Inventory of Land Degradation Using Geoinformatics in Cachoeiras de Macacu's Municipality, Rio de Janeiro, Brazil

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Abstract: This study defines the procedures applied to integrate the Geomatic techniques to characterize the spatial distribution of water erosion at Cachoeiras de Macacu, Rio de Janiro, Brazil. Different images from Landsat8, Airbus on Google Earth Pro, and drone DJI Air 2S were used to investigate the dominant erosion processes and evaluation trends, identify the various types of the stable areas, and producing the descriptive land degradation and the conservation priority maps. 841.49 km² was characterized as stable areas, while 79.46 km² was considered as unstable areas in which sheet and rill erosion remain active. Furthermore, a procedure was identified to determine the priority areas for remedial measures. A total of 81.74 km² was categorized in the priority conservation class, while 21.50 km² was classified under the high-priority class. An additional 49.26 km² fell into the unstable medium-priority class, and 10.78 km² was designated as unstable low-priority. Besides, a land-use/landcover change detection process was done to investigate those changes using Landsat images, showed a significant increase (0.76%) in urbanization, increase (1.21%) in pasture area, but 2.21% decrease in mosaic land uses. Finally, a set of remedial measures were selected to be applied in the hot spot areas.

Key words: Remote Sensing, GIS, water erosion, land degradation, land-use change, Cachoeiras de Macacu.

Cachoeiras de Macacu is a municipality located in the state of Rio de Janeiro in Brazil at 22°27′46"S south latitude and 42°39′10" west longitude (Fig. 1). It has an area of 954.749 km², (IBGE, 2022). According to the IBGE 2022 Census, the current population of Cachoeiras de Macacu is 56,943 inhabitants marking a 4.66% increase since the previous census in 2010. This places it 35th in population size among the municipalities in Rio de Janeiro state. The Cachoeiras de Macacu present biome is the Atlantic Forest. The area is divided into two main regions, the northern region which has a mountainous characteristic and the southern region with lowland characteristics and form the productive agricultural area, which plays a crucial role in the agricultural production for Rio de Janeiro's state. Cachoeiras de Macacu agricultural lands are based mainly in Cassava, sweet potato, guava, corn and others.

In general, the prevailing geomorphological compartments consist of rugged mountainous terrains and plains, comprising 35.5% and 37.6% of the total basin area, respectively (Paes & Silva, 2017). The montane and submontane Ombrophilous are dense forests in the region, especially in the higher parts of the hills. These forest remnants are crucial for the conservation of the Atlantic Forest. Approximately 68% of the total area is coverage with this vegetation. The land use and vegetation cover quality index indicates the trend of urbanization in rural areas, increasing pressure on forest remnants. The IBGE agricultural census documented 238.3604 km² of agricultural land, diminishing to 219.19 km² by 2006, constituting an 8% loss in total area (Bicalho & Machado, 2013). Climate in the area is a tropical with an average annual precipitation for Cachoeiras de Macacu typically ranges between 2000 and 2500 mm per year. The main soil classes found were Red Latosols, Red Argisols, Red-Yellow Latosols, Yellow Latosols, Yellow Argisols, Haplic Cambisols, and Fluvic Neosols. (Loss *et al*., 2011).

The study area has an excellent agricultural condition and impressive floristic richness. Cachoeiras de Macacu has a great vegetation biodiversity, with forests in stages very close to climax conditions. However, as a result of inappropriate agricultural practices, urban expansion, and deforestation, water erosion is becoming a major problem in several areas. Moreover, large areas of the rolling hills and gentle mountain slopes have been turned into areas with light vegetation cover, unable to protect soil from water erosion and run off. Many recent studies highlight the role of modern geoinformatics in effective land management and reducing ecological impacts. For instance, Ganasri and Ramesh (2016) discuss how Geographic Information Systems (GIS) can be utilized to analyze soil erosion processes. Their research examines how soil erosion is influenced by factors like soil properties, climate, topography, and land cover, showing the critical role of GIS in understanding and mitigating these dynamics for sustainable land use. Borrelli *et al*. (2017), discussed the

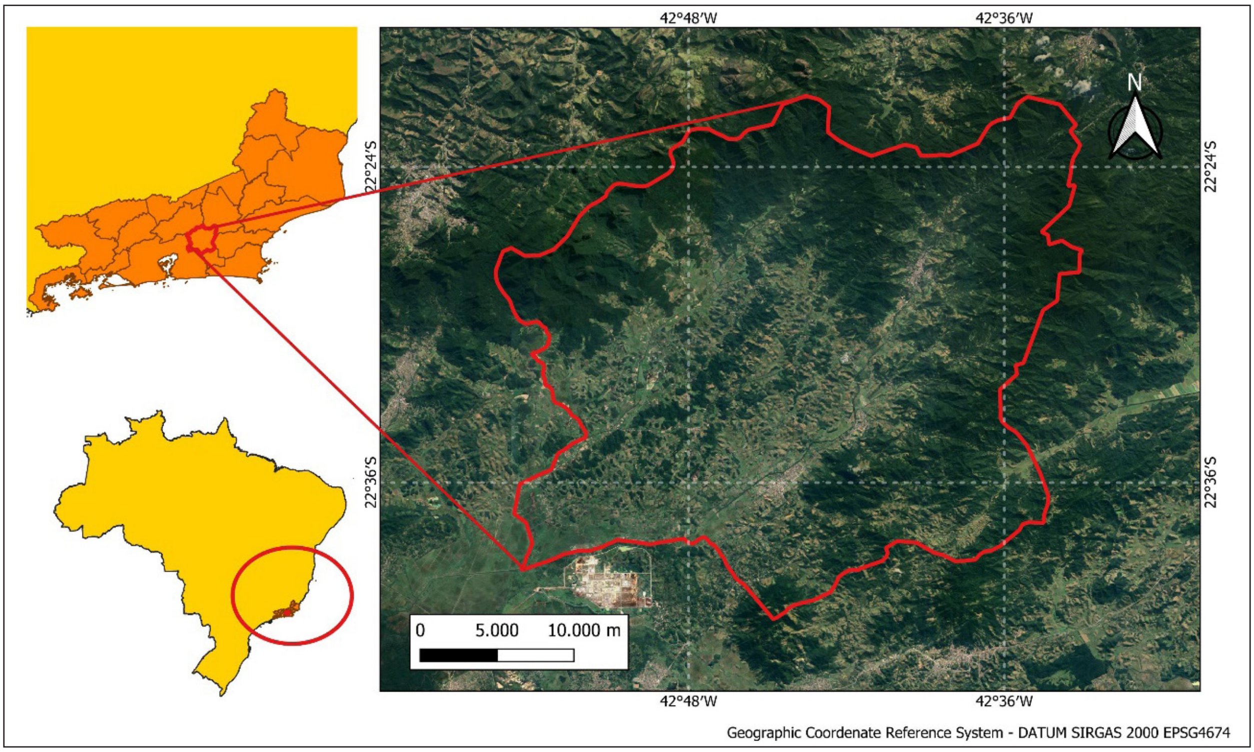

Fig. 1. Location map of Cachoeiras de Macacu municipality, Rio de Janeiro.

effects of land-use change on soil erosion and highlighted the importance of quantifying data through extrapolation. If soils are not properly protected and managed, soil erosion leads to a decrease in soil productivity in the short term and to a complete degradation of soils in the long term and can lead to catastrophic damage from runoff, landslides and mudslides caused by heavy rainfall. Therefore, an accurate prediction technology is needed to solve these problems and assess the extent and severity of soil erosion as well as to effectively develop and apply remote sensing and GIS for preserving farmland and forestland (Fernandez *et al*., 2003; UNEP, 2004; Gitas *et al*., 2009; Ganasri and Ramesh, 2016; Borrelli *et al*., 2017). These techniques have the ability to integrate data from different sources; satellite images, aerial images, topographic maps, thematic maps, reports, and field works in erosion mapping. Erosion mapping is a very essential tool for the assessment of the distribution and geographic extent of the phenomena, as well as for its qualitative characterization, and combating land degradation.

Materials and Methods

The current study applied image of Landsat 8 taken in August 2023, and image of Airbus 2024 on Google Earth Pro, as well as images form drone DJI Air 2S. The investigations of soil erosion in the Cachoeiras de Macacu were carried out using modern remote sensing techniques and modern methods of mapping erosion processes with the aid of GIS. Mapping of water erosion in the study area was carried out according to the methodology of the United Nation Environment Program (UNEP), Priority Actions Programme Regional Activity Centre (UNEP.MAP.PAP. 2000; PAP.RAC. 1997).

The method is based on elaboration of GIS in accordance with the criteria and standards for elaboration of the above-mentioned images and field observations, using ArcGIS, QGIS as well as ERDAS program packages. The descriptive approach consists of two procedures; images interpretation and field observation. The erosion process identification procedure divided the areas into stable areas or unstable areas. In general, field observations and erosion process identification procedures consist of two steps:

Step 1*:* For stable, non-erosion-affected areas, we identified the types and grades of erosion risks, along with the specific erosive agents involved. The procedure only applies to the stable areas which show very few or no evident sign of erosion, with well-developed top soil and good soil structure. Four main types of stable areas were identified based on land use, management practices, and erosion risk grade. Erosion risk was categorized on a scale from 0 to 3, with 0 indicating no risk (highest stability) and 3 representing critical risk (highest instability). In most cases, the primary causes of erosion risk were human activities and practices, indicated by an additional code (h) (UNEP. MAP. PAP. 2002).

Step 2*:* For unstable areas (erosion-affected areas), we identified the dominant types of erosion processes, their relative intensities, and their evolutionary trends. This procedure applies exclusively to areas affected by one or more erosion processes, with degradation levels ranging from slight to moderate to severe. Each specific process is assessed in relative terms of instability or spatial extent—categorized as localized, dominant, or generalized (UNEP. MAP. PAP. 2002).

Following the identification of stable and unstable areas within the Cachoeiras de Macacu perimeter, a prioritization procedure was developed on the descriptive erosion map to implement an effective land degradation control program. This process integrated 14 parameters derived from the descriptive mapping, alongside socio-economic factors exacerbating degradation, such as overexploitation, rural migration, and land tenure issues. Additionally, it considered both actual and potential land use values from multiple perspectives: local population perceptions, national policy directives, and assessments of suitability for forestry, agriculture, and other land uses. Each criterion was rated on a matrix from 1 (lowest score) to 3 (highest score) for these 14 parameters.

Results and Discussion

In total, about 950 sites have been described using Landsat8 image, Airbus 2024 on Google Earth pro, and drone DJI Air 2S. For each site we identified the type, grade of risk and causative agents for the stable area, as well as the type, grade of extent and expansion trend for unstable areas. Based on this description and investigation, the land degradation map

Table 1. Land degradation status and area calculation of Cachoeiras de Macacu

Area	Code	Area Type	Area (km²)	Area (%)	Area (Ha)
Stable areas	013h	Unmanaged areas with forest potential (01)	286.87	30.04	28686.80
	021h	Unmanaged areas with agriculture potential (02)	107.55	11.26	10754.87
	031h	Managed areas with forest use (03)	339.78	35.58	33978.33
	041h	Managed areas with agriculture use (04)	107.29	11.23	10729.10
	Total Stable		841.49	88.11	84149.1
	Urban	Resedential Area	34.08	3.56	3408.14
Unstable areas	L12	Localized sheet erosion (L1)	5.24	0.54	524.00
	L22	Dominant sheet erosion (L2)	36.94	3.86	3693.76
	L32	Generalized sheet erosion (L3)	27.47	2.87	2746.70
	D11	Localized rill erosion (D)	9.81	1.02	981.42
	Total Unstable		79.46	8.29	7945.88
	Total		955.03	99.96	95503.12

for Cachoeiras de Macacu was finalized, as shown in Fig. 2.

The map reveals that most areas within Cachoeiras de Macacu are stable, unaffected by active erosion, as shown in Table 1. According to the descriptive land degradation map, stable areas cover a total of 841.49 km², accounting for 88.11% of the study area. Human activities are identified as the primary causative agents of stability. Notably, the "Managed Areas with Forest Use (03)" class is the most prevalent type of stable area, comprising approximately 35.58% of the total area, primarily located in the northern and eastern regions. Meanwhile, unstable zones, where sheet and rill erosion are active, cover 79.46 km², representing 8.29% of the total area.

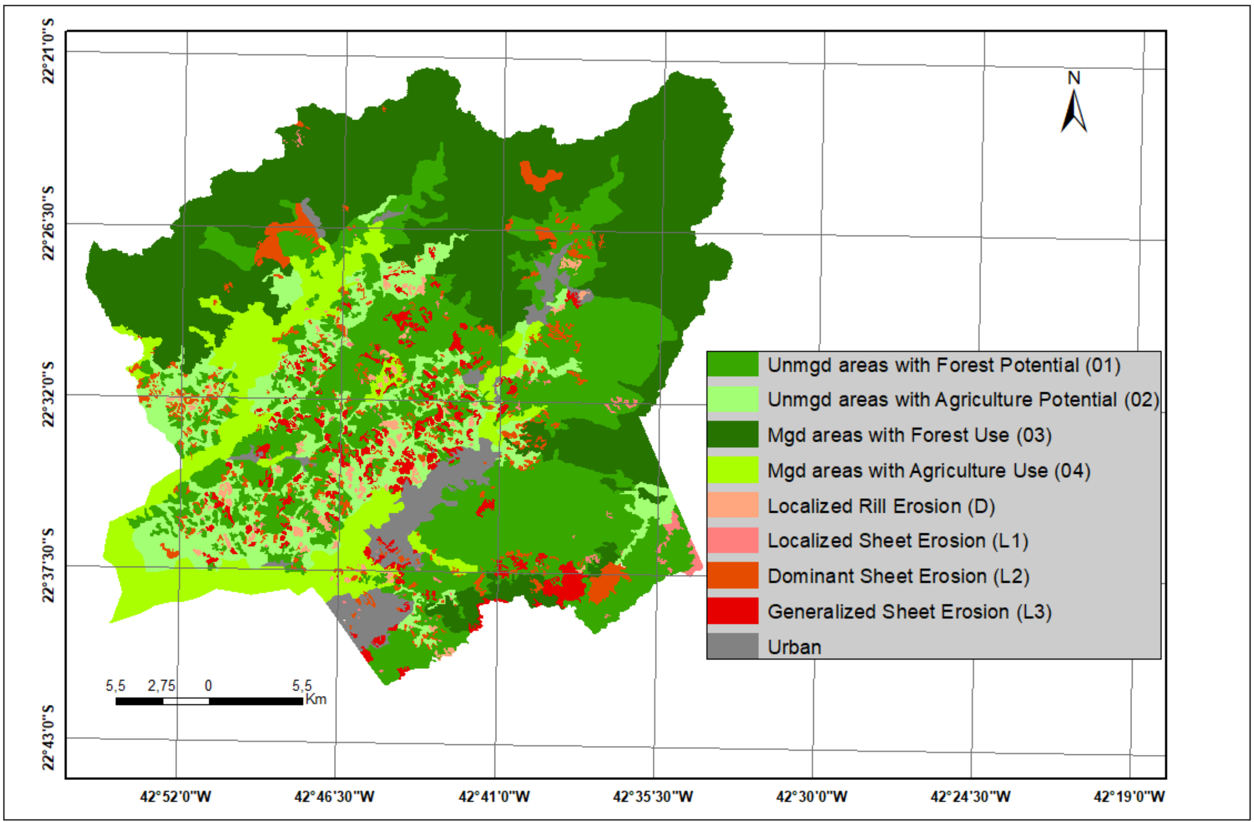

Fig. 2. The stable and unstable areas of Cachoeiras de Macacu map.

The Dominant sheet erosion (L2) class is the predominant form of unstable area; it covers about 36.94 km² and this form about 4% of the total area. In general, the main unstable areas mainly occur in southeaster parts of Cachoeiras de Macacu near Patis village, and along both sides of Rio Sao Joao. Furthermore, unstable areas also occur in the northwestern area to the west of Guapiacu village, as well as in many rolling hills in the center of the study area to the west of Japuiba town.

The results of this prioritization procedure presented in figure 3 which show the distribution of hot spots and where conservation priority classes over the study area. In addition, the priority classes with their areas were calculated in Table 2. The result of the assessment and related scores showed that the area of unstable environments in the study area which need priority in conservation form about 81.74 km²; where 21.50 km² fall into the high priority class, 49.26 km² classified as unstable medium priority class, and 10.78 km² as unstable low priority class.

For the unstable areas, the unstable high and medium priority areas in Cachoeiras de Macacu were identified as unstable areas showing active erosion processes mainly due to dominant sheet erosion (L22), generalized sheet erosion (L32), and dominant rill erosion (D23). While the low priority was identified as unstable areas due to the localized sheet (L11) and localized rill erosion (D11). In general, the main high hot spots mainly occur southeaster parts of Cachoeiras de Macacu along both sides of Rio Sao Joao, and to the west of Guapiaçu village in the northwestern area. These areas suffer from sheet and rill erosion

Table 2. Conservation priority classes with areas

Area type	Conservation priority	Area (km²)	Area (hec)
Stable Areas	Stable low priority	355.18	35518.12
	Stable medium priority	300.70	30069.81
	Stable high priority	184.97	18496.74
Unstable Areas	Unstable high priority	21.50	2149.68
	Unstable medium priority	49.46	4945.78
	Unstable low priority	10.78	1078.06
	Urban	32.54	3253.52
Total		955.12	95511.71

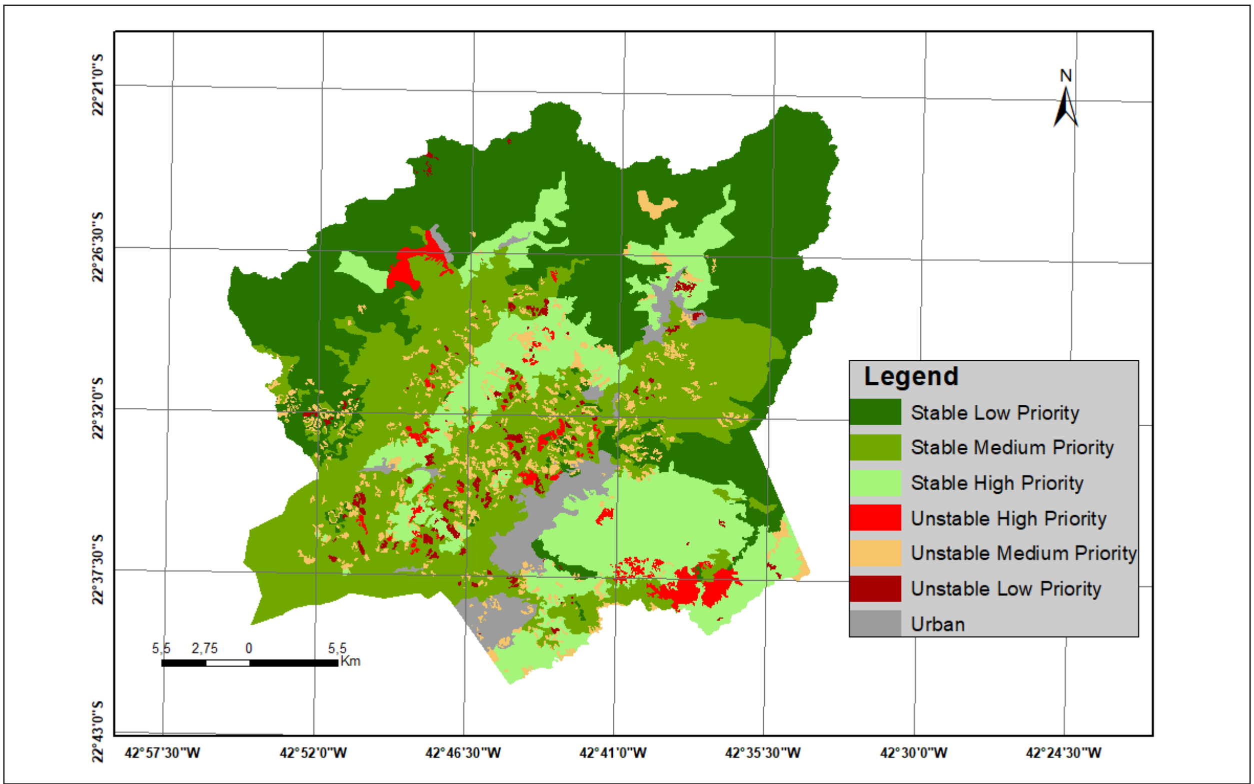

Fig. 3. Cachoeiras de Macacu conservation priority map.

due to deforestation activities on the hills and undulating mountains. Thus, these spots need the highest priority for remedial measures. For the main medium hot spots they spread over the southern parts near Derribada, the southwestern part to the south of Subaio town, where the dominant sheet and rill erosion processes are active. While, the low priority classes mainly located in the forestlands in the eastern and northern parts of the study area, as shown in (Fig. 3).

As for the stable areas, the result of the assessment showed that about 840.85 km² need priority in conservation; where 184.97 km² fall into the high priority class, 300.70 km² classified as unstable medium priority class, and 355.18 km² as unstable low priority class. The stable high and medium priority classes are adjacent to the unstable high priority classes, those areas suffer from instability risk due to human activities as deforestation and transforming forestlands to other uses. While the stable low priority class is dominant in the northern parts of the study area due to excellent spread of forestlands.

Impact of Land Use and Land Cover Changes on Soil Erosion

The resulted descriptive land degradation map and the conservation priority map showed the great influence of human activities on the spread of soil erosion. Therefore, a land-use/landcover change detection process was done based on the Brazilian MapBiomas methodology (MapBiomas 2023) to investigate those changes using Landsat images dated on 1985 and 2022 (Fig. 4). The methodology utilizes Landsat images with up to 30 m of spatial resolution. The MapBiomas databases was extracted using the script for Google Earth Engine, made available on the initiative website. Two Shapefile databases were then acquired for 1985 and 2022. Subsequently, for the percentage extraction of land use and land cover classes, the databases were clipped to the perimeter of Cachoeiras de Macacu, excluding classes outside this perimeter. The Plugin "r.report," provided by the native QGIS 3.34.1 add-on, GRASS 8.3.1, was then applied on the class occupancy per pixel, which was then converted to square meter areas. Finally, the data were processed in an Excel table to

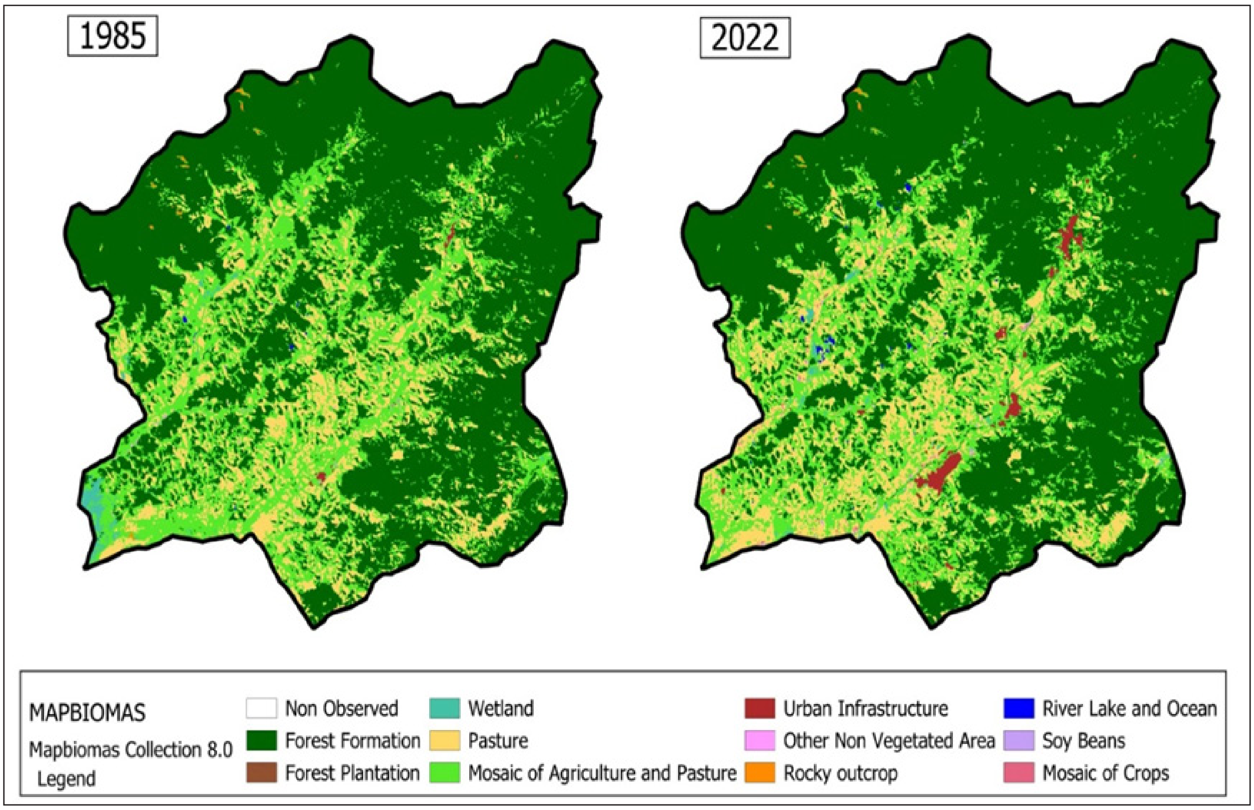

Fig. 4. Land-use/landcover changes (Mapbiomas Brazil 1985 and 2022).

Table 3. Land-use/landcover change detection between 1985 and 2022

ID	CLASS	1985 (km²)	2022 (km²)	Diference (km²)	Diference (%)
3	Forest formation	567.52	569.62	2.10	0.22
9	Forest plantation	0.00	0.01	0.01	0.00
11	Wetland	5.63	3.30	-2.32	-0.24
15	Pasture	129.67	141.17	11.50	1.21
21	Mosaic of uses*	247.37	226.28	-21.09	-2.21
24	Urban area	0.82	8.10	7.29	0.76
25	Other non-vegetaded areas	0.84	0.33	-0.50	-0.05
29	Rocky outcrop	1.07	0.90	-0.17	-0.02
33	River and lake	0.51	1.41	0.90	0.09
39	Soybean	0.00	1.02	1.02	0.11
41	Other Temporary Crops	0.00	1.27	1.27	0.13

*Mosaic of Uses: mixed arable land-use.

conduct a comparison of class changes within the study area (Table 3).

Table 3 demonstrates reliable results regarding class changes between the years 1985 and 2022. Significant increases can be observed, such as a 0.22% increase in forested areas, a 0.24% reduction in wetland areas, a 1.21% increase in pastures, and a significant 2.21% reduction in mosaic land uses, along with a 0.76% increase in urban areas.

Also indicates a loss of 0.05% Other non-vegetated areas, 0.02% loss for rocky outcrops, an increase of 0.09% for Rivers and Lake, an increase of 0.11% for soybean and 0.13% for other temporary crops. These results illustrate a significant loss and change of vegetative cover, primarily transforming into pasture and urban areas, which implies higher chances of erosion occurrence. (Aragão *et al*., 2000).

Management Recommendations for the Hot Spot Areas

After identifying the intervention areas and assigning priority levels, the next step was to select the appropriate remedial measures for each area. These steps are essential to any effective land degradation control program (UNEP, PAP.RAC, 2004). Accordingly, following the identification of intervention areas, a set of recommended remedial measures was selected for application in these areas, as summarized below

For stable areas, preventive measures should prioritize forest management and maintenance, terrace construction, contour tillage, anti-erosion structures (primarily check dams), and drainage control. Additionally, measures should include land consolidation on areas with active erosion processes to reduce disturbance in highly vulnerable zones. Curative actions in stable areas should focus on educating rural communities about the importance of forest and land management and implementing restoration projects.

For unstable areas, curative measures should concentrate on building water outlets, providing financial aid and training to rural communities, and implementing reforestation and forest management activities. Protective measures for these areas should also include educating local communities on forest and land management's significance and supporting reclamation projects.

Conclusion

The study has shown that the soils of Cachoeiras de Macacu suffer from sheet and rill erosion, covering more than 80 km², and that remedial measures to combat soil degradation must be given medium to high priority on about 70 km² of the area. If the soils in Cachoeiras de Macacu are not adequately protected and managed, soil erosion leads to a decline in soil productivity and can cause catastrophic damage to life and property through runoff, landslides and mudslides.

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