

Assessing the extinction risk of Malagasy orchids to develop effective conservation approaches – a case study of the Itremo Massif Protected Area

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Abstract

Background and aims – Madagascar harbours high numbers of threatened orchid species, making it critical for orchid conservation. The Itremo Massif Protected Area (Itremo Massif PA), a Key Biodiversity Area in the Central Highlands, comprises diverse habitats essential for orchid survival. Previously, only 30% of the 83 orchid species recorded in the Itremo Massif PA had been assessed for the IUCN Red List. This research documents and analyses their habitats and threats to propose conservation approaches.

Material and methods – We compiled a dataset of orchid species native to the Itremo Massif PA, including information on endemism, conservation status, habitats, and threats from IUCN Red List assessments and field observations. A species-by-habitat matrix was constructed, and species composition across habitats was analysed using a β -diversity framework. Overall β -diversity (β_{SOR}) was partitioned into species turnover and nestedness components. We also evaluated the proportion of threatened orchid species (Critically Endangered – CR, Endangered – EN and Vulnerable – VU) associated with the primary habitats and threats in the PA.

Key results – Of the 83 orchid species native to the Itremo Massif PA, 64% (53 spp.) are endemic to Madagascar and 41% (34 spp.) are threatened (1 CR, 16 EN, 17 VU). Species composition varies markedly between habitats ($\beta_{\text{SOR}} = 0.83$), primarily driven by species turnover (0.66). Bare soil and rock host the most orchid species (60%, 50 spp.). Bare soil and rock and grassland share the most species (14%, 12 spp.), while humid forest contains the most species restricted to a single habitat (16%, 13 spp.). Orchids are primarily threatened by mining and quarrying, increased fire intensity/frequency, logging and wood harvesting, and shifting agriculture.

Conclusion – Conservation should prioritise humid forest for its unique orchid species, and bare soil and rock for their richness in endemic and threatened species. Grassland also represents essential habitat for terrestrial orchids. Further research on population dynamics, pollination, and fungal interactions is needed to better assess extinction risk and manage conservation.

Keywords

conservation, fire, habitat preference, Important Plant Area, IUCN Red List, mining, Orchidaceae

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INTRODUCTION

Orchidaceae is one of the most species-rich families of flowering plants with around 31,000 species (Fay and al. 2025; POWO 2026). At the same time, it is one of the world's most threatened taxonomic groups (Wraith and Pickering 2018), as many species are vulnerable to habitat changes because of their strong ecological specialisation (Lussu et al. 2024). The IUCN Red List is regarded as the most comprehensive and authoritative source of global extinction risk for species (Nic Lughadha et al. 2020) and currently includes 2,123 orchid species, of which 1,062 (50%) are assessed as threatened (Critically Endangered – CR, Endangered – EN, or Vulnerable – VU; IUCN 2025; Fay et al. 2025). In response to these concerns, a global action plan was developed to identify the primary threats to wild orchid species and to provide recommendations for scientists, growers, and policymakers on how to protect orchid biodiversity (IUCN/SSC Orchid Specialist Group 1996). Given their exceptional diversity, vulnerability, and importance in cultivation and trade, orchids are recognised as a model group for biodiversity conservation (Hinsley et al. 2018). To mitigate the risks from unsustainable trade, international trade in orchids is regulated under the Convention of International Trade of Endangered Species (CITES 2024).

Madagascar is among the world's important centres of orchid diversity and endemism. The island hosts a high number of threatened orchid species (Wraith et al.

2020), making it a global priority for conservation due to the intense pressures affecting its natural habitats (Vitt et al. 2023). However, only 30% (312 spp.) of Madagascar's orchids have been published on the IUCN Red List (IUCN 2025), leaving major gaps in knowledge for conservation planning. Beyond the risks related to the collection and trade, many orchids occur in areas that are also important for agriculture, mining (Farminhão et al. 2024), and other subsistence activities (Droissart et al. 2023).

The Itremo Massif Protected Area (Itremo Massif PA), situated in Madagascar's Central Highlands, represents an important focus for plant conservation due to its notable botanical richness including 749 plant species, 353 genera, and 103 families (Rakotonasolo et al. 2025). Orchidaceae is the second most species-rich family in the area, with 83 species recorded, following Poaceae with 111 species (Rakotonasolo et al. 2025). Located 117 km west of Ivato along the National Road (RN 35) to Malaimbandy, the Itremo Massif PA lies within the district of Ambatofinandrahana, Amoron'i Mania Region, in Fianarantsoa province. It is bordered by the rural commune of Itremo in the east, by Amborompotsy in the west, and by Mangataboahangy in the northwest (Fig. 1). Covering 24,788 ha at elevations between 1,500 and 2,100 m, the Itremo Massif PA comprises diverse habitats (Fig. 2) including grassland (70%), bare soil and rock (10.5%), tapia woodland (6.4%), humid forest (1.3%), and wetland (0.4%) (Kew Madagascar Conservation Centre 2012). Inselbergs in the Central highlands of

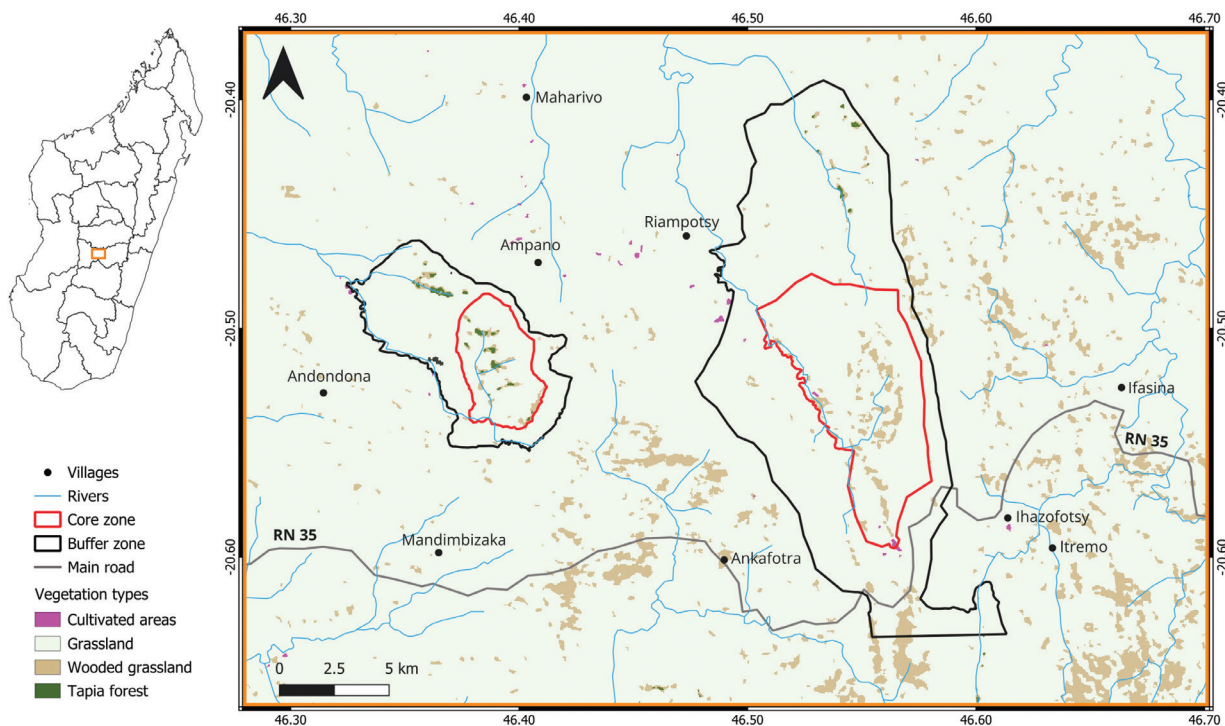


Figure 1. Location of the Itremo Massif Protected Area, in Amoron'i Mania region, South-Central Madagascar. The habit types by Moat and Smith (2007), such as the small patches of humid forest, tapia forest, and areas of bare soil and rocks that occur within the area are not clearly distinguished at the scale of the map and are included within the woodland grassland. Map prepared in QGIS Desktop v.3.34.1 (QGIS Development Team 2023).

Madagascar, characterised by bare soil and rock, harbour succulent plants, including orchids typically associated with arid environments, indicating unique microclimates and environmental stresses in these habitats (Porembski 2007; Rabarimanarivo et al. 2019). Tapia woodland is a characteristic element of the Malagasy flora occurring in the Central Highlands, consisting of a grassy herbaceous layer with a tree layer dominated by *Uapaca bojeri* Baill. (Phyllanthaceae), alongside species from families such as Anacardiaceae, Asteraceae, Asteropeiaceae, Rubiaceae, and Sarcolaenaceae. Designated as a protected area (PA) in 2005 and managed by Kew Madagascar, the Itremo Massif is classified as a protected harmonious landscape under IUCN Category V and was initially conceived as a PA through the Durban Vision initiative in 2003 (Ralimanana et al. 2022). It is recognised as an Alliance for Zero Extinction site (<https://zeroextinction.org/>), due to the presence of the endangered endemic plant *Podocarpus capuronii* de Laub. (Podocarpaceae). The Itremo Massif PA is also recognised as a Key Biodiversity Area (KBA) because it hosts endangered animals such as Verreaux's sifaka (*Propithecus verreauxi* A. Grandidier, 1867) and the harlequin mantella frog (*Mantella cowani* Boulenger, 1882) (Rakotonasolo et al. 2025). Despite

its botanical importance, the Itremo Massif PA has not yet been assessed using the criteria for Important Plant Areas (Darbyshire et al. 2017), leaving a significant gap in prioritisation of plant diversity conservation.

Of the 83 orchid species recorded in the Itremo Massif PA, only 34 species have been assessed on the IUCN Red List (IUCN 2025). Orchids are collected by local people and horticulturists for both local and international trade, with around 75% of species affected (Hermans and Rajaovelona 2022; UNEP-WCMC 2024). Expanding the number of species assessed on the IUCN Red List is critical, as it raises public awareness, unlocks conservation funding, guides prioritisation and site-based planning, and facilitates collaboration among stakeholders (Fay et al. 2025).

Orchid conservation in Madagascar's Central Highlands faces multiple interacting challenges. High endemism and narrow habitat ranges make orchids sensitive to environmental changes (Swarts and Dixon 2009; Phillips et al. 2024). Seasonal fires, a traditional practice associated with pasture and agriculture, help maintain grassland but can also degrade forest fragments and threaten orchid survival and regeneration, although it may also trigger flowering in some orchids (Keeley et



Figure 2. Vegetation types in the Itremo Massif Protected Area. A, B. Humid forest in a valley in the middle of grassland in Antanimenahy. C. Quartzitic bare soil and rock in Antsirakambiaty. D. Tapia woodland in Antsirakambiaty. Photos by Landy R. Rajaovelona.

al. 2011; Andela et al. 2017). Invasive pines (*Pinus kesiya* Royle ex Gordon, *P. elliotii* Engelm, *P. patula* Schiede ex Schltdl. & Cham.) further impact orchids by altering fire behaviour and modifying soil properties, reducing habitat suitability (Downing 2016; Rajaonarivelo et al. 2022). Pine eradication was implemented as part of the 2017–2019 Kew Madagascar project in the Itremo Massif PA funded by the Critical Ecosystem Partnership Fund. Mining activities, such as tourmaline, crystal, and gold extraction, have been observed in the field (Landy R. Rajaovelona pers. obs. 2023).

These combined pressures highlight the urgent need for targeted conservation. This study aims to assess the conservation status and set conservation priorities for orchids in the Itremo Massif PA by answering the following questions: (1) How many orchid species native to the Itremo Massif PA are currently classified under IUCN threatened categories? (2) What are the primary habitats of Itremo orchids and how does species composition vary across habitats? and (3) What are the main threats to orchids in the Itremo Massif PA? Finally, we propose actions to preserve orchid biodiversity in the area.

MATERIAL AND METHODS

Data collection

Data on endemism, IUCN conservation status, habitats, and threats were extracted and compiled from two main sources: (1) field observations and online databases, including data from Tropicos (2024), POWO (2024) and iNaturalist (2024); and (2) IUCN Red List assessments. The latter comprised published assessments for 34 species (published between 2015 and 2025, including nine generated for this manuscript), newly generated full assessments submitted to IUCN in 2024 after review by the Madagascar Plant Specialist Group for 47 species, and preliminary assessments for three species, i.e. *Bulbophyllum humbertii* Schltr., *B. oclusum* Ridl., and *Nervilia simplex* Schltr. (Suppl. materials 1, 2).

Endemism

Species were marked as endemic to Madagascar if they only occur in Madagascar based on the distribution data recorded in POWO (2024).

IUCN conservation status

We conducted full IUCN Red List assessments following the guidelines set out in the IUCN Red List Categories and Criteria (IUCN, 2024). Assessments were done at global scale and consider all regions in Madagascar where each species occurs. To determine threat categories, all known occurrence records from herbarium specimens and Research Grade iNaturalist observations were compiled to calculate the minimum Area of Occupancy (AOO), based on the standard 2 × 2 km² grid, and the estimated Extent of Occurrence (EOO) for each species using GeoCAT (Bachman et al. 2011). These assessments, primarily

based on Criteria B and D, have been reviewed by the Madagascar Plants Specialist Group. Of the 54 newly generated assessments, six have already been published on the online IUCN Red List, while 47 have been submitted to IUCN and are awaiting publication. Each species was assigned to one of the following categories: Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), or Least Concern (LC).

Habitat

The habitats of orchid species occurring in the Itremo Massif PA were defined by integrating the vegetation classification of Moat and Smith (2007) with the IUCN Habitats Classification Scheme Version 3.1 (IUCN 2012). Seven habitat categories were considered: bare soil and rock, cultivation, grassland (wooded, shrub-covered, plateau grassland), humid forest, tapia woodland, western dry forest, and wetland. Habitat assignment was based on presence-absence data from field observations and information from the IUCN Red List assessments and verified using online databases such as Tropicos (2024) and POWO (2024).

Bare soil and rock include granitic inselbergs and landscapes dominated by exposed rock in the Central Highlands. Cultivation includes croplands, rice fields, and areas used for agroforestry. Wetland comprises marshes, swamps and peatlands. In the Itremo Massif PA, humid forest corresponds to gallery forests maintained by water sources. Although the western dry forest is not present within the Itremo Massif PA, it was included in the analysis because some species with broad ecological niches that occur in western dry forest elsewhere in Madagascar are native to the Itremo Massif PA where they are found in other habitats such as humid forest. Including the western dry forest habitat category in the analysis is therefore necessary to represent the full ecological distribution of these species in Madagascar more widely.

Threats

The threats facing orchid species at global level were classified following the Guidance on Threats and Stresses Classification Scheme Version 3.3 (IUCN 2022) at appropriate levels (1, 2, or 3). Twelve threat categories were considered: abstraction of surface water, droughts, housing and urban areas, human intrusions and disturbance, increase in fire frequency/intensity, intentional use, invasive species/disease, logging and wood harvesting, mining and quarrying, nomadic grazing, shifting agriculture, and soil erosion and sedimentation. For each species, the threats most relevant to orchids occurring in the Itremo Massif PA were identified based on field observations and information documented in the previously published IUCN Red List assessments.

Fire regime and orchid flowering phenology

The flowering period of each orchid species was compiled from field observations and from the plant species checklist of the Itremo Massif PA (Rakotonasolo et al. 2025). Fire regime data were derived from monitoring

Table 1. Summary of endemism and extinction risk of orchids native to the Itremo Massif Protected Area. Species indicated with an asterisk (*) are endemic or near-endemic to the Itremo Massif Protected Area.

Endemism and extinction risk	Number of species	Species list
Endemic to Madagascar and threatened	30	<i>Aerangis ellisii</i> , <i>Aerangis fuscata</i> , <i>Aerangis pallidiflora</i> , <i>Aeranthes ramosa</i> , * <i>Angraecum coutrixii</i> , * <i>Angraecum magdalenae</i> , <i>Angraecum popowii</i> , <i>Angraecum protensum</i> , * <i>Benthamia praecox</i> , <i>Benthamia rostrata</i> , <i>Brachycorythis disoides</i> , <i>Bulbophyllum callosum</i> , * <i>Bulbophyllum humbertii</i> , <i>Cynorkis cardiophylla</i> , <i>Cynorkis cinnabarina</i> , * <i>Cynorkis melinantha</i> , * <i>Cynorkis sacculata</i> , <i>Eulophia ibityensis</i> , <i>Eulophia macra</i> , <i>Habenaria alta</i> , <i>Habenaria ambositrana</i> , <i>Habenaria bathieii</i> , * <i>Habenaria monadenioides</i> , * <i>Habenaria quartzicola</i> , * <i>Jumellea ibityana</i> , <i>Jumellea intricata</i> , * <i>Jumellea spathulata</i> , <i>Polystachya henrici</i> , <i>Polystachya monophylla</i> , <i>Tylostigma tenellum</i>
Endemic to Madagascar and non-threatened	23	<i>Angraecum arachnites</i> , <i>Angraecum compactum</i> , <i>Angraecum rutenbergianum</i> , <i>Angraecum sororium</i> , <i>Benthamia flavida</i> , <i>Benthamia glaberrima</i> , <i>Bulbophyllum baronii</i> , <i>Bulbophyllum bicoloratum</i> , <i>Cynorkis baronii</i> , <i>Cynorkis gibbosa</i> , <i>Cynorkis gigas</i> , <i>Cynorkis lilacina</i> , <i>Cynorkis papillosa</i> , <i>Cynorkis purpurea</i> , <i>Cynorkis uniflora</i> , <i>Disa incarnata</i> , <i>Eulophia ramosa</i> , <i>Eulophia reticulata</i> , <i>Eulophia rutenbergiana</i> , <i>Calanthe francoisii</i> , <i>Habenaria simplex</i> , <i>Jumellea densefoliata</i> , <i>Satyrium rostratum</i>
Non-endemic to Madagascar and threatened	4	<i>Aeranthes strangulata</i> , <i>Benthamia bathieana</i> , <i>Eulophia pileata</i> , <i>Tylostigma hildebrandtii</i>
Non-endemic to Madagascar and non-threatened	26	<i>Aerangis punctata</i> , <i>Angraecopsis parviflora</i> , <i>Angraecum calceolus</i> , <i>Angraecum leonis</i> , <i>Angraecum mauritianum</i> , <i>Angraecum pectinatum</i> , <i>Bulbophyllum oclusum</i> , <i>Calanthe sylvatica</i> , <i>Cynorkis fastigiata</i> , <i>Cynorkis flexuosa</i> , <i>Cynorkis graminea</i> , <i>Cynorkis lindleyana</i> , <i>Eulophia hians</i> , <i>Eulophia livingstoneana</i> , <i>Eulophia plantaginea</i> , <i>Habenaria incarnata</i> , <i>Jumellea stenophylla</i> , <i>Neobathiea grandidieriana</i> , <i>Nervilia simplex</i> , <i>Polystachya anceps</i> , <i>Polystachya concreta</i> , <i>Polystachya cultriformis</i> , <i>Polystachya fusiformis</i> , <i>Polystachya rosea</i> , <i>Satyrium amoenum</i> , <i>Satyrium trinerve</i>

reports by patrol agents of the Itremo Massif PA, documenting the timing of fires in relation to orchid flowering. Flowering events were categorised into two periods: orchids flowering during the fire season (July–October), and orchids flowering post-fire (November–June), to assess interactions between fire occurrence and orchid flowering phenology.

Analyses

Analyses were conducted in R v.4.3.1 (R Core Team 2024). Our dataset was formatted using the tidyverse collection of packages (Wickham et al. 2019), specifically dplyr v.1.2.0 (Wickham et al. 2020) for data manipulation, tidyr v.1.3.1 (Wickham et al. 2024) for data reshaping, and tibble v.3.3.1 (Müller et al. 2023) for creating a presence-absence data matrix following the structure described by Koleff et al. (2003). We created a presence-absence matrix dataset of orchid species in each habitat. β -diversity was calculated using the R package betapart v.1.6.1 (Baselga and Orme 2012; Baselga et al. 2023) to evaluate the variation of orchid species composition among habitats. The overall compositional dissimilarity (β_{SOR}) was measured using Sørensen dissimilarity index. Total β -diversity was partitioned into two components (Baselga 2010): (1) β_{SNE} : the nestedness component, measured as Sørensen dissimilarity and reflecting the loss of species without replacement; and (2) β_{SIM} : the turnover component, measured as Simpson dissimilarity and representing species replacement between habitats. Pairwise

β -diversity was also calculated using betapart v.1.6.1 to identify habitat pairs with the greatest compositional differences and to determine the contribution of turnover and nestedness to those differences. Species composition within each habitat was quantified. The number of orchid species unique to each habitat, as well those shared across habitats, were calculated using the R package matrixStats v.1.4.1 (Bengtsson 2024). To visualise the number of species shared across habitat combinations, an upset plot was generated using the R package ComplexUpset v.1.3.3 (Lex et al. 2014; Krassowski 2021). The proportions of endemic and non-endemic orchids in threatened categories (CR, EN, and VU) and in non-threatened categories (NT and LC) were analysed. The distribution of threatened and non-threatened orchid species across habitat types in the Itremo Massif PA, as well as the proportions of orchids affected by various threats were visualised using ggplot2 v.3.5.0 (Wickham 2016).

RESULTS

Endemism and extinction risk

The endemism in Madagascar and IUCN conservation status for each orchid species occurring in the Itremo Massif PA are provided in Suppl. material 1 and full rationales for newly assessed species are provided in Suppl. material 2. Fifty-three (64%) species native to the Itremo Massif PA are endemic to Madagascar. Overall, 34 orchid

species (41%) were identified as threatened according to the IUCN Red List categories, one species is classified as Critically Endangered (CR), 16 are assessed as Endangered (EN), and 17 as Vulnerable (VU). The orchids endemic to Madagascar that occur in the Itremo Massif PA mostly represent threatened species (36%, 30 spp.) while those that are non-endemic to Madagascar mostly correspond to non-threatened species (31%, 26 spp.). Examples of narrowly distributed, threatened orchids (Table 1) are: *Cynorkis sacculata* Schltr. (CR), restricted to the Ibity and Itremo Massif PAs, with a single subpopulation in the Itremo Massif PA; *Jumellea spathulata* (Ridl.) Schltr. (EN), restricted to the Amoron'i Mania region; *J. ibityana* Schltr. (EN), restricted to the Vakinankaratra and Amoron'i Mania regions; and *Cynorkis melinantha* Schltr. (EN) and *Angraecum coutrixii* Bosser (EN), both locally endemic to the Itremo Massif PA. However, the Itremo Massif PA also hosts orchids endemic to Madagascar that are non-threatened (27%, 23 spp.), and a few non-endemic orchids that are threatened (6%, 5 spp.) (Fig. 3). The list of orchid species grouped by endemism to Madagascar and conservation status is provided in Table 1.

Habitats of Itremo Massif PA orchids

Bare soil and rock, humid forest, and grassland are the three most orchid-rich habitats in the Itremo Massif PA (Fig. 4A). Bare soil and rock hosts the highest number of orchid species (60%, 50 spp.), followed by humid forest (45%, 38 spp.), and grassland (39%, 33 spp.). The number and list of threatened (CR, EN, VU) and non-threatened (NT, LC) orchid species found in each habitat are detailed in Suppl. material 6. All habitats in the Itremo Massif PA host threatened orchid species: bare soil and rock hosts the highest number of threatened species (26%, 22 spp.), humid forest (15%, 13 spp.), grassland (12%, 10 spp.), tapia woodland (7%, 6 spp.), wetland (4%, 4 spp.), and only one species *Cynorkis cinnabarina* (Rolfe) Hermans & P.J.Cribb

in the cultivation area (Suppl. material 6). Although the Itremo Massif PA does not include western dry forest habitat, four widespread species typically associated with Madagascar's dry forests elsewhere such as *Angraecum leonis* (Rchb.f.) André, *Nervilia simplex* (Thouars) Schltr., and *Polystachya fusiformis* (Thouars) Lindl. have been recorded at the edge of humid forest in the Itremo Massif PA. Additionally, *Eulophia ramosa* Ridl. occurs in the bare soil and rock habitat and tapia woodland habitat in the Itremo Massif PA. Their presence in the Itremo Massif PA indicates their ecological tolerance to seasonal drought stress and their ability to occupy a broad range of habitats.

Habitat-based orchid species composition and dissimilarity among habitats

A total of 28.9% (24 species) is restricted to a single habitat: 15.6% (13 spp.) are exclusive to humid forest, 10.8% (9 spp.) restricted to bare soil and rock, and 2.4% (2 spp.) to grassland. Bare soil and rock and grassland share the highest number of species 14.5% (12 spp.), followed by humid forest and bare soil and rock 9.6% (8 spp.), and grassland and wetland 6.2% (5 spp.). Seventy-one percent (59 spp.) occur in three or four habitats within the Itremo Massif PA (Suppl. material 3). The number of orchid species that are restricted to one habitat and those present in two, three, or four habitats are summarised in Fig. 5. The list of orchid species in each habitat combination is detailed in Suppl. material 3. The habitats where orchid species occur in the Itremo Massif PA are presented in the Suppl. material 4 and the presence-absence of each orchid species by habitat is shown in Suppl. material 5.

The overall β -diversity across all habitats was high ($\beta_{SOR} = 0.83$) indicating that each habitat is composed mainly of distinct orchid species. The turnover component or species replacement was high ($\beta_{SIM} = 0.66$), and the nestedness component or species loss was low ($\beta_{SNE} = 0.17$). These results indicated that difference in orchid composition is

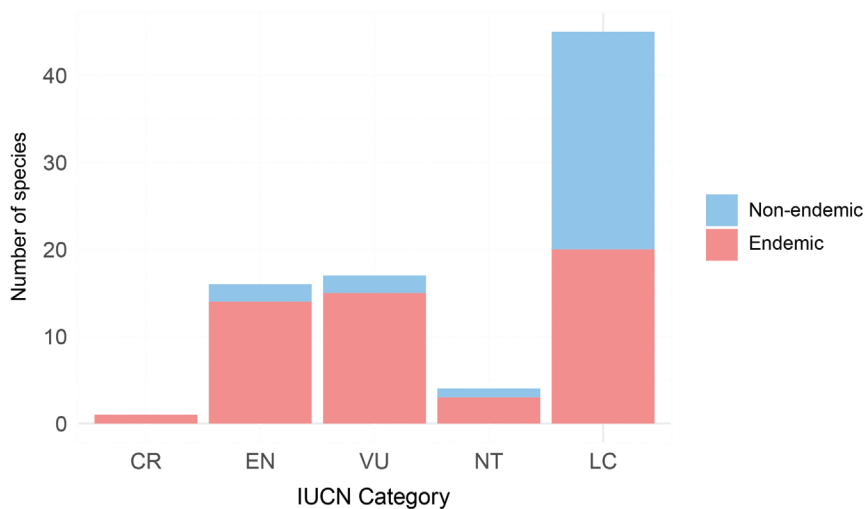


Figure 3. Endemism to Madagascar and extinction risk of orchid species in the Itremo Massif Protected Area. Number of endemic and non-endemic orchids across IUCN categories: Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), and Least Concern (LC).

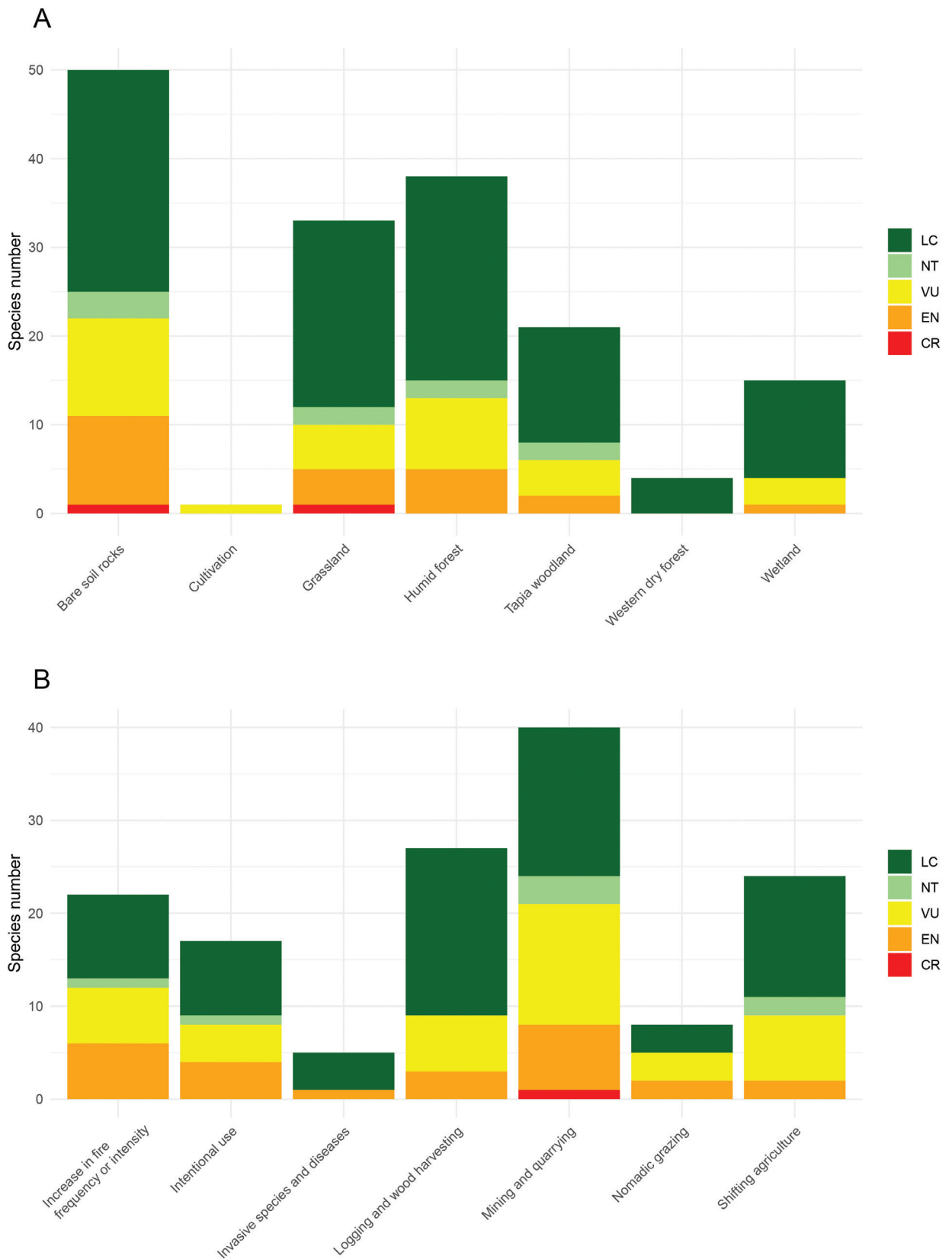


Figure 4. Conservation status of the orchid species native to the Itremo Massif Protected Area by habitat (A) and by threat (B).

Table 2. Summary of (β -diversity) analysis based on orchid species composition in different habitats in the Itremo Massif PA: β_{SOR} (overall β -diversity, measured as Sørensen dissimilarity), β_{SIM} (turnover component, measured as Sørensen metrix), β_{SNE} (nestedness component, measured as a Simpson metric). Cultivation was excluded from the analysis as it was represented by only one species.

Habitat1 & Habitat2	β_{SOR}	β_{SIM}	β_{SNE}	Shared species	Unique species Habitat1	Unique species Habitat2
Humid forest & Bare soil and rock	0.64	0.6	0.04	8	13	9
Humid forest & Tapia woodland	0.67	0.52	0.15	4	13	0
Humid forest & Grassland	0.84	0.82	0.01	1	13	2
Humid forest & Wetland	0.96	0.93	0.03	0	13	0
Humid forest & Western dry forest	0.86	0.25	0.61	3	13	0
Bare soil and rock & Tapia woodland	0.63	0.38	0.25	3	9	0
Bare soil and rock & Grassland	0.48	0.35	0.12	12	9	2
Bare soil and rock & Wetland	0.78	0.53	0.25	2	9	0
Bare soil and rock & Western dry forest	0.96	0.75	0.21	0	9	0
Tapia woodland & Grassland	0.71	0.62	0.09	2	2	2
Tapia woodland & Wetland	0.83	0.8	0.03	0	2	0
Tapia woodland & Western dry forest	0.92	0.75	0.17	0	2	0
Grassland & Wetland	0.55	0.27	0.28	5	2	0
Grassland & Western dry forest	1	1	0	0	2	0
Wetland & Western dry forest	1	1	0	0	0	0

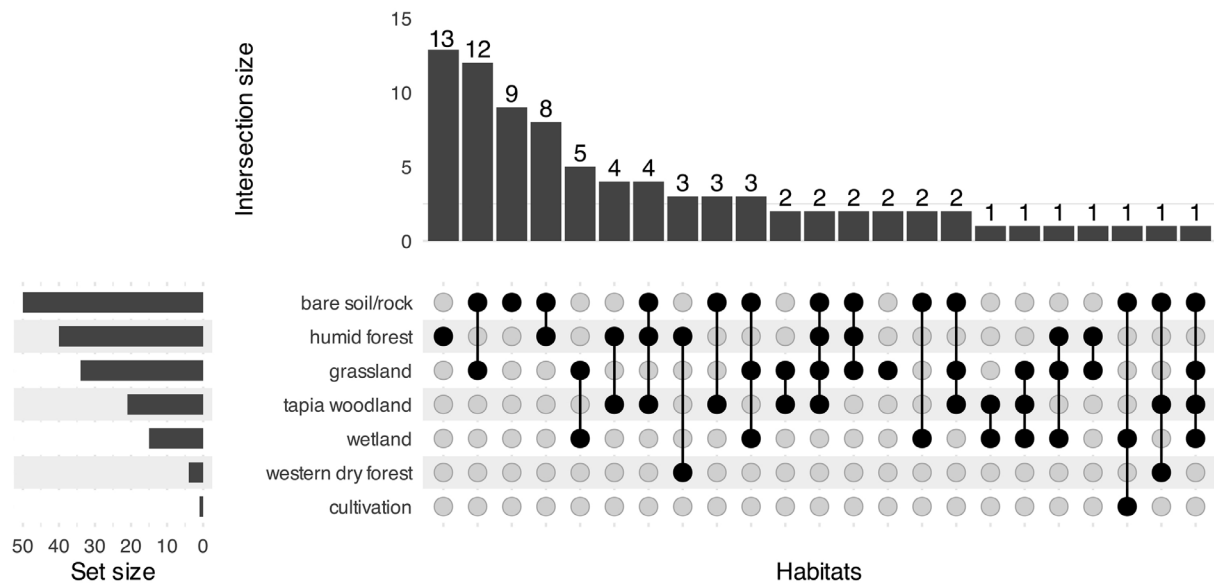


Figure 5. Species composition across vegetation types in the Itremo Massif Protected Area. UpSet plot showing the number of orchid species shared among different habitat combinations (2, 3, or 4 habitats) and species unique to each habitat. Each bar represents the number of species in each habitat combination, indicated by the connected dots below the bars. Individual dots represent species unique to a single habitat, while connected dots represent shared species between two to four habitats. The set size (0–50) is the total number of species recorded in each habitat, some habitats may have 50 species, others poor species (close to 0). The total number of species in each habitat includes species unique to that habitat and those shared with other habitats.

primarily due to species replacement between habitats. Pairwise β -diversity analysis (Table 2) revealed that the two habitats bare soil and rock and grassland had the most similar species composition ($\beta_{\text{SOR}} = 0.47$). In contrast, the four widespread species of western dry forest elsewhere in Madagascar do not occur in grassland and in wetland in the Itremo Massif PA ($\beta_{\text{SOR}} = 1$).

Threats to Itremo Massif PA orchids

Seven of the 12 threats based to the IUCN Classification Scheme affect orchid species native to the Itremo Massif PA. Four threats, i.e. mining and quarrying, increase in fire intensity/frequency, shifting agriculture, and logging and wood harvesting are the most significant threats to orchid species (Fig. 4B). The other five threats (abstraction of surface water, droughts, housing and urban areas, human intrusions and disturbance, and soil erosion and sedimentation) were excluded from the analysis because they were reported only for non-threatened orchids (1–3 species each) or were not applicable to the Itremo Massif PA (Suppl. material 4).

Mining and quarrying represent the major threat to orchids in the Itremo Massif PA by affecting 21 (60%) of the 34 threatened species recorded (1 CR, 7 EN, and 13 VU). Lithophytic orchids such as *Cynorkis sacculata* (CR), *Angraecum coutrixii* (EN), *C. melinantha* (EN), *Jumellea ibityana* (EN), and *J. spathulata* (EN) grow in small and fragmented orchid population, on bare soil and rock, affected by mining within the Itremo Massif PA (Landy R. Rajaovelona pers. obs. 2022).

The increase in fire frequency/intensity is the second threat by affecting 12 (34%) threatened species (6 EN, 6 VU). *Angraecum protensum* Schltr., *Jumellea ibityana*, and *J. spathulata*, are examples of orchids in the area that have aerial roots. As a result, these species may be sensitive to heat damage. In addition, *Polystachya monophylla* Schltr., *Eulophia ibityensis* Schltr., and *E. macra* Ridl. are examples of threatened orchid species at risk because fire can destroy the above ground pseudobulbs. Both shifting agriculture and logging and wood harvesting are a third threat by impacting each 9 (7%) threatened orchids (3 EN, 6 VU and 2 EN, 7 VU) (Suppl. material 7). The number and list of orchid species (threatened and non-threatened species) affected by each threat are detailed in Suppl. material 7.

Fire time and flowering period

Based on field observations, seasonal fires occur between July and October in the Itremo Massif PA. Based on the data presented in Suppl. material 8, 61% (51 spp.) of the orchid species flower post-fire because they bloom during the rainy season (November–June). They include mostly terrestrial orchids in the genera such as *Cynorkis* Thouars, *Benthamia* A.Rich., *Satyrium* Sw., and *Tylostigma* Schltr., which are geophytes with underground tubers. Only four species (*Aerangis ellisii* Schltr., *Angraecum arachnites* Schltr., *Angraecum calceolus* Thouars, and *Bulbophyllum*

callosum Bosser) have flowers during the fire season between July and October, and 33% (28 spp.) can bloom both between July and October or November and June, so both during and/or after the fire season.

DISCUSSION

Our research shows that the Itremo Massif Protected Area supports a rich orchid flora, with 53 species endemic to Madagascar—representing 64% of the 83 species recorded in the area. Of these, 34 species (41%) are classified as threatened according to IUCN Red List assessments. Although substantial, the proportions of endemic and threatened species in the Itremo Massif PA are lower than national estimates (83% and 76%, respectively; Droissart et al. 2023). These results provide essential baseline data for informing conservation planning (Ralimanana et al. 2022) and underscore the importance of integrating comprehensive biodiversity information—including habitat characteristics, species distributions, and threat patterns—into protected area management strategies (Cooke et al. 2022). Humid forest harbours unique, mostly epiphytic orchid species that depend on stable microclimate conditions and specific host trees; these species would not survive prolonged droughts and extreme temperatures (Linder et al. 2005). Humid forest is home to 13 species of epiphytic orchid that are restricted to this habitat. Other orchid species can occur across diverse habitats, including bare soil and rock, grassland, tapia woodland, wetland, and cultivation areas. In the Itremo Massif PA, bare soil and rock is the most species-rich habitat (50 spp.), highlighting the ability of orchids to withstand extreme conditions of drought, heat, and nutrient-poor soils (Pinheiro et al. 2014). Globally, endemic orchids are mostly threatened due to their limited geographic range and dependence on specific habitats such as forest and granitic outcrops (Fay 2018). This pattern is evident in the Itremo Massif PA, where 30 endemic species are threatened while only four non-endemic species are at risk.

Mining and quarrying, including extraction of stones like crystal and tourmaline, are the main threat to 21 threatened orchids in the Itremo Massif PA which aligns with findings by Nakade and Dhadse (2024), who reported that species with narrow ranges and small populations are particularly vulnerable to mining activities. Mosissa and Atinafu (2025) further demonstrated that habitat degradation from mining can deter mycorrhizal fungi necessary, for orchid survival.

Increase in fire frequency/intensity is the second most significant threat to orchids in the Itremo Massif PA, affecting 12 threatened species. Lithophytes, growing on exposed rocks, are vulnerable to fire as they lack underground tubers for resprouting after burning (Gill 1975; Whitman et al. 2011). Although fires threaten lithophytic orchids in the Itremo Massif PA, many terrestrial geophytic orchids are adapted to fire, and some require fire to stimulate flowering (Lamont and

Downes 2011; Bowman et al. 2012; Abreu et al. 2017; Wieczorkowski et al. 2024). In open habitats including grassland, bare soil and rock, and tapia woodland, peak flowering occurs from January to March (Wieczorkowski et al. 2026) whereas fire in the Itremo Massif PA occurs between May and October with a peak from June to September (Fenonirina Rakotoarison pers. comm. 2024). Approximately 61% of orchid species in the Itremo Massif PA flower after the fires during the rainy season. Among these, geophytic orchid genera notably *Benthamia*, *Cynorkis*, *Eulophia* R.Br., and *Habenaria* Willd. are dominant.

The role of fire is also linked to the spread of invasive *Pinus* L. species, which have been increasingly recorded in tapia woodland in Madagascar's Central Highlands (Rajaonarivelo et al. 2022). Reduced burning causes pine establishment (Flanary and Keane 2019), and expanding pine stands can alter forest structure and microclimatic conditions, reducing habitat suitability for epiphyte orchids (Besi et al. 2023). Although invasive species and disease affect only one threatened orchid species in the Itremo Massif PA (*Angraecum coutrixii*), pine invasion may further represent an emerging threat. Indeed, pines already represent a threat to tapia woodland vegetation in the Itremo Massif PA.

Shifting agriculture, and logging/wood harvesting represent the third major threat in the Itremo Massif PA, each affecting nine threatened orchid species. These threats mostly impact epiphytic species in the genera *Aerangis* Rchb.f., *Aeranthus* Lindl., and *Bulbophyllum* Thouars, which are restricted to humid forest and tapia woodland in the Itremo Massif PA. Shifting agriculture and logging/wood harvesting reduces canopy cover, increases exposure to heat and drought, and disrupts the fine-scale microhabitats for epiphytes (Zotz and Bader 2009). In addition, shifting agriculture fragments forest patches, and reduces the availability of mature host trees, limiting orchid dispersal and promoting small, isolated subpopulations of orchids dependent on forest (Harper et al. 2007; Besi et al. 2019).

Conservation priorities and actions

Protecting orchid diversity in the Itremo Massif PA requires habitat conservation strategies that address the ecological requirements of species and the varied threats across habitats. We suggest the following actions to preserve the orchid diversity in the Itremo Massif PA.

Research and citizen science

Further fieldwork is strongly recommended to better document rare orchids (Fig. 6) with a small distribution range, e.g. to locate additional subpopulations. Refined data on population size and distribution may affect the assessment of the extinction risk of orchids. There are significant gaps in knowledge concerning species distribution, natural history, taxonomy, and molecular phylogeny, which make prioritisation difficult (Vitt et al. 2023). To speed up the update of data on orchid

distribution, iNaturalist (2024) offers an unparalleled opportunity to accelerate data collection while engaging scientists, local community members and orchid enthusiasts to upload photos from their field expeditions on the platform. Botanists, researchers and field experts and local observers regularly review the contributions added by other users to verify the identifications.

Habitat protection and restoration

The highest concentration of threatened orchids is found in the bare soil and rock, humid forest, and grassland habitats and these are therefore the highest priority for conservation.

Sustainable fire management

Installing firebreaks around sensitive habitats, fire patrolling, and planning early season burns (May–July) to prevent high-intensity fires.

Reducing mining impacts

Designate orchid-rich outcrops, humid forest, and tapia woodland as strict no mining zones because mining practices are a major driver of biodiversity loss (Nakade and Dhadse 2024). In areas where extraction is permitted, enforce low-impact techniques, limit removal of only the necessary material, and avoid disturbance of surrounding soil and vegetation.

Control of *Pinus* invasion

The removal of invasive *Pinus* species combined with appropriate fire management is necessary to maintain the open structure of tapia woodland, which is essential for conserving orchid diversity. Epiphytic orchids depend on microhabitats shaped by canopy openness and light conditions, making them sensitive to changes in forest structure (Johansson 1974).

Ex situ conservation

Ex situ conservation is feasible for orchids when local communities are actively engaged in the maintenance of shade houses and/or nurseries, combined with understanding of orchid ecological requirements. This is particularly important for terrestrial and lithophytic orchids which have complex growth cycles, including seasonal dormancy, tuber formation, making their long-term cultivation challenging due to specific substrate, light and moisture requirements. Local shade houses and nurseries play a role in maintaining living collections, producing material for restoration or reintroduction, and supporting seed banking (Stévant et al. 2020; Fay et al. 2025).

Public awareness and education

To achieve successful conservation outcomes, it is important to promote stakeholder-inclusive and participatory conservation (Lees et al. 2021). Outreach activities include the production of educational leaflets, and posters similar to previous initiatives on one threatened orchid *Angraecum longicalcar* (Bossler) Senghas, (Rajaovelona and Gardiner 2016), as well as

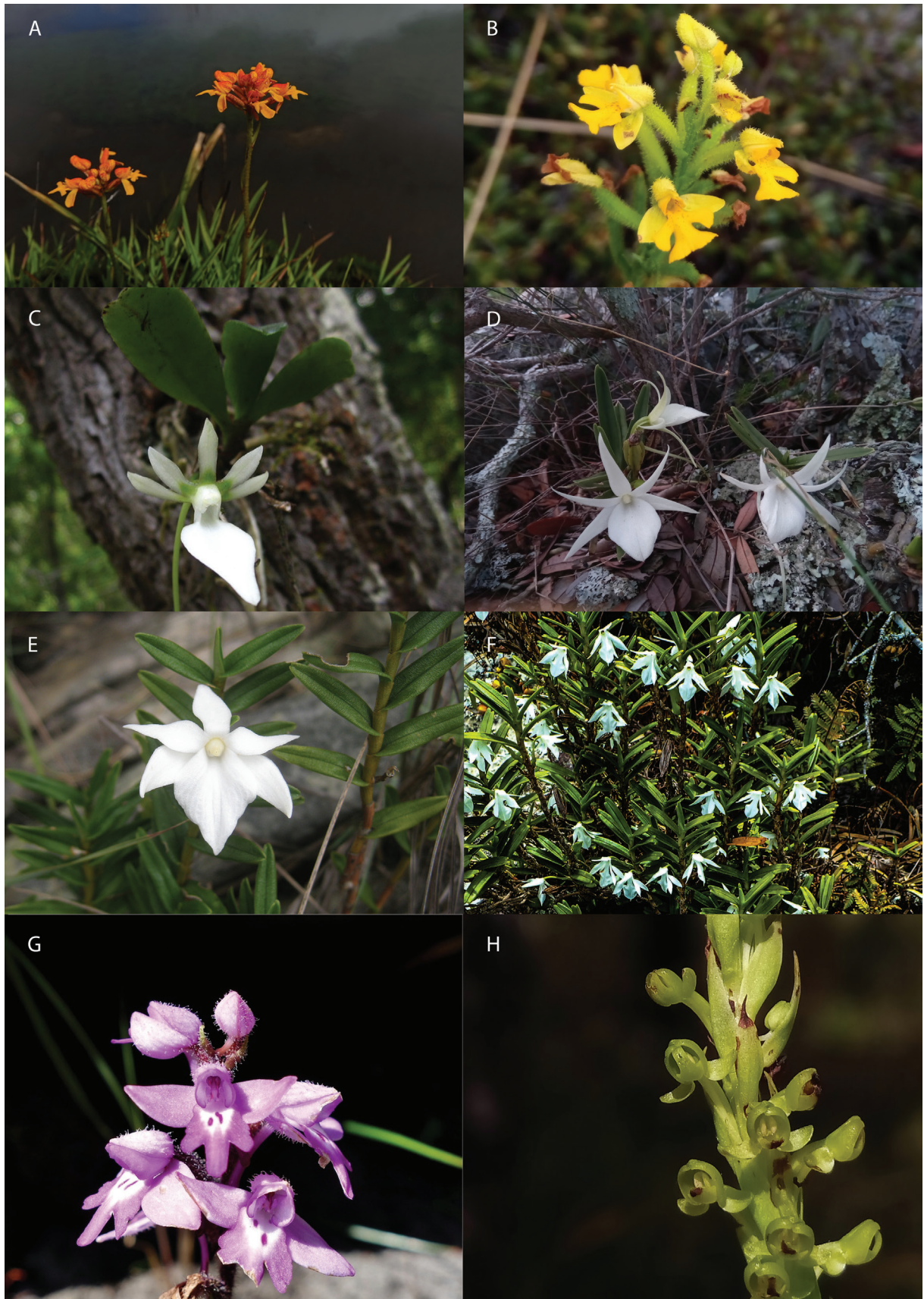


Figure 6. Examples of orchids occurring in the Itremo Massif Protected Area. **A.** *Cynorkis cinnabarina* (VU). **B.** *C. melinantha* (EN). **C.** *Neobathia grandidieriana* (LC). **D.** *Angraecum rutenbergianum* (LC). **E.** *A. coutrixii* (CR). **F.** *Jumellea spatulata* (EN). **G.** *Cynorkis cardiophylla* (VU). **H.** *Benthamia bathieana* (VU). Photos by Narindra Romer Rabarijaona (A, C) and Landy R. Rajaovelona (B, D–H).

field guides, tailored to local communities, include photographs, vernacular and scientific names, and IUCN conservation status of orchids of the Itremo Massif PA.

Recognition of Itremo Massif PA as an Important Plant Area

Already recognised as a Key Biodiversity Area (KBA), we suggest its designation as Important Plant Area (IPA) to strengthen site-specific plant management (Darbyshire et al. 2017). The recent plant checklist by Rakotonasolo et al. (2025), documenting endemic and threatened species including orchids, provides strong evidence to support the IPA designation and can guide future conservation priorities.

CONCLUSION

Orchidaceae are the second most species-rich family after Poaceae in the Itremo Massif PA. This study provides the first assessment of orchid extinction risk within the PA, located in the Madagascar Central Highlands, characterised by various habitats such as grassland, bare soil and rock, humid forest, and tapia woodland. Understanding habitat diversity, species composition, extinction risk and associate threats are essential for informing effective management strategies of this plant group. The Itremo Massif PA harbours threatened orchid species, which have restricted distributions and small population sizes. These species require urgent conservation actions, including habitat protection and both in situ and ex situ measures. Humid forest is particularly important as it hosts orchid species not found in other habitats. Grassland also represents essential habitat for terrestrial orchids in the Itremo Massif PA. Orchids of bare soil and rock are vulnerable to mining activities and increase in fire intensity/frequency. Long-term conservation actions include controlling pine invasion in the tapia woodland combined with implementing fire management.

Orchidaceae are among the most threatened plant families in part due to their complex life histories and highly specific interactions with pollinators and mycorrhizal fungi (Fay et al. 2025). Research on orchid fungal associations remains limited in Madagascar. Further research should therefore prioritise reproduction success, population viability, pollination ecology, and fungal interactions to support long term conservation of the region's orchid flora.

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SUPPLEMENTARY MATERIALS

Supplementary material 1

Endemism in Madagascar and extinction risk of orchid species in the Itremo Massif PA. Proportion of endemic and non-endemic orchids across IUCN categories: Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), and Least Concern (LC).

<https://doi.org/10.5091/plecevo.185223.suppl1>

Supplementary material 2

Rationales for the submitted IUCN Red List assessments.

<https://doi.org/10.5091/plecevo.185223.suppl2>

Supplementary material 3

Number and list of shared orchid species for each habitat combination (paired, three or four habitats) for Itremo Massif PA orchids.

<https://doi.org/10.5091/plecevo.185223.suppl3>

Supplementary material 4

Dataset of species, IUCN status, habitat, and threat to orchids in the Itremo Massif PA.

<https://doi.org/10.5091/plecevo.185223.suppl4>

Supplementary material 5

Habitat species binary: Presence (1) or absence (0) of each orchid species in each of the seven habitats (bare soil and rock, cultivation, humid forest, tapia woodland, grassland, western dry forest, and wetland) in the Itremo Massif PA.

<https://doi.org/10.5091/plecevo.185223.suppl5>

Supplementary material 6

Number and list of orchid species (CR, EN, VU, NT, LC) by the seven habitats for orchids found in the Itremo Massif PA.

<https://doi.org/10.5091/plecevo.185223.suppl6>

Supplementary material 7

Number and list of orchid species (CR, EN, VU, NT, LC) by the seven major threats found in the Itremo Massif PA.

<https://doi.org/10.5091/plecevo.185223.suppl7>

Supplementary material 8

Fire season and flowering time dataset of the Itremo Massif PA orchids.

<https://doi.org/10.5091/plecevo.185223.suppl8>