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Original article

Regional risk assessment of high-altitude field mosses

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ABSTRACT

The Itatiaia National Park protects important Atlantic Forest remnants as well as a large number of rare bryophyte species. We reassessed the conservation status of 45 species of endemic and/or threatened mosses occurring in high-altitude fields in the Park. The conservation analysis followed the International Union for Conservation of Nature guidelines. The GeoCAT software was used to calculate the Extent of Occurrence (EOO) and Area of Occupancy (AOO). The threat vectors were characterized based on field observations and data from the literature. After the reassessment, 31 species were considered threatened, with 16 being considered vulnerable (VU), seven critically endangered (CR), and eight endangered (EN). Two species were considered "near threatened" (NT) and three were considered "data deficient" (DD), and seven were considered "least concern" (LC). The main threats in that region are wildfires and excessive tourism – factors that lower habitat quality and reduce their EOO and AOO. Recommendations to minimize imminent losses of the local bryoflora include incentives for research and microhabitat protection. Our results are designed to aid in the elaboration of conservation strategies for mosses in the *Serra da Mantiqueira* mountains.

Keywords: bryophytes, IUCN, red list, Itatiaia National Park, *campos de altitude*.

Introduction

Global biodiversity is currently under extreme pressure, and many rare or threatened plant species throughout the world are facing risks of imminent extinction (Blackmore *et al.* 2000; Bachman *et al.* 2018). Red lists have been elaborated to orient governments and resource administrators to inform the general public of proactive measures designed to avoid biodiversity losses (Jackson & Kennedy 2009).

The analyses of bryophyte conservation in Brazil were initiated in the 1990's and included national and regional assessments. Among the studies undertaken at the national level, the chapter within the doctoral thesis of Costa (1999) concerning the conservation of the Metzgeriaceae family as well as assessments of the bryophyte families cited in the red book of plants in Brazil (Martinelli et al. 2018) stand out. At the regional level, analyses of the Brazilian states of Pernambuco – PE (Pôrto & Germano 2002), Rio de Janeiro – RJ (Costa *et al.* 2005; Costa & Santos 2009), Minas Gerais – MG (Costa *et al.* 2006), and Espírito Santo – ES (Yano & Peralta 2007; Santos *et al.* 2019) have been undertaken. Additionally, Messina (2015) analyzed

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the family Sphagnaceae in the Serra do Caraça Natural Private Reserve (MG) and in the Chapada dos Veadeiros National Park (Goias State), and Rezende (2015) studied the threatened liverworts in the Itatiaia National Park (RJ). Other workers have undertaken significant research concerning bryophyte conservation, although without assessing the risk of extinction to those species, including Costa and Rezende (2015) who prepared a field guide with photographs and illustrations of the threatened liverworts in the INP, and Gonçalves and Santos (2018) who compiled information concerning the threatened liverworts and mosses occurring in the high-altitude fields of the INP (with information concerning their taxonomy, geographic distributions, substrates, conservation status, and the principal collectors and collections).

The INP, located in the *Serra da Mantiqueira* mountain range, holds important remnants of the Atlantic Forest and has been highlighted since the beginning of the 20th century as a region of extreme potential for scientific research (Dusén 1903; Brade 1956) - which was a principal motivation for it becoming the first Brazilian National Park. Although the park is recognized as the center of diversity and endemism of several different plant groups, such as bryophytes, ferns, lycophytes and angiosperms, (Brade 1956; Morim & Barroso 2007; Monteiro & Guimarães 2009; Costa *et al.* 2015; Alves *et al.* 2016; Souza *et al.* 2021), there are still many gaps in our knowledge about the bryophyte ecology (*e.g.* life history, reproductive biology) and possible threats to biodiversity.

The INP has wide altitudinal variations (from 600 to 2,791 m.a.s.l.) that favor the occurrence of different Atlantic Forest phytophysiognomies, from dense low-elevation ombrophilous forests to high-altitude fields above the tree line (starting at approximately 2000 m. a.s.l) (Safford 1999a; Aximoff *et al.* 2016). Those high-altitude fields hold fragile and insular ecosystems that occur on the tops of mountain ranges in southeastern Brazil (Segadas-Vianna & Dau 1965; Safford 1999b). Although many of those high-altitude fields are protected within legally established conservation areas, they still suffer from natural as well as anthropogenic impacts (Aximoff 2011; Aximoff *et al.* 2014; Assis & Mattos 2016). Among the principal negative impacts affecting them are landscape degradation, wildfires, agriculture and grazing, and unresolved land ownership questions – all of which pose continuous threats to the local flora and fauna (Rocha *et al.* 2003; Safford 1999b; 2007; Aximoff 2011; Aximoff & Rodrigues 2011). Their geographic isolation and ongoing anthropic impacts put those ecosystems at great risk (Safford 1999a). These impacts can disrupt population dynamics, reduce genetic diversity, impair reproductive success, and increase vulnerability to other threats (Lughadha *et al.* 2020). This is even more concerning in insular and marginal environments, such as high-altitude fields, which harbor numerous rare species (Scarano 2009). Habitat losses and degradation pose significant threats to bryophytes worldwide (Gradstein & Raeymaekers 2000; Hallingbäck & Hodgetts 2000; Hodgetts *et al.* 2019). Environmental degradation reduces habitat quality and can lead to the loss of sensitive species. Fragmentation, on the other hand, isolates bryophyte communities and directly impacts their reproductive processes. These factors represent the greatest threats to endemic species or those with restricted distributions.

Bryophytes are important structural components of high-altitude fields (Safford 1999a), where they act as pioneer plants, *i.e.* stabilize soils and regulate the microclimate (Ribeiro *et al.* 2007; Vanderpoorten & Goffinet 2009), and nurse plants, *i.e.* providing suitable environmental conditions for germination and growth of other plants on soil or rock outcrops (Franco & Nobel 1989; Scarano 2002). Given these important ecosystem functions, bryophytes can represent keystone modifier species (sensu Mills *et al.* 1993), as they affect habitat type, energy flow, and the survival of many other species. Thus, their disappearance could cause significant impacts on the high-altitude fields, fragile and threatened ecosystems.

Conservation status assessment is considered the primary planning step for actions designed to reduce extinction rates and prioritize resources (Mace *et al.* 2008). Considering that the last regional analysis that included mosses in the high-altitude fields in the INP was carried out 16 years ago (Costa *et al.* 2005), the reassessment of their conservation status would be necessary to guide the planning of effective actions directed towards their conservation. Thus, we assessed the regional risk of endemic and/or threatened mosses in the high-altitude fields of the INP.

Material and methods

Characterization of the study area

The high-altitude fields in the INP are inserted within the Atlantic Forest phytogeographic domain in southeastern Brazil, at elevations above 2000 m.a.s.l (Fig. 1). The highest peak in the park is the *Agulhas Negras* at 2791 m. The high-altitude fields cover approximately 50 km² (Segadas-Vianna & Dau 1965; Martinelli 1996; Safford 1999a) and has a subtropical altitudinal climate, with a mean annual temperature of 11.5° C and mean annual rainfall levels ranging from 1000 to 2500 mm; the rainy season extends from December to February (Segadas-Vianna & Dau 1965; Safford 1999b).

Species list

To compile the list of moss species that are endemic and/or threatened in the high-altitude fields of INP, we consulted national and regional red lists (Costa *et al.* 2005; Fundação Biodiversitas 2007; Martinelli *et al.* 2018), the

diagnostic study by Costa *et al.* (2015) to Rio de Janeiro state, and the Flora e Funga do Brasil (2022). Additionally, we utilized online databases such as CRIA (http://splink.cria.org.br/), JABOT (http://jabot.jbrj.gov.br/v2/consulta.php), and GBIF (http://gbif.org). The initial list of 28 threatened moss species (Gonçalves & Santos 2018) was updated with new collections made in the study area between the years of 2018 and 2020 (deposited in herbarium R), as well as the identification of herbarium material (RBR, RB, R, SP). The resulting list consisted of 45 species: 15 species that are endemic to Brazil and considered threatened at a regional (in the states of Rio de Janeiro and/or Minas Gerais) or national scale, 20 species classified as threatened, and 10 species considered endemic to Brazil and not classified as threatened.

Extinction risk assessment

The conservation status classifications follow Hallingbäck *et al.* (1998), as adapted for bryophytes and the guide to IUCN criteria for national and regional analysis (IUCN 2012). The categories used were: CR (critically endangered), EN (endangered), VU (vulnerable), NT (near threatened), LC (least concern), and DD (data deficient).

The assessments primarily relied on criterion B due to the limited availability of data regarding the bryophyte population trend, which is essential for applying criteria A and C. Distribution data were predominantly sourced from published and unpublished records, herbarium specimens, and recent field surveys conducted by the authors.

Analyses using GeoCAT software (EOO and AOO calculations)

We utilized distribution data of moss species for calculating EOO and AOO by "Geospatial Conservation Assessment Tool" (GeoCAT), an open source developed by Kew Gardens (Bachman *et al.* 2011). This tool employs criteria B proposed by the IUCN (2022) and enables the automatic calculation of the Extent of Occurrence (EOO) and Area of Occupancy (AOO) of plant species based on their geographic distribution. The EOO for each species was determined using the minimum convex polygon method, while the AOO was calculated using the standard IUCN grid (2 km x 2 km), according to Puglisi *et al.* (2023).

After carefully confirming the identification of the records with the literature data (Frahm 1991; Sharp *et al.* 1994; Buck 1998; Gradstein *et al.* 2001; Yano & Peralta 2011; Costa & Pôrto 2022) and consulting specialists, the geographic coordinates of the species were obtained from the herbarium labels and online databases for the GeoCat assessments, and refined when necessary.

Threat characterizations

The classification of threats to mosses prepared by Salafsky *et al.* (2008) was used to describe threat vectors and conservation actions as well as the IUCN Threats

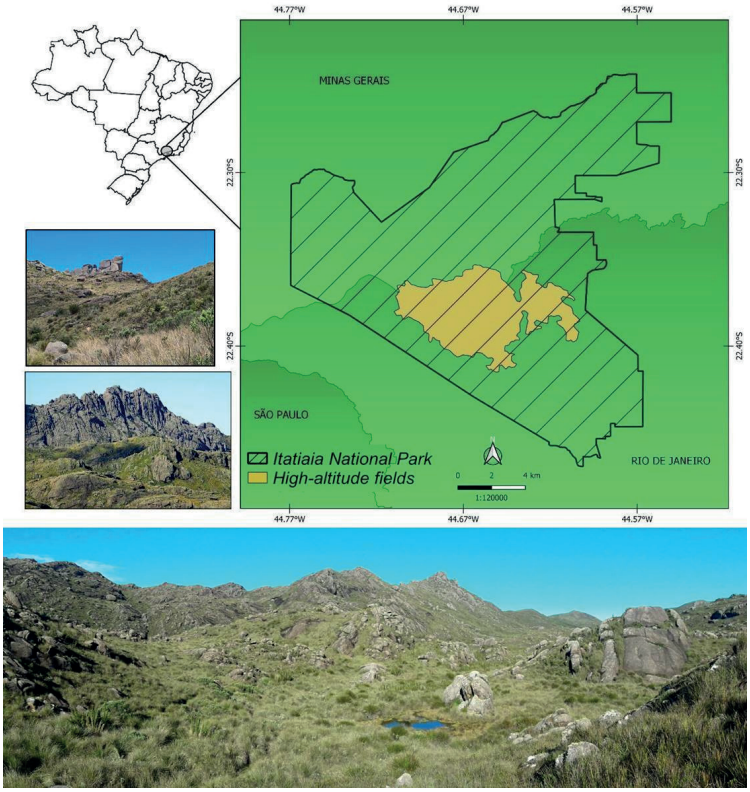

Figure 1. Location of the high-altitude fields in Itatiaia National Park and emphasis on their landscapes.

Classification Scheme - Version 3.3 (IUCN 2022). The classification of Salafsky *et al.* (2008) is organized into three classes: i) the identification of direct threats in their localities of occurrence, that is, the threats that can impact a given species (human dwellings, commercial buildings, agriculture, human activities, modifications of natural systems, invasive species, pollution, climate change, etc.); ii) combinations of the threats and actions based on detailed information from conservation analyses as well as proposed solutions (including the expansion of protected areas, management and restoration of species, environmental education, legislation, etc.); iii) crossing and sharing data to be able to describe, with precision, the links between threats and factors that contribute to them, seeking to reveal experiences and actions necessary for biodiversity conservation.

Threat characterization was determined by utilizing several methods, including field observations and information gathered from the literature. This information included informative bulletins from the INP, as well as studies conducted by Aximoff (2011), Safford (2001), evaluations performed by the National Center for the Conservation of the Brazilian Flora – CNCFlora, and Ramos *et al.* (1982). Additionally, tourism-related activities, annual and seasonal agriculture, raising domestic animals using natural resources and pasture lands within the park, land ownership questions, and the frequencies and/or intensities of wildfires were considered. The threats were then classified according to the categories outlined in the IUCN Threats Classification Scheme - Version 3.3 (IUCN 2022). To facilitate data visualization, we created a table, based on Messina (2015), where an asterisk (*) indicates the threats confirmed in the field. The symbol "+" expresses the intensity of the threat, representing low (+), medium (++) or high (+++). We used the symbol (0) when we did not have or lacked the information about the intensity of the threat or when it was not feasible to verify it in the field.

Results

We assessed 45 species of mosses (endemic and/or threatened) growing in the high-altitude fields of the INP (Tabs. 1, 2). We raised data from past categories (Costa *et al.* 2005; Fundação Biodiversitas 2007; Martinelli *et al.* 2018) and presented them in the table (Tab. 1) and we assessed for the first time 10 species that are endemic to Brazil and occur in the high altitude-fields of INP. After reassessing the risk of extinction for those 45 taxa, 31 were considered threatened at the regional level, seven classified as CR, eight as EN, and 16 as VU (Tab. 1).

Among the species previously assessed, 11 changed category after reassessment (four changing from VU to EN - *Atractylocarpus longisetus*, *Blindia magellanica*, *Chrysoblastella chilensis*, *Pogonatum perichaetile* subsp. *oligodus*; five from VU to CR - *Andreaea subulata*, *Eobruchia bruchioides*, *Oreoweisia brasiliensis*, *Tetraplodon mnioides,* and *Warnstorfia exannulata*; two from VU to LC - *Fissidens wallisii* and *Sematophyllum swartzii*) (Fig. 2).

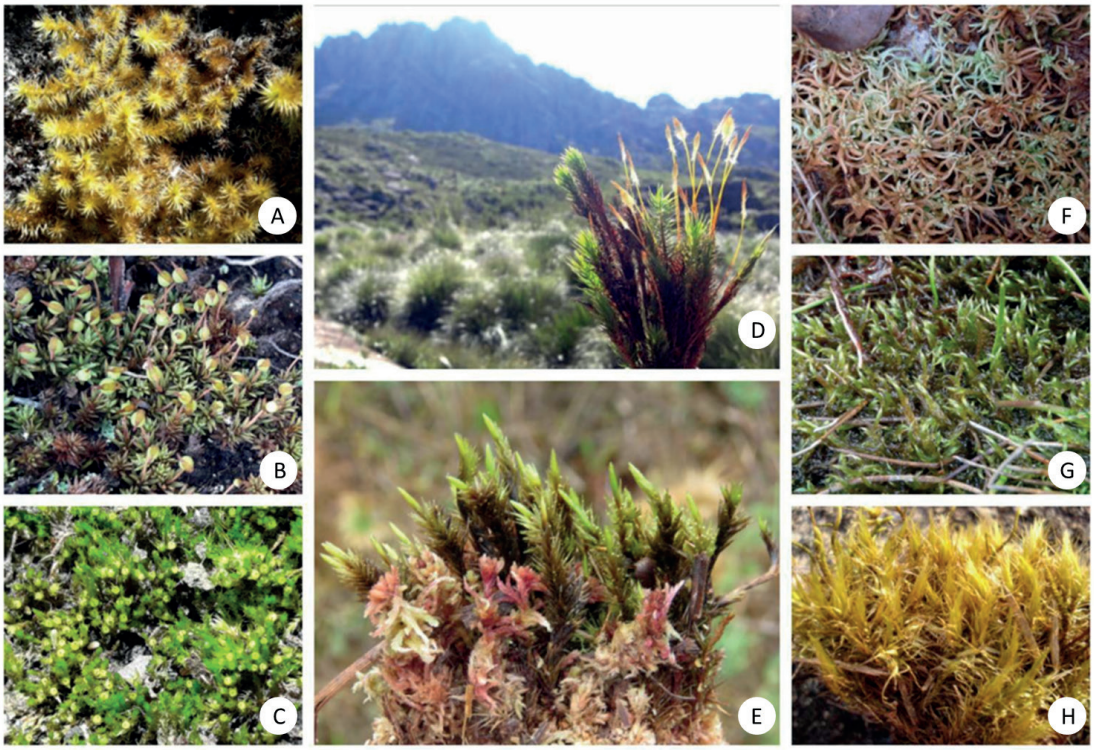

Figure 2. Examples of threatened and/or endemic mosses from the high-altitude fields of Itatiaia National Park. **A.** *Breutelia wainioi* **B.** *Itatiella ulei* **C.** *Cladastomum ulei* **D.** *Polytrichum angustifolium* **E.** *Campylopus cuspidatus* var. *dicnemoides* and *Sphagnum* sp. **F.** *Sphagnum pseudoramulinum* **G.** *Warnstorfia exannulata* **H.** *Campylopus jamesonii*

Table 1. Red List status and assessment criteria of the high-altitude fields mosses of the Itatiaia National Park, Brazil (* = collected in this work; Bold = species that changed category).

Family	Species	Older category	2021	Criteria	IUCN Threat Categorization	Justification
	Endemic to Brazil and threatened					
Dicranaceae	**Atractylocarpus brasiliensis* (Müll.Hal.) R.S. Williams	EN	EN	B1ab (i, ii, iii)	1.1; 2.2; 7.1.1; 11.2; 11.3	This species is endemic to the Atlantic Forest (occurring in BA and RJ states) (Flora e Funga do Brasil, 2023). The species has a limited occurrence in high-altitude fields and high mountain forests forming tufts of separated subpopulations. Has an EOO of 549,37 km². Both the species and its region of occurrence are threatened by activities such as urban expansion, agricultural activities, and wildfires that provoque continuing decline in habitat quality, EOO and AOO. The species was exclusively found in the area adjacent to the road between Posto do Marcão and Abrigo Rebouças, specifically in soil with leaf litter or among plants. Furthermore, it was not found in the previously documented localities mentioned in the herbarium samples, indicating a continuing decline in its AOO.
Seligeriaceae	*Brachydontium notorogenes* W.R.Buck & Schaf.-Verw.	CR	CR	B2ab (ii, iii, iv)	6.1; 7.1.1; 11.2; 11.3	This species is endemic to the INP. Historically found on the trail between *Abrigo Rebouças* and *Agulhas Negras* on rock outcrops. That trail was searched, but the species could not be found. Both the species and its region of occurrence are threatened by wildfires and predatory tourism, which has resulted in a continuing decline in its AOO as well as habitat quality; there have been few scientific collection records. The population on the type locality was not found, so we considered it as a continuing decline of its AOO.
Brachytheciaceae	*Brachythecium poadelphus* Müll.Hal.	VU	VU	B2ab (ii, iii)	6.1; 7.1.1; 11.2; 11.3	This species is endemic to the Atlantic Forest, with distribution within *protected areas* established in the states of RJ, MG, and SP. Few records in scientific collections. Has an AOO of 12,000 km², but even though the high-altitude fields of the INP represents one of the best-inventoried areas of the park, this species has not been seen or collected there, which indicates a significant decline in its population size. Both the species and the region in which it occurs suffer from wildfires and excessive tourism, leading to declining habitat quality.
Ditrichaceae	*Cladastomum robustum* Broth.	VU	VU	B2	6.1; 7.1.1; 11.2; 11.3	This species is endemic to Serra da Mantiqueira (MG and RJ). Poorly represented in scientific collections. This species evidence the strategy of annual plants, being strongly seasonal with a dormancy phase during which it survives through spore banks. Mortality is determined by abiotic factors (During 1979). Glime (2007) noted that annual species produce cleistocarpous capsules without specialized mechanisms for spore liberation. Has an AOO of 12,000 km² and an EOO of 284,478 km². Both the species and the region of its occurrence suffer from negative impacts from wildfires and excessive tourism that lead to declining habitat quality.
Ditrichaceae	**Crumuscus vitalis* W.R.Buck & Snider	EN	EN	B1ab (iii)	6.1; 7.1.1; 11.2; 11.3	This species is endemic to the INP. It grows on rocks along trails, which are habitats of elevated anthropic impact. Life strategy is normally annual and strongly seasonal; mortality is determined by abiotic factors (During 1979). It has an EOO of 2,859 km² and an AOO of 16,000 km². Both the species and its region of occurrence are threatened by wildfires and intensive tourism that lead to its continually declining AOO, habitat quality, and numbers of subpopulations. Additionally, during fieldwork it was observed that populations occur in distant patches the subpopulations are highly fragmented.
Ditrichaceae	*Ditrichum itatiaiae var. brevipes* (Müll. Hal.) Paris	VU	DD			Taxonomic knowledge deficient. The species has not been revised since publication.
Bruchiaceae	***Eobruchia bruchioides* (Müll.Hal.) W.R.Buck**	VU	CR	B1ab(ii, iii) + 2ab(ii, iii)	6.1; 7.1.1; 11.2; 11.3	This species is endemic to the INP. Distributed exclusively in high-altitude fields. Terricolous, encountered along trail sides, environments experiencing elevated anthropic impacts. Subject to damage from wildfires, trampling, diminishing habitat quality, and excessive tourism. Has an AOO of 4,000 km² and an EOO of 4,000 km². Known from only the type locality with a declining AOO and declining habitat quality. In addition to being poorly represented in scientific collections, it has not been collected recently.

Table 1. Cont.

Family	Species	Older category	2021	Criteria	IUCN Threat Categorization	Justification
Dicranaceae	**Paraleucobryum longifolium* subsp. *brasiliense* (Broth.) P.Müller & J.-P. Frahm	VU	VU	B2ab (iii)	6.1; 7.1.1; 11.2; 11.3	This species is endemic to the Brazilian Atlantic Forest (RJ and ES). Distributed in high-altitude fields and high-elevation forests. Has an AOO of 12,000 km², and is encountered only in established conservation areas (the Mestre Álvaro Biological Station and the INP). Recently collected along the trail to Agulhas Negras Peak at 2,434 m a.s.l on the trunks of small trees. Both the species and its region of occurrence suffer with the effects of excessive tourism and repeated wildfires, which has led to declines in habitat quality and extension.
Sphagnaceae	**Sphagnum exquisitum* H.A. Crum	VU	VU	B2ab (ii, iii)	5.2; 5.2.1; 11.2; 11.3	This species is endemic to the Brazilian Atlantic Forest (ES, MG, SP, RJ and SC). In spite of having a extensive EOO (70,608 km²), the species suffers from harvesting and commercialization as it is rarely cultivated but collected in the wild for floriculture use (Rancura *et al.* 2010; Negrelle *et al.* 2014; Glime 2007). Additionally, it has an AOO of 60,000 km², and is known from less than 10 locations. Those factors, combined with commercial harvesting, results in the species being threatened.
Sphagnaceae	***Sphagnum longicomosum* Müll.Hal.**	EN	VU	B2ab (ii, iii)	5.2; 5.2.1; 11.2; 11.3	This species is endemic to Brazil, encountered in the *Cerrado* and the Atlantic Forest (ES, MG, SP, RJ, DF, GO, PR and RS). In spite of its extensive EOO (70,945 km²), the species is not cultivated but is threatened by commercialization and harvesting directly in the field for floriculture use (Rancura *et al.* 2010; Negrelle *et al.* 2014; Glime 2007). It has an AOO of 64,000 km², and is known from less than 10 locations, which results in the species being threatened.
Sphagnaceae	*Sphagnum platyphylloides* Warnst.	VU	VU	B1ab (i,ii,iii)	5.2; 5.2.1; 11.2; 11.3	This species is endemic to Brazil, occurs in the Cerrado and the Atlantic Forest (ES, MG, RJ, GO e DF). In spite of its extensive EOO (162,366,682 km²), the species is restricted to mountain tops. It is not cultivated but it is threatened by extractivism and commercialization to attend the floriculture sector (Rancura *et al.* 2010; Negrelle *et al.* 2014; Glime 2007). It has na AOO of 24,000km², and is known from less than 10 locations, which results in the species being threatened.
Sphagnaceae	**Sphagnum pseudoramulinum* H.A. Crum	VU	VU	B2ab (ii, iii)	5.2; 5.2.1; 11.2; 11.3	This species is endemic to the Atlantic Forest (ES, MG, SP, RJ and RS). It has an EOO of 28,792 km². It presents threats arising from extractivism and commercialization, since, in general, they are not cultivated, but extracted directly from nature to meet the demands of the florist service (Rancura *et al.* 2010; Negrelle *et al.* 2014; Glime 2007). It has an AOO of 36,000 km², known for less than 10 locations, which places it in a threatened situation.
Sphagnaceae	*Sphagnum rotundatum* Müll.Hal. & Warnst.	VU	VU	B2ab (ii, iii)	5.2; 5.2.1; 11.2; 11.3	This species is endemic to Brazil, present in *Cerrado* and Atlantic Forest (GO, MG, RJ, SP, PR, SC). It has an EOO of 27,297 km² (RJ, MG) and an AOO of 12,000 km². It presents threats arising from extractivism and commercialization, since, in general, they are not cultivated, but extracted directly from nature to meet the demands of the florist service (Rancura *et al.* 2010; Negrelle *et al.* 2014; Glime 2007). It has an AOO of 12,000 km², known for less than 10 locations, which places it in a threatened situation.
	Threatened					
Andreaceae	**Andreaea acutifolia* Hook.f. & Wils.	NE	DD			This species presents disjunct distribution in the southern hemisphere. Species very similar to *A. rupestris*, what differentiates the species are the perichaetial leaves. For this reason, it has few collection records or misidentifications. Collecting efforts and investments in scientific research are necessary in order to certify the real geographic distribution of the taxon.
Andreaceae	**Andreaea rupestris* Hedw.	VU	VU	B2ab (iii)	6.1; 7.1.1; 11.2; 11.3	Wide worldwide distribution, especially in temperate regions. However, in Brazil, it is restricted to the high-altitude fields of the southeast region. It is threatened due to its distribution limited to rocky environments in high-altitude fields, an ecosystem threatened by climate change, excessive tourism and fires, which causes a decrease in habitat quality. It has an AOO of 44,000 km².

Table 1. Cont.

Family	Species	Older category	2021	Criteria	IUCN Threat Categorization	Justification
Andreaceae	***Andreaea subulata* Harv.**	VU	CR	A1c; B1b(i,ii,iii,iv) + B1c(i,ii,iii)	6.1; 7.1.1; 11.2; 11.3	Disjunct distribution in the southern hemisphere. It has small populations, restricted to rocky habitats with the presence of water (Gonçalves *et al.* 2022). In Brazil, it occurs in RJ state, with recent collection only in Agulhas Negras (INP). In addition, it has shown a reduction in population size in recent decades. It suffers threats due to excessive tourism and fires that reduce the quality of the habitat, and it is threatened due to its ecosystem (high-altitude fields) be threatened by climate change. It has an AOO of < 8,000 km².
Dicranaceae	***Atractylocarpus longisetus* (Hook.) E.B.Bartram**	VU	EN	B1ab(iii)+ 2ab(iii)	6.1; 8; 8.1; 8.2.1; 11.2; 11.3	Neotropical distribution. However, in Brazil it only occurs in the states of RJ, MG and ES. Found at altitudes ranging from 1,200 to 2,700 m a.s.l. in altitude fields and dense and mixed rain forest, environments that are being degraded by human activities, invasion of exotic species and climate change. It has an EOO of 547.32 km² and is subject to loss and decline in habitat quality as its main threat.
Seligeriaceae	***Blindia magellanica* Schimp.**	VU	EN	B2ab(ii,iii, iv)	6.1; 7.1.1; 11.2; 11.3	It presents disjunct distribution of temperate regions and tropical mountains. However, in Brazil it occurs only in the state of RJ (INP) and ES (Parque Nacional do Caparaó) in *Protected areas*. It has an EOO of 1,124,365 km² and an AOO of 12,000km². It is in a situation of threat, as its region of occurrence suffers from excessive tourism and fire, which leads to a decline in habitat quality, in addition to being known for two locations.
Dicranaceae	**Campylopus cuspidatus* var. *dicnemoides* (Müll.Hal.) J.-P.Frahm	VU	VU	B2ab(ii, iii)	6.1; 7.1.1; 11.2; 11.3	Despite having a neotropical distribution, in Brazil it occurs only in the states of RJ and SC. It has an EOO of 6,092 km² and an AOO of 12,000km². Frahm (1991) cites the occurrence of the species in the state of AM on Cerro Duida. However, this tepui is located in Venezuela, so it is an erroneous record for the state of AM. The species and its range suffer threats such as fire and predatory tourism, which leads to a continuous decline in AOO, EOO and habitat quality.
Dicranaceae	*Campylopus densicoma* (Müll.Hal.) Paris	EN	EN	B1ab(i,ii,iii)	6.1; 7.1.1; 11.2; 11.3	Despite its wide distribution in the Neotropics, in Brazil the species is restricted to the high-altitude fields of Rio de Janeiro (EOO=273.88 km²). Under-represented in scientific collections. Therefore, a greater collection effort is recommended for the species, in order to know its real geographic distribution.
Dicranaceae	**Campylopus jamesonii* (Hook.) A.Jaeger	VU	VU	B2ab(ii, iii)	6.1; 7.1.1; 11.2; 11.3	Disjunct distribution between Africa and Neotropics. In Brazil it is mainly known for regions of high-altitude fields in the southeast region (MG, RJ and SP). It has a preferential microenvironment in high-altitude fields at the base of *Chusquea* sp. Showcasing AOO of 52,000 km². The species and its range suffer threats such as fire and predatory tourism, which leads to a continuous decline in AOO, EOO and habitat quality.
Ditrichaceae	****Chrysoblastella chilensis* (Mont.) Reimers**	VU	EN	B1ab(iii)+ 2ab(iii)	6.1; 7.1.1; 11.2; 11.3	This species with Neotropical distribution (He 1998). It presents records in subantarctic islands, such as Tristan da Cunha, Marion Island, South Georgia and Macquarie Island, in addition to New Zealand and southeastern Australia (Larraín 2009). In Brazil, the species occurs in the states of Espírito Santo, Minas Gerais and Rio de Janeiro. In INP it was collected at altitudes above 2100 m a.s.l. It has an EOO of 775,854 km² and an AOO of 12,000 km². The frequency of fire in its occurrence regions is quite significant (INP) and the decline in habitat quality is the main threat to this species.
Amblystegiaceae	***Drepanocladus perplicatus* (Dusén) G. Roth**	VU	NT			This species is widely distributed in South America. In the resarch by Costa *et al.* (2005), the citation on the voucher was from *Drepanocladus brasiliensis* Broth., which is a synonym of *Warnstorfia exannulata*. However, it may be included in some threat category in the near future because it occurs in regions that suffer from urbanization, presence of fire and excessive tourism.
Fissidentaceae	***Fissidens wallisii* Müll.Hal.**	VU	LC			This species with neotropical distribution, widely distributed in the Atlantic Forest, occurring in the states of ES, MG, RJ, SC and RS. Occurs mainly in rainforest and mixed rainforest. In addition, it is located in *protected areas* throughout its distribution.

Table 1. Cont.

Family	Species	Older category	2021	Criteria	IUCN Threat Categorization	Justification
Pottiaceae	**Leptodontium flexifolium* (Dicks.) Hampe	VU	VU	B1ab(i, ii, iii)+B2ab(i, ii, iii)	6.1; 7.1.1; 11.2; 11.3	Wide distribution in the world. However, in Brazil, it is restricted to the mountains of the state of RJ with EOO of 17,414 km² and AOO of 12,000 km². In addition, it presents many subpopulations in high-altitude fields of the INP. Despite being within *protected areas*, the species is subject to decline in EOO, AOO and habitat quality due to frequent fires in the regions of occurrence.
Pottiaceae	**Leptodontium stellatifolium* (Hampe) Broth.	VU	VU	B1ab(iii)+ 2ab(iii)	1.1; 2.1; 6.1; 7.1.1; 8.1; 8.2.1; 11.2; 11.3	Neotropical distribution. In Brazil it is restricted to the Atlantic Forest (ES, MG, RJ, SP and SC). It has an EOO of 8,235,581 km² and an AOO of 48,000km². The species and its region of occurrence suffer threats from urban activities such as real estate expansion, implementation of agricultural activities, excessive tourism, presence of provoked fire and introduction of exotic species that cause a decline in the quality and extension of the habitat. It was recently collected from exposed rock and rocky outcrops.
Pottiaceae	**Leptodontium wallisii* (Müll.Hal.) Kindb.	VU	VU	B1ab(i,ii,iii)	6.1; 7.1.1; 11.2; 11.3	Disjunct between South America and Africa. In Brazil, the species occurs in rain forests and high-altitude fields in the states of SP and RJ (EOO=12,534.519 km²), and it may possibly occur in the state of MG. Despite being within *protected areas*, the species is subject to decline in EOO, AOO and habitat quality due to frequent fires and excessive tourism in the regions of occurrence.
Polytrichaceae	**Notoligotrichum minimum* (Cardot) G.L.Sm.	NE	EN	B1ab(i,ii,iii)	6.1; 7.1.1; 11.2; 11.3	Disjunct between Tierra del Fuego (Argentina) and RJ state. In Brazil, the species is restricted to the INP. With an AOO of 12,000 km², it has small isolated subpopulations. The species is subject to decline in EOO, AOO and habitat quality due to frequent fires and excessive tourism in the region of occurrence.
Rhabdoweisiaceae	****Oreoweisia brasiliensis* Hampe**	VU	CR	B1ab(iii)+ B2ab(iii)	6.1; 7.1.1; 11.2; 11.3	Rare species, with disjunct occurrence between the Andes and INP. It has an AOO of 8,000 km². The populations are restricted to the trail to Agulhas Negras. It faces the decline in the quality and extension of the habitat due to the presence of fire and excessive tourism in the region.
Polytrichaceae	****Pogonatum perichaetiale subsp. oligodus* (Müll. Hal.) Hyvönen**	VU	EN	B2ab (ii,iii, iv)	6.1; 7.1.1; 11.2; 11.3	This species is widely distributed in the Neotropics and Africa. In the American continent, it occurs in Central and South America (Hyvönen 1989). In Brazil, it occurs in the high-altitude fields of Serra da Mantiqueira in the states of Minas Gerais and Rio de Janeiro (Peralta 2009). It occurs in montane forests and high-altitude fields only in the area limited by the Atlantic Forest. This species normally grows on hummus between rock fissures in places directly exposed to the sun. It presents AOO of 12.000 km², due to the species presenting microhabitat specificity and facing the decline in habitat quality and extension due to frequent fires in the region and excessive tourism, it allows evaluating the species as EN.
Sematophyllaceae	****Sematophyllum swartzii* (Schwägr.)W.H.Welch & H.A. Crum**	VU	LC			This species have a Neotropical distribution. Widely distributed in the Atlantic Forest, occurring in rainforest and high-altitude fields. It presents many recent collection records.
Splachnaceae	***Tetraplodon mnioides* Müll.Hal.**	VU	CR	B1ab (i, ii, iii) + B2ab(i, ii, iii)	6.1; 7.1.1; 11.2; 11.3	Costa *et al.* (2005) considered *T. itatiaiae* Müll.Hal. as VU. However, the material was taxonomically revised, is considered a synonym of *T. mnioides*. Despite being well distributed in the northern hemisphere, in Brazil it is rare, restricted to the high-altitude fields of the INP. It has an AOO of 8,000 km². It is known from only one location, suffering from declining habitat quality. Individuals of the Splachnaceae family present dispersion mediated by flies and grow on animal dung, which may constitute a rarity factor for the species, since it has few collections, collection efforts and investments in scientific research are necessary in order to certify the real geographic distribution of the species and its ecology.
Calliergonaceae	****Warnstorfia exannulata* (Schimp.) Loeske**	VU	CR	B1b(i,ii,iii,iv) + B1c(i,ii,iii)	6.1; 7.1.1; 11.2; 11.3	This species has a wide distribution in the northern hemisphere. In South America it is restricted to tropical mountains. In Brazil, the species is restricted to the INP high-altitude fields with AOO< 8,000 km². The population is restricted to the region of the source of the Campo Belo River. It faces a decline in habitat quality and extension, due to the presence of fire and excessive tourism in the region.

Table 1. Cont.

Family	Species	Older category	2021	Criteria	IUCN Threat Categorization	Justification
	Endemic to Brazil					
Bartramiaceae	**Breutelia microdonta* (Mitt.) Broth.	NE	LC			This species is endemic and widely distributed in the Atlantic Forest (RJ, ES, MG, SP, SC and PR), found in rainforest and high-altitude fields. With EOO of 41,129 km². Throughout its distribution, it is found in *protected areas*.
Bartramiaceae	**Breutelia wainioi* Broth.	NE	LC			This species is endemic and widely distributed in the Atlantic Forest (RJ, MG, RS) with an EOO of 63,674 km². Throughout its distribution, it is found in *protected areas*.
Dicranaeceae	**Campylopus fragilis* ssp. *fragiliformis* (J.-P.Frahm) J.-P.Frahm	NE	DD			As it is a subspecies, herbarium collections need to be reviewed.
Dicranaceae	*Campylopus gemmatus* (Müll.Hal.) Paris	NE	LC			This species is endemic to Brazil, widely distributed throughout the country, occurs in the *Cerrado* and Atlantic Forest, with an EOO of 757,647,600 km². Along its distribution it is found in *protected areas*.
Ditrichaceae	**Cladastomum ulei* Müll.Hal.	NE	VU	B1ab(i,ii,iii)	6.1; 7.1.1; 11.2; 11.3	This species is endemic to the Atlantic Forest of southeastern Brazil with EOO of 1,022 km² and AOO of 20,000 km². Restricted to the high-altitude fields of the INP and the Parque Nacional do Caparaó (ES). It faces a decline in the quality and extension of the habitat, due to the presence of fire and excessive tourism in the regions of occurrence.
Ephemeraceae	**Ephemerum pachyneuron* Müll.Hal.	NE	CR	B1b(i,ii,iii,iv) + B1c(i,ii,iii)	6.1; 7.1.1; 11.2; 11.3	This species is endemic to the INP, with records only for the *Pedra do Altar* trail. It has AOO< 4,000 km². In addition, it has an annual life strategy and occurs on hummus. It faces a decline in the quality and extension of the habitat, due to the presence of fire and excessive tourism in the regions of occurrence. Only a recent collection (2020), was found in the same previously recorded location, Pedra do Altar.
Polytrichaceae	**Itatiella ulei* (Broth. ex Müll.Hal.) G.L.Sm.	NE	NT			This species is endemic to Brazil, with an EOO of 35,759 km² in the southeast region. It has records in the following *Protected areas*: Caparaó National Park (MG, ES), INP (MG, RJ), Serra dos Órgãos National Park (RJ), Campos do Jordão State Park (SP), Ibitipoca State Park (MG) (Yano & Peralta 2011). Furthermore, the species is restricted to upper montane forests and high-altitude fields. It may be included in some threat category in the near future due to the species occurring in regions that suffer from urbanization, presence of fire and excessive tourism.
Polytrichaceae	**Polytrichum angustifolium* Mitt.	NE	LC			This species is endemic to the Atlantic Forest, with a wide distribution, EOO of 117,152.538km², occurring in the states of ES, MG, PR, RJ, RS, SC, SP (Peralta 2009). It has records in the following *Protected areas* throughout its distribution: Caparaó National Park, Pedra Azul Forest Reserve, Nova Lombardia Biological Reserve, INP, Serra dos Órgãos National Park, Desengano State Park, Campos de Jordão State Park, among others (Peralta 2009).
Rhacocarpaceae	**Rhacocarpus inermis* (Müll.Hal.) Lindb.	NE	LC			This species is endemic and widely distributed in the Atlantic Forest, occurring in the states of RJ, MG, ES, SC and RS with EOO 110,237.324 km². In addition, the species occurs within the boundaries of several *Protected areas* throughout its range (CNCFlora 2012).
Sphagnaceae	*Sphagnum perforatum* Warnst.	NE	VU	B2ab(ii, iii)	5.2; 5.2.1; 11.2; 11.3	This species is endemic to the Atlantic Forest (RJ, MG, SP, PR), with an EOO of 51,135.844 km² and a reduced AOO (16,000 km²). Species restricted to high montane forests and high-altitude fields. It presents threats arising from extractivism and commercial harvesting, since, in general, they are not cultivated, but extracted directly from nature to meet the demands of the floriculture sector (Rancura *et al.* 2010; Negrelle *et al.* 2014; Glime 2007). And it is poorly represented in scientific collections.

Two species were classified as NT (*Drepanocladus perplicatus* and *Itatiella ulei*). Seven were considered as LC (*Breutelia microdonta*, *Breutelia wainioi*, *Campylopus gemmatus*, *Fissidens wallisii*, *Polytrichum angustifolium*, *Rhacocarpus inermis* and *Sematophyllum swartzii*). Three taxa were considered DD (*Andreaea acutifolia*, *Campylopus fragilis* subsp. *fragiliformis* and *Ditrichum itatiaiae* var. *brevipes*) (Tab. 1).

The taxa *Pringleella subulata* and *Trematodon pauperifolius*, which were mistakenly mentioned for the study area in past studies, have been excluded from our analysis due to appropriate justifications presented in Table 2.

Table 2. Excluded taxa.

Excluded taxa	Family	Justification
Pringleella subulata (Müll. Hal.) Broth.	Bruchiaceae	Erroneous registration for the INP (Brotherus 1924). Material type from Serra do Itacolomi (MG).
Trematodon pauperifolius Müll. Hal.	Bruchiaceae	Erroneous registration for the INP (Müller 1898). Material type from Ouro Preto (MG).

Description of the main threats to the high-altitude fields of INP

We characterize eight threats (Fig. 3), whose classification is presented in Table 3.

Table 3. Threats observed in the study areas. Threats identified in the field are indicated with *. The assigned intensity levels were marked according to the legend: low (+), medium (++), high (+++). For threats where the level could not be determined, they were considered unidentified, represented by the symbol (0).

Threats	IUCN threats classification	Region of Study (High-altitude fields of INP)
Agricultural and livestock activities	2. Agriculture & Aquaculture (2.3 Livestock Farming & Ranching)	++
Climate change	11. Climate Change & Severe Weather (11.2 Droughts; 11.3 Temperature Extremes)	0
Fire	7. Natural System Modifications (7.1.1 Increase in Fire Frequency/ Intensity)	+++
Inneficient surveillance	12. Other options (12.1 Other threat)	*++
Invasive species	8. Invasive & Other Problematic Species, Genes & Diseases (8.1 Invasive Non-Native/Alien Species/ Diseases; 8.1.2 Named Species; 8.2.1 Unspecified Species)	*++
Plant removal	5.2 Gathering Terrestrial Plants (5.2.1 Intentional Use (species being assessed is the target)	0
Pollution	9. Pollution (9.4 Garbage & Solid Waste)	*+
Tourism	6. Human Intrusions & Disturbance (6.1 Recreational Activities);	*+++

Figure 3. Main threats to the moss species in high-altitude fields of Itatiaia National Park. **A.** Wildfire occurring in the region **B.** Sign with recommendations for visitors to preserve the high-altitude fields. **C.** Road with tire tracks as the place is visited by a large number of vehicles. **D.** An extensive wildfire during the night. **E.** The fruit of the apple tree representing an exotic species. **F.** Park areas where bryophytes occur are being transformed into parking lots due to the high number of visitors. (Pictures A and D provided by the management team of INP, Picture E provided by our field guide Marco Aurélio)

Discussion

Species Categorization

The assessment of extinction risk in plant species often relies on geographic distribution as one of the key indicators (Lughadha *et al.* 2020). However, information such as individual counts, population reduction, generation time, and number of mature individuals is scarce and difficult to obtain. This challenge is even greater for bryophytes, as there is a lack of specialists in this research area. Therefore, for all assessed species, occurrence records were used as the main source of information, along with other relevant parameters. These parameters included the current distribution of the species, identified threats, endemism to Brazil, habitat quality in the studied area, and the number of collections made and how long it has been since the species was last collected. These elements guided the application of criteria and categories used in the assessment of extinction risk, enabling the use of the B criteria (IUCN 2001).

Hodgetts *et al.* (2019) observed that the threats to native bryophytes can be complex and difficult to categorize. There can also be synergistic effects among threats (for example between climate change and increasing wildfire frequencies) that are difficult to unravel but seriously impact bryophyte survival. Those same authors do, however, discuss the fact that modifications of natural systems, climate change, agriculture, and aquaculture, as well as pollution and human intrusion and disturbances, constitute the main threats to European bryophytes.

Threats to moss survival in the high-altitude fields of the INP

Agricultural and livestock activities - *IUCN: 2. Agriculture & Aquaculture - 2.3 Livestock Farming & Ranching*

Ramos *et al.* (1982) report that the high-altitude fields of the INP preserve rural characteristics associated with extensive cattle farming, which became one of the main economic activities in the *Serra da Mantiqueira* region starting from the 20th century. This agricultural activity has led to deforestation and forest fires due to the use of fire for pasture and native grassland management (Herrmann 2011). Farmers in the region bring their cattle to graze in high-altitude fields, establishing a cycle of grazing and burning that hinders the regeneration of tree vegetation in these areas. The land issue is one of the primary causes of conflicts and forest fires, particularly in high-altitude fields. Even before the expansion of the Park in 1982, breeders allowed cattle to roam inside and outside the Park, on public or private lands, resulting in fires to promote grass growth. Therefore, the issue of fire is directly linked to livestock and the land situation in the Park.

Fire - *IUCN 7. Natural System Modifications - 7.1.1 Increase in Fire Frequency/Intensity*

Ecosystems restricted to mountaintops tend to demonstrate high endemism levels of both their flora and fauna (Martinelli 1996; Safford 1999a; Geise *et al.* 2004). The high-altitude fields have extensive histories of wildfires, making burning the principal threat vector to that ecosystem (Dusén 1955; Brade 1956; Martinelli 1996; Martinelli 2007; Safford 2001; Aximoff 2011; Aximoff *et al.* 2016). Wildfires of natural origin are quite rare, however, with almost all burns being provoked by humans (Aximoff & Rodrigues 2011). Fire is traditionally used in high-elevation regions for managing agricultural and pasture areas – a practice that greatly increases the risk of burns spreading beyond the cultivated properties and damaging protected areas as well as species threatened with extinction (Aximoff 2011).

According to the Management Plan of INP (Ramos *et al.* 1982), wildfires occur more frequently in the winter season, the driest season, and affect large areas of the high-altitude fields. The dry climate, constant winds, frosts, and high amount of dried plants facilitate the occurrence and spread of fire (Safford 1999a). Fire has been the main factor contributing to the impoverishment of the flora in the area (Ramos *et al.* 1982; Aximoff *et al.* 2016). Dusén (1903) already mentioned the damage caused by fire to the vegetation of the high-altitude fields of the INP, noting that frost occurs with such intensity that it burns the entire vegetation, leaving it completely dry and highly flammable.

A wildfire in the high-altitude areas of the INP burned approximately 10,000 ha over a period of 40 days in 1963, destroying vast swaths of native vegetations (Aximoff & Rodrigues 2011). Based on records of fires that occurred in 2001 (600ha), 2004 (600 ha), and in 2007 (800 ha), Aximoff and Rodrigues (2011) suggested the existence of a three-year pattern of large fires, even in non-overlapping areas. There was a single large fire that burned through 1100 ha of high-altitude fields in 2010, impacting areas such as *Pedra do Altar* and *Agulhas Negras*, located in the high-altitude fields of INP (Aximoff 2011; Aximoff & Rodrigues 2011).

Recurrent fires can lead to the gradual disappearance of the rare and/or endemic species that act as genetic matrices for the re-colonization of negatively impacted areas (Aximoff 2011; Aximoff *et al.* 2016). Martinelli *et al.* (1989) estimated that 11% of the vascular plant species found in high-altitude fields in the INP are locally endemic, and 21% are endemic to the high-altitude fields in southeastern Brazil. The effect of fire on the bryophytes of high-altitude fields has not yet been tested. However, Wienskoski and Santos (2022), while studying bryophyte assemblages along a post-fire gradient in the INP region, observed significant changes in species composition. Similarly, Vale (2021) found that morphological functional traits present in leaves represent relevant mechanisms of resistance in acrocarpous moss species occurring along the same disturbance gradient. Thus, we highlight the importance of conducting studies that assess the direct influence of fire on threatened bryophytes occurring in this ecosystem.

Inefficient surveillance - *IUCN 12. Other options - 12.1 Other threat*

The region of the high-altitude fields in INP has many hard-to-reach locations, making it difficult to monitor the area. Additionally, there is a low number of staff members available for the territory. As a result, the surveillance of the area is carried out on a sporadic basis. However, many described threats (e.g., deliberate fires, species removal) could be prevented with more effective monitoring.

Invasive species - *IUCN 8. Invasive & Other Problematic Species, Genes & Diseases - 8.1 Invasive Non-Native/Alien Species/Diseases; 8.1.2 Named Species; 8.2.1 Unspecified Species*

According to Simberloff and Rejmanek (2011), invasive species constitute one of the main threats to biodiversity. In the studied region, we observed the presence of exotic species, such as ferns of the genus *Pteridium* Gled. ex Scop, *Melinis minutiflora* P. Beauv. (molasses grass), *Panicum maximum* Hochst. ex A.Rich. (guinea grass), *Urochloa decumbens* (Stapf) R.D.Webster (signal grass). Additionally, next to Abrigo Rebouças, there are fruit-bearing exotic species, such as *Malus pumila* Mill. and *Prunus persica* (L.) Batsch (apple and peach trees) (personal information) (Fig. 3). Furthermore, Ramos and Sylvestre (2010) and Moura and Morim (2015) document the occurrence of invasive species [lycophyte *Lycopodiella cernua* (L.) and *Ipomoea indica* (Burm.) Merr. (blue morning glory)] in the region. Regarding animals, an INP bulletin (Rosa 2015) highlights the occurrence of the wild boar species *Sus scrofa* L. in the plateau region and indicates that the species is harmful as it can cause a decrease in vegetation cover and soil erosion. Trampling directly affects mosses, resulting in an impact on their populations. Additionally, this disturbance can lead to a reduction in habitat heterogeneity, decreasing microenvironments and affecting the local microclimate.

Plant removal, pollution and tourism - *IUCN 5.2 Gathering Terrestrial Plants - 5.2.1 Intentional Use [species being assessed is the target]; 9. Pollution - 9.4 Garbage & Solid Waste; 6. Human Intrusions & Disturbance - 6.1 Recreational Activities*

In Brazil, National Park is a category of protected areas whose main objective is the preservation of natural ecosystems of ecological relevance and scenic beauty, and which has ecological tourism as one of its core activities, as outlined in the *Sistema Nacional de Unidades de Conservação* (Brasil 2000). The INP is an important tourist spot located between three major Brazilian urban centers, Rio de Janeiro, São Paulo and Belo Horizonte, and is sought after by a large number of visitors (Ramos *et al.* 1982). In the Park, one of the most visited places is the high-altitude fields region, mainly by mountaineers looking for the famous *Picos das Agulhas Negras*, *Pedra do Altar*, *Prateleiras*, *Asa de Hermes*, etc (Fig. 1). Highland fields are easily accessed by non-traction vehicles, which increases the number of vehicles and the direct impact on moss populations. Due to the high demand for vehicles, we observed that areas of occurrence of rare species of bryophytes were recently transformed into parking lots (Fig. 3). Ramos *et al.* (1982) reported the occurrence of illegal collection of plants by visitors to the Park, which probably continues to be a threat to moss species, especially the genera *Sphagnum* (the moss most used in the commercial sector), *Campylopus* and other acrocarpous mosses in the family Dicranaceae and *Rhacocarpus*, many of these present rare and/or threatened species in the INP. In addition, unauthorized camping generates garbage accumulation, destruction of vegetation and even fires (Ramos *et al.* 1982).The large numbers of tourists that can impact microenvironments sheltering mosses (by trampling, writing or drawing on rock faces, and discarding garbage [*e.g.*, toilet paper, plastic, pens, etc.]) represent important threats observed during this study and which, added to the difficulty of surveillance, can be considered of high intensity.

Climate change - *IUCN 11. Climate Change & Severe Weather - 11.2 Droughts; 11.3 Temperature Extremes*

The climatic change affects biological processes and patterns in plant communities (Hawkins *et al.* 2008). Patiño *et al.* (2022) emphasize the importance of understanding the impact of climate change on the distribution of threatened bryophytes and how it will affect their life history and risk of extinction. Palynofloras reveal that climatic fluctuations (warmer and wetter climate) have significantly reduced the areas of high-altitude fields in the past 10,000 years, and the current rates of climate change indicate the imminent risk of disappearance of these habitats (Safford 2007). It is worth noting that, although climate predictions for the coming decades indicate an increase in rainfall in the southeastern region of Brazil, especially during the summer (PBMC 2012), a decrease in fog in high-mountain regions is also expected (Still *et al.* 1999; Ohmura 2012), which will increase water stress in high-altitude fields. The reduction in fog would mean the loss of an important resource for bryophytes in high-altitude fields, as they, being poikilohydric, rely on atmospheric humidity as a direct source of water (Proctor & Tuba 2002). In addition, IPCC (2013) projections indicate that extreme climatic events, such as droughts, will be more frequent and longer in the coming decades, which may have drastic consequences for the high-altitude fields.

Scarano et al. (2016) emphasize a significant gap on climate change projections and the long-term ecological monitoring the for the high-altitude fields. The authors alerted for the vulnerability of island-like ecosystems that emerge at high elevations and highlight that expected effects of climate change include habitat reduction, population decline, and modifications in phenology of the species. Assis and Mattos (2016) reiterate the lack of knowledge hinder predictability about the response of high-altitude fields vegetation to climate change and reinforce the need to perform manipulative approaches and species distribution modeling.

Recommendations

Documenting information concerning threatened species can help prevent the imminent loss of biodiversity and subsidize effective proactive plans and activities directed toward their conservation. Hallingbäck and Hodgetts (2000), Costa & Paranhos (2008), Gradstein and Raeymaekers (2000), Hodgetts *et al.* (2019), and Sharrock (2020) published recommendations for bryoflora conservation: investments in research; the identification of critical areas and centers of diversity and endemism; habitat protection efforts that can guarantee the survival of bryophyte species and communities; and the formulation of multidisciplinary programs to promote conservation.

In support of those efforts, we propose the following orientations:

i) Acknowledge the importance of conserving the high-altitude field ecosystems in *Serra da Mantiqueira*, which are situated within the Atlantic Forest phytogeographic domain, along with the surrounding buffer zones, as crucial and priority areas for conservation.

ii) Protection of the microhabitats where bryophyte species occur is crucial, especially for terrestrial species found along trails such as *Agulhas Negras* (e.g. the watercourse stream along the *Agulhas Negras* massif that forms a microhabitat for *Andreaea subulata* Harv., see Gonçalves *et al.* 2022), *Prateleiras*, *Cinco Lagos*, *Pedra do Altar*, and other vulnerable locations affected by human activities. These habitats are particularly susceptible to trampling and the negative consequences it brings.

iii) Detailed mapping of the species occurring in the INP, especially those classified as CR and EN, to define their areas of occurrence and facilitate their preservation.

iv) Increasing knowledge through inventories and ecological studies is crucial. Therefore, it is essential to invest resources in research focusing on: (1) Ecological and reproductive biology studies that aid in understanding the life history of species (e.g., generation length, mature individuals, and severe fragmentation, as recommended by Bergamini *et al.* 2019). (2) Experimental studies that support conservation measures, including the evaluation of protocols for cultivation (ex situ conservation) and reintroduction of threatened species into their original habitats (in situ conservation). (3) Taxonomic studies of species classified as Data Deficient (DD). (4) Studies on the direct effects of disturbances such as fire and climate change on threatened species and their adaptability to environmental changes.

v) Publication of didactic material for dissemination to the visiting public (manuals, handouts, sites, videos, etc.), focusing on rare and/or threatened bryophyte species in the INP.

vi) Promote the sustainable use of trails by taking into consideration the bryophytes species that grow along them and in rock climbing areas (which are often not even perceived by visitors). This action can prevent the loss of entire bryophyte populations of near heavily used areas.

vii) Promote ecological tourism, environmental education, and nature interpretation during visits – which can aid in combating predatory tourism and preserving natural areas.

viii) Include considerations of bryophytes in the management plans of conservation areas, as those plants are frequently passed over during the preparation of orienting documents.

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