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Sand fraction estimation in the topsoil of the Pantanal Biome: a preliminary approach using emissivity data

Estimativa da fração areia do horizonte superficial dos solos no Bioma Pantanal: uma abordagem preliminar com dados de emissividade

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Abstract

The Pantanal Biome is characterized by its high biodiversity of fauna and flora, largely associated with its floodplain. With the increasing occurrence of extreme events such as droughts, floods, and fires, the risks of environmental degradation and the intensification of processes like the increase of sand in the floodplain (sandization) also rise. This study aims to estimate the sand fraction in the surface horizons of the soils in the Pantanal Biome using thermal infrared data. These estimates were obtained from the emissivity data of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Emissivity Dataset (GED). In addition to emissivity data, elevation and hydrography data were also considered. To estimate the sand fraction, an empirical regression model was employed. Spectral analysis of sandy terrains revealed features associated with the presence of silica (Reststrahlen features), enabling its distinction from green/dry vegetation and water. Normalization of thermal band data allowed the application of a logistic model to estimate the distribution of areas with higher concentrations of sand fraction in the Pantanal soils. The eastern, central, and central southern sections have higher concentrations of the sand fraction. The results suggest a partial a relationship between the sand percentage, small altimetry variations in the biome, and the absence of permanent drainage systems. Further studies should be conducted

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to validate the model, and caution is recommended when interpreting and using the results presented.
Keywords:
Remote sensing, ASTER, Restsrahlen, Sandization, Thermal infrared.

Resumo

O Bioma Pantanal é caracterizado por sua alta biodiversidade de fauna e flora, em grande parte associada à sua planície de inundação. Com o aumento da ocorrência de eventos extremos, como secas, inundações e incêndios, aumentam as chances de degradação ambiental e do agravamento de processos como a arenização. Este estudo tem como objetivo estimar a fração areia nos horizontes superficiais dos solos do Bioma Pantanal com uso de dados do infravermelho termal. Essas estimativas foram obtidas a partir dos dados de emissividade do produto *Advanced Spaceborne Thermal Emission and Reflection Radiometer* (ASTER) *Global Emissivity Dataset* (GED). Além dos dados de emissividade, também foram considerados dados de elevação e de hidrografia. Para estimativa da fração areia, foi utilizado um modelo de regressão empírico. A análise espectral dos terrenos arenosos mostrou a presença de feições associadas à sílica (feições de *reststrahlen*), permitindo sua distinção de vegetação verde/seca e água. A normalização dos dados da faixa termal possibilitou a aplicação de um modelo logístico para estimar a distribuição das áreas com maior probabilidade de concentração de fração areia nos solos do Pantanal. As regiões leste, central e centro-sul do bioma apresentaram maiores concentrações de fração areia. Em parte, os resultados sugerem uma relação entre o percentual de areia com as pequenas variações de altimetria no bioma e com a ausência de drenagens permanentes. Estudos adicionais são necessários para validar o modelo, sendo recomendada cautela na interpretação e uso dos resultados apresentados.
Keywords:
Sensoriamento remoto, ASTER, Restsrahlen, Arenização, Infravermelho termal.

I. INTRODUCTION

The Pantanal biome is characterized by the world's largest seasonal flood basin. In recent decades, it has experienced periods of intense water stress associated with droughts, large-scale fires and extreme rainfall. (Bergier; Assine, 2016; Garcia et al., 2021; Leal Filho et al., 2021; Libonati et al., 2022a, Libonati et al., 2022b; Tomas et al., 2019; SOS Pantanal, 2024). Additionally, the deforestation process of native vegetation has advanced, despite the warnings of monitoring and detection systems (ANA, 2024; INPE, 2024). All these factors tend to affect the quality of the soil, which is typically sandy, and can lead to degradation, including the formation of sandy patches in the topsoil (Suertegaray, 1995; Freitas et al., 2003; Breunig et al., 2024).

Although sandy areas are easily observable *in situ*, its identification on a large scale using remote sensing data for mapping is challenging. The satellite images obtained in the visible, near-infrared (NIR) and shortwave infrared (SWIR) spectral bands do not allow high-reflectance soils (e.g. bright soils) distinguishable

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from non-photo-synthetically active vegetation (NPV), causing frequently confusion in the scenes (Breunig et al., 2009; Breunig et al., 2008; Chen et al., 2021).

This scenario is frequent in the Pantanal biome during the dry season, like the patterns of the *Cerrado* Biome. However, in the thermal infrared, these top soils are subject to discrimination from other materials. Due to the of reemission features (Reststrahlen) in the thermal infrared (TIR) (Salisbury; D'Aria, 1992a, 1992b), silica composts can be easily detected in TIR spectra, allowing the separation of sandy top soils from the other scene elements. However, to explore the use of this quartz feature, it is necessary to use sensors that operate in a narrow range of the thermal infrared, specifically between 8 and 14 micrometers.

In the TIR range some orbital sensors operate in multiple bands, such as the *Advanced Spaceborne Thermal Emission and Reflection Radiometer* (ASTER), onboard the Terra satellite (Platnick, 2024), and the *Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station* (ECOSTRESS), installed on the International Space Station (ISS) (JPL/NASA, 2025). Both sensors have five bands with similar spectral positions. ASTER was one of the first orbital sensors with five bands covering the spectral range of the TIR between 8 and 14 micrometer (ERSDAC, 2007; Sobrino et al., 2007). In addition to these sensors, the *Thermal Infrared Sensor* (TIRS), aboard Landsat 8 and 9 satellites, and the *MODerate-resolution Imaging Spectroradiometer* (MODIS), which operate on the Terra and Aqua satellites, with two bands in the thermal infrared, stand out. Finally, some new sensors are proposed, focussing on the improvement of spatial resolution, such as the *Sustainable Development Science Satellite* 1 (SDGSAT-1) (Guo et al., 2023) and the sensor developed by Constellr GmbH (Spengler et al., 2024).

ASTER's TIR sensor allowed the generation of emissivity data, with a spatial resolution of 90 meters, since the 2000s (Gillespie et al., 1998). The presence of a multispectral sensor in the thermal wavelength has permitted important advances in the development of algorithms to discriminate temperature and emissivity data on a global scale with adequate accuracy (Gillespie et al., 1999). Given the availability of a large time series of emissivity data from ASTER, Hulley et al. (2015) developed the Global Emissivity Dataset (GED) product. The product represents a continuous database of surface emissivity, with two spatial resolutions of 100 meters or 1 km. This product consists of the average response of all emissivity images from 2000 to 2008 (TIR composite product), obtained with quality control and filtering for shadows, clouds and aerosols (Hulley; Hook, 2011). The GED offers a unique opportunity to test the application of emissivity data to discriminate sandy topsoil, characteristic of seasonally flooded areas, such as those in the Pantanal Biome.

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Considering the importance of this biome and the fragility of the ecosystem (Santos et al., 2006; Cardozo et al., 2016), this study evaluates the hypothesis that sandy topsoils can be identified based on a strategy of emissivity data normalization in the thermal infrared range. This is a contribution to understand the relationships between land use/land cover in the region and the possible impacts of extreme scenarios associated with the climate change.

The specific objective of this study was to estimate the sand fraction of the soils surface horizon located in the Pantanal, using the ASTER GED product. After its identification, the study discusses the geographical characteristics of these horizons in relation to the estimated sand fraction, as well as its variation in comparison to the typical pedological characteristics from the region.

II. Materials and Methods

Field of study

The study area covers the whole Pantanal Biome, totaling 150,988 km². It includes the Brazilian States Mato Grosso and Mato Grosso do Sul, as well as areas in Paraguay and Bolivia (**Figure 1a**), and is located upstream of the *Rio* Paraguay River basin. The soils of the Pantanal floodplain are predominantly sandy, with medium to small granulometry (Schiavo et al., 2012). The predominant soils are Neosols, Planosols, Plintosols, Vertisols, Gleisols, Fluvic Cambisols and Luvisols (Schiavo et al., 2012; Soares et al., 2006; Boin et al., 2019). In general, these soils present hydromorphism associated with the seasonality of rainfall in the biome floodplain.

The climate of the biome is characterized by two well-defined seasons: the rainy season, which occurs predominantly between the months November and March, and the dry season, which occurs between May and September (Tomas et al., 2019). The region is distinguished by its high biodiversity, encompassing diverse fauna and flora (Leal Filho et al., 2021). During the rainy season, drainage systems are the prominent features of the biome, extending across a significant portion of the landscape. In contrast, numerous rivers and lakes exhibit a perennial character, maintaining a constant presence throughout the year (**Figure 1**). The seasonal spatial dynamics of water bodies partly reflect changes in land use/land cover in the Pantanal biome and on the plateau where these drainages originate (Zorzetto, 2015; Assine et al., 2014; Kuerten et al., 2013; McGlue et al., 2012). Considering the future changes predicted by the climate models, the biome will undergo relevant changes in temperature and precipitation patterns at the end of the 21st century (Beck et al., 2023).

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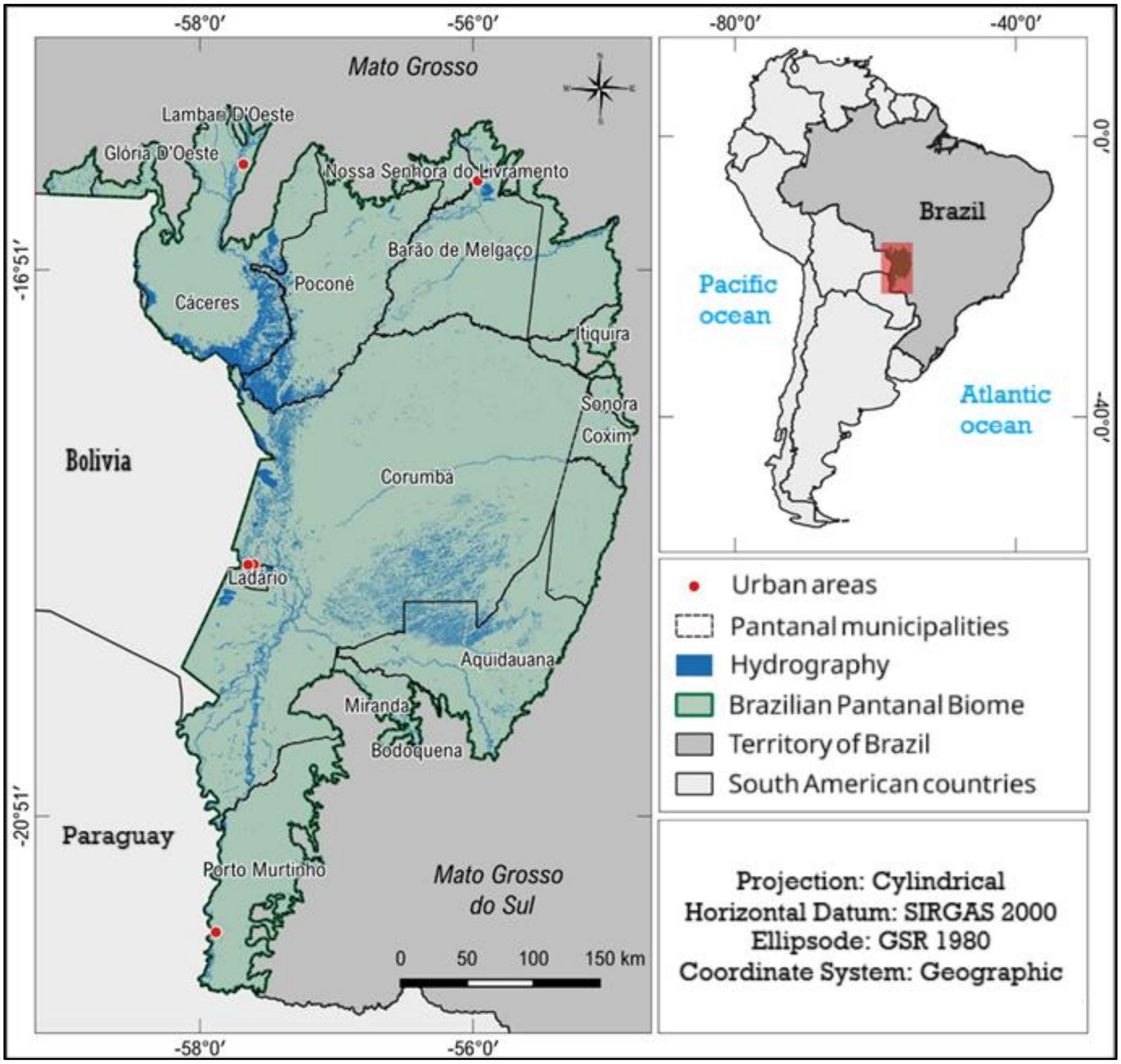

Figure 1 – Location of the Pantanal Biome in the center of the Paraguay River basin and in the center of South America. General hydrography in the Pantanal Biome. Source of vector data obtained from the Terrabrasilis platform (INPE, 2023 and IBGE 2024).

Data acquisition and processing

Data from the ASTER GED product (HDF5 V003) were used. In total, 53 tiles(1°x1°) were obtained for the entire Pantanal Biome with a spatial resolution of 100m. The data were downloaded from the EarthData platform, available at:<https://search.earthdata.nasa.gov/search>. Afterwards, the average emissivity for each tile was extracted. The Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1973) and the respective standard deviation values, also were extracted from the GED product with 100 m spatial resolution. For processing the tiles, the nearest neighbor resampling algorithm was used, preserving the consistency of the original product.

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Concurrently, data from the ECOSTRESS mission was used, to generate estimates for specific days, thereby enabling the results to be related to land use/ land cover. Level 2 (L2) product "Land Surface Temperature & Emissivity and Cloud Mask" was applied. ECOSTRESS data from 2024 and 2025 were used to facilitate a temporal comparison of recent reflected spectrum images available on Google Earth Pro® (Mountain View, California, USA) with TIR images, thereby allowing the interpretation of results. These data were used as a complement and qualitative analysis.

Additionally, the literature was searched for available data on the sand fraction of the Pantanal topsoils (Pires Filho et al., 1982; Coringa et al., 2012; Cardoso et al., 2011; Cardoso et al., 2016; Stieven et al., 2009; Pereira et al., 2007; RADAM Project - Folha Corumbá, 1982). Due to the estimated positional accuracy of the samples collected in these studies, considering the spatial resolution of the present investigation, only a small part of these data was useful in the analysis.

Data analysis

The initial analysis of the emissivity data was done with the examination of spectra from targets, including sand, vegetation, and water. Its extraction was conducted randomly within the biome, to highlight the differences in emissivity between soils characterized by a high sandy fraction and segments of the images with vegetation and water.

The Normalized Thermal Sandy Index (NTSI) was calculated using Equation I and bands 10 and 14, centered on 8.3 and 11.3 µm, respectively (Breunig et al., 2008; Breunig et al., 2009). This normalization procedure reduces the effects of bidirectional variations in the observation geometry, the residual atmospheric influence after pre-processing the data, and the signal-to-noise ratio of the sensor. Values in the range of -1 to 1 are expected, with values for pure sand (e.g., very sandy soils) tending to be positive, while values for targets with higher emissivity in ASTER bands 10 to 12 tend to be negative or very close to zero (e.g., clay soils, vegetation, and water).

$$NTSI = \frac{(\varepsilon 11{,}3\mu m - \varepsilon 8{,}3\mu m)}{(\varepsilon 11{,}3\mu m + \varepsilon 8{,}3\mu m)} \qquad \text{(I)}$$

where: ε represents the emissivity in the respective band.

A logistic function was used, based on a similar study carried out in NW Paraná State, Brazil, where an exponential equation was applied, as detailed in Equation II (Santos et al., 2024). This model must be adjusted locally in future studies, focusing on soil samples to be collected for different areas of the biome. Therefore, it is still necessary to evaluate its accuracy to estimate the topsoil sand fraction for the Pantanal, which was only

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partially done in this work. Another limitation that should be considered in the present analysis refers to the use of an eight-year composite product of ASTER images from 2000 to 2008. This can significantly change the value of the average emissivity, according to the season, presence of vegetation/water, among other constraints. The expectation is that soils with a higher concentration of sand tend to have less vegetation cover, and thus, higher NTSI values.

$$y = \frac{a}{\left(1 + exp\left(-k * (x - xc)\right)\right)} \quad \text{(II)}$$

where: *y* is the estimate of the sand fraction, *a* corresponds to the value of 91.7296 (±5.25305); xc to the value of 0.00664 (±9.65731E-4) and k to 241.42138 (±34.6913).

After the model application, data were spatialized and the resulting maps analyzed, considering the distribution of the patches with the highest and lowest estimated concentration of the sand fraction. Concomitantly, data were evaluated as a function of the FABDEM digital elevation model (version 1.2) (Hawker et al., 2022), geomorphological parameters and the drainage network (INPE, 2024).

To evaluate the results, two strategies were adopted. Initially, information available in the literature was considered (Filho et al., 1982; Coringa et al., 2012; Cardoso et al., 2013; Stieven et al., 2009; Pereira et al., 2007 as well as data from the RADAM project - (Folha Corumbá). Considering that not all data available had an adequate positional precision, they were filtered to maintain only more precise points. In a second step, following data were analyzed in an integrated form: (I) the field data; (II) the information resulting from the interpretation of high spatial resolution images from Google Earth Pro; (III) the interannual data of the average NDVI and its standard deviation obtained from the GED product; and (IV) the data of the estimated sand fraction. This combined data analysis showed areas with visible sand deposition (e.g. drainage sandbars), with medium and low sand concentration, and with estimates above 50% sand fraction. Finally, some field photographs were associated with their respective sand fraction estimates.

III. Results and Discussion

Spectral analysis showed differences in the emissivity between sandy topsoils, vegetation and water (**Figure 2**). In general, *reststrahlen* features were evident in exposed sandy soils to the satellite (Salisbury; D'Aria, 1992a, 1992b; Breunig et al., 2008). Due to this spectral characteristic of reemission, as the sand fraction increases, the emissivity in ASTER bands 10 to 12 (8.125 – 8.475 μm; 8.475 – 8.825 μm; 8.925 – 9.275μm,

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respectively) decreases. On the other hand, bands 13 and 14 (10.250 – 10.950μm and 10.950 – 11.650 μm) remain relatively stable for all targets evaluated.

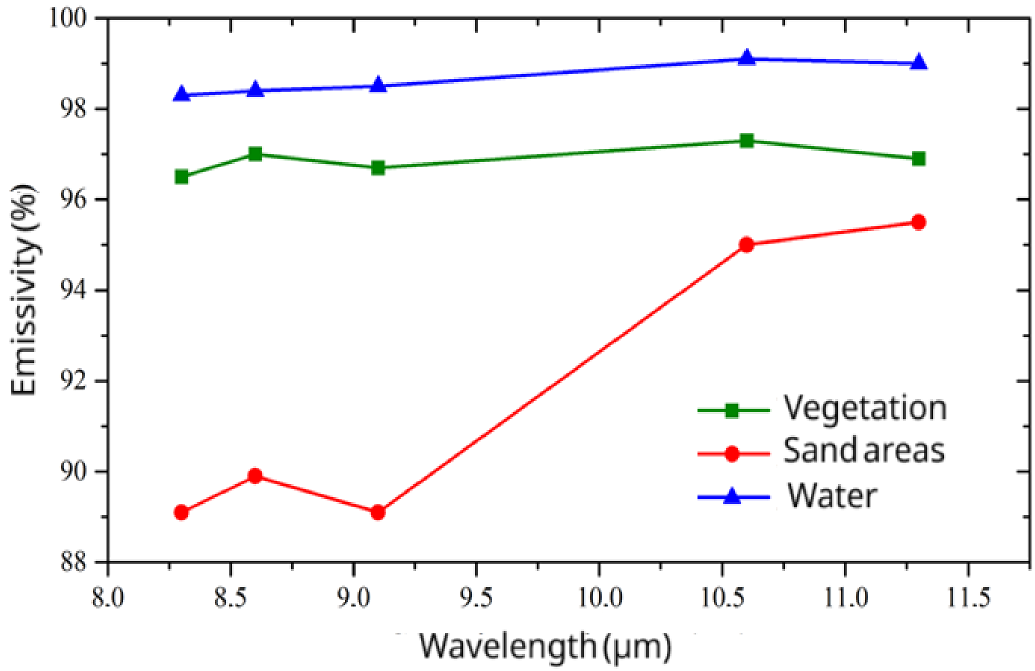

Figure 2 –Thermal infrared (TIR) emissivity spectra obtained from ASTER GED products for sandy soils and vegetation and water areas, from the Pantanal Biome.

The TIR normalization allowed obtaining dimensionless values, where the lighter tones represent those areas with higher sand concentration. Darker areas are usually associated with the occurrence of green, dry vegetation (NPV) or with water bodies (**Figure 3**). **Figure 3** shows some effects associated with the processing and acquisition of ASTER images over nine years (2000-2008), and some tiles can be visually identified.

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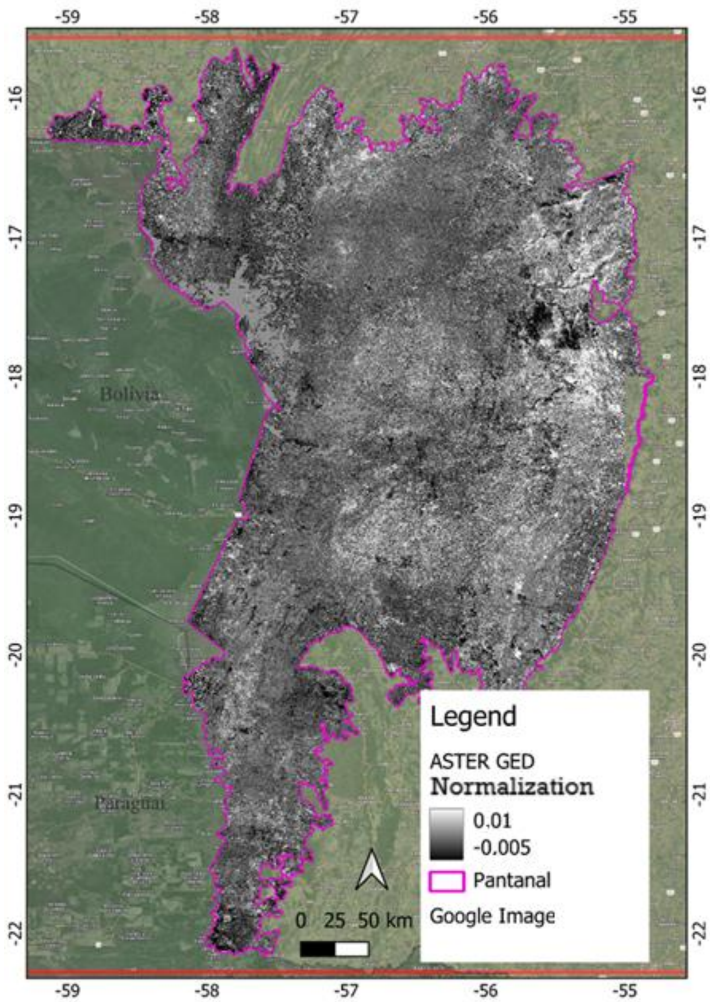

Figure 3 – Spatial distribution of normalization values from bands 10 and 14 of the ASTER GED for the Pantanal Biome. A Google Earth image is displayed as a background.

The spatialization of the topsoil sand fraction estimation, generated according to the equation from Santos et al. (2024), is shown in **Figure 4**. Data are visually similar to those in **Figure 3**, which depicts the thermal normalization index (NTSI). From this normalization it was possible to extract estimated values for the sand fraction, with the empirical model developed from field samples and a logistic regression (**Figure 4**). Clearly, there are patches with higher sand fraction represented by reddish tones in the central, east and south-central portions of the Pantanal. On the other hand, there are regions where most pixels have lower values of sand fraction estimation. This may be associated with soil characteristics or the presence of vegetation cover in the acquisition period of ASTER TIR images (2000 to 2008). In future studies, field campaigns and detailed soil surveys will help in the validation of estimates and on the explanation of associated geological-geomorphological processes, as done in studies conducted in Mato Grosso and Rio Grande do Sul States (Breunig et al., 2008, 2009, 2024).

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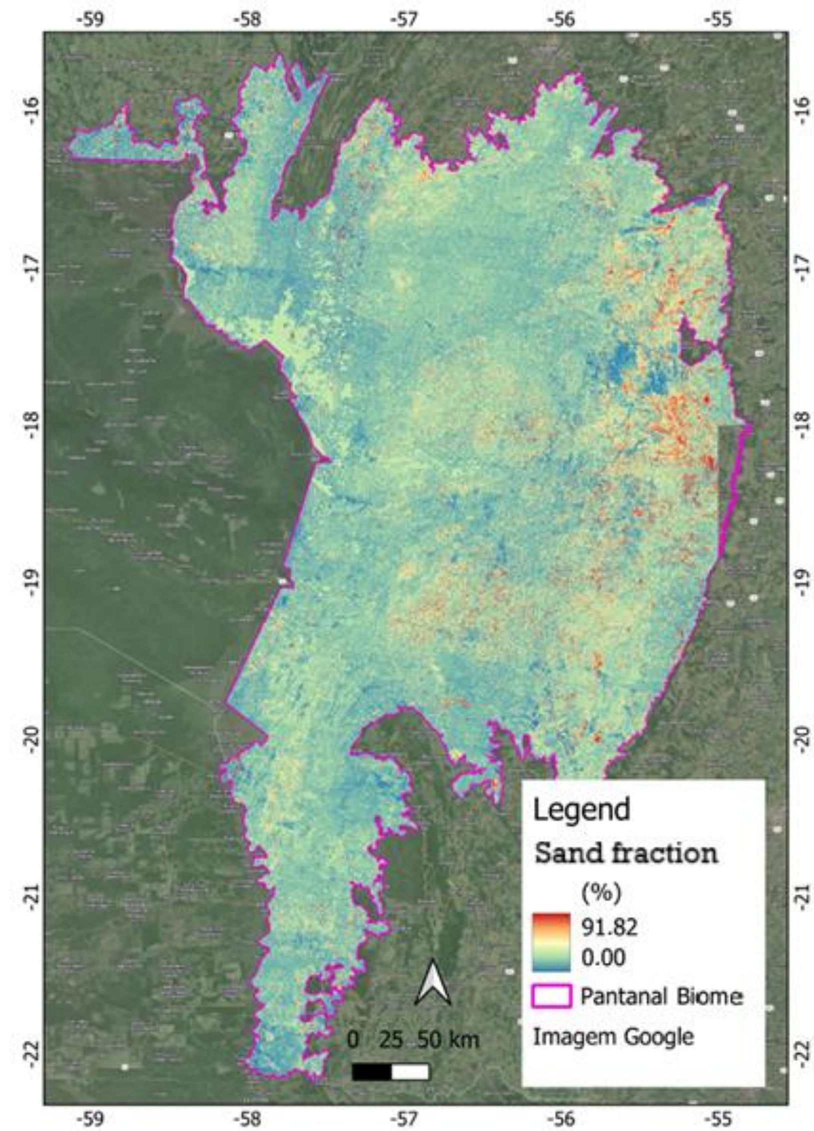

Figure 4 – Estimation of the sand fraction of the topsoil layer for the Pantanal biome, using ASTER GED data, with 100 meters of spatial resolution. A Google Earth image is displayed as a background.

During the qualitative evaluation from the sand fraction estimation (**Figure 5a**) as a function of the topographic biome characteristics, one observe a predominance of very sandy areas in higher regions (**Figure 5b**). This relationship was analyzed for the area of elevations between 140 and 160 meters, in the center-east of the study area. However, this possibility should be further investigated, with the support of field data. Apparently, there is a control associated with the altitude, although the elevation variations in the Pantanal Biome are small (Assine et al., 2014; Kuerten et al., 2013; McGlue et al., 2012). When the data is related to the drainage, it was also found that the areas with the highest estimates of sand fraction are located in places without the constant presence of water (**Figure 5c**).

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Using high spatial resolution data from Google Earth Pro®, along with NDVI observations, its standard deviations from the ASTER GED product and sand fraction estimates, some points of interest were selected for the validation of results. These results are presented for areas with high sand concentration in **Figure 6** (>70% with field samples), as well as for areas with median concentration of sand (**Figure 7**). It was expected that areas with a higher concentration of the sand fraction in the topsoil would present lower NDVI and standard deviation values. This expectation was confirmed in the cases examined, because those areas with high concentrations of sand tend to be spectrally more stable over the years, resulting in a smaller variation in NDVI values and, therefore, their respective standard deviation (**Figure 8**). Thus, the patches with higher concentrations of sand are more isotropic in the images, due to the sparse or thin vegetation cover and the lower spectral influence of its seasonal response in the images.

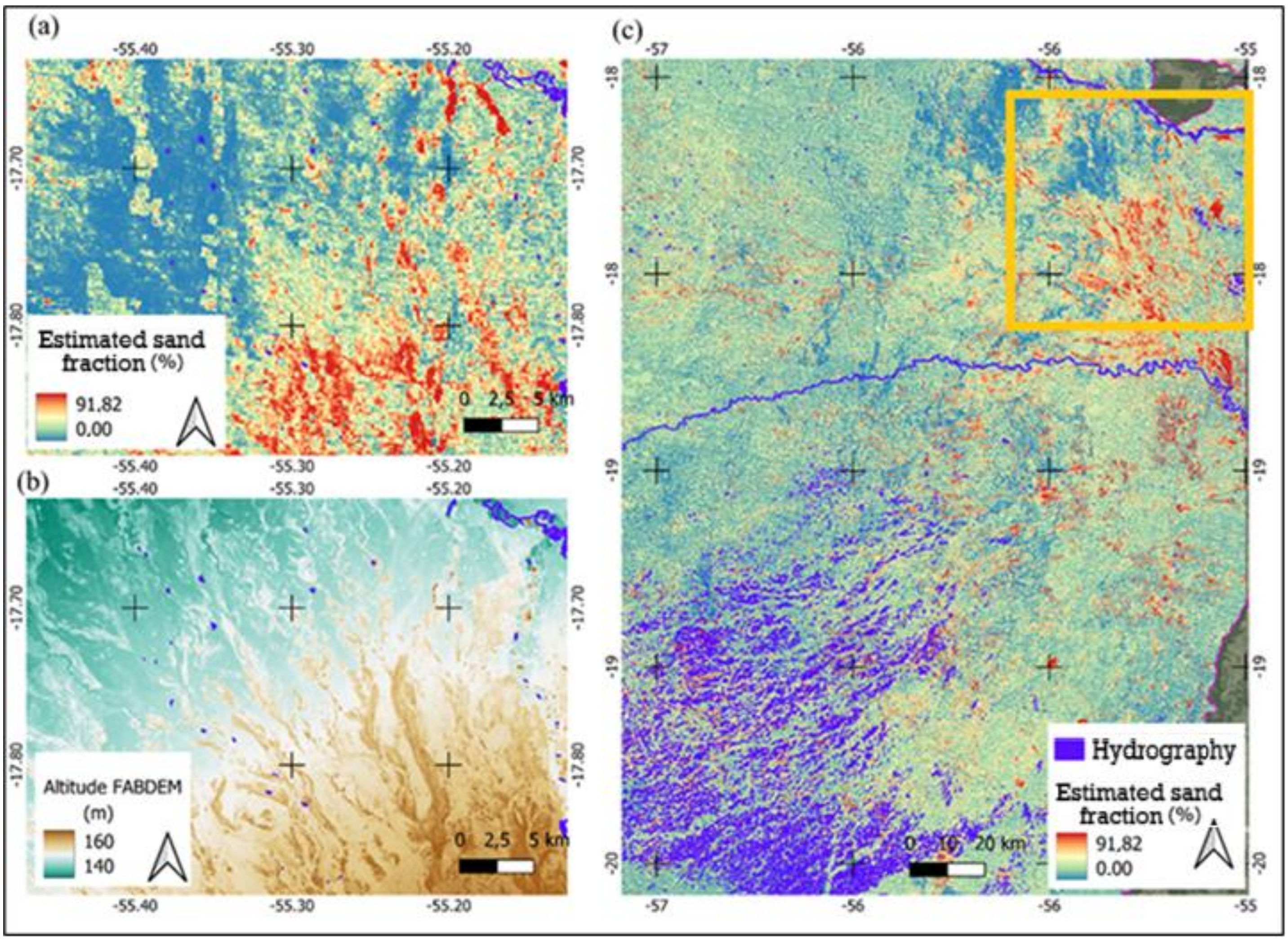

Figure 5 – (a) Comparison of the topsoil sand fraction estimation with data from (b) elevation of FABDEM model for the Pantanal Biome. (c) Overlay of drainage on the estimation of the sand fraction in the Pantanal. The yellow rectangle in Figure (c) indicates the approximate region highlighted in Figures (a) and (b).

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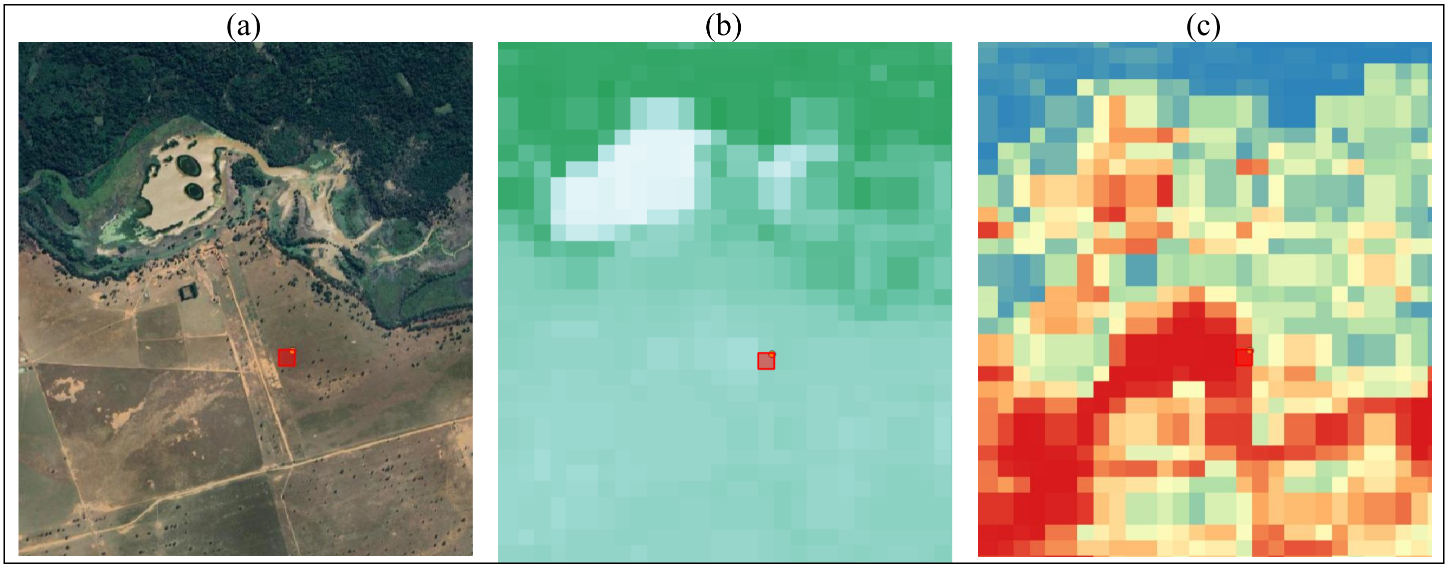

Figure 6 – Validation procedure based on field inspection of some samples, considering (a) the true color composition; (b) the average NDVI of the ASTER GED product and; (c) the estimation of the sand fraction for the same area. One pixel shows an estimated sand fraction of 86% against a value measured in a field sample of 71% in the topsoil. The NDVI corresponding to the pixel is 0.30.

Among the limitations of this study, the nine-year average of emissivity data used must be mentioned. Despite representing a long-standing pattern, this type of data does not allow the specific detection of land use/land cover patterns for each pixel for each acquisition date. Due to the limitations associated with the high cloud cover during the rainy season, data is frequently generated for the dry season. Furthermore, the dynamics of soil management is reflected in regular patterns of sand patches, which probably represents the region, but due to the temporal integration with the ASTER GED product, it is not possible to detect.

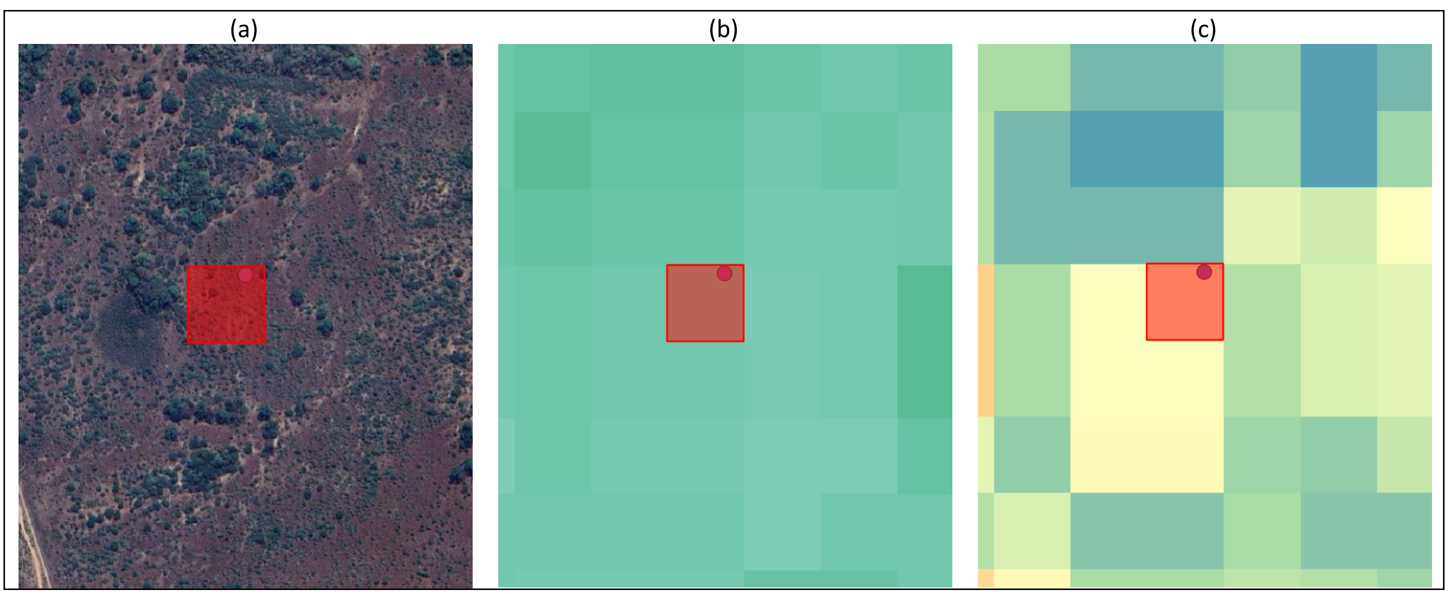

Figure 7 – Validation of the samples from the topsoil sand fraction with an average concentration of 44%, compared to the 40% value measured in field, with an average NDVI of 0.39, in a region with medium concentration of the sand fraction. The true color composite, the average NDVI of the ASTER GED product, and the estimated sand fraction are shown in (a), (b), and (c), respectively.

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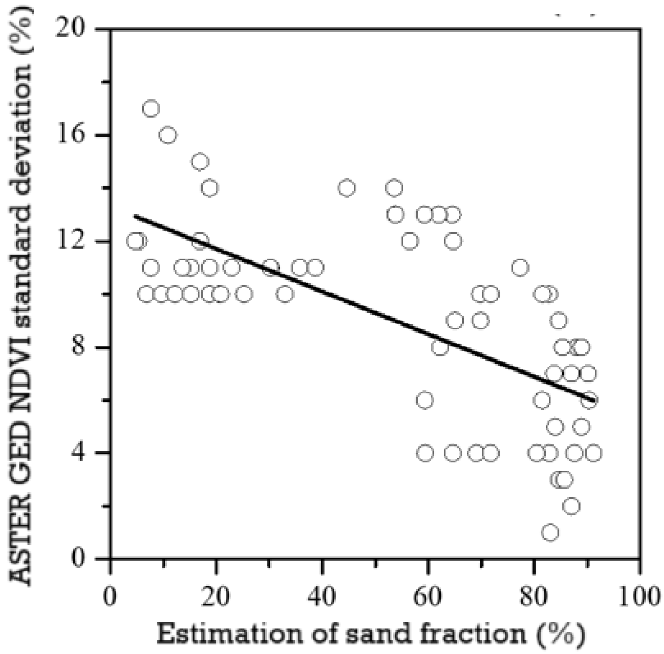

Figure 8 – Temporal variation of the NDVI standard deviation for areas of high, medium and low concentration of the estimated topsoil sand fraction, for some pixels in the study area.

IV. CONCLUSIONS

This study showed the potential on the use of ASTER GED emissivity data to estimate the topsoil sand fraction for the Pantanal Biome. The results indicate the occurrence of areas with higher sand concentration in the central, eastern and southern regions, coinciding with the regions with the highest elevation of the biome.

Those areas of estimated high sand fraction concentration show a seasonal pattern of lower NDVI variability, and a more isotropic emissivity. This result indicates an important potential for the utilization of these data to estimate the sand fraction of alluvial fans that are very common in this biome, and to evaluate the dynamics of sediment movement, as well as the risks of land degradation.

The results of this investigation were indirectly validated with field data available in the literature, high spatial resolution images of the visible spectral region and NDVI data. However, validations and cross-referencing of estimates with pedological data and field surveys should be further considered.

The use of TIR sensors, together with high-resolution images in the VNIR and SWIR ranges, is recommended for future studies. Among the data to be explored, those produced by missions such as ECOSTRESS, SDGSat-1 and Constellr have a strong potential for such works.

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