THE RELATIONSHIP BETWEEN LANDSLIDE OCCURRENCE AND LAND USE AND LAND COVER

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ABSTRACT

Landslides are widespread natural phenomena that may be triggered or intensified by human activities. In this context, this study aimed to analyse the relationship between land use and land cover (LULC) changes (LUCC) and landslides occurrence in *Petrópolis*, Brazil, using the Frequency Ratio (FR). We found 73 and 43 landslide scars in 2011 and 2022, respectively. In 2011, the most significant relationship was with non-forest natural formation, while in 2022, it was with the non-vegetated area. These results suggested that sparsely vegetated regions may reduce the soil shear strength. Finally, the LUCC analysis indicated that the conversion of forest areas was the most influential in the 2011 event, while the farming conversion into less vegetated areas presented greater FR values in 2022. Although this method presented relevant results, we suggest a deeper analysis of the relationship between LULC/LUCC and landslides, including understanding vegetation cover influence on soil structure.

Keywords — Slope stability, mass movement, LULC, land cover changes, frequency ratio.

1. INTRODUCTION

Landslides are natural geomorphological processes characterized by material displacement from slopes under gravity, which can be caused by earthquakes, snow melting, or intense precipitation [1]. Anthropic interventions, such as deforestation or slope cuts, may accelerate or increase landslide occurrences and/or intensity [2]. Furthermore, as human activities can change large areas quickly, this can weaken the soil shear strength, decreasing slope stability [3].

The anthropic activities impacts on slope stability may be evaluated through land use and land cover (LULC) data, representing both natural and anthropically changed Earth's surfaces. LULC and its changes (LUCC) impact hydrological processes and soil physical structure [4], contributing to landslide occurrence. For example, deforestation, road, or building construction may reduce slope stability [5] by decreasing soil root reinforcement, modifying soil moisture, or impacting surface water runoff [6].

In this sense, the main aim of this study was to analyse possible relationships between LULC, as well as LUCC, and landslide occurrence in the municipality of *Petrópolis*, in Rio de Janeiro state, Brazil. For that, we considered the landslide disasters that occurred in 2011 and 2022. In addition, we used LULC maps from Mapbiomas [7] to compose our LULC and LUCC data, and evaluated it using the Frequency Ratio (FR).

2. MATERIAL AND METHODS

2.1 Study Area

Petrópolis is a historical city in the *Serra do Mar*, *Rio de Janeiro* state, Brazil. The city was built in a mountainous relief in the XIX century and suffered an intense economic and population growth during the 1940s due to the Brazilian industrialization phase. *Petrópolis* presents a high Human Development Index (0.745), having one of the highest Gross Domestic Product (GDP) in the region [8].

Despite being a rich municipality, the rapid increase in population and the non-planned urbanization [9], exposed approximately 24% of the total population to landslides and floods. Since the municipality comprehends 307,144 inhabitants distributed over 791.14 km², near to 72,000 residents are exposed to these hazardous phenomena [10].

The area is prone to geo-hydrological hazards due to its geomorphological, geological, and pluviometric characteristics. The mountainous relief presents a significant influence on the rainfall spatial distribution, since *Serra do Mar* is one of the rainiest areas in the Brazilian Southeast region for being in the path of polar fronts and tropical squall lines [9].

Two extreme precipitation events caused disasters in *Petrópolis* in 2011 and 2022 (Figure 1). The worst disaster in Brazilian history occurred in January 2011, caused by a heavy rainfall events in Rio de Janeiro State mountainous region, affecting 23 municipalities [11] and represented a total of

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7,214 affected people, among displaced, homeless, and deaths [12]. In February 2022, occurred the deadliest landslide disaster registered in *Petrópolis*, which caused at least 231 fatalities [13]

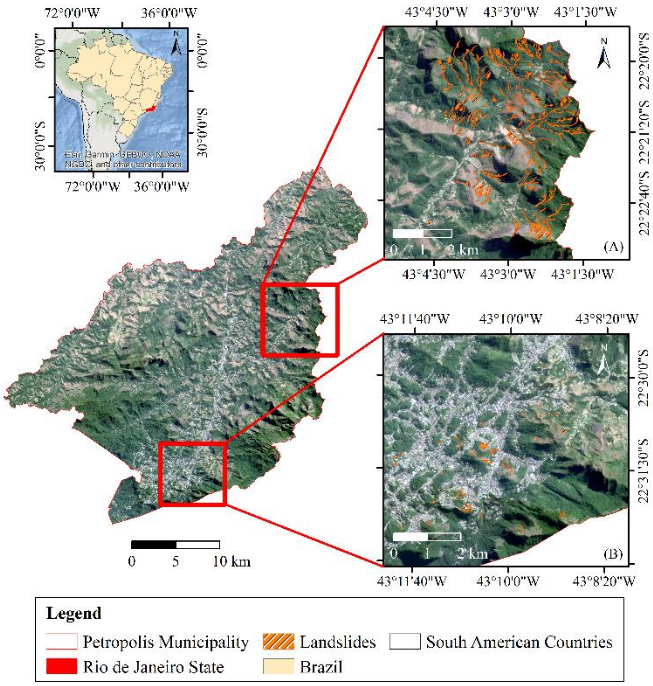

Figure 1 Study area location: A) landslide inventory regarding the 2011 landslide event; B) landslide inventory regarding the 2022 landslide event. The landslide inventories were generated by the authors for the present study.

2.2 Methods

This study was developed in three stages: i) LULC data acquisition; ii) 2011 and 2022 landslide inventory generation and data collection; iii) analysis of the relationship between LULC/LUCC and landslides through FR.

We obtained LULC data from the Mapbiomas project (https://mapbiomas.org/). The Mapbiomas provides LULC mapping from 1985 for the entire Brazilian territory, with 30m spatial resolution [7]. In this study, we used collection 7, which covers 1985 to 2021. This collection is composed of 36 classes, of which 11 were found in the study area and grouped into seven classes: i) forest (Ft): forest formation; ii) non-forest natural formation (NF): wetland, rocky outcrop, and hypersaline tidal flat; iii) farming (Fm): pasture, and mosaic of uses; iv) urban area (UA); v) non-vegetated area (NVA): mining, and other non-vegetated areas; vi) water (Wt): river, lake, and ocean; vii) silviculture (Sv): forest plantation. We used three dates to compare the LUCC: 1985, 2010, and 2021. We considered 1985 data since it is the first available LULC classification; the other two years are just before the recorded landslide events.

To analyse the LULC and LUCC classes present in the landslide-affected area, we generated the landslide inventories. The 2011 landslide inventory was generated using the Geo-Eye-1 satellite data (acquired on 20th January 2011) with the Object-oriented method (OOA). The 2022 landslide inventory was generated through visual interpretation and manual delimitation using high-resolution images [14]. For that, we used available images on Google Earth software and Planet imagery (www.planet.com), adquired on 5th August 2022, with 3m spatial resolution.

Considering that the 2011 and 2022 landslide events occurred in January and February, respectively, we analysed the LULC influence regarding data from the previous year (2010 and 2021). Furthermore, the LUCC was evaluated according to two periods: i) between 1985 and 2010; ii) between 2010 and 2021, i.e., the period between both landslide events.

Finally, we analysed the relationship between LULC and LUCC classes and landslide occurrence using the FR method [4]. The FR is a statistical approach used to identify the closeness of the relationship between landslides and landslide conditioning factors [15]. The higher the FR value, the greater the relationship between the LULC or LUCC class and the landslide occurrence. FR values less than one represent an irrelevant relationship and values greater than one represent a high probability of landslide occurrence [16].

$$FR = \frac{LA_i / A_i}{\sum LA_{total} / \sum A_{total}}$$

where FR represents the Frequency Ratio; LA indicates the landslide area in each LUCC class (i)*;* A_i *is the total area of class* i*;* A_{total} *represents the total area of Petrópolis.*

3. RESULTS

According to the Mapbiomas LULC maps, the study area is mainly composed of forest, farming, non-forest natural formation, and urban area (Figure 2). The other three classes (silviculture, non-vegetated area, and water) comprise together less than 1% of the total area in all analysed years.

In 1985, the study area was covered almost by Ft and Fm (93%), while the UA comprised only 7 km² (0.92%). The Ft area improved from 379 km² (48%) to 418 km² (53%) in 2010 and 429 km² (54%) in 2021. The increase in Ft area may be related to government reforestation programs [17]. Furthermore, there was an increase in UA, from 7 km² (0.92%) in 1985 to 25 km² (3%) in 2010 and to 30 km² (4%) in 2021, which reflects the rapid urbanization verified in Brazil.

Considering LUCC analysis, we found 29 classes between 1985 and 2010. In this first period, 87% of the study area presented no changes in LULC classes. The remaining area showed three main LUCC classes: i) 7% of the Fm area was converted into Ft; ii) 3% of Ft changed to Fm; iii) 2% of the Fm area has turned into UA. The second analysed period, between 2010 and 2021, presented 33 LUCC classes; however, most covered less than 1 km². During this period, 94% of the study area remained unchanged, which was expected since the first period covered 25 years while the second covered only 11 years. The largest LUCC class in this period was represented by the conversion of Fm to Ft area, covering 22 km² (3%).

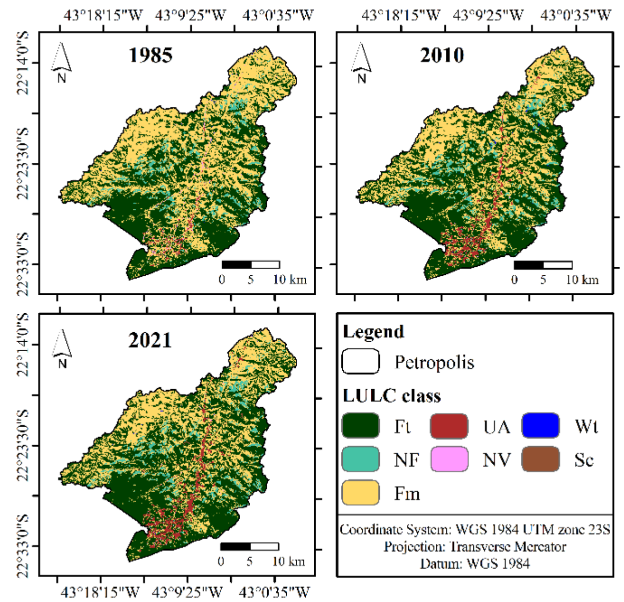

Figure 2 LULC maps for each analysed year: 1985 is the first LULC available, and 2010 and 2021 are the previous years of 2011 and 2022 landslide occurrence, respectively.

Subsequently, we generated landslide inventories for the 2011 and 2022 extreme events to compare the relationship between the two landslides occurrences and the LULC and LUCC classes. We found 73 landslide scars in the 2011 event, which covered 2.64 km². For the 2022 event, we found 43 landslide scars covering 0.4 km².

The relationship between landslide occurrence and LULC and LUCC classes was analysed according to each period. Among the 33 LULC classes, only five of them were found in landslide areas for the 2011 and 2022 events (Figure 3). The 2011 landslides presented the most significant relationship with NF areas, followed by Wt, Ft, and Sc. Fm class showed an irrelevant relationship with landslides this year since the FR value was less than one. The importance of Wt in landslide occurrence is related to LULC misclassification because some areas that presented shadow were classified as Wt. The 2022 landslides presented the greatest FR value for NVA, followed by NF, UA, and Fm. There was no relevant relationship between landslide occurrence and Ft areas. The influence of LULC classes in landslides explicit the different regions affected in each event: if, on the one hand, the 2011 event affected more vegetated areas in the Northern portion of *Petrópolis*, on the other hand, the 2022 event was concentrated in the Southern, reaching more urban areas.

The LUCC analysis evidenced 30 and 33 LUCC classes in the study area, considering the two analysed periods, respectively. Although only nine classes appeared in the 2011 landslides and eight in the 2022 inventory (Figure 4). Four LUCC classes presented a significant relationship with landslides between 1985 and 2010, being three of them related to the suppression of Ft areas, which were converted to Wt, Sc, and NF. In the second period, the most significant relationship was presented by the conversion of Fm into NVA, followed by Fm into NF, NF into Ft, NF into Fm, Fm into Ft, and Fm into UA. Areas with no changes in LULC presented no significant relationship with landslides in both events.

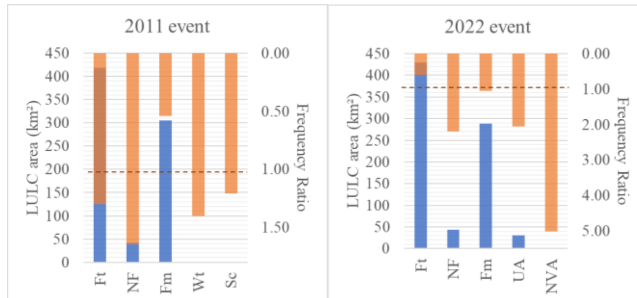

Figure 3 . Frequency Ratio of landslides for each LULC class.

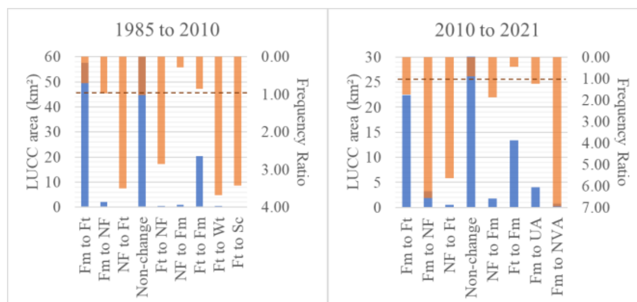

Figure 4 . Frequency Ratio of landslides for each LUCC class.

4. DISCUSSION

Understanding the impacts of LULC and LUCC on landslide occurrence remains a challenge. Different LULCs affect soil structure in many ways. For example, a developed forest may be better at improving slope stability through the root reinforcement mechanism than crop areas [18]. Furthermore, LUCCs are rapid processes that impact soil shear strength increasing slope instability and, in some cases, being a trigger for landslide occurrence [1]. In this sense, the free available LULC maps for different periods, such as the Mapbiomas Project [7], allow us to perform diverse analyses to understand this relationship.

In *Petrópolis*, we found different LULC classes related to landslide occurrence in different areas. In 2011, for example, the extreme precipitation was registered along the *Serrana* region due to the entrance of air masses from the Convergence Zone of the South Atlantic, reaching 273.8 mm in 24 h in *Petrópolis*, causing landslides in the Northern portion [12]. On the other hand, in the 2022 landslide disaster, the rainfall reached 258 mm in three hours, mainly in the

Southern region impacting the urban areas [13]. Moreover, we found the most significant relationship of 2011 landslides and NF areas; and the 2022 landslides with NVA, indicating that sparsely vegetated areas may reduce the soil shear strength [19].

The analysis of LUCC influence in the 2011 landslide event showed that most of the conversion of Ft areas impacted hillslopes [18]. Similarly, the 2022 landslides were more related to the conversion of Fm areas into less vegetated areas (NF, UA, and NVA). This LUCC influence may be related to the replacement of areas with good water management for areas without suitable management practices [20], as well as abandoned land crop areas [4].

Finally, the results indicate the need to analyse the effects of LULC on landslide susceptibility. It is noteworthy that landslides will not actually occur under the same conditions that occurred in the past because hillslopes have been undergoing drastic changes [21]. Moreover, understanding how LUCC influences the occurrence of landslides may aid local managers in improving territorial planning for disaster risk reduction.

5. CONCLUSIONS

This study explored the relationship between landslide occurrence and LULC and LUCC in *Petrópolis* municipality. The two landslide disasters presented spatio-temporal variation and showed that different LULC classes might influence landslide susceptibility. Moreover, we found that LUCC, mainly related to the conversion for sparsely vegetated areas, was more present in landslide areas, which may be related to a reduction of soil shear strength. For future studies, we suggest carrying out a broader analysis based on landslide susceptibility mappings to identify how LUCC may impact the susceptibility.

6. ACKNOWLEDGEMENTS

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