Geoheritage (2026) 18:268
https://doi.org/10.1007/s12371-026-01493-2

ORIGINAL ARTICLE

Tourist Carrying Capacity on the trail of the Site of Geological Interest 'Portal do Palmiro' (paleoburrow 'Toca do Tatu'), Caminhos dos Cânions do Sul UNESCO Global Geopark (Brazil)

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Received: 4 December 2025 / Accepted: 11 November 2026
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Abstract

The Portal do Palmiro trail serves as the primary route to the Toca do Tatu Paleotoca, situated in the municipality of Timbé do Sul, which is part of the Caminhos dos Cânions do Sul UNESCO Global Geopark (CCSUGGp) in Brazil. Following the establishment of the geopark in the area, this location has emerged as a significant attraction for geotourism. Assessing the Tourist Carrying Capacity (TCC) is essential for alleviating the possible environmental consequences associated with visitor activity. This research sought to characterize and establish the TCC of the Portal do Palmiro trail, which provides access to the Toca do Tatu Paleotoca. The methodology employed was grounded in the model suggested by Cifuentes (1992), with particular modifications tailored to the local context. The findings reveal that the Effective Carrying Capacity (ECC) of the trail is 69 visitors per day, a figure that signifies a recommended average and is subject to fluctuations based on daily visitation circumstances. Moreover, the assessment of handling capacity uncovered shortcomings in infrastructure and services, particularly in relation to signage and support equipment, elements that may jeopardize both the safety and the quality of the visitor experience. The implementation of this methodology illustrates its significance as a management and planning instrument for the sustainable utilization of geosites within the geopark.

Keywords Geoconservation · Environmental sustainability · Geotourism · Sustainable development

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Published online: 17 November 2026

Introduction

Brazil is distinguished by its diverse natural and cultural attractions, showcasing considerable geodiversity (Schobbenhaus and Silva 2012), which in turn enhances tourism in natural regions (Menegasso et al. 2021). Notably, the southern part of Brazil has been establishing itself as a sustainable tourist destination through the growth and establishment of UNESCO Global Geoparks (UGGp). The southern part of Brazil has emerged as a significant area on the national stage, recognized for having the highest concentration of UGGp (Silva et al. 2024). In particular, the territory that has been gaining attention lies between the states of Rio Grande do Sul and Santa Catarina, namely the Caminhos dos Cânions do Sul UNESCO Global Geopark (CCSUGGp) (Silva et al. 2025a).

This region encompasses 28 Sites of Geological Interest (SGI), which include geomorphological and paleontological features, as documented in its application dossier submitted to UNESCO, alongside a highly significant cultural heritage (Santos et al. 2024). Among these, the Canyons within the region, which aptly designate the territory, along with the coastal hills, are distinguished as SGI of global importance. Besides the canyons, other SGI of international relevance include the Paleotocas (paleoburrow), which represent a distinctive paleontological legacy (Miranda et al. 2026).

Paleoburrows are trace fossils formed within sandstone formations by South American native megafauna during the Pliocene and Quaternary epochs (Bergqvist and Maciel 1994; Buchmann et al. 2003; Valdati et al. 2024a). This geological inheritance provides the region with substantial potential for tourism development, particularly within the rapidly expanding field of geotourism. Globally, geotourism is consolidating as a key segment of sustainable tourism (Dowling 2013; Ólafsdóttir and Tverijonaite 2018; Chylińska and Kołodziejczyk 2025), driven by the growing prominence of destinations that leverage their geoheritage as primary attractions (Rivero et al. 2019; Guglielmi et al. 2026).

Geotourism is articulated here according to the definition put forth by the Global Geoparks Network (GGN) and the Center for Sustainable Destinations of the National Geographic Society. They characterize geotourism as "tourism that sustains and enhances the identity of a territory, taking into account its geology, environment, culture, aesthetic values, heritage, and the well-being of its residents" (Arouca Declaration 2011). This definition serves as a guiding principle for the actions of UGGps globally.

In pursuit of this goal, a rise in the number of visitors to the SGI that constitute the CCSUGGp (Silva et al. 2025b) has been noted, particularly regarding these biogenic formations. The surge in foot traffic along the trails that lead to paleoburrows illustrates the possibilities of this form of tourism, merging attractions like paleoburrows with the increasing interest in sustainable tourism experiences.

The CCSUGGp showcases three of these sites that are accessible to the public: paleoburrow Índios Xocleng located in the municipality of Jacinto Machado, paleoburrow Furnas Xocleng found in the municipality of Morro Grande, and paleoburrow Toca do Tatu situated in the municipality of Timbé do Sul. As this UGGp has solidified its presence in southern Brazil, these attractions have achieved significant recognition and have become alternative destinations for exploring natural environments.

In this context, there is a significant concern regarding the sustainability of this destination, particularly in relation to the Tourist Carrying Capacity (TCC) of the trails that provide access to these attractions, since tourist activities can inevitably affect destinations (Butler 1996).

In this context, McCool and Lime (2001) contend that there is a growing interest in the sustainability of tourism development projects, raising concerns regarding the ability of emerging tourist destinations, particularly in natural regions, to handle the heightened levels of recreation and usage in these areas.

The recognition of possible risks and the volume of visitors that each of these SGI accommodates must be taken into account, as paleoburrows may pose a potential danger given the circumstances they could present to visitors. Furthermore, it is not solely the presence of visitors that can affect the conservation of the structure.

Silva and Ferreira (2021) emphasize that the connection between tourism and sustainability is not a recent development; rather, it has increasingly become a focal point in discussions and policies related to tourism, primarily adopted by stakeholders actively engaged in tourism operations. These entities attract visitors from both international and domestic markets, with the domestic tourists being the majority.

Following the endorsement by CCSUGGp in 2022, these sites are utilized, among other purposes, for tourism. Consequently, this study seeks to delineate the TCC along the Portal do Palmiro trail, which serves as the access route to paleoburrow Toca do Tatu, a site that is open to visitors.

The TCC is defined as the highest number or quantity of visits to a specific location within a designated timeframe (day, week, month, year) with the objective of reducing adverse effects on resources while concurrently ensuring visitor satisfaction (O'Reilly 1986; Canestrelli and Costa 1991; Cifuentes 1992; Manning and Lawson 2002 and references therein). Research on TCC aims to alleviate the effects of tourism prior to their manifestation at the destination (O'Reilly 1986).

In this research, the methodology employed to establish the TCC will follow the approach suggested by Cifuentes (1992), with modifications tailored to the specific study location. This methodology is the most prevalent and commonly utilized across Latin American nations and represents a quantitative approach aimed at identifying the maximum daily visitor capacity of a protected area (Rocha et al. 2021; Galeano et al. 2023).

This project may be regarded as a preliminary initiative aimed at assessing the TCC in relation to the pathways of other visitor attractions at CCSUGGp, given that the scientific curiosity surrounding this domain is enhanced by the establishment of this UGGp within the region.

Study Area

At present, the CCSUGGp includes seven municipalities under its jurisdiction, four of which are situated in the state of Santa Catarina (specifically Praia Grande, Morro Grande, Timbé do Sul, and Jacinto Machado) and three in the state of Rio Grande do Sul (namely Torres, Mampituba, and Cambará do Sul). The total area encompassed by these municipalities is 2 830 km^2. Collectively, these seven municipalities accommodate a population of roughly 79 040 inhabitants (IBGE 2022). The particular focus of this study is the Portal do Palmiro trail, which serves as an access route to Paleotoca Toca do Tatu located in the municipality of Timbé do Sul (Fig. 1).

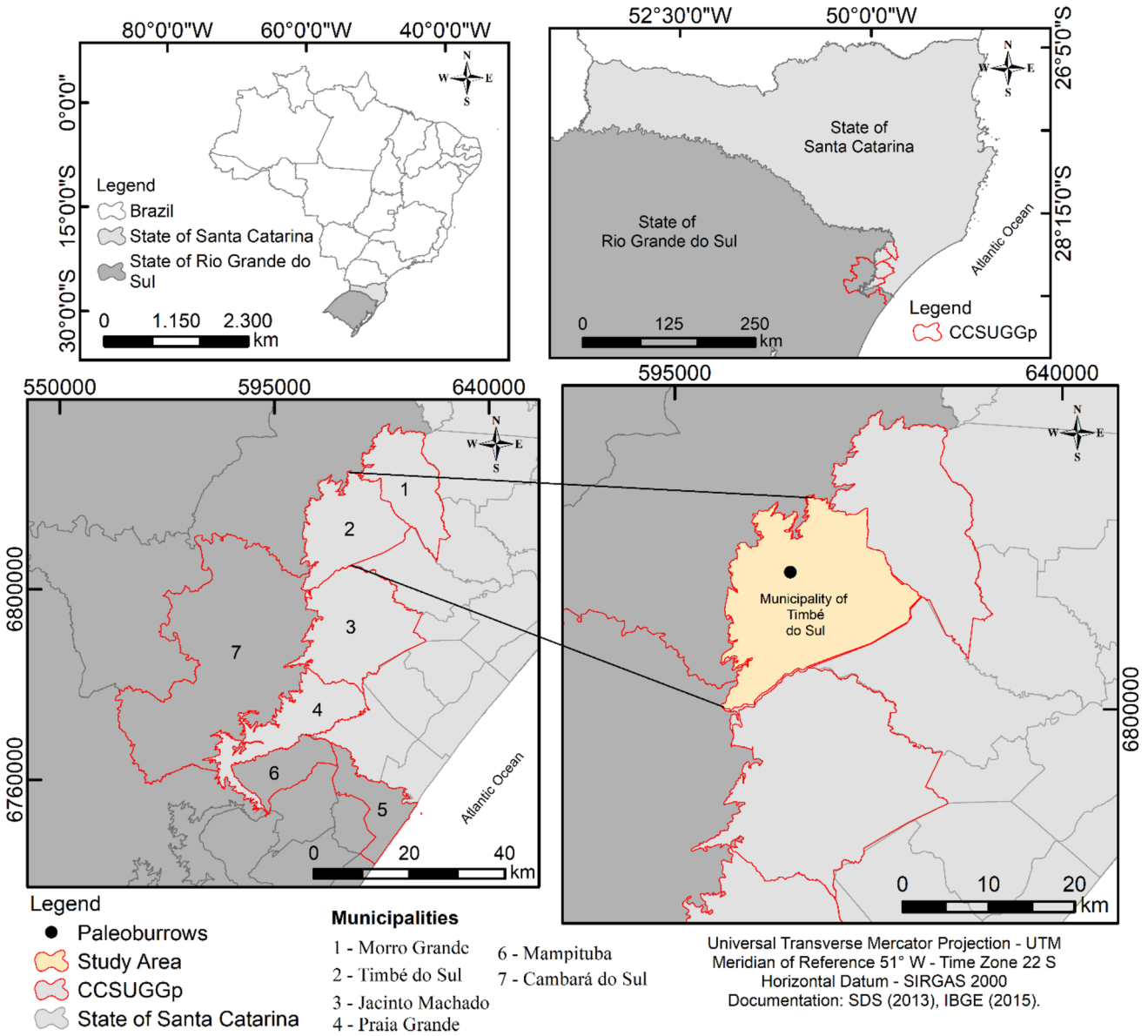

Fig. 1 CCSUGGp and study area location.Source: Authors, 2024

The geographic region that includes the seven municipalities of the CCSUGGp stretches from the coastal zone of Torres, Rio Grande do Sul, traversing canyons and cliffs, to the Serra Geral plateau. This spatial arrangement endows the geopark with an extraordinary variety of landscapes within a singular geographic area, thereby enhancing the availability of services and tourism activities, and generating a true landscape of opportunities. The CCSUGGp is characterized by its notable diversity of geological and geomorphological features, which include various structures, lithologies, landforms, and distinctive geomorphological processes (Rapanos and Valdati 2024).

This area is acknowledged for its geological significance, as it includes one of the most crucial magmatic events in the history of the Earth, occurring between 135 and 119 million years ago. This epoch is characterized by significant volcanic activity across the region, which is linked to the disintegration of the Gondwana continent (Dantas et al. 2005; Godoy et al. 2011). The magmatic characteristics found in the CCSUGGP region are exemplified by a variety of magmatic rocks, including basalts, diabases, and rhyolites, which constitute the Serra Geral Group (Rossetti et al. 2018). The particular SGI relevant to this research is the pathway leading to the Toca do Tatu paleoburrow site. This location, as previously indicated, features trace fossils created by the indigenous megafauna of South America, which have been excavated from sandstone formations that are part of the Botucatu Formation (Bergqvist and Maciel 1994; Buchmann et al. 2003; Valdati et al. 2024). Within the designated study area, evidence of human habitation can also be observed through rock engravings found on the inner surfaces of these structures (Frank et al. 2012; Cezaro et al. 2016). The information preserved within these paleoburrows represents one of the most significant remnants of human presence in the area (Fig. 2).

Methodology

The Portal do Palmiro trail was selected as it is the sole trail within the CCSUGGp that features a guide with decades of experience in this activity. Three field excursions were carried out:

i) Initial contact to request access permission from the site owner occurred on April 6, 2024. During this preliminary field survey, exploratory and data collection activities were carried out, encompassing field notes, spatial mapping, and photographic documentation;
ii) The second incursion took place on May 15, 2024, to verify certain points and coordinates gathered during the initial fieldwork, which, upon analysis, raised questions regarding some averages;
iii) The third incursion aimed to accompany a group of visitors experiencing the trail and paleoburrows for the first time. Scheduled for June 29, 2024, this event was designed to assess visitor attendance and behavior, travel duration, and to document images of both the trail and the interiors of the structures. All incursions were carried out with the presence of a guide.

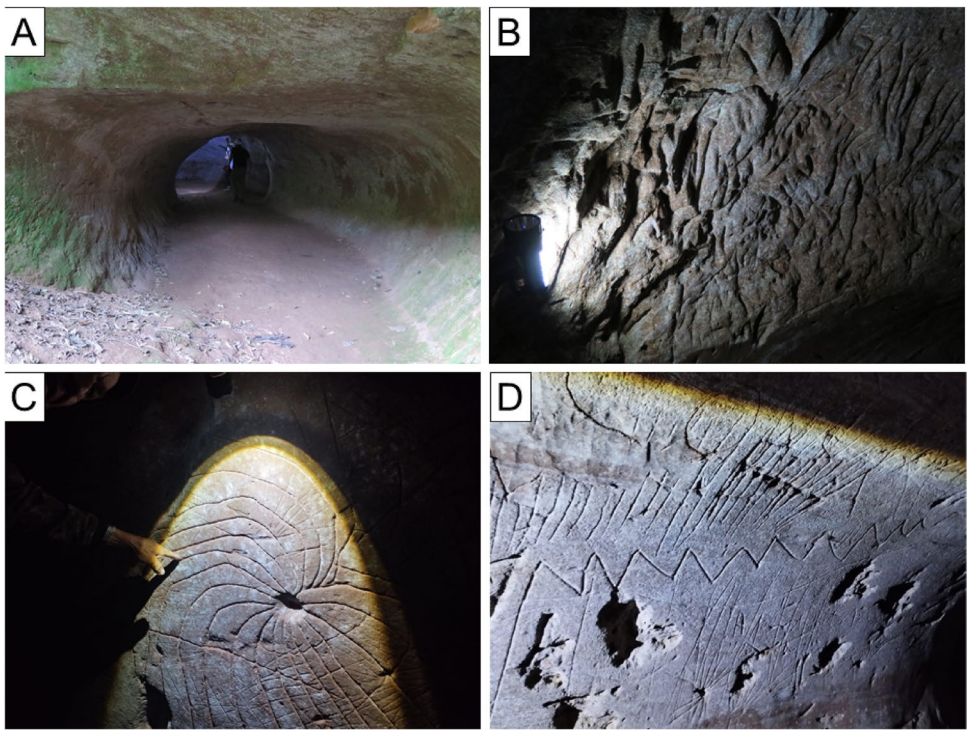

Fig. 2 Entrance to the Site of Geological Interest—Paleoburrows 'Toca do Tatu' (**A**). Claw marks of megafauna animals (**B**). Rock engravings made in sandstone by indigenous populations (**C**, **D**).Source: Authors, 2024

A GPS (Global Positioning System) operating in trail mode was utilized to chart the path. The route was automatically documented by capturing coordinates every 5 s. Additionally, points of interest were manually designated based on the characteristics of the trail. The gathered points were sequentially numbered and later processed and analyzed using GIS (Geographic Information System) software ArcGIS 10.3 to create thematic maps.

On that day, a digital camera was employed to document the trail. As previously noted, a tape measure was utilized perpendicular to the direction of the trail to assess its width, focusing solely on the ends and taking into account only the bed area, which is defined as the section lacking any vegetation cover.

The approach to calculation employed in this research for the TCC will adhere to the Cifuentes method (1992). The framework established by Cifuentes (1992) takes into account three key parameters: the Physical Carrying Capacity (PCC), the Real Carrying Capacity (RCC), and the Effective Carrying Capacity (ECC). The sequence in which each level appears reflects the adjusted capacity of its immediate predecessor.

Consequently, the PCC will invariably exceed the RCC. Following this, the RCC will either surpass or match the ECC, as the latter is determined by taking into account factors related to area and activity management. Ultimately, in the context of area management, which pertains to objectives attainable through human effort, all goals can be fulfilled, leading to the conclusion that the ECC will be equivalent to the RCC.

The connection among the three tiers can be interpreted in the following manner: PCC > RCC ≥ ECC.

The environmental impacts are extensive; consequently, site variables including slope, gradient, length, area, visitation hours, precipitation, erodibility, accessibility, flooding, temperature, relative humidity, wind speed, and others will be utilized to derive the TCC. The variables responsible for these impacts exhibit a variety of natures, intensities, directions, and magnitudes, potentially resulting in irreversible consequences.

Calculation of Physical Carrying Capacity

This parameter indicates the upper limit of visits permissible to the location, determined by the available space and time.

$$\textbf{Formula}: \quad \mathbf{PCC} = \frac{\mathbf{A}}{\mathbf{AP}} \times \mathbf{NV}$$

A: It is the available area (surface) in m^2;

AP: It is the area (surface) used by a person in m^2;

NV: It is the number of times a place is visited by the same person in a day;

Hv: This is the available visiting hours (h);

Tv: It is the travel time on the trail (round trip) (h).

$$\mathbf{NV} = \frac{\mathbf{Hv}}{\mathbf{Tv}}$$

Real Carrying Capacity

This represents the maximum number of visits permitted at a location, as determined by the PCC after applying the Correction Factors (CF) that potentially limit capacity.

Correction Factor (CF):

Environmental factors: Rain, wind, air humidity, temperature.

Physical factors: Accessibility, erodibility, flooding.

Social factors: Space occupied by one person, minimum distance between groups on the trail, internal access points.

Management: Operating time of the site.

$$\textbf{Formula}: \quad \mathbf{CFx} = 1 - \frac{\mathbf{MLx}}{\mathbf{MTx}}$$

being that:

CFx = Correction factor for the variable x.

MLx = Limiting magnitude of the variable x.

MTx = Total magnitude of the variable x.

After the Correction Factors have been established, the RCC is represented in the following manner:

$$\textbf{Formula}: \quad \mathbf{RCC} = \mathbf{FCC}\left(\mathbf{CF_1} \times \mathbf{CF_2} \times \mathbf{CF_3} \ldots \mathbf{CF_n}\right).$$

Multiple factors can significantly affect the load-bearing capacity; hence, it is essential to apply correction factors to prevent inaccuracies in the results. Examples of such correction factors encompass social influences, accessibility, and precipitation levels. Additional factors may be incorporated into the calculations, provided they are directly associated with the specific location under investigation.

i) Calculation of the Social Factor (CFsoc)

Considering factors related to the quality of the visitor experience, managing group visits is essential. To optimize visitor flow regulation while ensuring visitor satisfaction, group dynamics should be structured according to the following principles: establishing the maximum number of groups (NG) allowed on each trail simultaneously, with an additional 50 m buffer added to the required distance between consecutive groups.

$$\textbf{Formula}: \quad \mathbf{NG} = \frac{\textbf{Total length of the trail (m)}}{\textbf{Distance required by each group (m)}}$$

To determine the social correction factor, it is first necessary to establish the maximum number of individuals (P) that can simultaneously occupy each trail segment. This is calculated using the following equation:

$$\textbf{Formula}: \quad \mathbf{P = NG\,(Number\ of\ Groups) \times number\ of\ people\ per\ group}$$

In order to compute the Social Correction Factor (CFsoc), it is essential to determine the Limiting Magnitude (ML). In this context, the Limiting Magnitude refers to the segment of the path that remains unoccupied due to the necessity of maintaining a minimum distance between groups. Consequently, since each individual occupies 1 m of the path, the Limiting Magnitude can be expressed as:

$$\textbf{Formula}: \quad \mathbf{MLx\,(trail) = mt\,(Trail\ area) - P}$$

$$\textbf{Being that}: \quad \mathbf{CFsoc(trail)} = 1 - \frac{\mathbf{MLx}}{\mathbf{MTx}}$$

ii) Calculation of the Accessibility Factor (CFaces)

It assesses the level of challenge that visitors might face while traversing the trail, owing to the ascents and descents. The categories listed below were defined according to Table 1.

The segments that exhibit a medium or high level of difficulty are the sole ones deemed significant when determining usage restrictions. Given that a high grade indicates a greater level of difficulty compared to a medium grade, a weighting factor of 1 has been applied for the medium degree of difficulty and 1.5 for the high degree of difficulty.

$$\textbf{Formula}: \quad \mathbf{CFaces} = 1 - \frac{(\mathbf{ma}\times 1.5)+(\mathbf{mm}\times 1)}{\mathbf{mt}}$$

ma = meters of trail with high difficulty.

mm = meters of trail with medium difficulty.

mt = total meters (distance).

$$\textbf{Being that}: \quad \mathbf{CFaces\,(trail)} = 1 - \frac{(\mathbf{ma}\times 1.5)+(\mathbf{mm}\times 1)}{\mathbf{mt}}$$

iii) Calculation of the Precipitation Factor (CFpre)

This is a variable that hinders regular visitation. A period of twelve months with precipitation exceeding 5.5 mm will be taken into account, particularly the months from January to December 2023. In light of this variable, the computation will proceed as follows:

$$\textbf{Formula}: \quad \mathbf{F\,(pre)} = 1 - \frac{hl}{ht}$$

hl = Rainfall limit per year (days * hours/day = hours).

ht = Hours per year that the business is open (days * hours/day = hours).

Table 1 Degree of difficulty for movement on the trail

Difficulty	Slope
No difficulty level	≤ 10%
Medium difficulty (mm)	10%—20%
High difficulty (ma)	> 20%

Source: Adapted from Cifuentes (1992)

Calculation of Real Carrying Capacity (RCC) – Subjected to Correction Factors (CF)

Based on the application of the aforementioned correction factors for each trail, the Real Carrying Capacity is calculated using the following expression:

Correction Factor (CF).

Environmental factors: Precipitation, temperature, wind, and humidity;

Physical factors: Accessibility, erodibility, and flooding;

Social: Space occupied by one person, minimum distance between groups on the trail.

$$\begin{aligned}\textbf{Formula}: \ \mathbf{RCC} = \mathbf{PCC}\big(&\mathbf{CF}_{prec} \times \mathbf{CF}temp \times \mathbf{CF}vven \\ &\times \mathbf{CF}urel \times \mathbf{CF}aces \times \mathbf{CF}erod \\ &\times \mathbf{CF}alag \times \mathbf{CF}soc\big)\end{aligned}$$

Calculation of Management Capacity

Management Capacity (MC) represents the operational status of the tourist sector's administration in relation to its objectives, expressed as a percentage. To achieve a more precise calculation, Cifuentes (1992) proposes classifying these services and establishing subcategories and percentage scores based on the quality provided, which is essential for effective operational management.

This evaluation compares the ideal conditions required for effective site management (optimal capacity) against the actual existing conditions (installed capacity). It encompasses the full spectrum of management parameters, with specific evaluation criteria tailored to the unique attributes of each protected area.

To standardize the assessment, the following variables are evaluated: (i) infrastructure, (ii) equipment, and (iii) human resources. Quantity is measured as the percentage ratio of current resources relative to the ideal allocation. Ultimately, overall management capacity is calculated by averaging the individual percentage scores of these three variables, structured as follows:

$$\textbf{Formula}: \quad \mathbf{MC} = \frac{(\mathbf{Infrastructure})+(\mathbf{Equipment})+(\mathbf{humanresources})}{3} \times 100$$

Effective Carrying Capacity

It is characterized as the highest number of visits permissible, considering the operational capacity to facilitate and oversee them. The ECC is derived by modifying the carrying capacity of the designated area or the administration of the tourist space

Formula : $\mathbf{ECC = RCC \times MC}$

Being that : **RCC** = Real Carrying Capacity
MC = Management Capacity(em%)
MC = Infrastructure + Equipment + human resources

The findings related to the identification of the TCC will be displayed in accordance with the framework illustrated in Table 2.

Results

Trail Characterization

To define the trail, it was essential to first segment it (Fig. 3). This task was conducted in situ. The survey and information gathering took into account the route. The Portal do Palmiro trail, which grants access to the Toca do Tatu Paleotoca, traverses the slope of the Serra Geral mountain range, with the outward journey measuring 1 809,50 m. The return journey spans 642,93 m to the intersection point, which follows the same path back to the starting point, resulting in a total distance of 2 452,43 m. An elevation change of 85 m is observed along the route, as recorded by the GPS equipment, comparing the starting point of the trail to the paleotocas. The highest elevation along the route reached 97 m above the lowest point, which is the trail's starting point.

Despite the fact that the Portal do Palmiro Trail includes segments categorized as medium difficulty, featuring inclines ranging from 10 to 20%, which account for 22.75% of the total route, and sections deemed high difficulty with inclines exceeding 20%, comprising an additional 13.75%, the predominant portion of the trail, which constitutes 63.5%, consists of inclines below 10%, classified as having "no degree of difficulty" as categorized by Miranda et al. (2026). This trail provides an opportunity for visitors to appreciate the natural environment, gain insights into various species of flora and fauna, and explore the historical narratives, myths, and legends associated with the area, thereby rendering the trail both appealing and highly enjoyable.

Table 2 Model for classifying results

Tourist carrying capacity	Trail: paleotoca toca do tatu/portal do palmiro, in the municipality of timbé do sul
Physical (PCC)	**visits/day**
Environmental Correction Factor	**(%)**
CF*pre*	%
CF*temp*	%
CF*urel*	%
CF*vven*	%
Physical Correction Factor	**(%)**
CF*erod*	%
CF*aces*	%
CF*alag*	%
Social Correction Factor	**(%)**
CF*soc*	%
Real (RCC)	**visits/day**
Management Capacity (MC)	%
Effective (ECC)	**visits/day**

Source: Adapted from Cifuentes (1992)

Calculation of Tourist Carrying Capacity

As previously noted, the methodology established by Cifuentes (1992) takes into account three parameters: PCC, RCC and the ECC. The sequence in which these levels are presented will be outlined below.

Calculation of Physical Carrying Capacity

For the PCC, the following data is available:

A represents the available area (surface) measured in square meters (m^2), considering the total surface area of the trail, which amounts to 2 452,43 m^2. The widths of the trail range from a minimum of 0,70 m to a maximum of 6.0 m, with an average width of 1,84 m, leading to a calculated area of 4 512,47 m^2.

AP refers to the area (surface) allocated for an individual, taking into account a spacing of one meter (1 m^2) between each person;

NV denotes the frequency with which the same individual visits the site within a single day. In this context;

Hv represents the total available visiting hours, which span from 8:00 am to 6:00 pm, thus remaining operational for 10 h daily;

Additionally, **Tv** indicates the total travel time required for the round trip on the trail, which is 4.2 h.

In calculating the FCC, the following maximum visit numbers were obtained using the formula below:

$$\mathbf{FCC} = \frac{\mathbf{A}}{\mathbf{AP}} \times \mathbf{NV} = \frac{\mathbf{Hv}}{\mathbf{Tv}}$$

$$\mathrm{FCC} = \frac{4\,512{,}47}{1} \times \mathrm{NV} = \frac{10}{4.2} - \mathrm{FCC} = 10\,744 \text{ visitors}$$

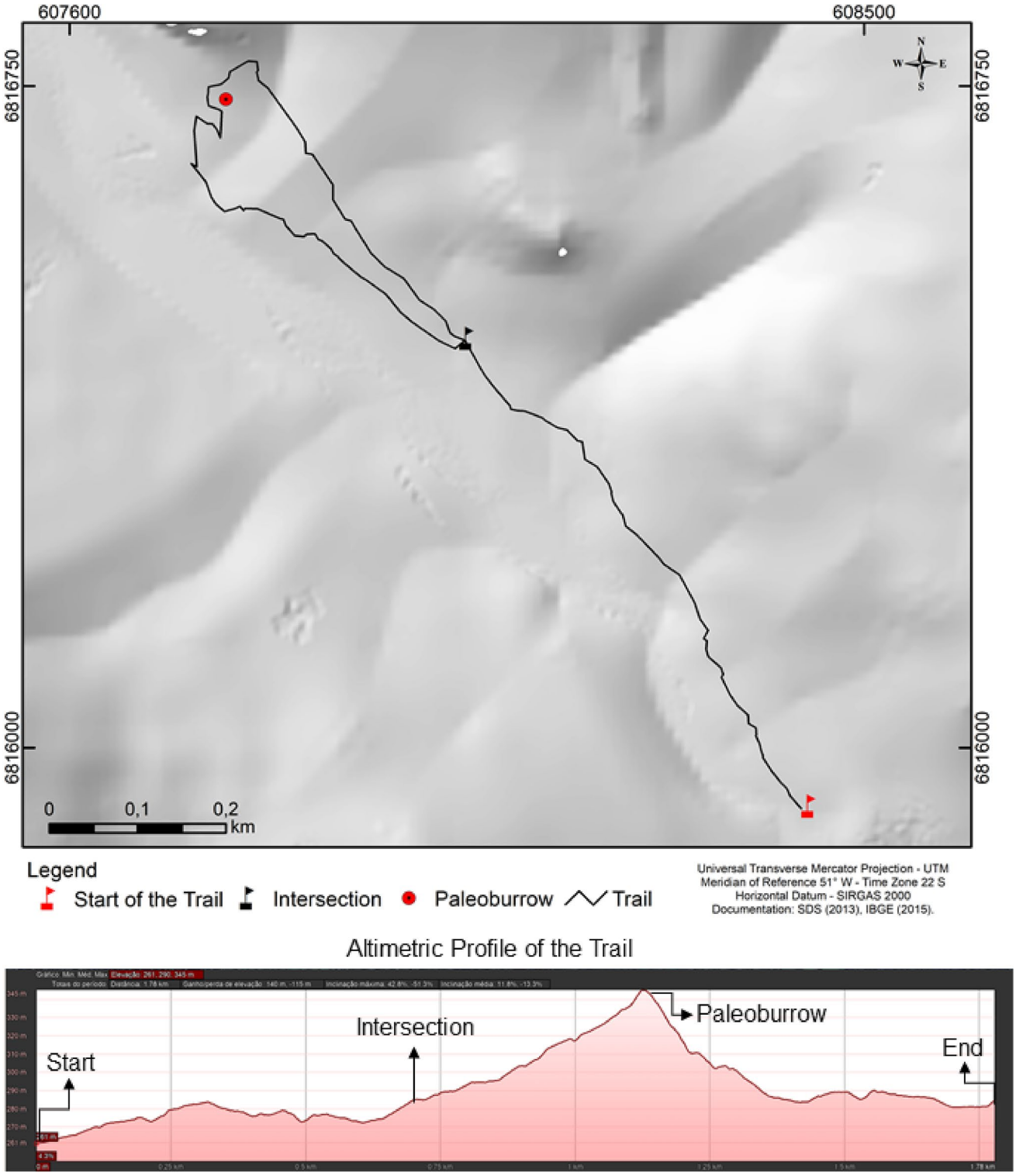

Fig. 3 Segments of the Portal do Palmiro Trail.Source: Miranda et al. (2026)

Calculation of Real Carrying Capacity

In the case of the Portal do Palmiro trail, various factors including environmental, physical, social, and management aspects were taken into account, and these are presented sequentially for each of the levels illustrated below: For the RCC, the subsequent data is accessible:

CFx is the Correction Factor for the variable **x**;

MLx is the Limiting Magnitude of the variable **x**; and.

MTx is the Total Magnitude of the variable **x**, expressed by the formula:

$$\mathbf{CFx} = 1 - \frac{\mathbf{MLx}}{\mathbf{MTx}}$$

The results for each Correction Factor will be obtained below.

Environmental Correction Factor

For the environmental factors, the following factors were considered: i) precipitation, ii) temperature, iii) relative humidity, and iv) wind speed.

Atmospheric data were compiled based on raw data availability from the monitoring station during the analyzed timeframe. Relative humidity measurements were available for 359 days, of which 117 days (33.05%) exceeded the 90% threshold defined by Cifuentes (1992) as a limiting factor and were consequently incorporated into the capacity calculation model. In contrast, the wind dataset was complete, spanning a full 365 days.

i) Precipitation Factor (CFpre)—Because Cifuentes (1992) does not define specific minimum or maximum precipitation thresholds for intense or continuous rainfall, a daily threshold of 5,5 mm was designated as a baseline reference for the Portal do Palmeiro trail site, following the methodology previously established by Miranda et al. (2026) for the trail route classification. This 5,5 mm benchmark is particularly significant given the study area's position on a mountain slope, a region historically subject to elevated rainfall levels and associated environmental challenges (Back 2022; Souza et al. 2022). Orographic uplift of warm, humid air drives the formation of cumuliform clouds, generating higher localized precipitation. Because key segments of the trail intersect water bodies, establishing this threshold on the basis of historical regional averages was crucial to prioritizing visitor safety.

Data were obtained from the Timbé do Sul rain gauge station (2,849,019) (Table 3), located within the city's urban boundaries and serving as the only station near the study area. This research analyzed the most recent ten-year period (2013–2023), matching the project's operational timeframe and allowing for the calculation of minimum, average, and maximum rainfall values.

Table 3 Daily precipitation between 2013 and 2023

Daily rainfall	N° days	(%)
Daily rainfall > 5,5 mm	4 113	24.26
Daily rainfall < 5,5 mm	12 844	75.74
Total number of days	16 957	100

Source: Taken from EPAGRI-SC, 2024

Across the 16 957 observed days between 2013 and 2023, 12 844 days (75.74%) recorded precipitation below 5,5 mm, whereas 4 113 days (24.26%) exceeded this threshold. This substantial variation prevented site visits during the study period. Table @@@5 details the daily precipitation statistics categorized above and below the 5,5 mm threshold from 2013 to 2023.

According to data provided by EPAGRI-SC, the period identified as the rainiest from 2013 to 2023 recorded a Maximum Monthly Precipitation of 469,8 mm, an Average Monthly Precipitation of 175,55 mm, and a Minimum Monthly Precipitation of 5,5 mm.

The values utilized for the correction factor were based on the count of days during which daily precipitation exceeded 5,5 mm. Specifically, there were 4 113 days (hl) out of a total of 16 957 days in the period, which equates to 24.26%, along with the total number of hours per year that the facility is accessible for visitation, which is ten hours daily, amounting to 3 650 h (ht) annually.

The result is obtained using the formula:

$$\mathbf{CF}\boldsymbol{pre} = 1 - \frac{hl}{ht}$$

$$\boldsymbol{CFprec} = 1 - \frac{4113}{3650} : \mathrm{CF}prec = 1 - 1{,}12 : \mathrm{CF}prec = 0{,}12$$

ii) Temperature Correction Factor (CF*temp*): The yearly minimum daily temperature was regarded as a constraining element. Information from 2023, supplied by Epagri (2024), was utilized to derive the outcomes for the correction factor (Table 4).

In this instance, the temperature applied was 5,79 °C, which corresponds to a duration of twenty-one (21) days. Consequently, the temperature correction factor (CFtemp) is determined by taking into account the days that the trail is accessible to visitors (MT*vano*) throughout the year, as well

Table 4 Air temperature – 2023

Instantaneous air temperature	(ºC)
Minimum Daily (Annual)	5,79
Daily Average (Annual)	17,26
Daily Maximum (Annual)	24,79

Source: Taken from EPAGRI-SC, 2024

as the days that experience the limiting annual minimum daily temperature (ML*tdia*).

The outcome is derived using the subsequent formula:

$$\mathbf{CFx} = 1 - \frac{\mathbf{MLx}}{\mathbf{MTx}}$$

$$\mathbf{CF}\boldsymbol{temp} = 1 - \frac{21}{365} : \mathrm{CF}temp = 1 - 0{,}057 : \mathrm{CF}temp = 0{,}94$$

iii) Correction Factor for Relative Air Humidity (CF*urel*): Regarding relative humidity, the adopted threshold follows the methodology of Cifuentes (1992), which defines relative humidity levels exceeding 90% as a limiting factor. During the analyzed period, daily relative humidity surpassed this 90% threshold on 117 days, accounting for 33.05% of the observed timeframe. Consequently, these 117 days were utilized in the calculation model (Table 5).

The outcome is derived using the formula:

$$\mathbf{CFx} = 1 - \frac{\mathbf{MLx}}{\mathbf{MTx}}$$

$$\mathbf{CF}\boldsymbol{urel} = 1 - \frac{117}{354} : \mathrm{CF}urel = 1 - 0{,}33 : \mathrm{CF}urel = 0{,}66$$

iv) Wind Speed Correction Factor (CF*vent*): The analysis considers the high probability of exposure to strong or cold winds as a limiting factor. According to Epagri (2024), twelve (12) days representing 3.34% of the monitored period in 2023—recorded wind speeds ranging from 50 to 61 km/h. This range is categorized as a "Strong Wind" (Force 7 on the Beaufort scale), a condition in which large trees sway and walking against the wind becomes difficult (Hasse 2015).

Based on data from the Criciúma weather station, the corresponding values recorded for 2023 are detailed in Table 6.

The outcome is derived using the formula:

$$\mathbf{CFx} = 1 - \frac{\mathbf{MLx}}{\mathbf{MTx}}$$

$$\mathbf{CF}\boldsymbol{vven} = 1 - \frac{12}{359} : \mathrm{CF}vven = 1 - 0{,}033 : \mathrm{CF}vven = 0{,}96$$

The Solar Incidence Correction Factor (CFsol), which is relevant when sunlight intensity is excessive due to clearings or fallen trees that leave the trail exposed, was not taken into account in this research. This omission is justified as the trail is predominantly shielded by vegetation; only 32 m were identified as having potential solar incidence, representing 1.3% of the total route. The correction factor was excluded because 98.7% of the trail's length is covered by vegetation, facilitating normal use even during sunny conditions. Consequently, it is advised that for trails with vegetation cover surpassing 75%, this factor may be ignored, while also considering the terrain and the pace of walking.

Table 5 Relative air humidity – 2023

Instantaneous relative humidity	(%)
Minimum Daily (Annual)	58.99
Daily Average (Annual)	87.30
Daily Maximum (Annual)	99.94

Source: Taken from EPAGRI-SC, 2024

Table 6 Wind speed– 2023

Intervals	Days	% of days
< 1 km/h	0	0.00
1–5 km/h	0	0.00
6–11 km/h	4	1.11
12–19 km/h	65	18.11
20–28 km/h	152	42.34
29–38 km/h	91	25.35
39–49 km/h	28	7.80
50–61 km/h	12	3.34
62–74 km/h	6	1.67
75–88 km/h	0	0.00
89–102 km/h	1	0.28
103–117 km/h	0	0.00
> 118 km/h	0	0.00

Source: Taken from EPAGRI-SC, 2024

Physical Correction Factor

In terms of physical factors, the following aspects were taken into account: i) accessibility, ii) erodibility, and iii) flooding, based on the terrain's characteristics.

i) Erodibility Correction Factor (CF*erod*): The analysis takes into account only those points along the trail that exhibit signs of soil erosion as limiting factors. Consequently, the erodibility correction factor (CFerod) is computed based on MLeros, which refers to the segments of the trail affected by erosion issues. A total of 312,00 m was identified along the path, while MTcomp represents the overall length of the trail, amounting to 2 452,43 m.

The result is obtained using the formula:

$$\boldsymbol{CF\,(erod)} = 1 - \frac{\mathbf{ML}\boldsymbol{eros}}{\mathbf{MT}\boldsymbol{comp}}$$

$$\mathrm{CF}erod = 1 - \frac{312{,}00}{2452{,}43} : \mathrm{CF}erod = 1 - 1{,}12 : \mathrm{CF}erod = 0{,}87.$$

ii) Accessibility Correction Factor (CF*aces*): The analysis takes into account the total of the segments of each trail categorized as having a medium difficulty level (mm) ranging from 10 to 20% incline, assigned a weighting factor of roughly 1.0, or classified as high (mm), exceeding a 20%

incline with a weighting factor of about 1.5. This classification may impose limitations on visitor mobility along the trail, given the inclines and declines throughout its overall length (mt), which measures 2 452,43 m. Consequently, the equation can be expressed in the following formula:

$$\mathbf{CF}(\boldsymbol{aces}) = 1 - \frac{(\mathbf{ma}\times 1.5)+(\mathbf{mm}\times 1)}{\mathbf{mt}}$$

$$\mathrm{CF}aces = 1 - \frac{(337{,}56\times 1.5)+(557{,}95\times 1)}{2452{,}43} \qquad \mathrm{CF}aces = 1 - \frac{(506{,}34)+(557{,}95)}{2452{,}43}$$

$$\mathrm{CF}aces = 1 - \frac{(1064{,}29)}{2452{,}43} \qquad \mathrm{CF}aces = 0{,}57$$

iii) Flood Correction Factor (CF*alag*): This factor accounts for sections prone to water accumulation, which, when combined with pedestrian traffic, exacerbates trail degradation. The Portal do Palmiro trail ascends the slope of the Serra Geral range, exhibiting marked elevation changes from its lowest point at the trail head to its peak at 97 m above sea level. Consequently, the pathway features minimal flooded areas due to these slope gradients. Three specific vulnerable locations were identified, totaling 50 m (ma) of flood-prone trail segments out of a total trail length (mt) of 2 452.43 m. These parameters yield the following formula:

$$\mathbf{CFx}\boldsymbol{alag} = 1 - \frac{\mathbf{MLx}}{\mathbf{MTx}} \qquad \mathbf{CFx}\boldsymbol{alag} = 1 - \frac{\mathbf{MLma}}{\mathbf{MTmt}} \qquad : 1 - \frac{50}{2452{,}43}$$

Social Correction Factor

It takes into account: i) space occupied by a person, ii) minimum distance between groups on the trail, and iii) internal access points.

To enhance the management of visitor flow and improve overall satisfaction, it is suggested that visits be structured into groups based on the following conditions, particularly when multiple guides are available. In such instances, it is advisable to add 50 m to the distance necessary for each group, contingent upon the number of groups (NG) that can concurrently traverse each path. The outcomes can be derived using the subsequent equation:

$$\textbf{Formula}: \qquad \mathbf{NG} = \frac{\textbf{Total trail length(m)}}{\textbf{Distance required by each group(m)}}$$

$$\mathrm{NG} = \frac{2452{,}43\mathrm{m}}{50m} \qquad \mathrm{NG} = 49{,}04\mathrm{m}$$

Following the identification of the number of groups (NG), calculating the social correction factor requires determining the number of individuals (P) that can concurrently occupy each track, with the outcome derived from the formula:

$$\mathbf{P} = \mathbf{NG}\,(\textbf{Number of Groups}) \times \textbf{number of people per group}$$

$$\mathrm{P} = 49 \times 35 \qquad \mathrm{P} = 1725$$

Upon establishing the number of groups, the calculation of the Social Correction Factor (FCsoc) necessitates the identification of the Limiting Magnitude (ML). In this context, ML refers to the segment of the path that remains unoccupied due to the requirement of maintaining a minimum distance between groups. Consequently, considering that each individual occupies 1 m of the path, the limiting magnitude is equivalent to:

$$\textbf{Formula}: \quad \mathbf{MLx} = \mathbf{mt} - \mathbf{P} \qquad \mathrm{MLx} = 4512{,}47 - 1725 \qquad \mathrm{MLx}\,(\mathrm{trail}) = 2787{,}47\mathrm{m}$$

$$\mathbf{CF}\boldsymbol{soc} = 1 - \frac{\mathbf{MLx}}{\mathbf{MTx}} \qquad \mathrm{CF}soc = 1 - \frac{2787{,}47}{4512{,}47} \qquad \mathrm{CF}soc = 0{,}38$$

A significant point to note is that the group size was estimated to be 35 individuals, which is the largest group recorded on the Portal do Palmiro trail, as stated by the guide and proprietor of the site. By applying the correction factors established based on the trail's characteristics, one can determine the Real Carrying Capacity (RCC), which is represented as follows:

$$\mathbf{RCC} = \mathbf{FCC}\left(\mathbf{CF}_{\boldsymbol{prec}} \times \mathbf{CF}_{\boldsymbol{temp}} \times \mathbf{CF}_{\boldsymbol{urel}} \times \mathbf{CF}_{\boldsymbol{vvent}} \times \mathbf{CF}_{\boldsymbol{erod}} \times \mathbf{CF}_{\boldsymbol{aces}} \times \mathbf{CF}_{\boldsymbol{alag}} \times \mathbf{CF}_{\boldsymbol{soc}}\right)$$

$$\mathrm{RCC} = 10744\,(0{,}12 \times 0{,}94 \times 0{,}66 \times 0{,}96 \times 0{,}87 \times 0{,}57 \times 0{,}97 \times 0{,}38)$$

$$\mathrm{RCC} = \mathrm{FCC}\,(144{,}70)$$

Calculation of Management Capacity

Reflect on the endeavor and the resources provided in the service for the visitor, including personnel, facilities, tools, and the operational hours of the location. It is assessed by contrasting the ideal conditions required for effective management of the area (sufficient capacity) with the actual conditions present (installed capacity). This is quantified as the current state represented as a percentage and fluctuates based on the specific characteristics of each area (Cifuentes 1992). Table 7 illustrates the categories and variables used for assessing Management Capacity.

Management capacity is determined by averaging the factors associated with the three variables, expressed as a percentage, structured as follows:

$$\mathbf{MC} = \frac{(0,43) + (0,59) + (0,40)}{3} \times 100$$

$$\mathbf{MC} = 47.33\%$$

Based on the project specifications, a comparison with its actual implementation revealed several categories and subcategories for evaluating management capacity (Cifuentes 1992). Figure 4 illustrates the project's current infrastructure.

Table 7 Categories and variables for evaluating management capacity

Category	Management Variable	Existing Capacity (A)	Ideal Minimum Capacity (B)	intersection A/B (%)
Infrastructure	Parking	1	1	100
	Meeting Point	1	1	100
	Women's Restroom	1	1	100
	Men's Restroom	1	1	100
	Internet (Wi-Fi)	1	1	100
	Guesthouses[1]	2	9	22
	Showers	2	2	100
	Restaurant/Snack Bar	0	1	0.00
	Trail start and end signs	1	2	50
	Guidance signs along the route (arrows indicating the way)	0	8	0.00
	Information signs: Historical/Archaeological	6	4	100
	Information signs: Biodiversity (fauna and flora)	0	2	0.00
	Information signs: Geodiversity (Geological and geomorphological formations)	0	1	0.00
	Stand for selling souvenirs and local crafts	0	1	0.00
	Payment methods: Cash, (Card (Debit/Credit)), PIX[2]	2	3	66
	Rest areas (benches, chairs)	0	4	0.00
	Dissemination, information and contact			
	Informative brochure/Trail map	0	1	0.00
	Social media (WhatsApp, Instagram, and Facebook)	2	3	66
	Own website	0	1	0.00
	Promotion on other platforms (Airbnb, Booking, Geopark website)	0	1	0.00
	Telephone (exclusively for customer service)	0	1	0.00
Equipment	Walkie-talkies	2	2	100
	Leg guards	10	35	28
	Caps	35	35	100
	Protective helmets	10	35	28
	Rescue stretcher	0	1	0.00
	First aid kit (mask/gloves/gauze/adhesive tape/splints/slings)	1	1	100
Human resources	Guides/Drivers First Aid Responder	2	2	100
	Secretary/Receptionist	0	1	0.00
	Organization/Cleaning Staff	1	1	100
	Housekeeping Staff	0	1	0.00
	Guides/Drivers First Aid Responder	0	1	0.00

[1]In this instance, the highest number of individuals (35) ever recorded for visitation within the same group was taken into account

[2]PIX is a rapid payment system developed in Brazil and extensively utilized by its citizens

Figure 5 illustrates the current offerings in equipment development.

Calculation of Effective Carrying Capacity (ECC)

ECC represents the highest number of visits permitted in a specific location during a designated time frame, contingent upon the Operational Capacity to effectively organize and oversee these visits. The determination of ECC is achieved by modifying the Management Capacity of the administration responsible for the tourist area or space. Its computation is carried out using the following formula:

$$\mathbf{ECC} = \mathbf{RCC} \times (\mathbf{CM}\%)$$

$$\mathrm{RCC} = 144{,}70 \times 47.33 \quad \mathrm{ECC} = 68.62$$

The findings related to the identification of the TCC are illustrated in accordance with the model displayed in Table 8.

Discussions

In the context of geotourism activities, even on privately owned land, it is crucial to take into account several significant factors regarding these trails. Crafting a tourism



Fig. 4 Project infrastructure. Legend: (**A**, **B** and **C**) guesthouses, parking, restrooms; (**D**, **E** and **F**) information signs; (**G**, **H** and **I**) social media.Source: Author, 2024

strategy that aligns more effectively with the evolving circumstances of the area where a UGGp is situated is vital for establishing a long-term sustainability outlook for the destination. Consequently, determining a sufficient number of visitors for a specific site ought to be among the primary considerations in tourism planning for a particular business (Delgado 2007).

Consequently, the determination of the TCC for a given location is contingent upon its unique characteristics, necessitating a separate assessment for each individual site. It is crucial to establish and execute a monitoring program aimed at evaluating the effects of visitation on the CCSUGGp GIS (Lima et al. 2017), with regular modifications to management strategies, as establishing the TCC would be futile without effective trail monitoring.

The establishment of the TCC for the Portal do Palmiro trail marks a significant achievement in the sustainable management of natural spaces under the CCSUGGp framework. This research offers a model that quantifies visitor capacity while also encouraging dialogue regarding suitable management strategies in delicate environments.

The findings suggest that the ECC of the trail accommodates an average of 69 visitors daily. It is important to clarify that this figure represents the average number of visits the trail is capable of receiving; minor fluctuations on a daily basis may occur. Additionally, this figure takes into



Fig. 5 Equipment available at the site. Legend: (**A**) walkie-talkie; (**B**) leg protectors and helmets; (**C**, **D** and **E**) first aid kit (mask/gloves/gauze/adhesive tape/splints).Source: Author, 2024

Table 8 TCC results for attraction visitation

Tourist carrying capacity	Trail: paleotoca toca do tatu/portal do palmiro, in the municipality of timbé do sul
Physical (FCC)	**10 744 visits/day**
Environmental Correction Factor	**(%)**
CF*pre*	0.12
CF*temp*	0.94
CF*urel*	0.66
CF*vven*	0.96
Physical Correction Factor	**(%)**
CF*erod*	0.87
CF*aces*	0.57
CF*alag*	0.97
Social Correction Factor	**(%)**
CF*soc*	0.38
Real (RCC)	**144,70 ~ 145 visits/day**
Management Capacity (CM)	**47.3**
Effective (ECC)	**68,62 ~ 69 visits/day**

Source: Source: Author, 2024

account the particular environmental, physical, and social constraints of the study area.

It is crucial to emphasize that the activities undertaken on the Portal do Palmiro trail occur within a natural setting that necessitates careful management due to its delicate nature. This management is effectively executed by the property owner, who ensures that the trail remains clean for visitors.

The analysis indicated that elements such as precipitation (CFprec = 0.12) and relative air humidity (CFurel = 0.66) significantly limit the situation, illustrating the climatic conditions of the region and their direct effects on visitor safety and experience. The vegetation cover, which shields the trail from excessive solar exposure (98.7%), has been shown to be beneficial for the sustainable utilization of the area. This modification underscores the significance of correction factors, which guarantee that the management of the area aligns with environmental conservation and visitor safety.

The results support research conducted by Rocha et al. (2021), which highlight the necessity for regional modifications in the implementation of Cifuentes' methodology (1992). Nevertheless, disparities arise when contrasting regions with milder climatic conditions, such as those found in areas with reduced rainfall.

The information provided establishes a robust foundation for the formulation of management policies. By restricting visitation to 69 visitors per day, the pressure on the trail's delicate ecosystem is alleviated, especially in regions vulnerable to erosion and flooding along the path. This measure also enhances the experience for tourists, facilitating a more genuine and secure engagement with the natural surroundings, thereby fostering geotourism.

The constraints of this study are inherently associated with the methodology employed. While numerous methodologies are available for assessing the TCC, the one most

commonly utilized in Latin American nations is that proposed by Cifuentes (1992) (Galeano et al. 2023). Certain scholars (Delgado 2007; Soria-Díaz et al. 2022) argue that Cifuentes' (1992) methodology is lacking, as the criteria applied are significantly subjective, both in quantitative and qualitative terms. Nevertheless, investigations such as those conducted by Rocha et al. (2021) suggest that adaptations and modifications to the methodology are feasible and should be implemented variably across different locations.

Delgado (2007) highlights that a significant weakness in this methodology is found in the correction factors employed, as the author notes that in the majority of studies concerning TCC, connections are drawn between disparate elements that lack a scientific correlation with the binomial: number of visitors and the impacts generated.

In order to tackle this issue, the present study aimed to employ correction factors that were considered essential for the study area and for which data was accessible. Specifically, the trail under analysis is situated in a mountainous slope region characterized by a significantly high rainfall index; thus, rainfall was regarded as the main reference point.

As noted earlier, the approach suggested by Cifuentes (1992) does not define a specific quantity of rainfall to be taken into account; this will differ from one region to another.

As posited by Soria-Díaz et al. (2022), it is inappropriate to define a specific 'magic' number of visitors that would have no effect on the environment being visited. While the method introduced essentially yields a quantitative outcome for the particular trail, it should not be regarded as a fixed figure; rather, it ought to function as a reference point for estimating future activities (Pires 2005).

Moreover, the evaluation of handling capacity uncovered deficiencies in the infrastructure and services provided, including inadequate signage, which may jeopardize the safety and overall experience of visitors. Consequently, from a management standpoint, it is essential to enhance the trail's infrastructure, especially in terms of signage, rest areas, marketing, and the sale of souvenirs. The implementation of informational signs pertaining to geodiversity and local biodiversity would represent a substantial advancement, benefiting both environmental education and emergency preparedness.

The significance of enhancing the infrastructure of information boards is emphasized, as they possess the ability to convey information to visitors in a more straightforward and accessible manner. According to Lima et al. (2017), interpretive panels serve to inform and elucidate specific facts about the region, foster visitor engagement, and promote awareness of appropriate conduct during their visit. A crucial sign at the start of the route should, at the very least, provide information regarding distance, route conditions, trail difficulty level, and its carrying capacity.

It is important to highlight that while this study establishes the carrying capacity for the access trail, the internal management of the paleoburrow requires specific operational controls due to its confined and fragile subterranean environment.

Although trail groups may comprise larger numbers (historically up to 35 individuals), access to the interior of the Toca do Tatu paleoburrow is strictly regulated by local guides and tour operators. In accordance with guidelines established by the Geopark's technical team, visitors enter the cavity in smaller sub-groups of no more than 10 people at a time to prevent overcrowding and safeguard the delicate geological and paleontological features (Ricetti et al. 2024) (Fig. 6).

Additionally, mandatory safety protocols, such as the use of protective helmets and a strict prohibition against touching or vandalizing the sandstone walls, are enforced during all internal visits. Recent work by Miranda et al. (2026), which aims to classify this trail, already clearly demonstrates local concerns regarding visitation to these structures.



Fig. 6 Entrance of the paleoburrow. Legend: (**A**) Visitors receiving instructions before entering; (**B**) Observing the engravings on the ceiling.Source: Author, 2024

Final Considerations

Since the inception of the UGGps in Brazil, there has been a notable rise in new tourist destinations and regions, alongside a marked increase in visitor numbers, particularly following 2022, when new territories were officially recognized (Silva et al. 2024, 2025).

However, the rapid identification, development, and promotion of new attractions can lead to irreversible adverse impacts if not supported by rigorous planning and qualified professionals. To address this, this study characterized and defined the TCC of the Portal do Palmiro trail, which leads to the Paleotoca Toca do Tatu. The main conclusions of this study are outlined below:

(i) The TCC, taking into account the most specific categories and characteristics based on the maximum number of permitted visits, including factors such as personnel, infrastructure, and equipment, culminated in a final total of 69 individuals per day;
(ii) While not a significant element in determining the effective capacity of the trail, the absence of signage can serve as a beneficial aspect during emergencies. It is advisable to place informational signs that direct individuals and emergency services, such as firefighters, who may need to reach the trail for rescue operations.
(iii) It is evident that, frequently, the assessment of TCC is conducted post-exceedance of the capacity, rather than serving as a tool for prior planning. Despite the Portal do Palmiro trail being frequented for many years, the surge in visitation took place following the endorsement by CCSUGGp and the promotion through national networks;

The defined TCC for the Portal do Palmiro trail should not be viewed as a definitive endpoint in the overall analysis; rather, it serves as a diagnostic tool that facilitates a comprehensive understanding of the project's specific requirements. This, in turn, enables the implementation of targeted solutions that effectively address identified challenges and objectives, providing a baseline for future planning and management.

Given the importance of this methodology in guiding managerial actions and operational procedures, it can be applied systematically at specific intervals, such as weekly, monthly, semi-annually, or annually. Cifuentes (1992) recommends adapting the framework to suit each unique context, taking into account the distinct biophysical and operational characteristics of the site.

In the case of the Portal do Palmiro trail, the primary methodological adaptations focused on adjusting correction factors to account for local environmental, physical, and social conditions—particularly in areas already degraded or vulnerable due to high visitor volume. These modifications allowed the method proposed by Cifuentes (1992) to be refined according to site-specific conditions, incorporating parameters such as slope, erodibility, precipitation, and management infrastructure, all of which directly influence carrying capacity and visitor experience quality. Although the Portal do Palmiro trail currently lacks a formal visitor management system, these findings indicate that the methodology is an effective decision-support tool for spatial and environmental planning.

The application of this approach enhances visitor flow management, balancing tourism activities with environmental conservation and mitigating adverse impacts that could compromise the ecological and geological integrity of the site. Consequently, effective oversight of tourist activities is essential to safeguarding natural and cultural heritage, preventing uncontrolled degradation that could lead to irreversible environmental or heritage damage.

More broadly, this research highlights the strategic importance of UGGp in Brazil as catalysts for sustainable geotourism. By integrating conservation, education, and community development, these areas serve as key models for implementing innovative territorial management strategies.

Ultimately, this study underscores the necessity of policies and frameworks that reconcile geoconservation and ecosystem protection with sustainable tourism development. Such integration yields tangible socio-economic benefits for local communities, thereby strengthening the synergy between geoconservation, sustainability, and regional development.

Acknowledgements The authors express their gratitude to the Caminhos dos Cânions do Sul UNESCO Global Geopark for the technical assistance provided throughout the research. They extend special thanks to the proprietors of the Portal do Palmiro trail, Mr. Valdivino Alano and Mrs. Marta Licks Baumarth, for their hospitality and support during the researchers' visit.

Author Contributions The study's conception and design involved contributions from all authors. Data collection was carried out by Luciano Miranda, José Gustavo Santos da Silva and Juliano Bitencourt Campos. The preparation and analysis of materials were conducted by Luciano Miranda, Álvaro José Back, Gabriel da Silva Souza, Jairo Valdati, Gustavo Simão and José Gustavo Santos da Silva. The initial draft of the manuscript was authored by Luciano Miranda and José Gustavo Santos da Silva and Juliano Bitencourt Campos, with all authors providing feedback on earlier drafts. Each author reviewed and approved the final version of the manuscript. The concluding review was undertaken by Juliano Bitencourt Campos, Jairo Valdati, Gustavo Simão and Álvaro José Back.

Funding The Article Processing Charge (APC) for the publication of this research was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) (ROR identifier: 00x0ma614). This study was financed in part by the 'Coordenação de

Aperfeiçoamento de Pessoal de Nível Superior'—Brazil (CAPES)—Finance Code 001. This study was financed in part by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the postdoctoral fellowship awarded to the last author (150258/2025–9) and the Research Productivity Scholarship awarded to the second author (312543/2022–0).

Data Availability The author confirms that all data generated or analysed during this study are included in this published article.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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