**Management of degraded trails in protected natural areas worldwide: a systematic review of scientific literature**

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**Abstract**

The increase in the use of trails for outdoor recreation observed in recent decades has led to greater pressure on existing trails and the creation of informal new trails, resulting in damage and degradation of these infrastructures. This degradation is concerning because many of these trails are located in protected natural areas, which aim to conserve natural resources and associated biodiversity. Concurrently, ecosystems worldwide have also been experiencing increased degradation, prompting the United Nations to declare the current decade as the Decade for Ecosystem Restoration. In this context, through a systematic review of the scientific literature, we aimed to better understand what science has discovered to enhance the management of degraded trails in protected natural areas worldwide. We observed that the number of research studies has been growing, particularly in the last decade, and is concentrated in countries with developed economies and by researchers from these countries. The terms used to describe a trail are quite diverse in the literature. Furthermore, some terms used in trail management, such as building or construction, maintenance, and repair, are uniformly utilized by authors. However, terms to address the reversal of trail degradation, such as restoration, recovery, and rehabilitation, are used quite variably among authors. Thus, future research could help clarify the use of these terms. We also noted that many studies have been dedicated to investigating the state of degradation of the trails in protected areas. However, only a minority of articles have addressed strategies to reverse the scenario of trail degradation, especially through experiments to identify the most effective strategies for different situations. This observation is concerning since the degradation of ecosystems and trails can become extremely costly or even irreversible. Therefore, further scientific studies are crucial to improve trail management, especially to reverse the scenario of trail degradation in protected natural areas.

**Keywords**

Outdoor recreation management

Path rehabilitation

Trail degradation

Trail erosion

Trail restoration

Trail maintenance

**1. Introduction**

Effective management and restoration of environments degraded by human activities currently stand as a global priority (Nelson et al., 2024). Anthropogenic actions have affected diverse environments, including trails used for outdoor recreation. The use of trails for commuting and access to certain places dates back to the origins of humanity. Trails have been the primary means of connecting people among small human settlements and, more recently, to natural environments such as forests and mountains. Historically, trails have been created intuitively, with the goal of accessing certain areas in the shortest and most direct way possible or exploring environments with geological, natural, historical, or cultural attractions (Bratton et al., 1979; Marion, 2023; Campbell, 2024). Thus, little attention has been paid to the sustainability of these infrastructures, especially regarding the conservation of their natural resources and the practicality of their management (Rangel et al., 2019).

The lack of planning and sustainable design of trails can, over time, result in environmental impacts that may require high investments for their maintenance or repair (Marion, 2023). This scenario can worsen with the increase in the number of users or due to users' behavior, such as off-trail trampling (Spernbauer et al., 2023). When located in protected natural areas, such impacts can become incompatible with the main objectives of these areas, which are often precisely the conservation of their biological, geological, and cultural attributes. Especially since the second half of the 20th century, visits to protected natural areas (hereinafter, PNAs) have increased. As a result, the heightened interest in outdoor recreation activities on trails, particularly in PNAs, presents a new global challenge (Evju et al., 2021). Consequently, research into the impacts of outdoor recreation on trails has expanded to better understand the effects of these activities on natural resources (Ballantyne and Pickering, 2015; Salesa and Cerdà, 2020).

Much has been discovered about the inherent impacts of outdoor recreation activities on the ecosystem and biodiversity (Barros and Pickering, 2017; Sumanapala and Wolf, 2019), including effects on animals (Miller et al., 2020), plants (e.g. Thurston and Reader, 2001), geology and especially soil loss (Tomczyk and Ewertowski, 2011; Fang and Ng, 2024). Soil loss occurs mainly through erosion processes, which implies the removal of topsoil layers that can occur through natural processes such as water runoff or wind, and can be accelerated by anthropogenic activities (e.g. vegetation removal, soil compaction). Soil erosion due to water is the main form of soil loss and is considered an irreversible process (Bratton et al., 1979; Marion et al., 2006; Salesa and Cerdà, 2020). This phenomenon can also lead to degradation, a persistent deterioration of an ecosystem due to human actions that affect both the ecosystem's ability to provide benefits to people and nature (MEA, 2005; Nelson et al., 2024) and its capacity to naturally return to its original or pre-impact state (Reis et al., 1999). Nevertheless, several authors have demonstrated the beneficial effects of nature-based outdoor activities on people's physical and mental health and well-being, including for people undergoing treatment for some illness (Coventry et al., 2021; Gobster et al., 2023). Therefore, PNA managers must strike a balance between the benefits of outdoor activities as cultural ecosystem services and their impacts that negatively affect the provision of supporting and regulating ecosystem services, such as erosion regulation (MEA, 2005; Tomczyk et al., 2016; Marion, 2023).

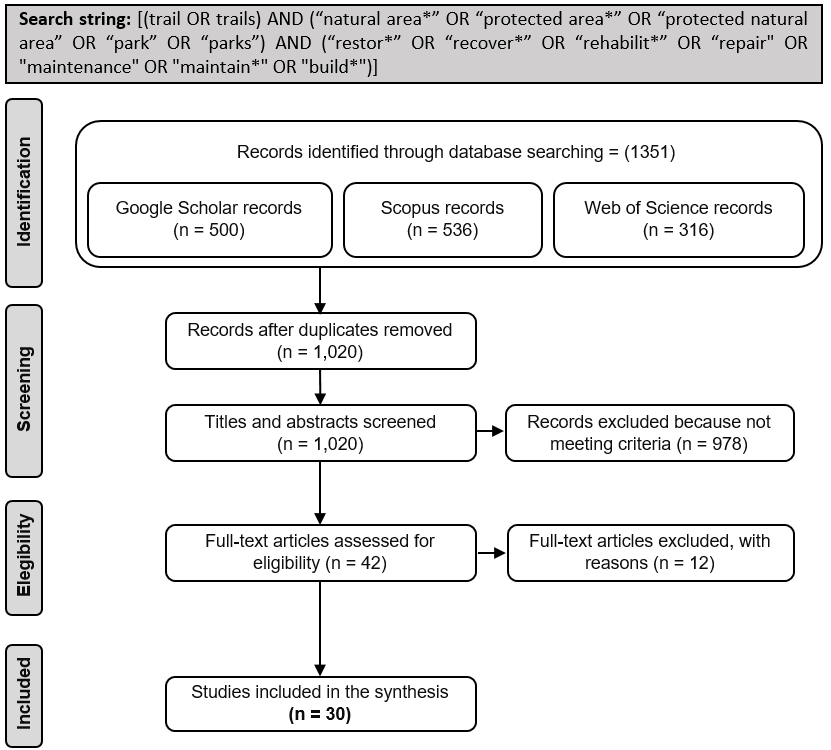
Research has been investigating the main bases of trail sustainability, namely managerial, resources, social, and economic pillars. Research regarding all these factors has significantly improved the sustainability of new trails. However, there are already widespread networks of trails in PNAs whose sustainability needs to be analyzed. Some of them were created unintentionally (visitor-created informal trails) and have been established over time. Those created intentionally were mainly built intuitively, rarely based on technical recommendations grounded in scientific evidence (Marion, 2023). In some cases, trails remain stable, but in many others, due to the interaction of various aforementioned factors, trails require constant maintenance to remain in adequate condition. Without such intervention, they can be severely damaged and reach a stage of degradation (Bratton et al., 1979; Rangel et al., 2019), which deteriorates the aesthetics of the area and makes its use more difficult and less safe. In more advanced stages, if no maintenance is done to curb degradation, it can spread (Nepal, 2003; Marion et al, 2006). In these cases, what can be done? What has trail science evidenced about practices for the management of degraded trails in PNAs worldwide? Considering that the world is entering the United Nations - UN Decade on Ecosystem Restoration (2021 - 2030) (Nelson et al., 2024), have scientists given due attention to the restoration of degraded trails in protected natural areas? To advance scientific knowledge in this area, it is crucial to have a clearer and broader understanding of the state of the art regarding the management of degraded trails.

In this context, this systematic literature review aims to provide insights into the management of degraded trails in protected natural areas by answering the following questions: (1) When was the research published? (2) Where was the research conducted? (3) Who did the research? (4) In which journals was the research published? (5) What terminologies were used in science for trail management? (6) What were the main subjects of study and their main findings?

# **2. Methodology**

Within the scope of this review, we considered articles that investigated any actions or practices aimed at curbing, mitigating, or reversing trail damage or degradation processes—including building, maintenance, repair, restoration, recovery and rehabilitation—in PNA´s worldwide. Consequently, to be selected, a scientific article must have explored at least one of the managerial, resource, social, or economic factors related to trail sustainability (Marion, 2023) that are in some way associated with reversing trail damage or degradation. In this review, we adopted a broad approach to what was considered a trail, taking into account any linear segment that has been described as used by people for conducting outdoor activities in PNAs. Also, as no definitions for “damage” and “degradation” were found, we considered any mentions or descriptions of impacts on the physical structure of the trail and its surroundings, such as soil compaction, erosion, and changes in the surrounding biota. Thus, we also conducted an analysis of the main terms used, both in the title and throughout the article, to refer to a trail and the practices for reversing degradation.

To access published research in this scope, we conducted this review using the systematic quantitative literature review (SQLR) methodology proposed by Pickering and Byrne (2014). In addition, we followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) recommendations (Moher et al*.*, 2009). We analyzed Google Scholar, Scopus and Web of Science databases. For the Google Scholar database, we used the method proposed by Pickering and Byrne (2014), analyzing blocks of 50 articles (abstracts) starting from the first selected one. We stopped analyzing the blocks when the last one had no abstract considered within the review ́s scope by at least two of the three evaluators, indicating a low probability of finding another relevant paper in the following blocks. Using the search string (Fig.1) we selected articles published in English until February 6, 2024, filtering by title, abstract and keywords. This way, we encompassed the majority of scientific articles related to the main issue of this systematic review. Excluding the repeated papers, we analyzed the abstracts of 1,020 articles. Those considered aligned with the main goal of this study were selected for full reading. After a thorough examination, 30 were deemed relevant and were carefully analyzed. We found 28 research articles and two review articles.



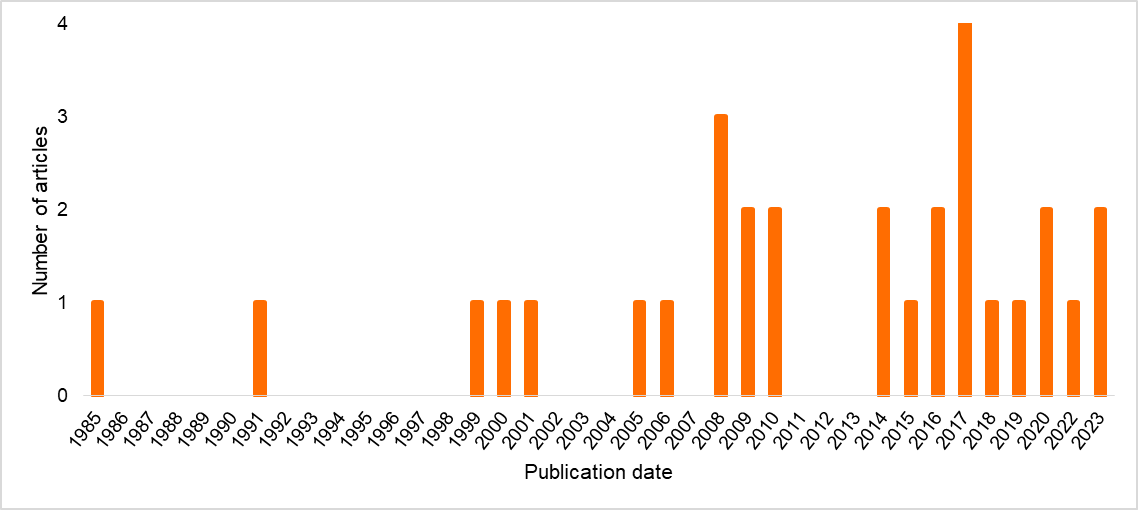
**Fig. 1.** Methodological flowchart showing the number of articles retained at each stage of the systematic search of the scientific literature.

The data obtained through the detailed analysis of the selected articles were analyzed using various tools. The map showing the distribution of articles in their respective countries was created using ArcGIS PRO software (ESRI, 2024). The citation network was developed using Litmaps software (Litmaps, 2024). The word cloud was created using R software (R Core Team, 2023) with the WordCloud (Fellows, 2018) and RColorBrewer (Neuwirth, 2022) packages.

**3. Review finds**

**3.1.** **When was the research published?**

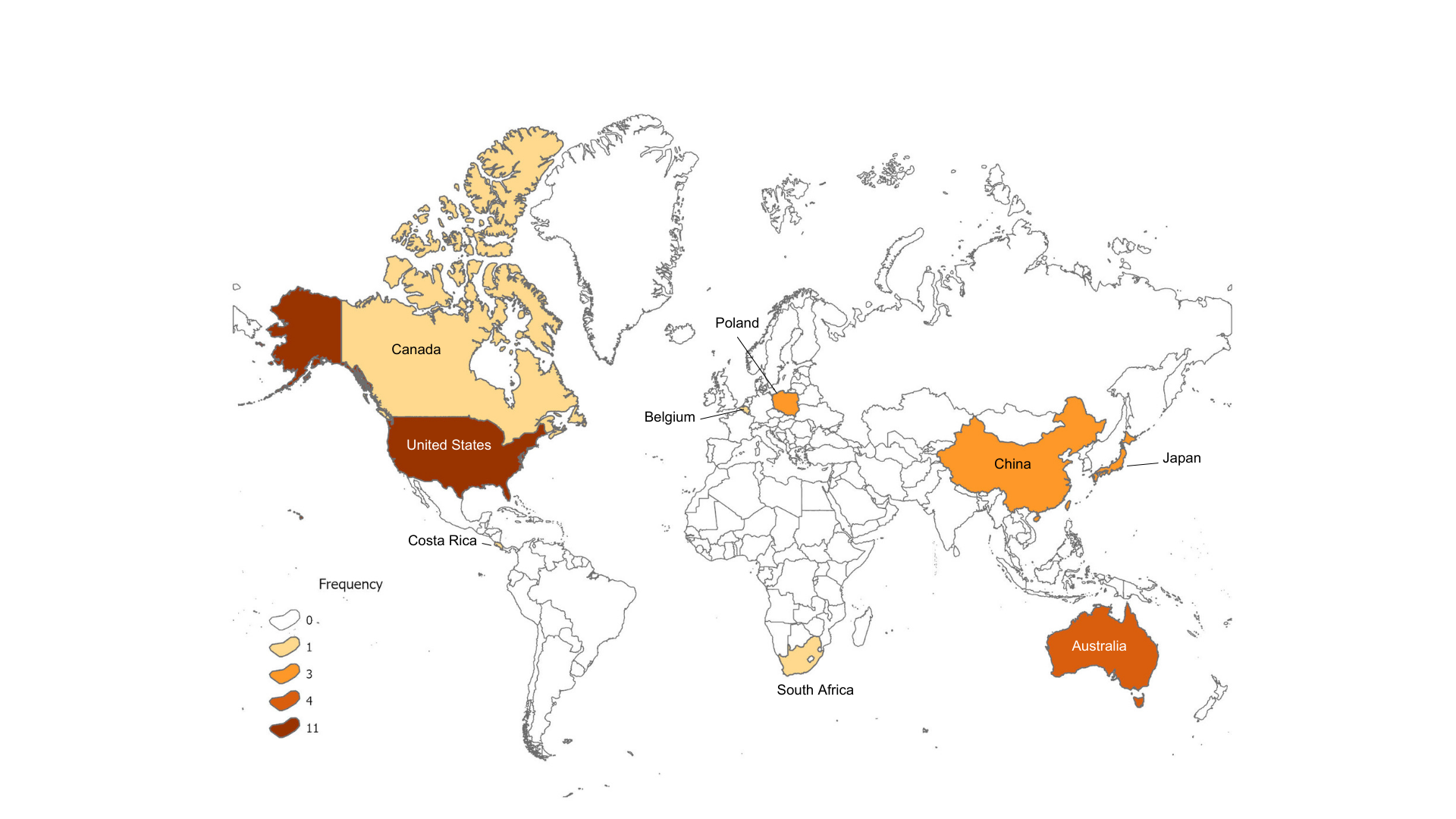
Fitting the inclusion criteria of this SQLR, 30 articles were found. The oldest article identified by this literature search dates back to 1985. During certain periods, there were no publications in this area, such as from 1992 to 1998. The number of articles has shown an increasing trend in recent years (2014-2023), both in total count and in annual frequency of publications (Fig. 2).



**Fig. 2.** Number of articles published on the management of degraded trails.

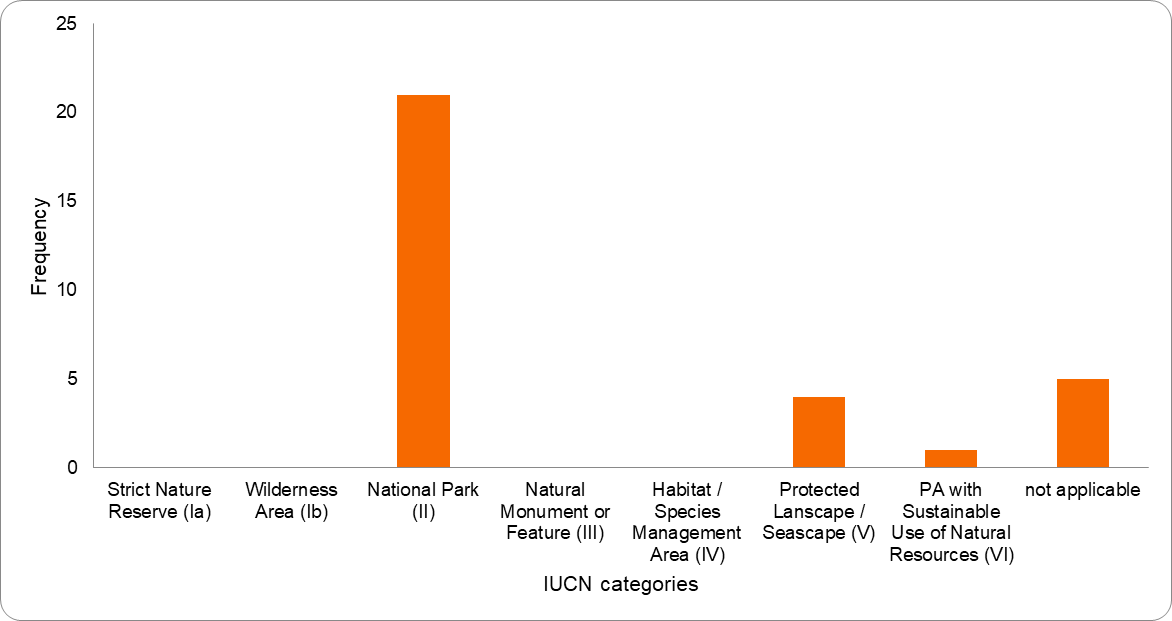
**3.2. Where was the research conducted?**

The majority of research has been conducted in countries with advanced economies such as the United States (11), Australia (4), and Japan (3), as well as in emerging and developing economies (IMF, 2023) such as China and Poland (3 each) (Fig. 3). The remaining studies were distributed in South Africa, Belgium, Canada, and Costa Rica (1 each).

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**Fig. 3**. Number of research studies conducted in each country around the world.

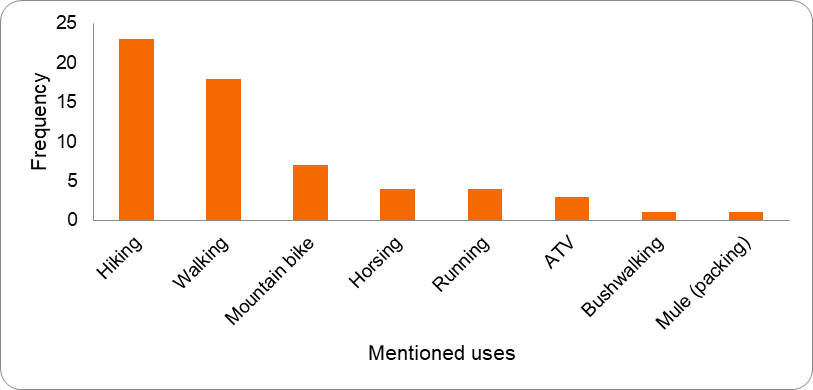
Taking in consideration the specific site where the study was conducted, the majority of the articles (25) sampled some PNA. In three articles, it was unclear whether the sample was a legally established PNA, but all three appear to have been conducted in public PNAs. The conservation status of these PNAs falls into three out of six categories according to the International Union for Conservation of Nature (IUCN) criteria (Dudley, 2008). Notably, the majority of articles (21) were conducted in areas classified as National Parks (IUCN category II). Four articles were in Protected Landscape/Seascape (category V), one in the Sustainable Use of Natural Resources category (category VI), and four protected areas could not be classified under IUCN categories (Fig. 4).



**Fig. 4.** Number of articles conducted in PNAs, classified by the IUCN categories.

We also attempted to identify whether the trails studied were located in forested or non-forested environments. Seven articles analyzed trails in forested environments, three in non-forested environments, and three in both. However, clear information on this aspect was not provided in most articles (17 articles).

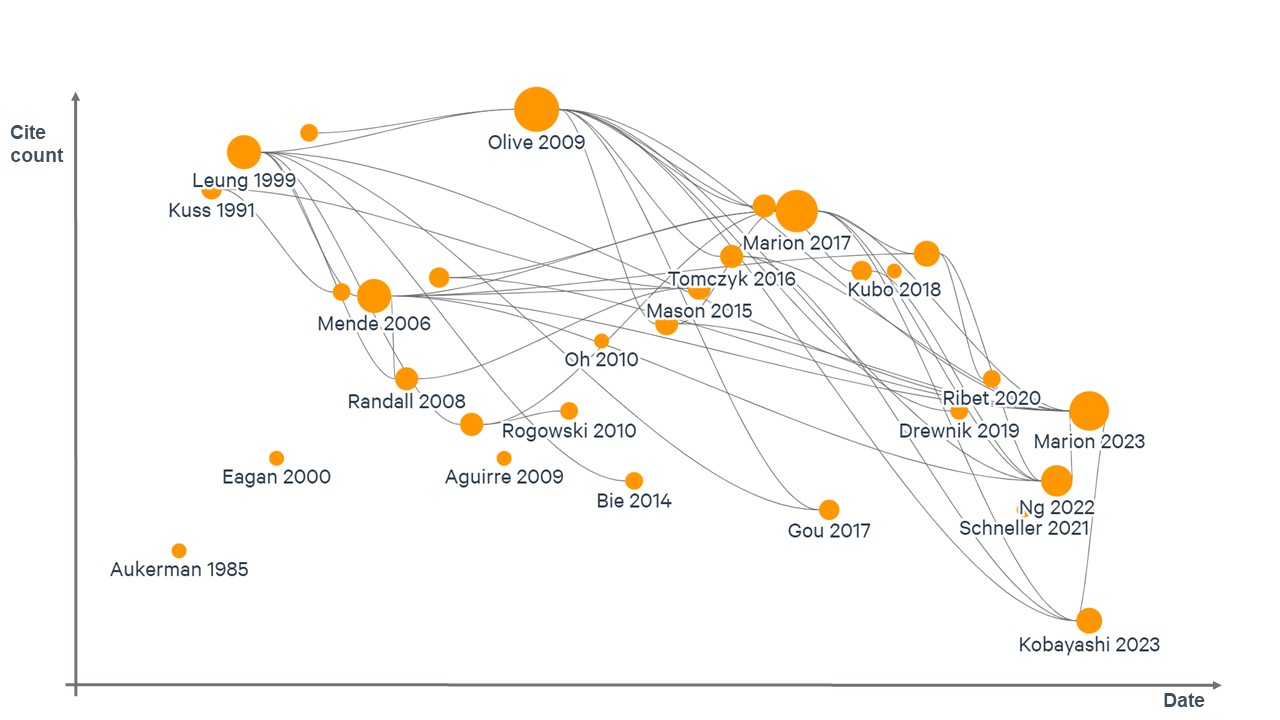
Regarding the activities conducted on these trails or mentioned as being carried out, hiking was prominently featured (mentioned in 23 articles), followed by walking (18), mountain biking (7), horseback riding, and running (mentioned in 4 articles each). All-terrain vehicle (ATV) use was mentioned in 3 articles, while bushwalking and mule (for packing) were each cited once (Fig. 5). None of the articles described or mentioned any criteria used to categorize their activities, such as the measured metabolic equivalent (MET) proposed by Herrmann et al., 2024, to distinguish between activities like hiking, walking, or bushwalking.



**Fig. 5.** Number of articles citing each activity as being carried out on the trails.

**3.3. Who did the research?**

The affiliations of authors in the reviewed articles presents a similar distribution across countries: United States (14), Australia (5), China, Japan, and Poland (3 each), with additional contributions from South Africa, Belgium, Canada, Costa Rica, the Netherlands, and the United Kingdom (1 each). Notably, the review highlights significant contributions from Olive and Marion (2009), cited in nine articles, and Leung and Marion (1999), cited seven times, marking notable trends in the field (Fig. 6). Additionally, the articles by Leung and Marion (1999), Mende and Newsome (2006), Olive and Marion (2009), Marion and Wimpey (2017), Ng (2022) and Marion (2023) stand out for their general relevance in the literature. Marion stands out for his prolific output, being the primary author of three articles and a co-author on four others.



**Fig. 6.** Network chart representing articles from this paper's database. The articles are connected by lines, indicating citations between them. The vertical axis represents the citation count (logarithmic), and the horizontal axis represents the publication date of the article, from 1985 to 2023. The size of the circles represents the relevance of each article (based on various metrics of significance).

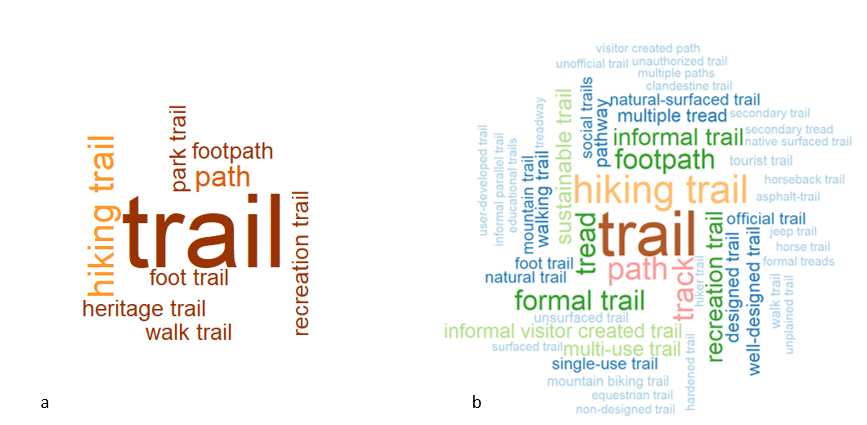
**3.4. In which journals was the research published?**

The articles were published in 21 scientific journals, but were concentrated in five journals. Six articles were published in the Journal of Environmental Management, which has been the foremost forum for the discussion of the theme of this review. In the journals Conservation Science Western Australia, Environmental Management, Journal of Park and Recreation Administration, and Land Degradation and Development, two articles were published in each. The other 16 journals had one article each. Notably, 62% of these journals are classified under Environmental Science in the Scimago Journal & Country Rank, with other subject areas such as Social Science (33%), Agriculture and Biological Sciences (24%), and Business, Management, and Accounting (19%) also represented (Fig. 8).

### **3.5. What terminologies were used in science for trail management?**

In the scientific community, there is no universally accepted definition of terms such as trail, path, or track for outdoor recreation based on objective parameters such as minimum/maximum width and length, type of surface, types of uses, etc. For instance, distinctions between narrow trails for solitary use versus wider trails for groups, forest roads, or paths for horseback riding are not consistently defined in the literature. This lack of conceptualization underscores the need for clarity in describing and naming these essential infrastructures for outdoor recreation.

Analysis of article titles, considering only the strict term, reveals "trail" (present in 21 titles) and "path" (in three titles) as common terms. Expanded forms include "trail" (13), "hiking trail" (3), "path" (2), "foot trail" (1), "footpath" (1), "heritage trail" (1), "park trail" (1), "recreation trail" (1), and "walk trail" (1) (Fig. 7a). Considering the entire article three terms were observed to be the main term used to define a trail: trail (observed in 28 articles), path (1) and track (1). Considering their derivatives, 50 compound terms were observed to name or classify types of trails in the studies (Fig. 7b, Appendix in Supplementary Materials). Various terms describe trails not officially designated by PNAs or the act of going off official trails, including "off-trail" (8 articles), "multiple-treads" (5), "informal trails" (4), "trail proliferation" (4), and "trail braiding" (4). "Informal visitor-created trail," "shortcuts," and "social trails" appeared in 3. "Off-tread" and "visitor created trail" were mentioned twice. Finally, "informal trail proliferation," "multiple-paths," "multiple-rut," "secondary tread formation," and "visitor created path" were all mentioned once.



**Fig. 7.** **a.** Word cloud with the main terms used to name "trails" in article titles. The font size and color of each word are proportional to the number of titles in which the word was used. **b.** Word cloud with the compound terms used to name “trails” in the full text of the articles. The font size is proportional to the number of articles the words appeared.

Regarding the terms used to describe trail impacts, we observed that the terms “damage” and “degradation” were used without a clear definition in the scientific literature. Often, the presence of a characteristic in a given trail, regardless of its intensity or stage of evolution, was used as a criterion to express that there is a degradation process on the trail. Trail degradation was mainly associated with trail deepness and width, even though they also associated degradation with trail braiding, soil compaction, impacts on surrounding vegetation, exposure of tree roots or the bedrock (*e.g.* Bratton et al., 1979, Nepal, 2003; Randall and Newsome, 2008; Ng et al., 2017; Marion, 2023).

The actions or strategies to mitigate or curb trail damage or degradation was directly or indirectly labeled using different terms. When analyzing the article titles, the most frequently term was “management” (present in eight titles), followed by “maintenance”, “restoration”, and “surfacing” (2 each), and “closure”, “hardening”, “preventing trail erosion”, “recovery”, “reducing off-trail”, “renaturalization”, “repair” (1 each). Additionally, the reversal of the degradation process of a trail, which can occur through different strategies, was labeled in different ways. Analyzing the articles in their entirety, we observed that eight main terms were used to name such strategies. The term "maintenance", including its various conjugations (maintaining, maintained, etc), was observed in 19 articles. "Restoration" was found in 11 articles. "Recover" was used in 10 articles. The terms "building" and "construction" were seen in seven articles each, the term "repair" in four, "rehabilitation" in three, and "renaturalization" in one.  In Table 1, we present how the terms were used in the literature, provide examples of their usage in the articles, and analyze whether the terms were used uniformly or variably among the articles.

**3.6. What were the main subjects of study in the research, and what were their main findings?**

Trail management in PNAs involves managerial, resource, social, and economic issues, which are fundamental to sustainability in this field of study (Marion 2023). This perspective is supported by the results of this review, which indicate that the selected articles addressed various subjects to investigate topics related to the sustainability of degraded trail management. Taking a broad overview of the article's results, articles were grouped based on their main subjects of study related to the management of degraded trails (Table 2). Some articles focused on analyzing how the condition of trail infrastructure influences its sustainability (group 1). Others examined what happens to the soil and vegetation when a trail is closed and abandoned (group 2). Some studies evaluated the effectiveness of active interventions through the implementation of trail features and restoration measures (group 3). Others investigated user-preferred trail management practices (group 4), economic aspects such as willingness to pay for trail maintenance (group 5), and the impact of users' off-trail behavior on natural areas (group 6). Finally, two studies reviewed aspects related to recreation ecology and trail sustainability (group 7).

**Table 1**

Overview of terms used in trail degradation mitigation strategies.

|  |  |  |
| --- | --- | --- |
| **Terms** | **Examples of the use of the terms** | **Summary of usage in literature** |
| **Construction /**  **Building** | Schneller et al. (2020) mentioned the construction of new trails to reduce erosion. | Uniformly applied to describe the creation of new trails. |
| **Maintenance** | Randall and Newsome (2008) described a trail that received regular volunteer maintenance. | Uniformly related to conserving trail conditions, including cleaning, drainage, and minor amendments to maintain passability. |
| **Repair** | Kobayashi and Watanabe (2023) recorded repair work as part of maintenance activities in areas where degradation was most severe. | Uniformly used, mainly as a component of trail maintenance, to address specific issues on the trail, such as major eroded or degraded areas. |
| **Restoration** | Aukerman (1985) used the term to name a project at a PNA. Ramos-Scharrón et al. (2014) used the term to describe from the installation of infrastructure like water bars to the seeding of damaged trails. Tomczyk et al. (2016) used the term “natural restoration” to describe the return of vegetation to an abandoned trail. | Variably applied, both to describe comprehensive projects developed in protected areas or specific improvement actions on the trail. |
| **Recovery** | Mason et al. (2015) used the term “vegetation recovery” following trail closure to describe the return of vegetation to trail path. | Variably employed, generally to a trail no longer in use. Used as the return of vegetation to trail path, as synonym of “renaturalization”, “recolonization” or “revegetation”. Also used to the return of soil properties to the pre-disturbance conditions. |
| **Rehabilitation** | Mende and Newsome (2006) applied the term to describe the final state of a trail after maintenance, indicating it remained in use. Tomczyk et al. (2016) and Kobayashi and Watanabe (2023) used "rehabilitation" to refer to active repair work. | Variably used either to refer to the final condition of a trail following maintenance and to the active form of trail repair. |

**Table 2**

Overview of the main subjects of study of the articles covered by this systematic review, including their purposes and key findings.

|  |  |  |  |
| --- | --- | --- | --- |
| **Subjects of study** | **Main research goals** | **Key findings** | **Studies** |
| Group 1: Trail infrastructure condition assessment | Examines how trail features like drainage influence erosion and vegetation around trails in PNAs | * Primary damages to trails are impacts on the surrounding vegetation and, most notably, soil erosion, which is often irreversible. Certain trail features and proper management practices can mitigate these impacts. * Drainage features such as water bars and grade reversals are used to manage water flow and reduce soil loss. * Full-tread grade reversals are preferred due to their efficiency and low maintenance requirements. * Trail hardening and surfacing practices are useful tools for trails under high visitation pressure. * The effectiveness of trail features depends on their proper installation and maintenance. | Leung and Marion (1999); Mende and Newsome (2006); Grab and Kalibbala (2008); Randall and Newsome (2008); Olive and Marion (2009); Buchwal and Rogowski (2010); Mason et al. (2015); Marion and Wimpey (2017); Gou and Shibata (2017); Ng (2022) |
| Group 2: Trail restoration dynamics | Focuses on natural restoration processes of trails after closure or abandonment. | * Most of trail damages occur on its first few uses. If it is abandoned, natural revegetation is influenced by previous trail use, climate, soil compaction and other soil properties. * In certain cases, after few passes, one year can be enough to the revegetation of a trail. In others, recovery can require significant more time, but management strategies can accelerate this process. | Kuss and Hall (1991); Thurston and Reader (2001); Roovers et al. (2005); Bie and Vesk (2014); Ng et al. (2017); Drewnik et al. (2019) |
| Group 3: Trail maintenance, repair and restoration practices | Investigates the implementation of maintenance features and restoration practices | * Implementation of maintenance features and restoration activities can significantly reduce erosion and facilitate revegetation, especially if timed to avoid vulnerable climate periods. * Effective repair enhances trail sustainability, reduce long-term degradation and recuperate the provision of ecosystem services. However, trail maintenance cost is significantly lower than trail repair work. | Eagan et al. (2000); Ramos-Scharrón and Reale-Munroe (2014); Tomczyk et al. (2016); Kobayashi and Watanabe (2023) |
| Group 4: Trail management preferences | Studies visitor preferences regarding trail management practices in PNAs. | * In more accessible locations, visitors accept trail developments (hardening and surfacing) and oppose restrictions on the number of visitors, whereas in more remote areas, they support limiting visitors and prefer trails maintained with little or no trail development. * In dry conditions, visitors prefer more natural surfacing (gravel), while in rainy conditions they favor more artificial surfacing (asphalt, concrete). * Stakeholders of PNAs support trail developments, hiring more rangers, the enhancement of educational programs on trail use and increasing funding to support these activities. | Cahill et al. (2008); Aguirre (2009); Schneller et al. (2020) |
| Group 5: Visitors willing to pay for trail maintenance | Analyzes visitor willingness to pay for trail improvements and maintenance. | * Visitors and trail running race participants are willing to pay an extra fee at the entrance to the PNA or upon race registration to improve trail maintenance, with amounts ranging from $4 to $24, respectively. * The presence of park staff at the donation site increases the number of people willing to pay for trail maintenance. * The announcement of the government's initial budget and the fundraising target increase both the number of donors and the total contributions. | Oh and Hammitt (2010); Kubo et al. (2018); Ribet and Brander (2020) |
| Group 6: Off-trail behavior studies | Discusses the impact of poorly designed trails on natural resources and visitor behaviors. | * Off-trail activity can be reduced installing informational signs to keep users on the marked trails (well-defined trails) and planning access to places of interest (lookouts, lakes, etc.). * Off trail behaviors also can be decreased obstructing informal trails (brushing at the start of off-trail points), and developing personal communication for educational messages and effective communication about park rules, as well as the reasons behind these rules. | Aukerman (1985); Hockett et al. (2017) |
| Group 7: Trail management reviews | Reviews strategies for trail management and visitor capacity, minimizing environmental impacts. | * Reviews emphasize a holistic approach to trail sustainability, integrating scientific insights into practical management. * Systematic approaches to trail building, maintenance, and rehabilitation (trail management) are essential for sustaining the integrity of PNAs. | Marion (2016); Marion (2023) |

**4. Discussion**

**4.1. Trends and characteristics of trail management research**

In recent decades, numerous studies have focused on describing the impacts of trail usage. Salesa and Cerdà (2020) identified 126 articles related to soil erosion on mountain trails as a consequence of recreational activities. Although this review had broader inclusion criterion, not limited to PNAs, it found significantly more articles than the present review (30). From 2010 to 2018, Salesa and Cerdà (2020) reported 62 articles on trail erosion compared to 12 articles in the present review focusing on strategies to mitigate trail degradation in PNAs. Between 2019 and 2023, only six additional articles were added in this review (Fig. 2). This discrepancy highlights a notable gap between studies documenting trail degradation and those addressing strategies to mitigate it, posing challenges to meeting the goals of the UN Decade on Ecosystem Restoration (2021 - 2030) (Nelson et al., 2024).

Moreover, among the articles addressing the mitigation of trail degradation, the majority examined existing trail features (group 1 – Table 2). Only four studies conducted novel experimental actions to evaluate their effectiveness (group 3). These include Eagan et al. (2000), who restored abandoned degraded trails by filling erosion gullies and planting tree saplings; Ramos-Scharrón and Reale-Munroe (2014), who installed water bars and seeded a closed trail; Tomczyk et al. (2016), who refilled and hardened trail treads and constructed wooden steps or logs on degraded trails; and Kobayashi and Watanabe (2023), who utilized soil-filled palm-fiber bags and wooden steps to control erosion with volunteer assistance. Many articles only analyzed the effect of ceasing trail use (its abandonment) on revegetation (group 2). A possible explanation for this is the fact that the development of repair, rehabilitation, or restoration activities on trails requires more resources and personnel with specific knowledge. Furthermore, research on the effectiveness of these activities requires an extended timeframe to implement actions to reverse degradation and subsequently monitor and measure the outcomes or effectiveness of such measures. This set of challenges may limit research in this field. So, the lack of research in soil erosion curbing or mitigation actions is a gap in trail erosion research (Salesa and Cerdà, 2020).

The majority of research being conducted in countries with advanced or emerging and developing economies (IMF, 2023) suggests that economic resources may be limiting research in this area (Fig. 3). Even in countries with advanced economies, there have been reports of declining budgets for PNAs over the past years, restricting trail maintenance. For instance, this has been observed in the United States (Leung and Marion, 1999), Japan (Kubo et al., 2018), and Costa Rica (Aguirre, 2009). This limitation in resources for trail management investment can also lead to a reduction in the number of studies in advanced economies and, even more significantly, in countries with smaller economies. This scenario is similar to what was observed by Salesa and Cerdà (2020), who noted the United States had the highest number of publications (45% of the articles), followed by Australia, Poland, and Spain. Sumanapala and Wolf (2019) also observed that the majority of studies in recreational ecology (59%) had been conducted in developed countries such as the United States, followed by Australia, New Zealand, China, and Canada. The affiliation countries of the authors follow the same distribution pattern, as observed by Mota and Pickering (2020) in a review on the use of social media to assess nature-based tourism.

Further analyzing the characteristics of the study areas, the majority of the reviewed studies (70%) were conducted in IUCN category II - National Parks. This category generally experiences the highest visitation and, consequently, has more financial resources for management. Therefore, the larger number of studies in this category can be attributed to a combination of three factors. First, there is the greater impact on trails resulting from increased usage pressure. Second, the increased impact heightens management concern about these issues. Finally, more investment is needed in measures to curb trail degradation. These factors together can lead to more opportunities and investment in research on this topic.

In the studied PNAs, three main types of trail use were described: hiking, walking, and mountain biking. Various studies have already researched and compared the impacts of these activities on natural resources (soil compaction, erosion, damage to vegetation, etc.). Some studies have found no significant difference between the impacts caused by hiking and mountain biking (e.g., Thurston and Reader, 2001), while others have observed minor differences in specific situations (e.g., Evju et al., 2021). For instance, Kuwaczka et al. (2023) presented a review on the rise of electrically assisted mountain biking (eMTBing). They highlighted that the increase in this type of activity could expand the frequency of cyclists and the area they cover, potentially generating more informal trails and consequently a greater potential for trail degradation. On the other hand, Hruza et al. (2021) showed that constructing specific trails for mountain biking, which results in what they called controlled recreation, can reduce off-trail practices. This planning can diminish impacts on natural resources by concentrating the flow on formal trails (Hruza et al., 2021) while continuing to provide cultural environmental services to user groups and avoiding conflicts between fast and slower activities (Farías-Torbidoni et al., 2023).

Similarly, it is important to understand patterns of user types and conflicts among these groups to enhance social and environmental benefits while diminishing negative impacts (Campbell et al., 2021; Farías-Torbidoni et al., 2023). Additionally, it is relevant to note that the debate on this theme has been concentrated in a few scientific journals. We observed that nearly half of the articles were published in five scientific journals, a concentration pattern also noted by Salesa and Cerdà (2020), who also found the Journal of Environmental Management among the main journals publishing on their review topic.

### **4.2. Terminologies used in science for trail management**

### The term “trail” was prevalent in the literature encompassed by this review. Historically, this term has been utilized in both scientific and non-scientific literature to denote corridors ranging from extremely narrow trails, such as centimeters-wide trails also known as single-tracks trails (IMBA, 2004; IMBA 2007), to wider forest roads that accommodate four-wheel-drive vehicles, horses, and pedestrians in natural areas (Bratton et al, 1979; Marion 2023). Other compound terms derived from "trail," "path," and "track" primarily include variations that describe the trail’s main use types (e.g., horsing trail, hiking trail, walking trail, biking trail, etc.), the trail's purpose (educational, recreational, multi-use), the planning of the trail (well-designed, unplanned), and the trail's legality (formal, informal, clandestine), as well as the formation of the trail, among other aspects.

### Off-trail behavior can lead to the formation of new trails due to trampling. We identified at least 15 terms for describing the act of leaving the main trail or the formation of informal trails due to off-trail behavior, such as “off-trail”, “multiple treads”, “informal trails”, “trail proliferation”, “trail braiding”, “informal visitor-created trail”, “shortcuts”, “social trails” and others. These off-trail behaviors can be intentional, when a person knowingly goes off the legal trail, or unintentional, when trails are poorly signed and a person takes secondary trails thinking they are on the formal trail (Goh, 2023).

### Regarding degradation, the literature classifies a degraded environment as one persistently deteriorated due to human actions that affect its ability to provide benefits to people and nature (Nelson et al., 2024) and that cause difficulty or inability to return to its original or pre-impact state without human assistance (Reis et al., 1999). Trails suffer various types of impacts that cause damage or degradation to surrounding ecosystem components such as animals (mammals, birds, and others) (Miller et al., 2020), plants (herbaceous, understory plants and trees species) (Thurston and Reader, 2001; Roovers et al., 2005; Müllerová et al., 2011) and the trail substrate itself (Spernbauer et al., 2023). In this review, we noticed that the articles used the terms "damage" and "degradation" interchangeably, but always as synonyms with the meaning expressed by the aforementioned concept. In this context, we noticed these terms referring to the same aspect.

### Regarding the terms used to describe the creation of new formal trails (building or construction), the maintenance of appropriate trail characteristics (maintenance), and the repair of specific damages on the trail (repair), we observed considerable uniformity in the usage of these terms among the articles in this review. In contrast, with respect to the concepts used to address the mitigation or curtailment of trail degradation, we noted that three terms (restoration, recovery or rehabilitation) were employed variably. Frequently, the same term was used to describe different actions or objectives. Thus, while the usage of such terms remains variably and unclear in the literature, it is important that their meanings be clarified, especially to improve communication and interaction in interdisciplinary research and trail management approaches (Bracken and Oughton, 2006).

**4.3. Main approaches to curb trail degradation and findings of the studies**

Generally, the majority of studies focused on trail infrastructure assessment. No studies were found on the process of constructing new, well-designed trails in PNAs and analyzing potential damage over time. This may be due to the fact that constructing well-designed trails requires specialized personnel (Marion, 2023), which demands funding that many PNAs report not having (Schneller et al., 2020). Additionally, the likelihood of coinciding the beginning of a trail construction project with the availability of a researcher to investigate it is low, which hinders scientific research. When constructing a new trail in a PNA, whether for scientific research or public use, studies on visitor preferences regarding trail management have revealed useful results that can assist managers in making decisions that balance the management objectives of the PNA with user expectations, resulting in a win-win situation (Cahill et al., 2008; Aguirre, 2009). The gray literature can also be useful, as many institutions have decades of practical experience in trail building and management. Some of them dedicate significant efforts to disseminating their experiences through gray literature, such as books and technical reports (e.g. IMBA, 2004; IMBA, 2007).

In parallel, the willingness of visitors or participants in sports events in PNAs to pay additional fees on top of entrance or event registration fees can also result in a win-win situation. Visitors benefit from safer, longer-lasting, and well-maintained trails, while the PNA, often lacking financial resources for trail maintenance, gains access to additional funds for sustainable trail management (Leung and Marion, 1999; Aguirre, 2009; Kubo et al., 2018). The increase in financial resources, whether from the managing entity, typically governmental, or supplemented through visitation fees or donations, can significantly improve trail management (Schneller et al., 2020) and research on this issue. These resources can be employed to address major bottlenecks in trail management, such as hiring staff, purchasing materials, and installing informational signs with injunctive-proscriptive and attribution wording (Hockett et al., 2017). Additionally, resources can be used for conducting personal communications for educational purposes, effectively conveying the PNA's rules, and enforcement, all of which can substantially reduce off-trail behavior. Many of these trail management strategies, supported by recreation ecology research on carrying capacity and visitor use management decision-making, were well discussed by Marion (2016). Moreover, Marion (2023) provided a detailed summary of the main factors that influence trail sustainability and proposed a sustainability rating and management guide on how to manage each key factor to enhance trail sustainability.

**5. Conclusion** **and future directions**

The management of degraded trails presents multiple challenges in the context of escalating outdoor recreation activities. In this literature review, we investigated what trail science has revealed about strategies for managing degraded trails in PNAs across the world. We observed that the number of research studies related to this theme has been increasing in recent years, especially over the last decade. This research is concentrated in countries with advanced economies and by researchers from these countries. Therefore, it is crucial to devise strategies to overcome this economic barrier that may be limiting the advancement of this field of science in countries with less advanced economies. The increase in the number of studies mainly concerns topics such as the analysis of trail conditions and the impacts of use on resources (especially soil and vegetation). These factors leading to trail degradation appear to be reasonably well investigated and understood, though gaps remain to be filled. Despite this, we identified less addressed subjects, such as studies on strategies to reverse trail degradation. There is a concerning lack of experimental research aimed at developing and selecting effective strategies to curb or reverse the escalating problem of trail degradation. This shows that, despite being in the United Nations Decade on Ecosystem Restoration, little effort has been devoted to researching practices for the repair, rehabilitation, or restoration of degraded trails. Additionally, we identified key concepts related to trail terminology and strategies for managing degraded trails, primarily within the pillars of management and resources. We observed a notable lack of clarity and consensus regarding definitions and applications of terms used for strategies regarding curbing degradation on trails, which needs to be addressed in future research. Other scientific fields, such as Restoration Ecology (e.g. Gann et al., 2019), can provide relevant insights into the definitions and applications of these terms in trail management. Consequently, our results contribute to the growing body of knowledge on trail management, shedding light on the studies focused on reversing trail degradation in protected natural areas globally.

# **6. Limitations**

Research results on trail management (including trail building, maintenance, restoration, and rehabilitation) are published in scientific literature, but many empirical studies are disseminated in gray literature. Moreover, many of these studies are conducted in natural areas not recognized as PNAs. Though, one limitation of our study is that we exclusively investigated research published in scientific journals and conducted in PNAs. Therefore, we certainly did not cover the entire body of literature in this field. Our search was limited to articles published in English, introducing a potential bias that may overlook significant scientific contributions from non-English speaking countries or researchers who communicate in languages other than English. Consequently, we recognize that future investigations could greatly benefit from including these additional sources to achieve a more comprehensive understanding.

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**9. Credit author statement**

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**11. Data availability**

Data will be made available on request.

# **12.** **References**

Aguirre, J. A. 2009. **Sustainable Trail Management in Costa Rica National Parks: The use of photography for trail surfacing decisions under tropical rainforest conditions.** PASOS Revista de Turismo y Patrimonio Cultural. Vol. 7. N 1. pp 29 – 42.

Aukerman, R. 1985. **The effectiveness of signing, pamphlets, and restoration in reducing off-trampling**. Tourism Recreation Research, 10:2, 35-39.

Ballantyne, M.; Pickering, C. M. 2015. **The impacts of trail infrastructure on vegetation and soils: Current literature and future directions.** Journal of Environmental Management. 53 – 64.

Barros, A.; Pickering, C. M. 2017. **How networks of informal trails cause landscape level damage to vegetation**. Environmental Management, 60: 57-68.

Bie, K.; Vesk, P. A. 2014. **Ecological indicators for assessing management effectiveness: A case study of horse riding in an Alpine National Park.** Ecological Management and Restoration. Vol 15 n 3.

Bracken, L. J.; Oughton, E. A. 2006. **‘What do you mean?’ The importance of language in developing interdisciplinary research.** Transactions of the Institute of British Geographers, 31 371–382.

Bratton, S. P.; Hickler, M. G.; Graves, J. H. 1979. **Trail erosion patterns in Great Smoky Mountains National Park**. Environmental Management, vol. 3, pp. 431-445.

Buchwal, A.; Rogowski, M. 2010. **The methods of preventing trail erosion on the examples of intensively used footpaths in the Tatra and the Babia Góra national parks.** Geomorphologia Slovaca.

Cahill, K. L.; Marion, J. L.; Lawson, S. R. 2008. **Exploring Visitor Acceptability for Hardening Trails to Sustain Visitation and Minimise Impacts.** Journal of Sustainable Tourism. vol. 16, No. 2.

Campbell, T.; Kirkwood, L.; McLean, G.; Torsius, M.; Florida-James, G. 2021. **Trail Use, Motivations, and Environmental Attitudes of 3780 European Mountain Bikers: What Is Sustainable?** Int. J. Environ. Res. Public Health 2021, 18, 12971. https://doi.org/10.3390/ ijerph182412971

Campbell, T. 2024. **Sustainable mountain bike trails: towards a holistic approach**. In: Cherrington, J. (Ed.), Mountain Biking, Culture and Society (125-140). London: Routledge.

Coventry, P. A.; Brown, J. V. E.; Pervin, J.; Brabyn, S.; Pateman, R.; Breedvelt, J.; Gilbody, S.; Stancliffe, R.; McEachan, R.; White, P. C. L. 2021. **Nature-based outdoor activities for mental and physical health: Systematic review and meta-analysis**. SSM - Population Health, 16. 100934

Drewnik, M.; Musielok, L.; Prędki, R.; Stolarczyk, M.; Szymański, W. 2019. **Degradation and renaturalization of soils affected by tourist activity in the Bieszczady Mountains (South East Poland)**. Land Degradadation and development. 30: 670-682.

Dudley, N. (Editor). 2008. **Guidelines for Applying Protected Area Management Categories.** Gland, Switzerland: IUCN. x + 86pp. WITH Stolton, S., P. Shadie and N. Dudley (2013). IUCN WCPA Best Practice Guidance on Recognising Protected Areas and Assigning Management Categories and Governance Types, Best Practice Protected Area Guidelines Series No. 21, Gland, Switzerland: IUCN.

Eagan, S.; Newman, P.; Fritzke, S.; Johnson, L. 2000. **Restoration of Multiple-Rut Trails in the Tuolumne Meadows of Yosemite National Park.** USDA Forest Service Proceedings RMRS-P-15-VOL-5.

ESRI. 2024. ArcGIS Pro. [software] https://www.esri.com/es-es/arcgis/products/arcgis-pro/overview (Accessed 13 March 2024).

Evju, M.; Hagen,D.; Jokerud, M.; Olsen, S. L.; Selvaag, S. K.; Vistad, O. I. 2021. **Effects of mountain biking versus hiking on trails under different environmental conditions.** Journal of Environmental Management. 278.

Fang, W.; Ng, Sai-Leung. 2024. **Trail degradation caused by mountain biking and hiking: a multi-dimensional analysis**. Journal of Environmental Management. 351.

Farías-Torbidoni, E. I.; Rossi, S. D.; Pickering, C. M. 2023. **Visitation patterns in a peri-urban natural park: Comparing mountain bikers, runners, walkers and hikers**. Journal of Outdoor Recreation and Tourism 44.

Fellows, I. 2018. **wordcloud: Word Clouds**. R package version 2.6. URL: [https://CRAN.R-project.org/package=wordcloud](https://cran.r-project.org/package=wordcloud).

Gann, G. D.; Mcdonald, T.; Walder, B.; Aronson, J.; Nelson, C. R.; Jonson, J.; Hallett, J. G.; Eisenberg, C.; Guariguata, M. R.; Liu, J.; Hua, F.; Echeverría, C.; Gonzales, E.; Shaw, N.; Decleer, K.; Dixon, K. W. 2019. **International principles and standards for the practice of ecological restoration. Second edition**. Restoration Ecology Vol. 27, No. S1, pp. S1–S46.

Gobster, P.H.; Kruger, L.E.; Schultz, C.L.; Henderson, J.R. 2023. **Key Characteristics of Forest Therapy Trails: A Guided, Integrative Approach**. Forests, 14, 186. https://doi.org/10.3390/f14020186

Goh, E. 2023. **Walking Off-Trail in National Parks: Monkey See Monkey Do**. Leisure Sciences, 45:1, 1-23, DOI: 10.1080/01490400.2020.1755750

Gou, S.; Shibata, S. 2017. **Assessing heritage trails: trail conditions and influential managerial factors for the Nakahechi route on the Kumano Kodo pilgrimage network**. Landscape and Ecological Engineering. 13: 251-263.

Grab, S.; Kalibbala, F. 2008. **‘Anti-erosion’ logs across paths in the southern uKhahlamba–Drakensberg Transfrontier Park, South Africa: Cure or curse?** Catena. 73. 134 – 145.

Herrmann S.D., Willis E.A., Ainsworth B.E., Barreira T.V., Hastert M., Kracht C.L., Schuna Jr. J.M., Cai Z., Quan M., Tudor-Locke C., Whitt-Glover M.C., Jacobs D.R. 2024. **2024 Adult Compendium of Physical Activities: A third update of the energy costs of human activities.** Journal of Sport and Health Science. 13(1): 6-12.

Hockett, K. S.; Marion, J. F.; Leung, Yu-Fai. 2017. **The efficacy of combined educational and site management actions in reducing off-trail hiking in an urban-proximate protected area.** Journal of Environmental Management 203, 17 e 28.

Hruza, P.; Pelikan, P.; Olisarová. 2021. **Single-track bike trails in the Moravian Karst as part of forest recreation.** Forests.

IMF. 2023. **World Economic Outlook database: Groups and Aggregates Information.** <https://www.imf.org/en/Publications/WEO/weo-database/2023/April/groups-and-aggregates> (Accessed 14 March 2024).

International Mountain Bicycling Association – IMBA. 2004. **Trail Solutions: IMBA´s guide to build sweet singletrack**. 272 p.

International Mountain Bicycling Association – IMBA. 2007. **Managing Mountain Biking: IMBA´s guide to provide great riding**. 256 p.

Kobayashi, Y.; Watanabe, T. 2023. **Evaluation of the Effectiveness of Trail Repair Works Based on Three-Dimensional Monitoring around Mount Kurodake, Daisetsuzan National Park, Japan**. Sustainability. 15, 12794. https://doi.org/10.3390/ su151712794

Kubo, T.; Shoji, Y.; Tsuge, T.; Kuriyama, K. 2018. **Voluntary Contributions to Hiking Trail Maintenance: Evidence From a Field Experiment in a National Park, Japan.** Ecological Economics. 144. 124-128.

Kuss, F. R.; Hall, C. N. 1991. **Ground Flora Trampling Studies: Five Years After Closure.** Environmental Management. Vol. 15. Pp. 715 – 727.

Kuwaczka, L. F.; Mitterwallner, V.; Audorff, V.; Steinbauer, M. J. 2023. **Ecological impacts of (electrically assisted) mountain biking.** Global Ecology and Conservation. 44.

Leung, Yu-Fai; Marion, J. L. 1999. **Assessing trail conditions in protected areas: application of a problem assessment method in Great Smoky Mountains National Park, USA.** Environmental Conservation. 26 (4): 270-279

Litmaps. 2024. **Litmaps software for citation mapping**. [software] <https://www.litmaps.co>. (accessed 11 June 2024).

Marion, J. L.; Leung, Y-F.; Nepal, S. K. 2006. **Monitoring trail conditions: new methodological considerations.** The George Wright Forum. vol. 23, n°2, pp. 36-49.

Marion, J. L. 2016. **A Review and Synthesis of Recreation Ecology Research Supporting Carrying Capacity and Visitor Use Management Decisionmaking**. Journal of Forestry, 114(3):339–351

Marion, J. L.; Wimpey, J. 2017. **Assessing the influence of sustainable trail design and maintenance on soil loss**. Journal of Environmental Management. 189. 46-57

Marion, J. L. 2023. **Trail sustainability: A state-of-knowledge review of trail impacts, influential factors, sustainability ratings, and planning and management guidance.** Journal of Environmental Management.

Mason, S.; Newsome, D.; Moore, S.; Admiraal, R. 2015. **Recreational trampling negatively impacts vegetation structure of an Australian biodiversity hotspot.** Biodiversity and Conservation. 24:2685–2707.

MEA, 2005. **Millennium Ecosystem Assessment: Ecosystems and Human Well-being: Synthesis.** Island Press, Washington, DC.

Mende, P., & Newsome, D. 2006. **The assessment, monitoring and management of hiking trails: A case study from the Stirling Range National Park, Western Australia**. Conservation Science Western Australia, 5(3), 285–295.

Miller, A. B.; Kays, R.; Leung, Yu-Fai. 2020. **Wildlife response to recreational trail building: An experimental method and Appalachian case study**. Journal of Nature Conservation. 56.

Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group. 2009. **Preferred Reporting Items for Systematic Reviews and MetaAnalyses: The PRISMA Statement.** PLoS Med 6(7): e1000097. doi:10.1371/ journal.pmed.1000097

Mota, V. T.; Pickering, C. 2020. **Using social media to assess nature-based tourism: Current research and future trends.** Journal of Outdoor Recreation and Tourism. 30.

Müllerová, J.; Vítkova, M.; Vítek, O. 2011**. The impacts of road and walking trails upon adjacent vegetation: Effects of road building materials on species composition in a nutrient poor environment**. Science of the Total Environment. 409. 3839 – 3849.

Nelson, C.R., Hallett, J.G., Romero Montoya, A.E., Andrade, A., Besacier, C., Boerger, V., Bouazza, K., Chazdon, R., Cohen-Shacham, E., Danano, D., Diederichsen, A., Fernandez, Y., Gann, G.D., Gonzales, E.K., Gruca, M., Guariguata, M.R., Gutierrez, V., Hancock, B., Innecken, P., Katz, S.M., McCormick, R., Moraes, L.F.D., Murcia, C., Nagabhatla, N., Pouaty Nzembialela, D., Rosado-May, F.J., Shaw, K., Swiderska, K., Vasseur, L., Venkataraman, R., Walder, B., Wang, Z., and Weidlich, E.W.A. 2024. **Standards of practice to guide ecosystem restoration – A contribution to the United Nations Decade on Ecosystem Restoration 2021-2030**. 2024. Rome, FAO, Washington, DC, SER and Gland, Switzerland, IUCN CEM. <https://doi.org/10.4060/cc9106en>

Nepal, S. K. 2003. **Trail impacts in Sagarmatha (Mt. Everest) National Park, Nepal: a logistic regression analysis.** Environmental Management. Vol. 32, n 3, pp 312-321.

Neuwirth, E. 2022. **RColorBrewer: ColorBrewer Palettes.** R package version 1.1-3. URL: https://CRAN.R-project.org/package=RColorBrewer

Ng, S. L.; Yu‐Fai, L.; Suet‐Yi, Cheung; Wei Fang. 2017. **Land degradation effects initiated by trail running events in an urban protected area of Hong Kong.** Land Degradadation and development. 1 – 11.

Ng, S. L. 2022. **Is surfacing a good choice for trail management? Evidence from four high-use hiking trails in Hong Kong**. Journal of Soil and Water Conservation. Vol. 77, n 6.

Oh, C. O.; Hammitt, W. E. 2010. **Determining Economic Benefits of Park Trails: Management Implications**. Journal of Park and Recreation Administration. Vol. 28. N.2, pp. 94 – 107.

Olive, N. D. & Marion, J. L. 2009. **The influence of use-related, environmental, and managerial factors on soil loss from recreational trails.** Journal of Environmental Management 90, 1483–1493.

Pickering, C.; Byrne, J. 2014. **The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early-career researchers.** Higher Education Research and Development. Vol. 33, No. 3, 534–548.

Ramos-Scharrón, C. E.; Reale-Munroe, K.; S. C. 2014. **Quantification and modeling of foot trail surface erosion in a dry sub-tropical setting.** Earth Surface Processes and Landforms 39, 1764–1777.

Randall, M. Newsome, D. 2008. **Assessment, evaluation and a comparison of planned and unplanned walk trails in coastal south-western Australia.** Conservation Science Western Australia. 7 (1): 19-34.

Rangel, L.; Jorge, M. C.; Guerra, A.; Fullen, M. 2019. **Soil Erosion and Land Degradation on Trail Systems in Mountainous Areas: Two Case Studies from South-East Brazil**. Soil Systems, 3, 56.

R Core Team. 2023. **R: A language and environment for statistical computing.** R Foundation for Statistical Computing, Vienna, Austria. [software] URL [https://www.R-project.org/](https://www.r-project.org/).

Reis, A.; Zambonim, R. M.; Nakazono, E. M. 1999. **Recuperação de áreas florestais degradadas utilizando a sucessão e as interações planta-animal.** Série Cadernos da Biosfera, 14. Conselho Nacional da Reserva da Biosfera da Mata Atlântica, São Paulo, Brasil. 42 p.

Ribet, S.; Brander, L. M. 2020. **Willingness to pay of trail runners for sustainable country park use in Hong Kong.** Journal of Outdoor Recreation and Tourism. 31.

Roovers, P.; Bossuyt, B.; Gulinck, H.; Hermy, M. 2005. **Vegetation recovery on closed paths in temperate deciduous forests**. Journal of Environmental Management 74. 273–281.

Salesa, D.; Cerdà, A. 2020. **Soil erosion on mountain trails as a consequence of recreational activities. A comprehensive review of the scientific literature.** Journal of Environmental Science. 271.

Schneller, A. J.; Binzen, G. L.; Cameron, C.; Vogel, S. T.; Bardin, I. 2020. **Managing Recreation in New York's Adirondack Park: A Case Study of Public Perceptions and Preferences for Reducing User Impacts to the High Peaks Wilderness Complex.** Journal of Park and Recreation Administration.

Spernbauer, B. S.; Monz, C.; D`Antonio, A.; Smith, J. W. 2023. **Factors influencing informal trail conditions: implications for management and research in urban-proximate parks and protected areas.** Landscape and Urban Planning.

Sumanapala, D.; Wolf, I. D. 2019. **Recreational Ecology: A Review of Research and Gap Analysis.** Environments. 6, 81.

Thurston, E.; Reader, R. J. 2001. **Impacts of experimentally applied mountain biking and hiking on vegetation and soil of a deciduous forest.** Environmental Management.

Tomczyk, A. M.; Ewertowski, M. 2011. **Degradation of recreational trails, Gorce National Park, Poland**. Journal of Maps, 7:1, 507-518, DOI: 10.4113/ jom.2011.1195

Tomczyk, A. M; White, P. C. L.; Ewertowski, M. W. 2016. **Effects of extreme natural events on the provision of ecosystem services in a mountain environment: The importance of trail design in delivering system resilience and ecosystem service co-benefits.** Journal of Environmental Management. 156 – 167.