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Articles

Mapping of environmental fragility in Atlantic Forest protected areas through multicriteria analysis

Mapeamento de fragilidade ambiental em unidades de conservação da Mata Atlântica por meio de análise multicritério

Marcello Pinto de Almeida[I]
Gumercindo Souza Lima[I]
Sabrina Lourdes Pereira de Cristo[I]
Camila Nascimento Neves[I]
José Cola Zanuncio[I]
Ludimila Grechi Campostrini[I]
Marcos Vinícius Ribeiro de Castro Simão[II,III]

[I]Federal University of Viçosa, Viçosa, MG, Brazil
[II]Federal Institute of Education, Science and Technology of Amazonas, Tefé, AM, Brazil
[III]University of Lleida, National Institute of Physical Education of Catalonia, Spain

ABSTRACT

The zoning of protected areas reduces the environmental impacts caused by the recreational use of such locations. Thus, this study aims to develop a predictive model of environmental fragility to support ecotourism planning. A Geographic Information System were used to produce thematic maps of the slope, soil type, precipitation, flow accumulation, and land cover, which were then overlaid to generate the environmental fragility map. The results showed that 73.6% of the Serra Negra da Mantiqueira State Park and 72.7% of the Serra Negra Private Reserve lie within the moderate fragility class, followed by the high (19.3% and 18.6%), very high (5.5% and 6.4%), and low (1.7% and 2.3%) fragility classes, respectively. The long-distance trail that follows the crest of the Serra Negra traverses the territory of the park and the private reserve, showing predominantly moderate (47.5%) to high (41.5%) fragility. The resulting cartographic product allows the definition of new trails, reducing the environmental fragility of the routes, and can be replicated in other protected areas.

Keywords: AHP; Ecotourism; GIS; State park; Trail planning

RESUMO

O zoneamento de unidades de conservação reduz os impactos ambientais causados pelo uso recreativo desses locais. Assim, este estudo tem como objetivo desenvolver um modelo preditivo de fragilidade ambiental para apoiar o planejamento do ecoturismo. Um Sistema de Informação Geográfica foi utilizado para produzir mapas temáticos de declividade, tipo de solo, precipitação, fluxo acumulado e cobertura do solo, que foram então sobrepostos para gerar o mapa de fragilidade ambiental. Os resultados mostraram que 73,6% do Parque Estadual Serra Negra da Mantiqueira e 72,7% da Reserva Particular do Patrimônio Natural Fazenda Serra Negra encontram-se na classe de fragilidade moderada, seguida pelas classes de fragilidade alta (19,3% e 18,6%), muito alta (5,5% e 6,4%) e baixa (1,7% e 2,3%), respectivamente. A trilha de longo curso que se desenvolve na crista da Serra Negra perpassa o território do parque e da reserva particular, apresentando fragilidade, predominantemente, moderada (47,5%) a alta (41,5%). O produto cartográfico resultante permite a definição de novas trilhas, reduzindo a fragilidade ambiental dos percursos, e pode ser replicado em outras unidades de conservação.

Palavras-chave: AHP; Ecoturismo; SIG; Parque estadual; Planejamento de trilha

1 INTRODUCTION

The response of natural environments to disturbance is influenced by the vegetation present and physical attributes such as relief, soil type, and climate (Adami; Coelho; Chiba; Moraes, 2012). Predictive models of environmental fragility render it possible to define zoning and set rules that can guide the management of protected areas and maintain the environmental balance (Carvalho; Silva; Salvio, 2022). The design of tools for environmental zoning is therefore a priority for the preservation of natural resources (Manfré; Silva; Urban; Rodgers, 2013).

Protected areas are usually established in areas of high biodiversity (Coetzee; Gaston; Chown, 2014), requiring the reconciliation of conservation with the negative environmental impacts of tourism (Pickering; Rossi; Hernando; Barros, 2018). This is crucial especially for trails, which are the most important infrastructures that are open to visitors in parks and other protected areas (Tomczyk; Ewertowski, 2013).

The intensity of negative impacts on trails varies according to factors such as vegetation, relief, soil type, climate, and the recreational use of trails, including the type of use and the number and behavior of visitors (Pickering, 2010). The removal of vegetation renders trails more prone to erosion due to increased runoff and the transport of soil particles (Rangel; Jorge; Guerra; Fullen, 2019).

Mapping environmental fragility enables the appropriate use of the financial resources allocated to trail management (Tomczyk, 2011) as the cost of recovering degraded trails is much higher than that of periodic maintenance (Tomczyk; White; Ewertowski, 2016). Therefore, trail planning is the most effective way to reduce such environmental impacts (Hawes; Dixon, 2014).

The use of predictive models to determine which stretches of a trail are most prone to degradation provides useful information for their management and indicates the necessary management actions in each situation (Tomczyk, 2011). The management of trails in protected areas includes the planning, construction, maintenance, and repair of routes while also establishing the adequacy of the use and the number of visitors (Tomczyk; Ewertowski; White; Kasprzak, 2017).

The use of geographic information systems (GIS) in environmental studies has increased due to its versatility (Adami; Coelho; Chiba; Moraes, 2012) and has led to the incorporation of this technology into tourism planning, thus assisting in understanding the impacts that tourism has on the environment (Tomczyk, 2011).

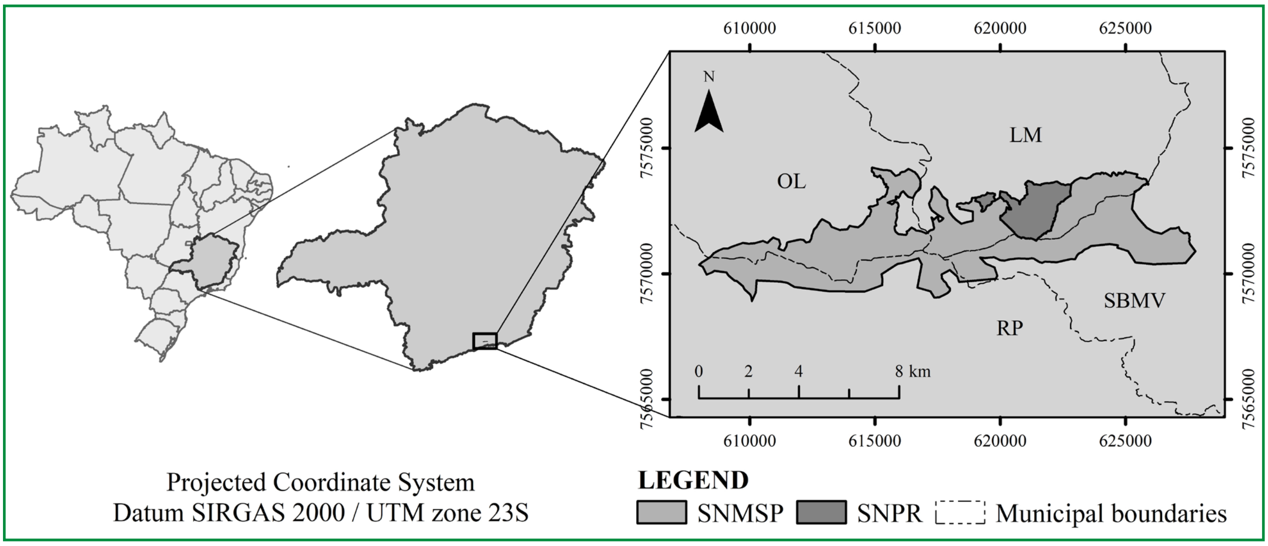
The Serra Negra da Mantiqueira State Park (SNMSP) and the Fazenda Serra Negra Private Natural Heritage Reserve (hereinafter referred to as the Serra Negra Private Reserve – SNPR) are located in a priority area for conservation in the state of Minas Gerais, Brazil, due to its high biological importance, and also in the Atlantic Forest biome, a global biodiversity hotspot (Myers; Mittermeier; Mittermeier; Fonseca; Kent, 2000). The main objective of this study was to develop a predictive model of the environmental fragility for the SNMSP and SNPR that is replicable in other protected areas (PAs).

2 MATERIALS AND METHODS

2.1 Study area

The Serra Negra da Mantiqueira State Park (SNMSP), created by State Decree No. 301 on July 4, 2018 (Minas Gerais, 2018), is one of the most recently established parks in the state of Minas Gerais in Brazil and has no zoning. The park covers an area of 4203.96 hectares, with 23.4%, 27.8%, 20.4%, and 28.4% lying in the municipalities of Lima Duarte, Olaria, Rio Preto, and Santa Bárbara do Monte Verde, respectively. The SNPR, established by IEF Ordinance No. 109 on June 5, 2009, covers 434.65 hectares, contiguous to the SNMSP (Figure 1).

Figure 1 – Location and distribution of the Serra Negra Private Reserve (SNPR) and the Serra Negra da Mantiqueira State Park (SNMSP) over the municipalities of Lima Duarte (LD), Olaria (OL), Rio Preto (RP), and Santa Bárbara do Monte Verde (SBMV) in Minas Gerais, Brazil



Source: Authors (2023)

The climate of the study area is Cwb according to the Köppen-Geiger climate classification, which is warm temperate with well-defined seasons (dry winter and rainy summer) (Alvares; Stape; Sentelhas; Gonçalves; Sparovek, 2013). The altitude varies between 845 and 1630 m, although approximately 95% of both PAs lie above 1000 m.

The geomorphological unit that encompasses the study area is known as Serras do Ibitipoca (SIb), a sub-unit of the Serra da Mantiqueira complex (IBGE, 2018). The SIb comprises two soil classes, Cambisols and Litholic Neosols (UFV; CETEC; UFLA; FEAM, 2010), extending around Serra Negra.

The vegetation types of the Atlantic Forest biome that occur within the boundaries of these PAs are: Semideciduous Seasonal Forest (SSF), predominantly, and High-Montane Dense Ombrophilous Forest (HMDOF), thus constituting a vegetation transition zone (IBGE, 2018). The first is characterized by the presence of deciduous trees, in the proportion of 20 to 50% of the forest, which lose their leaves in the dry season, lasting four to six months a year. SSF can be found between 500 and 1,500 meters of altitude. The second vegetation type is an evergreen forest, i.e. its trees retain their foliage all year round. HMDOF occurs at higher altitudes, generally above 1,500 meters (IBGE, 2012).

2.2 Analyzed factors

The proposed model followed three basic premises: (i) selecting factors that have been used previously in the literature; (ii) the use of freely available and easily obtainable data as input; and (iii) applicability in other protected areas, especially those located in the Atlantic Forest biome.

The data were processed and analyzed with version 10.5 of the ArcGIS Desktop software (Esri, 2021). The information plans (IP) were prepared in the raster format and reclassified to a standardized scale (1 to 5), enabling the use of map algebra. The slope, soil type, precipitation, flow accumulation, and land cover were analyzed.

2.2.1 Slope

Slope data were obtained from the Digital Elevation Model (DEM) at a spatial resolution of 12.5 m that was provided by the ALOS satellite (PALSAR sensor), which is available from the Alaska Satellite Facility website (https://search.asf.alaska.edu).

A Hydrologically Consistent Digital Elevation Model (HCDEM) was generated by removing spurious depressions in the DEM. The slope map was obtained from the HCDEM with the Slope tool. The classification adopted was based on the intervals proposed by Santos, Jacomine, Anjos, Oliveira, Lumbreras, Coelho, Almeida, Araújo-Filho, Oliveira and Cunha (2018) (Table 1).

Table 1 – Slope, soil type, precipitation, flow accumulation, and land cover classes with the associated degrees of environmental fragility (DEF)

Factor	Classes	DEF
Slope (%)	0 – 3.00	1
	3.01 – 8.00	2
	8.01 – 20.00	3
	20.01 – 45.00	4
	> 45.00	5
Soil type	Latosols	1
	Nitosols; Luvisols	2
	Podzols; Planosols	3
	Cambisols	4
	Plinthosols; Litholic Soils	5
Precipitation	~ 1000 mm annually, no dry months	1
	~ 2000 mm annually, no dry months	2
	1300 to 1600 mm annually, 2 to 3 dry months, heavy summer rainfall	3
	1600 to 1800 mm annually, 3 to 6 dry months, concentrated rainfall in summer (70 to 80 % of total)	4
	> 2500 mm annually, no dry months or < 900 mm annually (semiarid), with dry months and heavy rainfall	5
Flow accumulation (pixels)	0 – 30	1
	31 – 100	2
	101 – 300	3
	301 – 500	4
	> 500	5
Land cover	Forest formation	1
	–	2
	–	3
	Rupestrian grassland	4
	Rocky outcrop; other non-vegetated areas	5

Source: Authors (2023)

2.2.2 Soil type

The soil map of Minas Gerais, produced on a scale of 1:650,000 by the State Foundation of the Environment (FEAM) and its partners (UFV; CETEC; UFLA; FEAM, 2010), was obtained in vector format from IDE-Sisema (https://idesisema.meioambiente.mg.gov.br). The degrees of fragility for each soil type were defined in accordance with the classification proposed by Crepani, Medeiros, Hernandez-Filho, Florenzano, Duarte and Barbosa (2001) (Table 1).

2.2.3 Precipitation

The precipitation data were obtained from the average annual isohyets from 1977 to 2006, which are available in vector format on the Geological Service of Brazil (CPRM) website (https://www.sgb.gov.br). A constant value of 4 (high fragility) was assigned to the study area in this information plan, based on the criteria proposed by Ross (2012) (Table 1). This procedure is justified by the disposition of the mountain range in which both PAs are located, which favors the occurrence of orographic rains with relatively uniform precipitation (Valle; Francelino; Pinheiro, 2016).

2.2.4 Flow accumulation

The accumulated flow data were obtained from the previously created HCDEM. The preferential path for rainfall runoff was determined with the Flow Direction tool followed by Flow Accumulation to obtain the flow accumulation map. The value associated with each cell (pixel) of this IP corresponds to the number of upstream cells that converge the runoff to this particular pixel. The intervals adopted for the classification of this thematic map were empirically proposed based on the visual analysis of the associated histogram (Table 1).

2.2.5 Land cover

The land cover was determined via the supervised classification of a Sentinel-2 satellite image with the Maximum Likelihood Classification method, which is the most widely used technique for this purpose (Moiane; Machado, 2019). The satellite image (captured on June 2020) was obtained from the United States Geological Survey (USGS) website (https://earthexplorer.usgs.gov), with a spatial resolution of 10 m that covers the red, green, blue (RGB), and near-infrared bands. The classes chosen for mapping were forest formation, rupestrian grassland, rocky outcrop, and other non-vegetated areas, along with their respective degrees of fragility according to Ross (2012) and Crepani, Medeiros, Hernandez-Filho, Florenzano, Duarte and Barbosa (2001) (Table 1). The accuracy of the supervised classification was evaluated at 0.73 using the Kappa Index, which indicates the good performance of the image classification (Landis; Koch, 1977).

2.3 Map algebra

The environmental fragility map was produced by superimposing the information plans describing the slope, soil type, precipitation, flow accumulation, and land cover. Each IP corresponds to a thematic map in the raster format, with each pixel representing a value from 1 to 5 that indicates very low to very high fragility. The pixel-to-pixel overlap between layers was obtained by aligning the maps with a reference image.

The weights of each IP were defined using the Analytic Hierarchy Process (AHP) method (adapted from Saaty, 1987) before the map algebra was executed. The scale of values (weights) proposed by Saaty (1987) ranges from 1 to 9. In this study, the values adopted included 1, 3 and 5 (Table 2). The contribution of each factor to the erosive processes was determined by comparing the factors in a paired comparison matrix. This matrix was filled out according to the relative importance of each pair of factors and their corresponding values (Table 2). The value assigned to each pair of factors, i.e., each cell in the matrix, was based on the literature that describes erosive processes.

Table 2 – Relative importance of pair of factors and their respective values used in the paired comparison matrix (adapted from Saaty, 1987)

Relative importance	Value
Significantly more important	5
Moderately more important	3
Equally important	1
Moderately less important	1/3
Significantly less important	1/5

Source: Authors (2023)

The paired comparison matrix was filled out following two basic principles: (i) if the comparison of factor *a* with factor *b* produces the value *x*, then comparing factor *b* to factor *a* will produce the inverse, i.e., 1/x; and (ii) any factor that is compared with itself produces a value of 1 (Table 3). The weights of the factors and the consistency ratio (CR) of the matrix were calculated using version 11.1 of the Expert Choice software (Expert Choice Inc., 2021).

Table 3 – Paired comparison matrix and weights obtained for slope (SL), soil type (ST), precipitation (P), flow accumulation (FA), and land cover (LC)

Factor	SL	ST	P	FA	LC	Weights
Slope (SL)	1	3	4	2	1	0.306
Soil type (ST)	1/3	1	2	1/2	1/4	0.100
Precipitation (P)	1/4	1/2	1	1/3	1/5	0.063
Flow accumulation (FA)	1/2	2	3	1	1/3	0.164
Land cover (LC)	1	4	5	3	1	0.367

Source: Authors (2023)

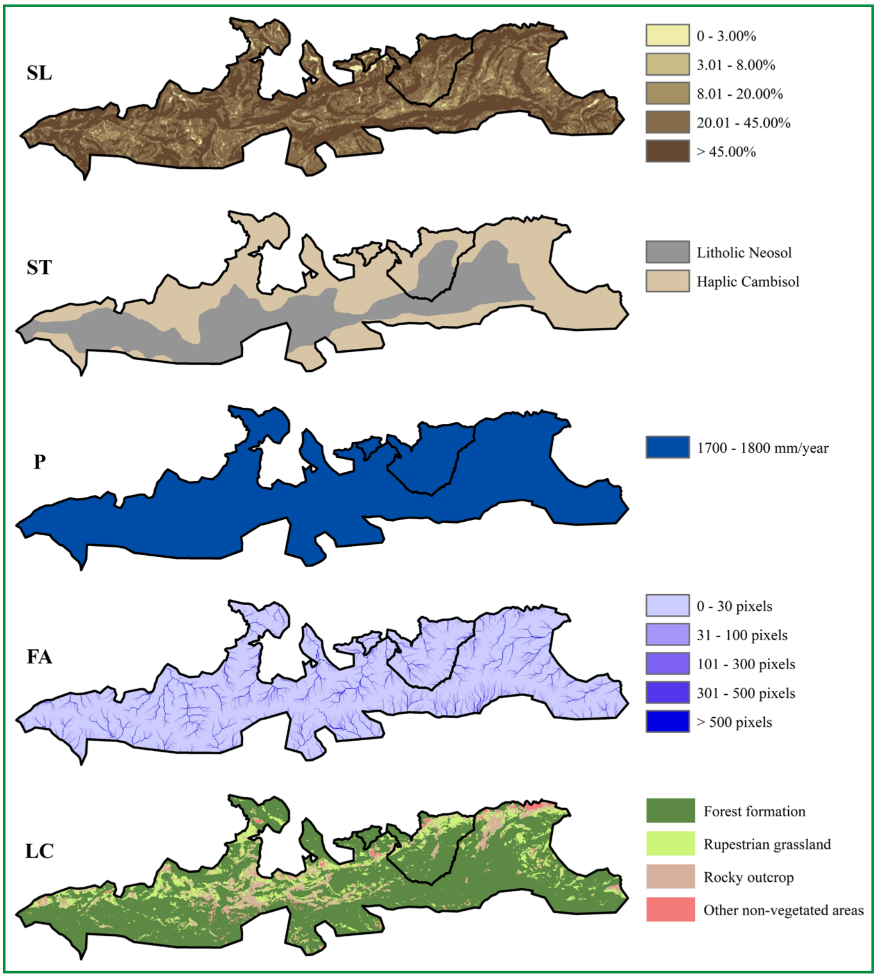
The calculated CR of 0.0137 was considered satisfactory as it is below 0.1 and indicates that the obtained weights are consistent. Map algebra was performed using the Raster Calculator tool, resulting in an environmental fragility map with a spatial resolution of 12.5 m.

3 RESULTS AND DISCUSSIONS

3.1 Analyzed factors

The slope is greater than 20% in 86.44% of the park and 84.11% of the private reserve (Table 4; Figure 2). Such inclination (> 20%) is a characteristic of strongly wavy to hilly or steep terrains (Santos; Jacomine; Anjos; Oliveira; Lumbreras; Coelho; Almeida; Araújo-Filho; Oliveira; Cunha, 2018), typical of parks in the Atlantic Forest because of their location in mountainous regions, which are inappropriate for agricultural practices (Moraes; Mello; Toppa, 2017; Silva; Millington; Moran; Batistella; Liu, 2020). The rugged terrain exposes mountainous areas to erosive processes, which are aggravated by surface runoff, thus increasing the environmental fragility (Almeida; Lima; Martins; Bontempo, 2019).

Figure 2 – Slope maps (SL), soil type (ST), precipitation (P), flow accumulation (FA), and land cover (LC)



Source: Authors (2023)

Table 4 – Areas per class of slope, soil type, precipitation, flow accumulation, and land cover in the Serra Negra da Mantiqueira State Park and the Serra Negra Private Reserve, Minas Gerais, Brazil

Factor	Classes	SNMSP		SNPR	
		Area (ha)	**Area (%)**	**Area (ha)**	**Area (%)**
Slope (%)	0 – 3.00	41.66	0.99	5.08	1.17
	3.01 – 8.00	63.84	1.52	8.75	2.01
	8.01 – 20.00	464.36	11.05	55.31	12.71
	20.01 – 45.00	2015.38	47.94	196.06	45.06
	> 45.00	1618.72	38.50	169.94	39.05
Soil type	Litholic Neosol	1744.88	41.51	187.91	43.18
	Haplic Cambisol	2459.08	58.49	247.30	56.82
Precipitation (mm/year)	1700 – 1800	4203.96	100.00	434.65	100.00
Flow accumulation (pixels)	0 – 30	3725.25	88.61	0.00	0.00
	31 – 100	283.66	6.75	9.88	2.27
	101 – 300	93.41	2.22	316.45	72.72
	301 – 500	26.05	0.62	81.13	18.65
	> 500	75.59	1.80	27.69	6.36
Land cover	Forest	3207.82	76.30	330.27	75.88
	Grassland	567.84	13.51	68.97	15.85
	Rocky outcrop	356.32	8.48	31.56	7.25
	Other non-vegetated areas	71.98	1.71	4.44	1.02

Source: Authors (2023)

The soils found at altitudes above 1200 m are Litholic Neosols, while Haplic Cambisol occurs between 860 and 1380 m (Table 4; Figure 2). The presence of Litholic Neosols only above 1200 m is a common feature because they occur at the interface with rocky outcrops (Santos; Jacomine; Anjos; Oliveira; Lumbreras; Coelho; Almeida; Araújo-Filho; Oliveira; Cunha, 2018). The texture of these soils, which are sandy to slightly stony, increases their erodibility and explains their low capacity for water retention (Alho; Júnior; Campos, 2007). Haplic Cambisols are soils in early stages of pedogenesis, with an incipient B horizon and a medium, clayey texture (Santos; Jacomine; Anjos; Oliveira; Lumbreras; Coelho; Almeida; Araújo-Filho; Oliveira; Cunha, 2018). They occur on strongly wavy to mountainous terrains, contributing to the constant rejuvenation of this type of soil (Dortzbach; Pereira; Anjos; Fontana; Silva-Neto, 2016).

The annual precipitation ranges from 1700 to 1800 mm (Table 4; Figure 2), which is one of the highest precipitation rates in the state of Minas Gerais. The critical period is from November to January, during which approximately 50% of the annual precipitation occurs (CPRM, 2011). The rainfall is predominantly orographic as a result of the east-west arrangement of the mountain range in which both PAs are located (Valle; Francelino; Pinheiro, 2016). The erosive potential of rainfall in tropical regions is high (Panagos; Borrelli; Meusburger; Yu; Klik; Lim; Yang; Ni; Miao; Chattopadhyay; Sadeghi; Hazbavi; Zabihi; Larionov; Krasnov; Garobets; Levi; Erpul; Birkel; Hoyos; Naipal; Oliveira; Bonilla; Meddi; Nel; Dashti; Boni; Diodato; Van Oost; Nearing; Ballabio, 2017), but varies with the slope and the vegetation cover (Halecki; Kruk; Ryczek, 2018). Vegetation reduces soil loss by intercepting some of the rain, thus increasing infiltration and the stability of the soil through the presence of roots (Zhang; Yu; Li; Li, 2014).

The flow accumulation was higher on the northern aspect of the mountain range (Serra Negra), with the maximum value observed in the São João River (Figure 2) due to a larger drainage basin. The soils in the study area (Haplic Cambisol and Litholic Neosol) are shallow (Santos; Jacomine; Anjos; Oliveira; Lumbreras; Coelho; Almeida; Araújo-Filho; Oliveira; Cunha, 2018), and the terrain is steep, favoring surface runoff, which in turn potentializes erosion. Watercourse banks are critical areas, as they concentrate the largest amount of surface runoff (Silva; Silva; Owens; Curi; Oliveira; Candido, 2016). The detachment and transport of soil particles into the watercourses contributes to their degradation (Karamage; Shao; Chen; Ndayisaba; Nahayo; Kayiranga; Omifolaji; Lui; Zhang, 2016), and riparian vegetation is essential to mitigate these impacts (Saad; Silva; Silva; Guimarães; Sousa-Júnior; Figueiredo; Rocha, 2018).

Forest formation and rupestrian grassland corresponds to 76.30% and 13.51% of the SNMSP area, respectively, while the remaining 10.19% is composed of rocky outcrops and other non-vegetated areas. In SNPR, these percentages are 75.88%, 15.85%, and 8.27%, respectively (Table 4; Figure 2). The predominance of the forest vegetation indicates adequate soil protection, reducing the erosive process (Valle;

Francelino; Pinheiro, 2016). The protection provided by the native vegetation cover is even more important in areas that are particularly susceptible to erosion, such as steep terrains or areas with high precipitation rates (Karamage; Shao; Chen; Ndayisaba; Nahayo; Kayiranga; Omifolaji; Lui; Zhang, 2016). In the study area, where steep slopes account for most of the PAs, some of these areas that are particularly susceptible to erosion are naturally covered by rupestrian grasslands (Oliveira; Marques Neto, 2014).

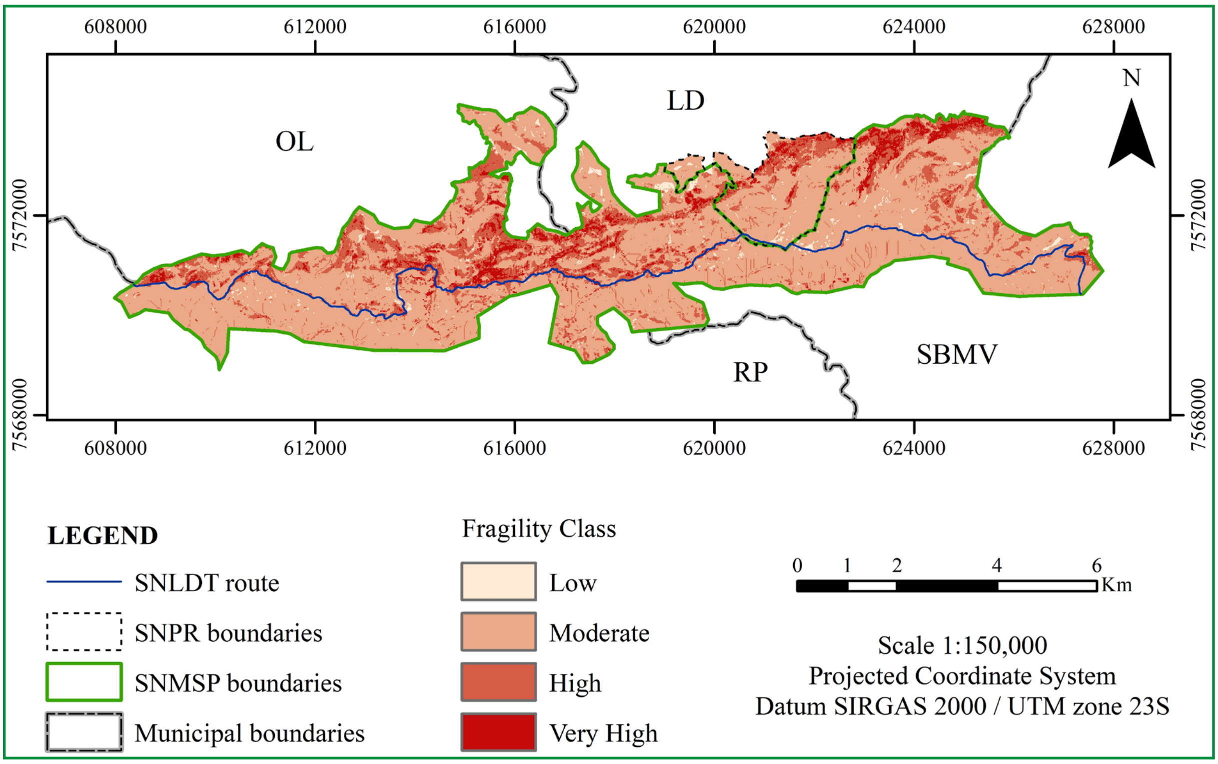
The conclusion that grasslands are less efficient than forests in reducing surface runoff and erosion (Anache; Wendland; Oliveira; Flanagan; Nearing, 2017) could suggest that the ideal vegetation to reduce the environmental fragility of these areas would be forest formations. However, it should be noted that the native vegetation of some of these sites consists of rupestrian grasslands, which were established naturally as a result of a combination of geomorphological, climatic, pedological and hydrological factors (Oliveira; Marques Neto, 2014). In these sites, where tree vegetation cannot establish itself, rupestrian grasslands play a crucial role in reducing surface runoff, erosion and, consequently, environmental fragility, even though their susceptibility to erosion is greater when compared to an area with forest cover.

Furthermore, steep slopes combined with the absence of vegetation in some areas can significantly increase soil loss (Cerdan; Govers; Le Bissonnais; Van Oost; Poesen; Saby; Gobin; Vacca; Quinton; Auerswald; Klik; Kwaad; Raclot; Ionita; Rejman; Rousseva; Muxart; Roxo; Dostal, 2010). In the study area, it is precisely on sloping terrain that the non-vegetated areas occur, mainly originated from natural processes of sanding of quartzite rock outcrops (Oliveira; Marques Neto, 2014). This explains why the steepest areas of both PAs, where there are rocky outcrops and other non-vegetated areas, are classified as very fragile. On the other hand, the steep areas covered by forest, which provides greater protection against soil loss (Anache; Wendland; Oliveira; Flanagan; Nearing, 2017), were classified as moderately fragile.

3.2 Map algebra

Most of the SNMSP (73.6%) and SNPR (72.7%) were classified as moderately fragile, followed by the high, very high, and low classes, in that order (Table 5; Figure 3). The predominance of the moderate fragility class and the absence of the areas that are denoted as very low is similar to the situation observed in the Pico Paraná State Park (PPSP), a protected area in the Atlantic Forest in the state of Paraná, in which 54% of the territory is in the moderate class (Vashchenko; Favaretto; Biondi, 2007). The steep terrains and the fragile soils (Litholic Neosols and Haplic Cambisols) in the PPSP, SNMSP and SNPR increase the environmental fragility of these PAs, while the forest cover reduces it, resulting in the predominance of the moderate class. In this study, the absence of the very low class is due to the precipitation (high fragility degree) and the soil types (high and very high fragility degrees).

Figure 3 – Environmental fragility map of the Serra Negra da Mantiqueira State Park (SNMSP) and the Serra Negra Private Reserve (SNPR), Minas Gerais, Brazil



Source: Authors (2023)

Table 5 – Distribution of degrees of environmental fragility (DEF) in the Serra Negra da Mantiqueira State Park (SNMSP), the Serra Negra Private Reserve (SNPR) and the Serra Negra long-distance trail (SNLDT), Minas Gerais, Brazil

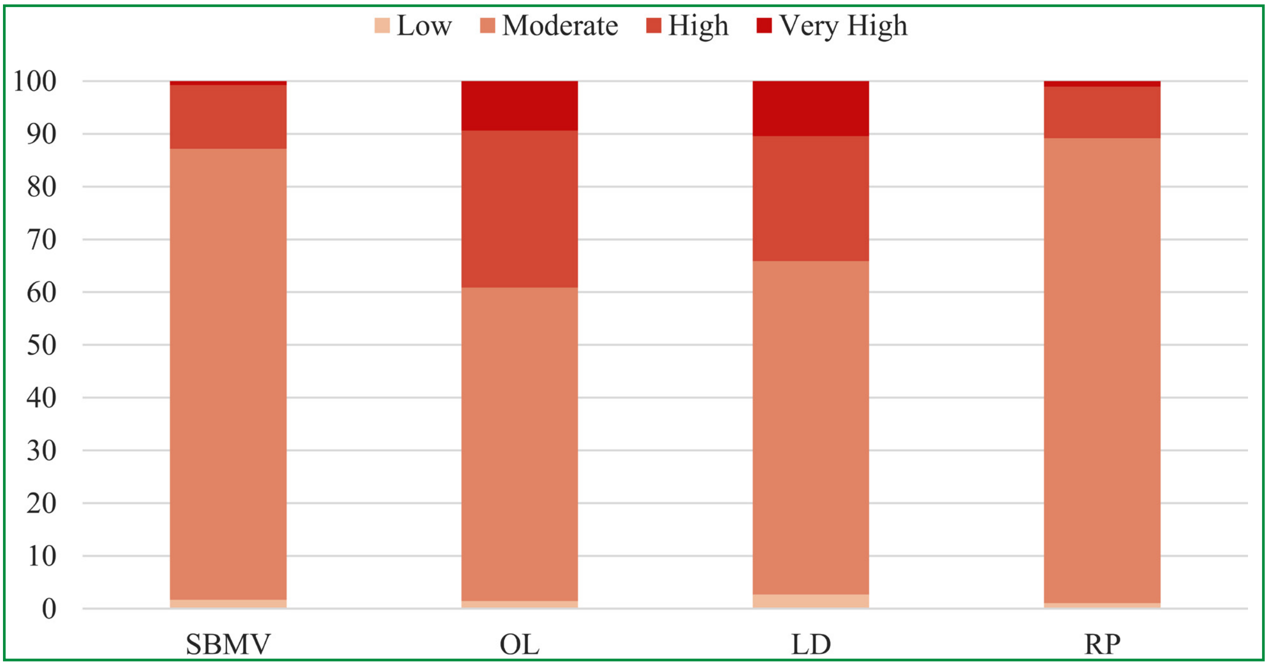
	Area (ha)	Length (m)	Area (ha)	Length (m)
DEF	**SNMSP[1]**	**SNLDT Stretch[1]**	**SNPR[2]**	**SNLDT Stretch[2]**
Low	71.64 (1.7%)	572.20 (2.4%)	9.88 (2.3%)	121.16 (11.2%)
Moderate	3092.49 (73.6%)	11127.90 (46.3%)	316.45 (72.7%)	797.71 (73.7%)
High	809.43 (19.3%)	10255.38 (42.7%)	81.13 (18.6%)	163.60 (15.1%)
Very high	230.40 (5.5%)	2086.80 (8.7%)	27.69 (6.4%)	-
Total	4203.96 (100.0%)	24042.27 (100.0%)	435.14 (100.0%)	1082.48 (100.0%)

Source: Authors (2023)

The areas of the SNMSP in the high and very high environmental fragility classes were smaller in RP and SBMV than in LD and OL, in relative (Figure 4) and absolute values. This indicates that the portion of the SNMSP in the municipalities of RP and SBMV is more suitable for tourism. In contrast, the higher environmental fragility observed in the portion located in LD and OL can restrict visitation to specific locations or limit the number of visitors allowed on the trails, ensuring the protection of natural resources (Salesa; Cerdà, 2020). Impact mitigation by limiting the number of visitors is already carried out in Ibitipoca State Park (ISP), where only 1000 people are allowed each day (IEF, 2018). The ISP is also partially located in Lima Duarte and is the most visited state park in Minas Gerais (Sancho-Pivoto; Alves; Dias, 2020).

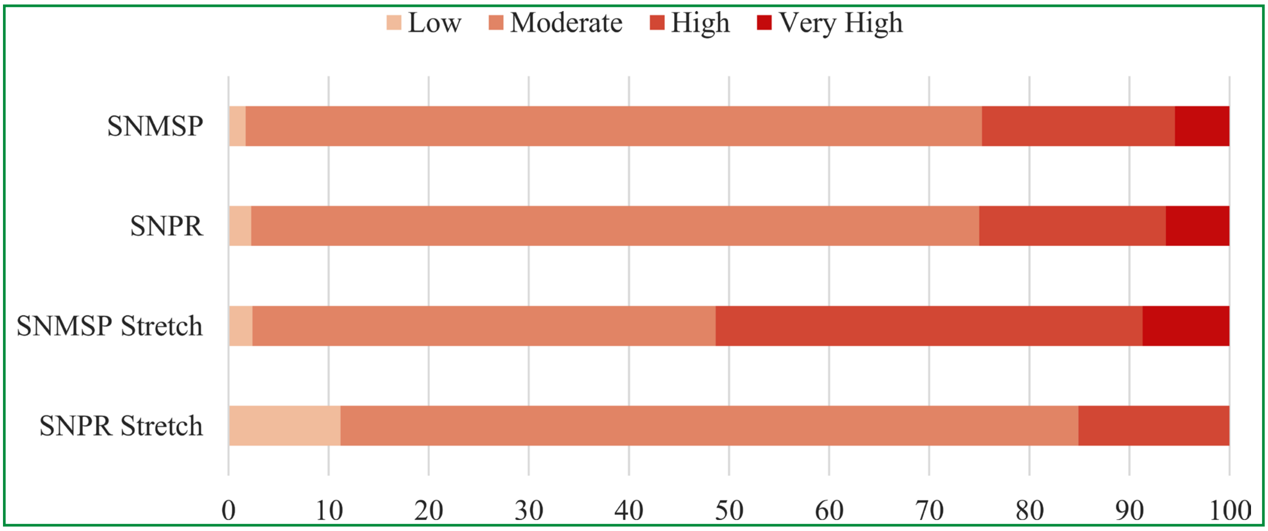
The SNMSP and SNPR share a long-distance trail called Travessia da Serra Negra (Figure 3). This trail follows, for the most part, the crest of the Serra Negra, connecting many other trails and natural attractions. The length of this trail is around 25 km, with altitudes ranging from 875 to 1,630 meters. The environmental fragility map generated shows that the predominant classes on this trail are moderate and high (Table 5). The specific stretch of about 1 km that traverses the SNPR reveals a better scenario than the rest of the trail (Figure 5). It is worth noting that there are stretches (≈2 km) with very high fragility, included exclusively in the territory of the SNMSP, which require special attention for the purposes of visitor impact management.

Figure 4 – Percentage of environmental fragility classes in relation to the area covered by the Serra Negra da Mantiqueira State Park (SNMSP) in the municipalities of Lima Duarte (LD), Olaria (OL), Rio Preto (RP), and Santa Bárbara do Monte Verde (SBMV), Minas Gerais, Brazil



Source: Authors (2023)

Figure 5 – Percentage of environmental fragility classes in the Serra Negra da Mantiqueira State Park (SNMSP), the Serra Negra Private Reserve (SNPR), and the Serra Negra long-distance trail (SNLDT), Minas Gerais, Brazil



Source: Authors (2023)

3.3 Trail planning and management

Trails implemented in rupestrian grasslands should be given special attention due to the significant fragility of these ecosystems, which show low resilience to anthropogenic disturbances (Le Stradic; Buisson; Fernandes, 2013; Silveira, Negreiros, Barbosa, Buisson, Carmo, Carstensen, Conceição, Cornelissen, Echternacht, Fernandes, Garcia, Guerra, Jacobi, Lemos-Filho, Le Stradic, Morellato, Neves, Oliveira, Schaefer, Viana, Lambers, 2015). Although limiting the number of daily visitors to a PA is a legitimate management strategy, other approaches can be adopted (Marion, 2023). The allocation of trails should prioritize areas classified as having low to moderate fragility.

The planning and construction of trails must be carried out within technical parameters that are suitable for their sustainability, especially with regard to the trail alignment in relation to the fall line (Trail Slope Alignment – TSA), which can vary from perpendicular to parallel, and the longitudinal inclination of the trail surface (Trail Grade – TG). The fall line can be defined as the preferred direction of surface runoff, perpendicular to the contour lines. The most effective way to reduce runoff and, consequently, erosion on trails is to plan and construct them with a TSA between 31º and 90º and a TG between 3 and 10%. Trails with a TG of less than 3% promote the accumulation of rainwater, causing the surface of the trail to become waterlogged. As a result, visitors begin to deviate from the flooded areas, widening the trail or creating informal trails, which increases the impact on natural resources. On the other hand, trails with a TG of more than 10% suffer a significant increase in runoff, leading to greater soil loss (Marion, 2023).

The high annual precipitation observed in the study area, and its distribution, concentrated in a few months of the year, highlights the need for actions aimed at reducing surface runoff on the trails, since rainwater is one of the main causes of erosion. On steeper stretches or in areas of the terrain where rainwater tends to accumulate, physical barriers should be installed to contain water runoff, such as wooden logs (Grab; Kalibbala, 2008), water bars (made of wood or stone), drainage dips, or grade reversals (Olive; Marion, 2009).

Furthermore, the formation of informal trails by visitors represents a threat to the integrity of the environment, given that most impacts on trails occur in their early stages of use. Thus, informal trails can substantially increase the area impacted by visitors (Spernbauer; Monz; D'Antonio; Smith, 2023). On the other hand, formal trails should be adequately signposted in order to prevent visitors from unintentionally deviating from the main route. Signage inhibits inappropriate behavior, such as incursions outside the boundaries of formal trails, thereby reducing trampling of the soil and surrounding vegetation (Hockett; Marion; Leung, 2017).

4 CONCLUSIONS

The environmental fragility of the SNMSP and SNPR is predominantly moderate, but the absence of areas in the very low fragility class and the small percentage of areas in the low class reinforce the need for strategies to reduce environmental impacts, especially, on the trails. The areas of higher fragility are concentrated in the municipalities of Lima Duarte and Olaria, due to a combination of factors, especially land cover and slope. The presence of non-vegetated areas, resulting from sanding processes of quartzite rocky outcrops, contributes to the rating of some areas as having high or very high fragility.

The diagnosis of the environmental fragility of the park makes it possible to plan tourism activities, indicating places in which there is a high potential for degradation and those more suitable for public use. Pre-existing trails that are partially located in areas of greater fragility can have their routes relocated, prioritizing areas that are less susceptible to impacts. In those situations, in which relocation is not feasible, the construction of surface runoff containment and drainage structures is a valuable strategy for preventing erosive processes or containing those already established.

The proposed model can be replicated for other protected areas, especially those in the Atlantic Forest biome, thus reducing the need for field surveys and optimizing the resources available for tourism planning. This tool is especially useful for PAs without management plan or with low budgets. The model can be continuously improved as new spatial data, such as satellite images and digital elevation models, become freely available in better resolution

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Authorship Contribution

1Marcello Pinto de Almeida

Forest Engineer, PhD
https://orcid.org/0000-0002-0461-4101 • marcello.almeida@ufv.br
Contribution: Conceptualization; Investigation; Data curation; Methodology; Software; Writing – original draft; Writing – review & editing

2 Gumercindo Souza Lima

Forest Engineer, PhD
https://orcid.org/0000-0002-8446-3592 • gslima@ufv.br
Contribution: Resources; Supervision; Validation

3 Sabrina Lourdes Pereira de Cristo

Surveying Engineer and Cartographer, M.Sc.
https://orcid.org/0000-0003-3926-0742 • sabrinapereiracristo@gmail.com
Contribution: Methodology; Software; Validation

4 Camila Nascimento Neves

Forest Engineer, M.Sc.
https://orcid.org/0000-0001-6175-9609 • nnevescamila@gmail.com
Contribution: Conceptualization; Investigation; Visualization

5 José Cola Zanuncio

Forest Engineer, PhD
https://orcid.org/0000-0003-2026-281X • zanuncio@ufv.br
Contribution: Formal analysis; Supervision; Writing – review & editing

6 Ludimila Grechi Campostrini

Forest Engineer, M.Sc.
https://orcid.org/0000-0002-4733-3713 • ludigc.22@gmail.com
Contribuition: Conceptualization; Investigation; Visualization

7 Marcos Vinícius Ribeiro de Castro Simão

Forest Engineer, M.Sc.
https://orcid.org/0000-0002-8738-6350 • marcos.simao@ifam.edu.br
Contribution: Software; Validation; Writing – review & editing

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