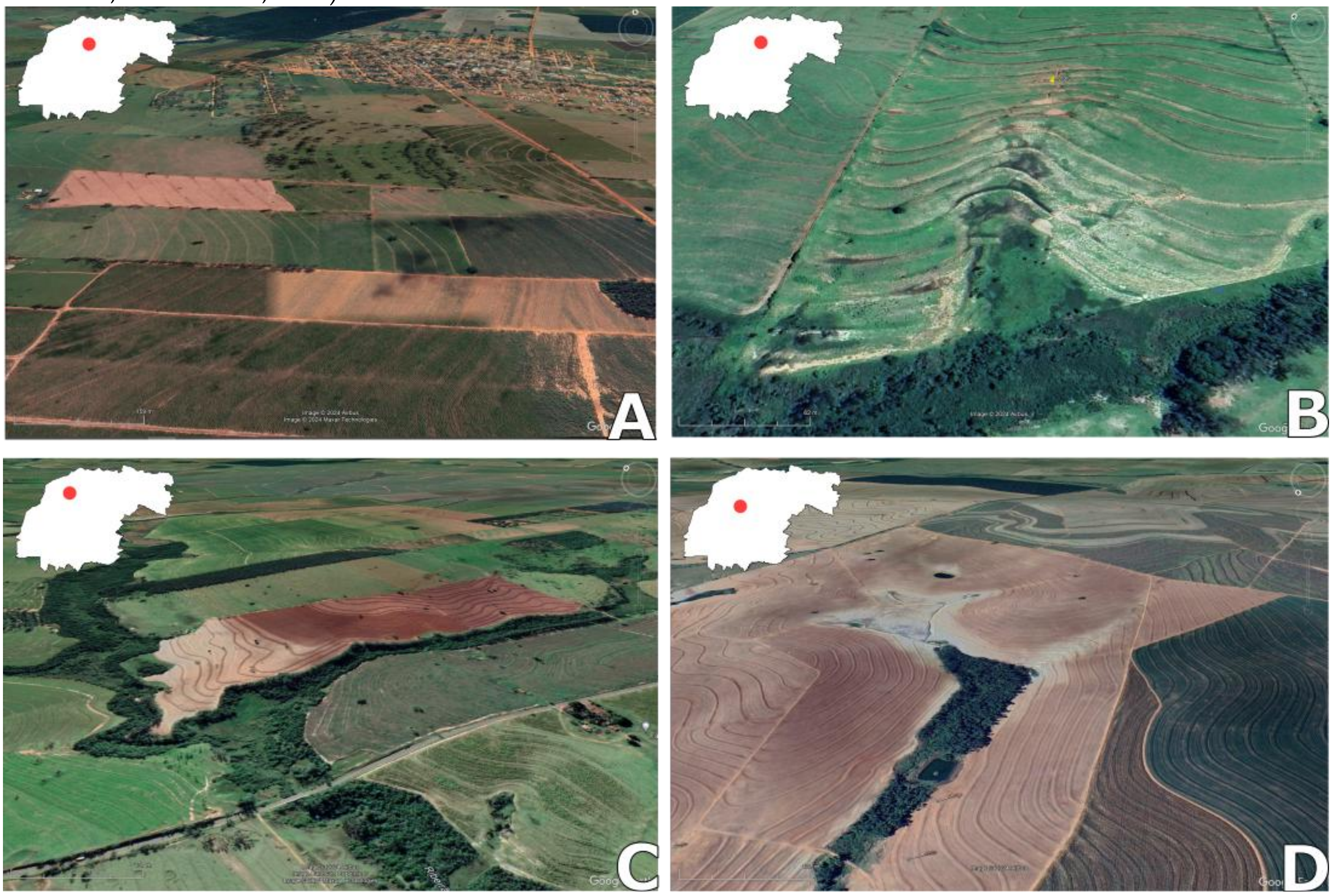

Figure 4. A) Regular geometric shapes associated with areas prepared for planting; B) Erosion caused by trails and cattle trampling.; C) Gradual transition from reddish soils to whitish soils at the bottom of valleys; D) Amphitheaters where the mechanical removal of clay occurs due to the convergence of surface water flows. Images from the Google Earth Pro collection.

In the upstream segments, Ferralsols and Acrisols exhibit a progressive decrease in clay content, both vertically and laterally, as one moves downstream, ultimately forming Arenosols in the lower sections of the slopes (CUNHA; CASTRO; SALOMÃO, 1999; OLIVEIRA; SANTOS; CALEGARI, 2020; NÓBREGA et al., 2023) (Figure 4C). These soils, when lacking a surface horizon, are characterized as sand deposits without any aggregation (i.e., stacking structure). The thickness of the sandy surface horizons increases toward the lower sectors of the slopes, reflecting the evolution of the eluvial-illuvial transformation system, frequent in the region (CUNHA; CASTRO; SALOMÃO, 1999; BECKAUSER; SILVEIRA, 2020). The mechanical loss of clays is also evident in small amphitheaters and drainage headwaters, where the convergence of surface rainwater flows leads to the mechanical removal of clays (Figure 4D) and the concentration of the middle soil fraction (SANTOS; OLIVEIRA, 2020).

4.2. Genesis of sand patches in the landscape

The intrinsic relationship between the pedogenetic history of the soil and the environment in the northwestern region is evident in its attributes, such as granulometric composition and low nutrient availability, which are inherited from the source material: the sandstones of the Caiuá Group (MARCOLIN et al., 2023). As a result, the soils in northwestern Paraná predominantly have a texture ranging from medium to sandy and are classified as Feralsols, Acrisols and Arenosols (BHERING, 2007).

Surface runoff from rainwater converges in the amphitheaters, enhancing the selective removal of fine particles (silt and clay) from the surface horizons and promoting the elutriation process (OLIVEIRA; SANTOS; CALEGARI, 2020; SANTOS; OLIVEIRA, 2020). In the field, these authors observed that the more deeply carved a valley becomes following the installation of a perennial drainage system, the more intense the elutriation process is, increasing the likelihood of ravines and gullies forming. In landscape areas where the A horizon has been depleted due to agricultural use, these features commonly occur in association with the exposure of the E horizon of Acrisols and the C horizon of Arenosols.

Although the process of lateral soil transformation is primarily attributed to natural environmental conditions, it is notably accelerated in northwestern Paraná, particularly in medium-textured soils derived from the sandstones of the Caiuá Group, where natural vegetation has been removed and replaced by pasture (CALEGARI, 2000). This alteration increases the susceptibility of these soils to erosion processes. The extensive occupation and deforestation have stripped the soil of its natural protection against the direct impact of rain (splash effect), drastically affecting the incorporation of organic matter, which is essential for soil aggregation.

The processes of vertical and lateral clay translocation can be more clearly understood through the observation of soil micromorphology. Figure 5 illustrates the arrangement of constituents in different horizons of a Acrisol (Argissolo Vermelho) profile studied in a toposequence in the municipality of Cidade Gaúcha, PR (CUNHA; CASTRO; SALOMÃO, 1999). As the sand content increases, a noticeable change in porosity and organization of soil components is evident across the more clayey Bt horizon (Figure 5A), the Bt/E horizon (Figure 5B), and the E and A horizons (Figures 5C-D). This variation in porosity and component organization is characteristic of this soil class in the region, which typically occupies the middle third of the slopes and the slope rupture sectors associated with slope higher than 15-20% (CALEGARI, 2000).

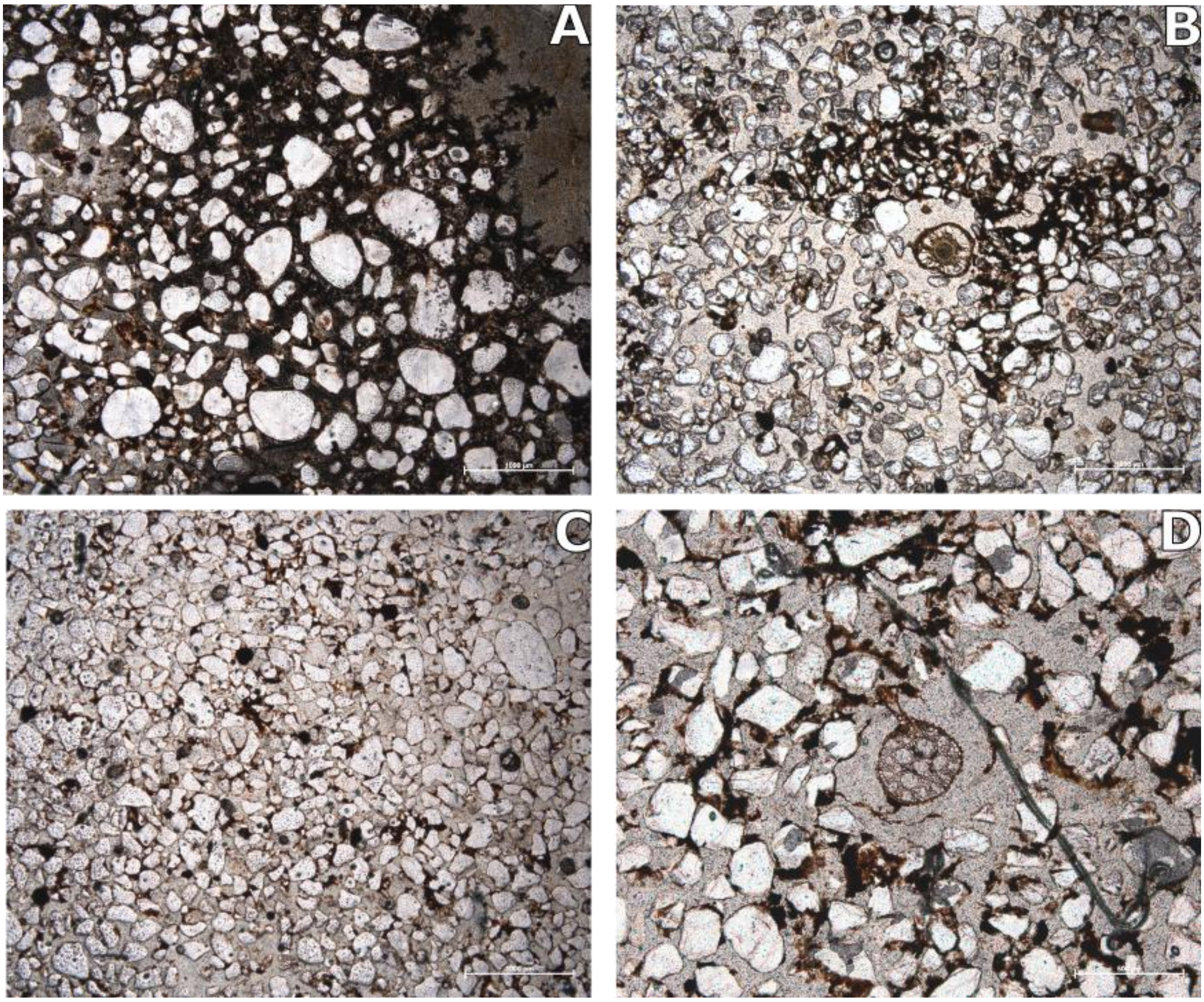

Figure 5. Microscope images illustrating the arrangement of constituents in different horizons of a Acrisol (Argissolo Vermelho) profile. A) Bt horizon, characterized by higher clay content; B) Horizon with reduced clay content, where clay is present only in small aggregates; C) Horizon with minimal clay, predominantly consisting of quartz; D) Detailed view of the horizon shown in C. (CUNHA; CASTRO; SALOMÃO, 1999)

The interpretative model of soil micromorphology (Figure 6) illustrates the evolution of microstructures along the soil profile, from the deeper horizons to the surface. As we move upward through the profile, there is a noticeable increase in the sand fraction at the expense of the clay fraction, leading to higher porosity in the surface horizons. In terms of microstructures, they become increasingly residual, characterized by sand grains of varying sizes without clay coatings. This residual sand accumulation is responsible for the formation of the sand patches observed on the soil surface in the field, confirming and reinforcing the interpretations made at the micromorphological scale.

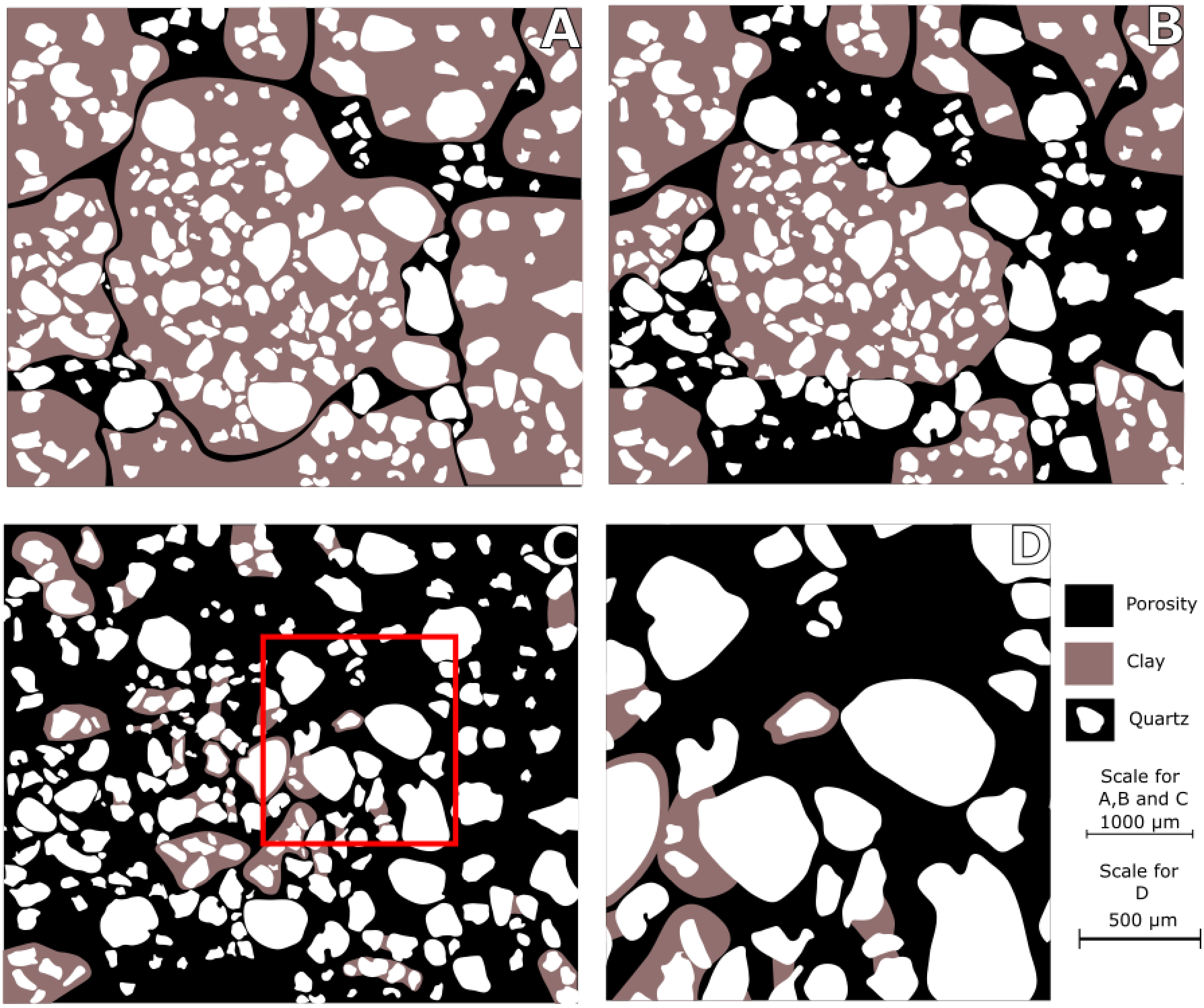

Figure 6. Interpretative model of soil micromorphology. A) Clay matrix incorporating quartz grains; B) Reduced clay matrix containing quartz and other grains dissociated from the clay and dispersed within pores; C) Quartz grains scattered within the pores, connected by clay bridges or surrounded by clay; D) Detailed view of the distributions described in figure C.

In the northwestern region, the lateral transformation system is the most suitable model to explain the formation of sandy A horizons and the occurrence of Arenosols near valley bottoms (NAKASHIMA, 1999; CALEGARI, 2000; CUNHA, NÓBREGA; CASTRO, 2008).

In the upper sectors, where medium-textured Ferasols predominate, water flow tends to be vertical. In areas with Acrisols, water flows laterally and at higher speeds at the tops of the A, E, and Bt horizons, and vertically at slower speeds at the bases of these horizons. This dynamic promotes the thickening of the E horizon and the formation of sandy pockets in valley bottoms, which supports the development and thickening of Arenosols (NAKASHIMA, 1999; CALEGARI, 2000; CUNHA, NÓBREGA; CASTRO, 2008; OLIVEIRA; SANTOS; CALEGARI, 2020; OLIVEIRA; SANTOS, 2020).

Figure 7 presents a summary model of the lateral soil transformation process, following the work of Oliveira; Santos and Calegari (2020). It indicates where processes such as elutriation, illuviation, and eluviation predominantly occur along the slopes. Field observations suggest that the waxiness present among the aggregates in the Bt horizon (textural B horizon) is not sufficient to fully explain its formation. Instead, the Bt horizon seems to form through the relative accumulation of clay in relation to its lateral loss, which is transported directly to drainage areas. This model also highlights that the significant thickening of sandy horizons in valley bottoms may be linked to the deposition of sand transported from slope erosion, combined with pedogenetic processes such as elutriation.

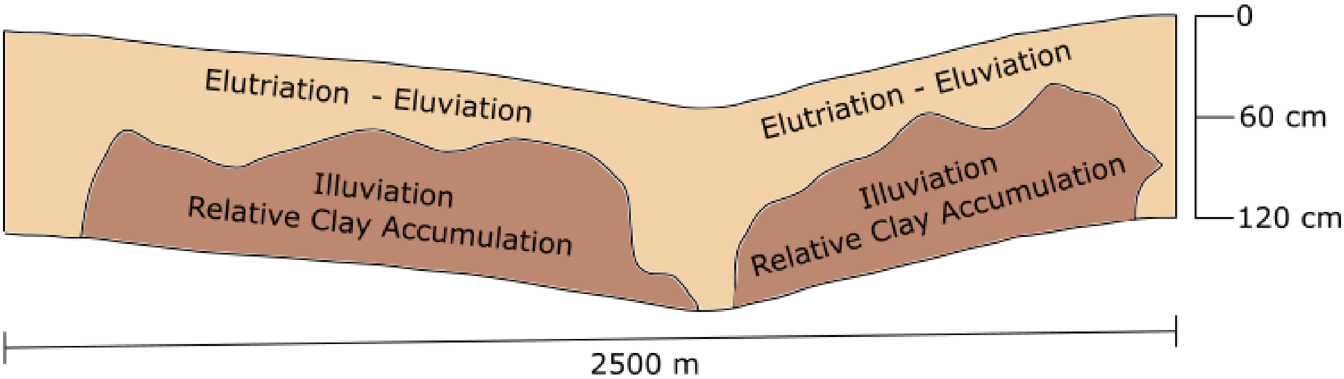

Figure 7. Diagram of pedogenetic processes in two slopes based on Oliveira, Santos and Calegari (2020)

5. Discussion

5.1. Environmental implications of sandy patches

While sandy soils are inherently fragile due to their texture, the pressure from human activities has exacerbated the formation and spread of sandy patches in various environments. In northwestern Paraná, the soil's textural fragility plays a crucial role in the development of water erosion processes (FIDALSKI; HELBEL JUNIOR, 2020). This issue has been further aggravated by deforestation in the region, which began in the 1950s, and by the manner in which urban and agricultural areas have been established (BIGARELLA; MAZUCHOWSKI, 1985; MAACK 1968).

The predominance of soils with a sandy surface texture coupled with a lateral transformation system that increases the sand content downstream and at greater depths in Acisols and Arenosols increases the risk of environmental problems. These issues can become more severe in with extreme rainfall events.

Once linear erosion processes are installed, they can rapidly evolve upstream on the slopes. The occurrence of Arenosols and Acrisols in the lower and middle slopes favors and enhances this evolution. An example of the upstream evolution process of a gully is in the district of Sumaré (BECKAUSER; SILVEIRA, 2020), municipality of Paranavaí (Figure 8). Over the last 20 years, this gully has expanded longitudinally, going from 6,494.14 m^2 in 2004 to 15,119.24 m^2 in 2024, reaching the upstream (upper middle) sectors of the slope.

Figure 8. Evolution of Gully in the district of Sumaré, Paranavaí (latitude: 23° 4'35.79"S; longitude: 52°23'37.74"O). In red perimeter of the gully over the years. Source: Google Earth pro

In addition to the landscape's position, land use is another key factor that contributes to the onset and development of linear erosion processes. Pasture is the most prevalent form of land use in the northwest region of Paraná, occupying the largest areas (FIDALSKI, 1997a). Since the 2000s there has been a notable increase in sugarcane and cassava production, replacing pastureland. This region is now the largest producer of alcohol in the state (PAIVA; NÓBREGA, 2010). With numerous processing plants currently in operation, sugarcane has become the dominant agricultural crop in the area. These agricultural practices are supported by the landscape's gently sloping relief, with gradients around 6%, and the presence of wide, medium-sized hills.

According to Nóbrega et al. (2023), the primary land uses responsible for triggering erosion processes in the region are pastures, along with sugarcane and cassava crops. The environmental impacts of these activities are distinct. In the case of sugarcane and cassava, the soil is left exposed to rainfall during the early growth stages, and the common practice of burning during harvest inhibits the replenishment of organic matter. Pasture, on the other hand, has an indirect effect on erosion due to soil compaction caused by cattle trampling (FIDALSKI et al., 2021). As compaction increases, along with the high sand content of the soil, porosity—especially macroporosity—decreases, reducing water infiltration (FIDALSKI et al., 2021). Another common impact related to cattle is the formation of trails leading to valley bottoms for drinking water (FIDALSKI, 1997a). These trails become preferential pathways for surface water runoff, accelerating the development of erosion processes.

The characterization of sandy patches in the northwestern region of Paraná can significantly inform conservation efforts aimed at soil and water management, particularly in areas dominated by fine and coarse sand (FIDALSKI et al., 2013; FIDALSKI; HELBEL JUNIOR, 2020). These practices, when combined with maintaining vegetation cover in sandy soils, contribute to the accumulation of organic matter, improve soil structure, reduce surface runoff, and mitigate soil losses from water erosion. Additionally, they enhance water availability for plants (MERTEN; ARAÚJO; BARBOSA, 2016; FIDALSKI et al., 2021; GOBBI et al., 2022; FIDALSKI; TORMENA, 2022).

6. Conclusions

The use of various scales of analysis—from satellite imagery and field observations to microstructural analysis—enabled the identification and estimation of the percentage of areas with sandy patches in the studied region, as well as a better understanding of the processes responsible for their formation. These sandy patches are primarily caused by the removal of vegetation cover, which leaves the soil exposed to the direct impact of rainfall and reduces the input of organic matter. Such areas are identified as priorities for integrated conservation practices focusing on sustainable land use and management.

Despite the limitations of the method, such as the timeframe used for the composite thermal infrared images and the potential masking of sandy soils by vegetation or agricultural practices, the granulometric data from the surface horizons of 72 soil profiles increased the reliability of the model used.

In both agriculture and livestock farming, the removal of natural vegetation cover, the reduction of organic matter incorporation, and changes in soil structure contribute to the formation and expansion of sandy patches and rural linear erosion in the region. These impacts are considered severe, as the recovery of these areas is challenging, even with changes in land use, highlighting their low resilience.

Supplementary Materials: The table with the geographic coordinates of the points used for validation, including bibliographic source, description, and the condition of the original lithological material, as well as the raster data of the estimated sand distribution patches, is available at: https://doi.org/10.5281/zenodo.13929536.

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