Description of the Parc National de Marojejy, Madagascar, and the 2021 biological inventory of the massif

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Abstract

Between 2 October and 15 November 2021, an elevational transect of the eastern slopes of the Parc National de Marojejy was conducted. Five different zones and vegetation types were surveyed, and these included 480 m (lowland moist evergreen forest), 750 m (lowland moist evergreen forest with transitional aspects to medium altitude moist evergreen forest), 1300 m (medium altitude moist evergreen forest), 1550 m (upper portion of medium altitude moist evergreen forest), and 1875 m (montane ericoid thicket and montane grassland). In general, each of these zones was surveyed as an altitudinal swath of 200 m, which was generally centered on the associated camping site for each zone. Groups covered by the inventory included: plants, stick insects, amphibians, reptiles, birds, small mammals, bats, and primates. The 2021 survey was a repeated exercise of an inventory at the same sites conducted in 1996 and following in fine detail the same zones and calendar dates, as well as field survey techniques. Herein we present different details on the protected area, the itinerary, the five zones surveyed, and the local weather data during the 2021 work. In many of the contributions in this monograph, finer details are presented on the results of the 2021 survey and often with comparisons to 1996 to assess the level of change in the local biota over the course of 25 years.

Keywords: Marojejy, 2021, elevational transect, plants, invertebrates, vertebrates

Résumé détaillé

Entre le 2 octobre et le 15 novembre 2021, un inventaire biologique le long de gradient altitudinal a été mené sur le versant Est du Parc National de Marojejy, traversé par le circuit touristique. Cinq sites et différents types de végétation ont été étudiés et ceux-ci comprennent 480 m (forêt dense humide sempervirente de basse altitude), 750 m (forêt dense humide sempervirente de basse altitude avec des aspects de transition vers la forêt dense humide sempervirente de moyenne altitude), 1300 m (forêt dense humide sempervirente de moyenne altitude), 1550 m (partie supérieure de la forêt dense humide sempervirente de moyenne altitude) et 1875 m (fourré éricoïde de montagne et prairie de montagne). Quelques biologistes de l'équipe 1996 ont dirigé l'expédition de 2021, et appuyés par des chercheurs et des diplômés de l'Association Vahatra. En général, chacun de ces sites a été inventorié dans une bande altitudinale de 200 m et généralement centré sur le lieu de camping associé à chaque site. Les groupes couverts par l'inventaire incluent : la flore, les phasmes, les amphibiens, les reptiles, les oiseaux, les petits mammifères, les chauves-souris et les primates. L'inventaire de 2021 était le renouvellement de l'investigation réalisée en 1996, tout en reprenant dans les moindres détails le gradient altitudinal, le calendrier des activités, et les méthodes de collecte des données. C'était également une occasion pour chercher et collecter des spécimens en cours de description mais en attente faute du manque des éléments morphologiques, anatomiques, moléculaires ou photographiques pour appuyer les données existantes. Nous présentons ici différents détails sur l'aire protégée, l'itinéraire, les cinq zones étudiées et les données météorologiques locales lors de l'inventaire et l'évolution des structures spatiale et fonctionnelle des écosystèmes entre les années 1996 et 2022. Dans la monographie, des détails plus fins sont présentés sur les résultats de l'inventaire de 2021 et des comparaisons avec ceux de 1996 effectuées pour évaluer le niveau de changement du biote local au cours de ces 25 ans.

Mots clés : Marojejy, 2021, transect altitudinal, plantes, invertébrés, vertébrés

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Introduction

The past decades have seen a dramatic increase in documented information on the biodiversity of numerous forest ecosystems of Madagascar. These advances have been associated with different factors. For example, the installation of biological stations in different natural vegetation habitats of the island, such as at Ranomafana (Ifanadiana) in moist evergreen forest (Wright *et al*., 2012), Kirindy CNFEREF in dry deciduous forest (Kappeler *et al*., 2022), and Tsimanampesotse in the dry spiny thicket (Bohr *et al*., 2011; Ratovonamana *et al*., 2011). Regular visits from research groups to these sites provide the means to conduct long-term studies on the local ecosystems, their dynamic over time, and their constituent species. Further, a considerable number of rapid biological inventories have been conducted across numerous areas of remaining natural or largely natural habitats (see Andriamialisoa & Langrand, 2022, for an overview). These studies and associated publications have helped to better understand the biological diversity of Madagascar and have led to conservation actions associated with the protected area system, including the designation of new conservation sites and the utilization of scientific information for management plans.

In many cases and for different reasons, scientific teams conducting biological surveys incorporate in their field methodology, the collection of reference specimens. These include proper documentation of the organisms encountered, as well as the need for tools to properly identify specimens via classical taxonomical studies, molecular genetics, or both in an integrative manner. In many ways, these specimens represent the archives of the natural patrimony of Madagascar. The number of plant and animal taxa new to science described from the island over the past 20 years is rather remarkable and with few parallels in other tropical countries. Between 2003 and 2022, for a range of largely endemic Malagasy groups, the number of new species, including in some cases confirmed candidate species, have increased dramatically: a few examples include the family Sapotaceae from 84 to 125 species (+33%), Rubiaceae from 650 to 1010 species (+36%), terrestrial snails from 671 to 1123 species (+40%), ants from 393 to 1252 species (+69%), amphibians from 199 to 365 species (+46%), and terrestrial mammals from 101 to 174 species (+42%) (Goodman, in press). Hence, this type of research with associated voucher specimens provides an important window into the biological richness of the island, its unique endemic organisms, their geographical and ecological distributions, and, in a most fundamental manner, the means to properly execute prioritization exercises to enhance the coverage of the island's protected area system capable to ensure long-term conservation of the representative biodiversity and its ecosystems. Conservation is particularly important given the continued destruction of remaining natural habitats on the island (Vieilledent *et al*., 2018) and the associated local extirpation of organisms occurring in forests that have been heavily degraded, especially those species with particular habitat preferences and limited distributions. One excellent example for the importance of collecting voucher specimens to understand biodiversity patterns is the Marojejy Massif, where close to 450 new species to science having been named since 1988, based on a type specimen or referred material coming from the mountain and surrounding areas in the original taxonomical publication (Goodman *et al*., 2023, herein).

Even with these advances, many areas of Madagascar remain to be properly inventoried for the local flora and fauna and it is important to continue to survey poorly known or unknown areas of forest. Another aspect that also needs to be seriously considered - particularly given the continued levels of deforestation and clear implications of the impact of human-induced climate shifts on the island's natural biological systems at a local and national level (Morelli *et al*., 2020) - is repeating biological inventories at a site after a relatively long period, that is to say at least a decade, to examine possible change through time. This is particularly important and useful to monitor different types of vicissitudes, particularly when the repeated inventory can follow technical and temporal aspects of the original field study in fine detail, making the comparisons of certain results and variables relatively straightforward.

One superb natural experimental design to obtain applicable data for such investigations is along ecological gradients, such as elevational transects of mountains, where variables to help explain the distribution of different biotic elements, including shifts in temperature, humidity, and rainfall, change in a continuous manner. This style of field inventory provides insights into the dynamic and evolution of the ecological landscape along topographic continuums. During the 1990s, a number of mountains on Madagascar were the subject of biological inventories along altitudinal gradients and a range of organisms were studied in different vegetation types from lowland forest to the summital zone; one such study was the Marojejy Massif in late 1996, when the eastern sector was inventoried at five different sites between 450 and 1875 m (Goodman, 2000a, see below). Herein we present the results of a repeat investigation of Marojejy in late 2021, of a range of organisms studied along the same transect as in 1996, keeping the calendar dates between the two studies and field methodologies in parallel.

Abbreviations used in the monograph

ANGAP	Association National pour la Gestion des Aires Protégées
BIOCOM	Biodiversity Conservation and Sustainable Natural Resource Management for Integrated Community Development in National Parks of Madagascar
CLP	Communautés locales du Parc (Local communities of the park)
CNFEREF	Centre National de Formation d'Etude et de Recherche en Environnement et Forestier
CNRS	Centre National de la Recherche Scientifique
COMATSA-Nord	Réserve de Ressources Naturelles du Corridor Marojejy-Anjanaharibe-Sud-Tsaratanàna-Nord (COMATSA Nord)
COMATSA-Sud	Réserve de Ressources Naturelles du Corridor Marojejy-Anjanaharibe-*Sud*-Tsaratanàna-Sud
CSB	Centre de Santé de Base
DEF	Direction des Eaux et Forêts
dbh or dhp	diameter at breast height or diamètre à hauteur de poitrine
DREDD	Direction Régionale de l'Environnement et du Développement Durable
FIV	Family Importance Value or Valeur d'Importance des Familles
FMNH	Field Museum of Natural History
FOFIFA	Foibe Fikarohana Ampiharina Fampandrosoana ny Ambanivohitra (Centre National de la Recherche Appliquée au Développement Rural or National Center for Applied Research in Rural Development)
GBIF	Global Biodiversity Information
GLAD	Global Land Analysis and Discovery
GPS	Global Positioning System
GRID[3]	Geo-Referenced Infrastructure and Demographic Data for Development
ha	Hectare
IDH	Intervalle de hauteur or interval of height
IKA	Index of Kilometric Abundance
IPSIO	Insect and People of the South-Western Indian Ocean
IRD	Institut de Recherche pour le Développement
IRSM	Institut de Recherche Scientifique de Madagascar
IVI	Importance Value Index or Indice de Valeur d'Importance
IUCN	International Union for the Conservation of Nature
KOICA	Korea International Cooperation Agency
MBG	Missouri Botanical Garden
MNHN	Muséum national d'Histoire naturelle (Paris)
MNP	Madagascar National Parks
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
ORSTOM	Office de la Recherche Scientifique et Technique Outre-Mer now Institut de Recherche pour le Développement (IRD)
PN	Parc National
PBZT	Parc Botanique et Zoologique de Tsimbazaza
PSSE	Plan de Sauvegarde Social et Environnemental (Social and Environmental Safeguard Plan)
RCP	Recherche Coopérative sur Programme No. 225, organized by the Centre National de la Recherche Scientifique
REM	Rapid-eye movement

RN	Route Nationale
RNI	Réserve Naturelle Intégrale
RS	Réserve Spéciale
SARA	Service Availability and Readiness Assessment
SAVA	Administrative region in northeastern madagascar and acronym stands for **S**ambava-**A**ntalaha-**V**ohémar-**A**ndapa
SRTM	Shuttle Radar Topography Mission
TAN	Herbarium of Parc Botanique et Zoologique de Tsimbazaza, Antananarivo
TEF	Herbarium of Centre National de la Recherche Appliquiée au Developement Rural or Foibe Fikarohana Ampiharina amin'ny Fampandrosoana ny Ambanivohitra (FOFIFA), Antananarivo
UADBA	Université d'Antananarivo, Département de Biologie Animale, which is now known as Mention Zoologie et Biologie Animale
UNESCO	United Nations Educational, Scientific and Cultural Organization
WHO	World Health Organization
WWF	World Wide Fund for Nature

The Parc National de Marojejy

The Marojejy Massif in northeastern Madagascar is part of a chain of mountains that spread across a portion of the northern region of the island. The southern part of the massif is accessible along a tarmac road (RN3b) linking the towns of Sambava and Andapa (Figure 1). The site is biologically diverse, with, as of early 2018, a documented flora of 1302 species (78.5% endemic to Madagascar), 74 species of frogs, 84 species of reptiles, 119 species of birds, and 61 species of native mammals (Goodman *et al*., 2018a; Phillipson *et al*., 2018). With 338 species of land vertebrates, the site has the greatest known non-arthropod diversity of any protected area on the island (Goodman *et al*., 2018b).

In January 1952, after the botanical exploration of the French botanist Henri Humbert and his recommendations to the French government, the Marojejy Massif was named as Réserve Naturelle Intégrale (RNI) No. 12 (Nicoll & Langrand, 1989; Goodman *et al*., 2018a). Subsequently in May 1998, the protected area's status was changed to Parc National and based on that decree it has a total surface area of 60,050 ha. One of the reasons for this status change was to open the site to ecotourism, which is not allowed in protected areas with the statute of Réserve Naturelle Intégrale.

During the early stages, the site was managed by the Direction des Eaux et Forêts (DEF) with a reserve director and based in the Chef de Cantonnement office in Andapa. During the period from 1991 to 1998, the protected area was jointly administered by DEF and the World Wide Fund for Nature (WWF). Thereafter, from 1999 to mid-2004, the site was managed by WWF under the coordination of the Association National pour la Gestion des Aires Protégées (ANGAP), which changed its name in 2008 to Madagascar National Parks (MNP). Starting in July 2004, the park was managed exclusively by MNP.

The change from Réserve Naturelle Intégrale to Parc National led to different forms of improved or new infrastructure along the eastern trail leading from the village of Mandena to the summital zone. This included amelioration of the trail system and the installation of bungalows (Figure 2), cooking facilities, and toilet and shower facilities at three sites at 450, 775, and 1325 m, as well as a look-out point just below the latter site. The number of visitors to the park increased substantially over the past decades, at least before the COVID-19 epidemic, from an average of 307 per year from 1998-2001, 1104 per year from 2002-2011, to 1399 per year from 2012-2016 (Goodman *et al*., 2018a).

In 2007, the park was one of several protected areas incorporated into a UNESCO World Heritage site known as "Ala Atsinanana". It was subsequently classified in 2010 as a natural heritage in Danger after local ecological perturbation resulting at least in part from political turmoil on the island in 2009. A few years thereafter, it was necessary to conduct a biological assessment to determine if the park, despite human-induced ecological perturbations, maintains the integrity of its outstanding universal values that defined its nomination as a World

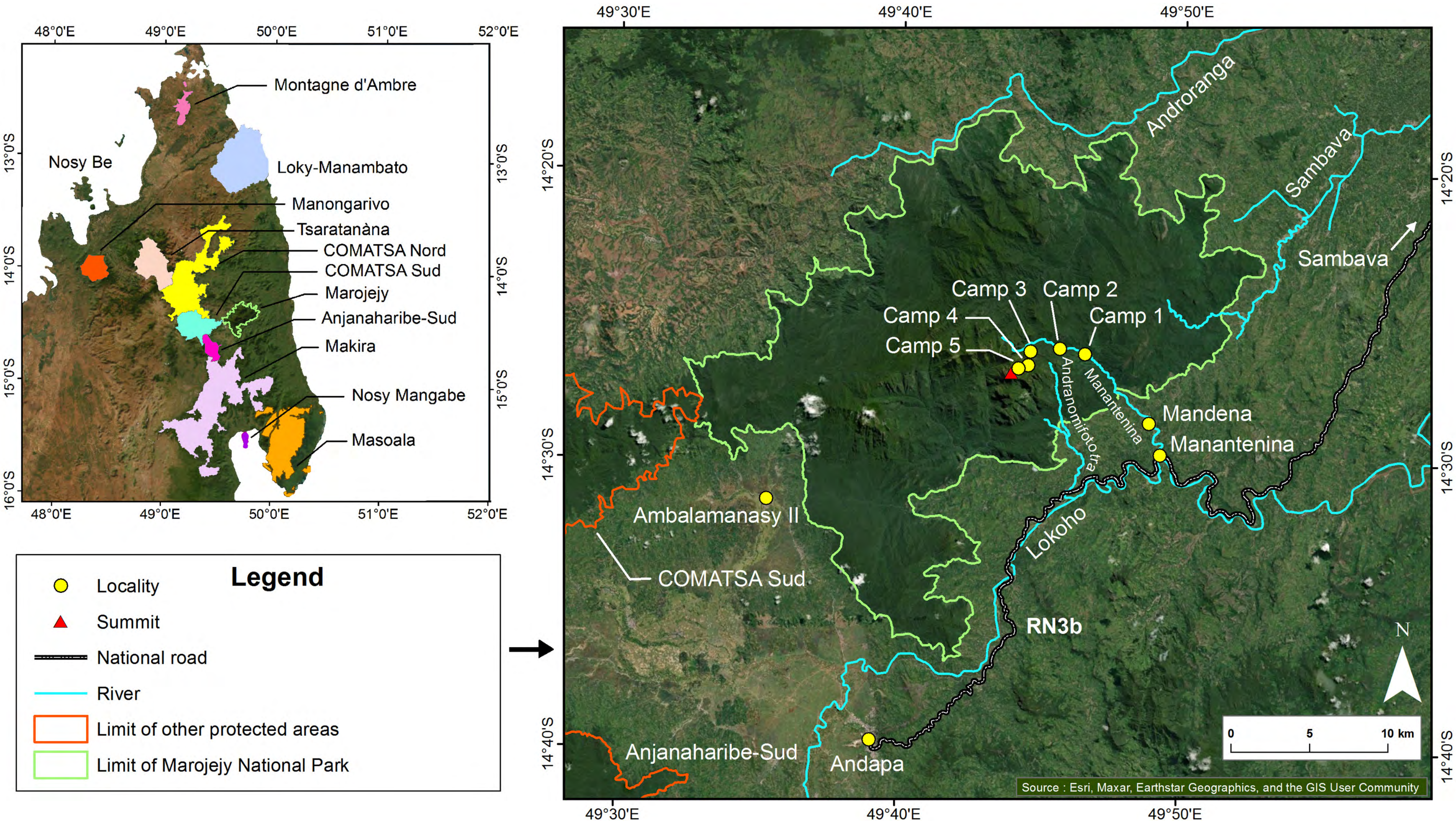

Figure 1. Map of the Parc National de Marojejy, the five camp sites that constituted the 1996 and 2021 transect from 450 to 1875 m, and different localities and rivers in and around the park. The inset in the upper left is the configuration of different protected areas in northeastern Madagascar that constitute an expansive connected corridor or near corridor system, as well as other protected areas in the northern portion of the island. The legend in the lower left is associated with the detailed Marojejy map.

Figure 2. To enhance the visits of ecotourists at Marojejy, some infrastructure has been built over the past years along the Mandena-summit trail, including bungalows, cooking and eating structures, and sanitary facilities. After the recent passage of a cyclone in northeastern Madagascar, which impacted the Parc National de Marojejy, the previously built bungalows were severely damaged. With funding from Lemur Conservation Foundation, a considerable portion of the damaged infrastructure was rebuilt, such as the bungalows shown here at Camp Mantella at 450 m. (Photo by Erik Patel.)

Heritage site (Raherilalao *et al*., 2016); the conclusion was yes. In the context of gathering further data on the flora and fauna of the protected area associated with a Korea International Cooperation Agency (KOICA) project in collaboration with UNESCO and MNP, Association Vahatra was engaged to conduct a biological inventory of the eastern portion of the park to assess aspects of local biodiversity. The results of that fieldwork and associated analyses, as well as some other studies are reported herein.

Marojejy also has an important role as part of a linking forested corridor to the north via the Réserve de Ressources Naturelles du Corridor Marojejy-Anjanaharibe-Sud-Tsaratanàna-Nord (COMATSA Nord) to Tsaratanàna and another linking corridor via Réserve de Ressources Naturelles du Corridor Marojejy-Anjanaharibe-Sud-Tsaratanàna-Sud (COMATSA-Sud), to Anjanaharibe-Sud, Makira, and Masoala (Figure 1, upper left inset), with the complex covering a considerable area of forested protected areas.

The Marojejy Massif is notably steep, particularly at higher elevations, with precipitous slopes and spectacular cliff faces (Figure 3). To give a better sense of the mountain's topography, approximately 80% of the protected area is found between 500 and 1500 m, with over 6.5% (3631 ha) above 1500 m. Most rain-bearing weather systems arrive from the Indian Ocean, and the eastern slopes, as compared to the western slopes of the massif, have more abundant rainfall and to a large extent no pronounced dry season. The high mountain section in the eastern portion presumably acts to create a partial rain shadow and the western and northwestern portions of the massif have a drier local climatic regime, as reflected by the presence of certain floristic and faunistic elements. With increasing elevation, temperatures decrease and precipitation from mist and rain is more frequent (Marline *et al*., 2023, herein). The climatic conditions at the summit, which is above the upper limit of the forest, alternate between bouts of intensive solar radiation and fog, which in turn create rapid and pronounced changes in humidity, for which the local biota is adapted to.

A considerable amount has been written in the past few decades about the flora and fauna

Figure 3. The Parc National de Marojejy contains rather scenic landscapes and portions of the protected area are notably steep, mostly in the upper portions of the massif. This image was taken just below the Marojejy summit at about 1950 m, showing some areas with precipitous slopes and spectacular cliff faces. The three massifs to the left are known as the "trois dents" or "three teeth". (Photo by Erik Patel.)

of Marojejy, the nearby massif of Anjanaharibe-Sud, and the connecting corridor that was formerly referred to as the Betaolana Forest and now is part of the protected area known as COMATSA-Sud (e.g., Guillaumet *et al*., 1975; Safford & Duckworth, 1990; Evans *et al*., 1992; Durbin *et al*., 1998; Duckworth *et al*., 1995; Andreone *et al*., 2000; Ross *et al*., 2020). A few monographs, covering a variety of different organisms have also been published (Goodman 1998, 2000a; Goodman & Wilmé, 2003).

Transect sites

Both the 1996 and 2021 inventories of the eastern slopes of Marojejy were conducted as a series of five consecutive sites or camps placed in ascending elevational zones (Figure 1). The inventoried sites occurred along the classic Mandena-summit trail system established by earlier explorers of the massif, including Henri Humbert (Capuron, 1952), and then employed by Pierre Griveaud (1960), a Centre national de la recherche scientifique (CNRS) team under the direction of Renaud Paulian (Guillaumet *et al*., 1975), field botanists from the Missouri Botanical Gardens (MBG), a research group from Cambridge University (Safford & Duckworth, 1990), and others. The only exception was Camp 4 at 1550 m, which was added in 1996 to the classic circuit with the purpose of filling in a site of upper medium altitude moist evergreen forest (= medium altitude forest or montane humid forest) in the transect. Access to Camp 4 is via a path about 500 m long and cut from the main summital trail to the south and the bifurcation is about halfway between Camp 3 and Camp 5 (Figure 1). The five camps in all cases, except for 1875 m site (Camp 5), formed the central point to each of the surveyed elevational zones, also referred to herein as transect zones of transect sites. In general, in each transect zone the surveyed area was ± 200 m of elevation above and below each camp. At Camp 5, which was close to the forest line, most of the survey work took place below the camp and the surrounding open area and scrubs.

The Malagasy Government changed its system of administrative areas in 2009 from one of six provinces to one of 22 regions (régions). Hence, the Parc National de Marojejy in 1996 was in the Province d'Antsiranana and in 2021 in the Région SAVA. As mentioned above, another modification that took place between the 1996 and 2021 inventories is that tourist infrastructure was installed at or near the first three camps used in 1996, and these sites have been given names (Table 1). The generalized localities for each of the camps during the 2021 survey and used in most of the associated field catalogs are listed below.

450 m (Camp 1 or Camp Mantella) 2-11 October 2021

Madagascar: Région SAVA, District Sambava, Parc National de Marojejy, 6.0 km NW Mandena, 14.438°S, 49.776°E, 480 m.

750 m (Camp 2 or Camp Marojejya) 12-20 October 2021

Madagascar: Région SAVA, District Sambava, Parc National de Marojejy, 6.5 km NW Mandena, 14.435°S, 49.761°E, 750 m.

1300 m (Camp 3 or Camp Simpona) 21-29 October 2021

Madagascar: Région SAVA, District Sambava, Parc National de Marojejy, 9.5 km NW Mandena, 14.437°S, 49.743°E, 1300 m.

1550 m (Camp 4) 30 October-6 November 2021

Madagascar: Région SAVA, District Sambava, Parc National de Marojejy, 9.0 km NW Mandena, 14.444°S, 49.742°E, 1550 m.

1875 m (Camp 5) 7-15 November 2021

Madagascar: Région SAVA, District Sambava, Parc National de Marojejy, 9.3 km NW Mandena, 14.446°S, 49.736°E, 1880 m.

Itinerary of the 2021 expedition

Contrary to the biological inventory of 1996, no reconnaissance mission was necessary for the work conducted in 2021, as the trails and camp sites are largely maintained by Madagascar National Parks. The single exception was the trail leading from the summit trail to Camp 4 and the short section to Camp 5. Indeed, the three first camps, including Camp 1 or Camp Mantella, Camp 2 or Camp Marojejya, and Camp 3 or Camp Simpona, now have operational infrastructure, including cooking areas, toilets and showers, camping areas, and bungalows (Figure 3). Another simplification of logistical aspects as compared to 1996 is that porters living in the neighboring villages, particularly Mandena and Manantenina, have fixed prices for carrying baggage from Mandena to different points on the massif and clear limitations on baggage weight. Another important aspect to mention is that many local villagers have previously worked with members of our team, including now more senior individuals that assisted the 1996 mission or more recent inventories in and around the massif associated with Association Vahatra or other research groups. Finally, in 1996 there was no telephone communication from the slopes of Marojejy, but in 2021 this was possible from most sites, although often necessary to climb up to prominent ridges to obtain a connection.

Eleven members of the inventory team left Antananarivo on 28 September 2021 in two 4 x 4 vehicles loaded with provisions and camping and research materials. In route, Hachim Ali was picked up in Ambilobe; he was responsible during the mission for purchasing provisions (fresh food supplies and wanting research related materials) and the coordination of sending supplies with porters to the field team as the group moved up to different camps on the massif and receiving specimens for storage after each displacement. The other members of the expedition flew to Sambava on 30 September 2021 and met the team that drove from Antananarivo. To expedite different steps, some members of the expedition team took care of administrative aspects with the local authorities, most notably having research permits stamped by the Direction Régionale de l'Environnement et du Développement Durable (DREDD) of the Sambava Region, and different courtesy visits. Others were responsible for the local purchase of rice, lentils, and beans, and these provisions for all five camps were arranged in rice sacks labelled by camp number. On 1 October 2021, a car loaded with dry provisions for Camps 2 to 5 left Sambava for Andapa, where these goods were stored.

Very early the morning of 2 October 2021, three 4 x 4 cars brought the researchers and the baggage for Camp 1 to Mandena, where about sixty porters had been engaged to carry the equipment and different types of supplies to Camp 1 (Figure 4). It was originally planned to stay at the same camp used in 1996 on the left bank of the Manantenina River and towards the Cascade de Humbert, but due to an important rise of the river level, it was decided to stay at Camp Mantella located on the right bank where touristic infrastructure had been installed. This camp is a 3 h 30 to 4 h walk from the village of Mandena.

In total, five different elevational zones were worked during the inventory, each occupied for nine days including displacement and setting up camps and research installations. The list of supplies needed for the next camp was communicated to Hachim

Figure 4. Porters from villages neighboring the Parc National de Marojejy were engaged to carry supplies and scientific supplies up and down the massif during the inventory. Certain displacements involved more than 60 individual porters. Here is shown a portion of the porters at the base operation in the village of Mandena and just before distributing baggage for them to carry up the massif. (Photo by Voahangy Soarimalala.)

Ali in Sambava or Andapa via telecommunication two or three days before shifting a camp, and he ensured purchases. Moving food supplies and field gear up the massif to the different sites took some coordination. The morning of the day before the group moved up to the next camp, or - as distances from Mandena to camps became longer - two days before, fresh food supplies were purchased in a regional market and placed into rice sacks. These goods and all the sacks left in the Andapa storage facility numbered for the next site were delivered to Mandena - the closest village to the park entrance accessible by car – and were given to the local person responsible for organizing the porters. Early the following morning, the porters left Mandena, joined the team at the camp that was ready to be vacated, picked up the baggage (tents, cooking materials, research gear, etc.) from the site to be taken to the next, and the group and all the materials moved up to the following site. After delivering the baggage, the porters descended the massif, picked up packaged specimens left at the vacated camp, dropped the specimens off at a temporary rented storage facility in Mandena, and returned to their homes. Starting with the displacement to Camp 4, the roundtrip between the lowlands and next camp could not be done in a single day and it was necessary for the porters to bivouac at Camp 3 for a night, where cooking facilities and utensils were available, as well as sleeping infrastructure.

Above Camp 3, portions of the summit trail were damaged due to water erosion, and some repair work was needed. In addition, the trails leading to Camp 4 and Camp 5 were overgrown with vegetation. We engaged two local assistants for two days to open up these trails to allow porters to pass. This was particularly necessary for large and cumbersome baggage, including a small refrigerator to maintain samples at cool temperatures for zoonotic disease research (Kramer *et al*., 2023, herein), the solar panels needed to power the large car battery for running the refrigerator, two large trunks for stocking research materials; such material was carried by two porters with the item attached with rope to and suspended between them from a large piece of 2 m or more bamboo or narrow tree truck. During each displacement, more than 60 porters were employed and the duration of each trip between camp sites was from 1½ to 4 hours (Figure 5).

Figure 5. Sign post at the eastern entrance of the Parc National de Marojejy along the Mandena-summit trail and with indications of distances to the three lower camps with infrastructure, which were installed after the 1996 inventory. (Photo by Voahangy Soarimalala.)

Figure 6. Group photo of the 2021 field team at Camp 3. Lower row (left to right): Marie Jeanne Raherilalao, Fifaliantsoa Rasolobera, Fandresena Rakotoarimalala, Achille P. Raselimanana, and Voahangy Soarimalala; middle row (left to right): Herlin, Nicholas Cliquenois, Tahiry Langrand, Christian Manana, Desiré Razamimahatratra, Rindrahatsarana Ramanakirahina, Steven M. Goodman, Veno, and Jacquis Tahianarivony; upper row (left to right): "Ledada" Razafindravao, Alain Patrick Rasolonjatovo, Anjenot Marcelin, and Edouard Mahazandry. (Photo by Voahangy Soarimalala.)

On 16 November 2021, once the field survey was completed, the team and all the equipment and remaining supplies descended from Camp 5 in the very early morning to arrive in Mandena at the start of the afternoon. Three cars were on hand to drive the team back to Andapa. The following day the team made a presentation to officials from MNP-Marojejy and the BIOCOM project. Following this restitution, the team was transported to Sambava and at the regional DREED office in Sambava they gave a detailed report on the mission and started different administrative aspects of transporting specimens back to Antananarivo.

During the 2021 expedition, unlike the 1996 mission, the team was mainly composed of Malagasy researchers and students. The group included the following 15 individuals (organized alphabetically by family name): Hachim Ali (driver and logistics-based in Sambava and Andapa), Nicholas Cliquennois (stick insects) principally Camp 3 and other camps visited for collections, Fifaliantsoa Rasolobera (small mammals), Steven M. Goodman (birds, bats and small mammals) up to and including Camp 3, Tahiry Langrand (birds), Christian Manana (bats), Marie Jeanne Raherilalao (birds), Fandresena Rakotoarimalala (amphibians and reptiles), Andry Rakotomanga (driver based near Mandena), Rindrahatsarana Ramanakirahina (primates), Achille P. Raselimanana (amphibians and reptiles), Alain Patrick Rasolonjatovo (plants), Rachel Razafindravao or "Ledada" (logistics and camp cook), Voahangy Soarimalala (small mammals), and Andonanahary Jacquis Tahianarivony (plants). Six individuals from local communities were engaged on a full time basis as research assistants and helping with food preparation. Rachel Razafindravao was responsible for overseeing the preparation of three meals per day for at least 21 people every day (Figure 6).

Descriptions of the five transect zones

In this section, we adopt the system of Gautier *et al*. (2018) for the names of vegetation formations on Madagascar and specific details on Marojejy from Gautier (2018). When appropriate, we also mention other vegetation terms used in the literature for the different formations. For further details on the vegetation structure of the five surveyed sites see Tahinarivony (2023a, herein).

450 m (Camp 1 or Camp Mantella)

We installed our camp at the MNP tourist site known as Camp Mantella, which is on the left bank of the Manantenina River and adjacent to the main tourist trail. This camp was about 300 m to the southeast from the 1996 camp at 450 m altitude, which was placed on the trail towards Cascade de Humbert. The walk from Mandena to Camp Mantella is about three to four hours. Griveaud's (1960) location known as Ambinantelo is slightly lower and at the place the three rivers Manantenina, Sahanisoavana, and Beamalona come together and in close proximity to the Piscine Noire.

The portion of the lower eastern slopes of the Marojejy Massif in the general vicinity of Camp 1 is described in detail by Humbert (1955a), which at that time was a mosaic of relatively intact lowland moist evergreen forest (= lowland humid forest or lowland rainforest), disturbed areas with secondary growth (*savoka*), swidden agriculture (slash-and-burn agriculture or *tavy*), and dense areas dominated by a formation of bamboo mixed with *Aframomum angustifolium* (Zingiberaceae), pineapple (*Ananas comosus*, Bromeliaceae), and banana (*Musa acuminate*, Musaceae) associated with regenerating areas previously cleared for agricultural activities. Today, this zone is similar in many ways to Humbert's description some 70 years ago. The regeneration of forest habitat in disturbed areas presumably started sometime after the designation of the protected area in 1952. The last two families cultivating the area around Camp 1 were expelled in 1965 after violating certain agreements (Garreau & Manantsara, 2003) and presumably forest regrowth started soon thereafter. This process takes many decades and for the moist evergreen forests of the island, there appears to be no quantitative data on how long recolonization and regeneration takes (Grinand & Nourtier, 2022). It was our impression that in 2021, as compared to 1996, the zone had a greater amount of secondary forest than old *tavy* and this aspect was confirmed by a local guide that has worked in the park for several decades. Indeed, this conclusion is supported by Tahianarivony (2023b, herein) using spatial and landscape approach.

The vegetation in this elevational zone grows on deep soils and is topographically less steep than higher zones. The local natural forest formation is lowland moist evergreen forest or also referred to as dense humid forest at low altitude, with distinct characteristics defined by Humbert (1955b), including the presence of *Anthostema madagascariense*

Figure 7. The natural vegetation formation around Camp 1 at 450 m is lowland moist evergreen forest and characterized by being dense, with several vertical stratifications, and distinctly rich in woody trees. **A**) The understory is often relatively open and includes composed of monocots, ferns, and young woody trees. **B**) In some areas the canopy can form a nearly 100% cover and large trees reach between 25 to 35 m in height. (Photos by Jacquis Tahinarivony.)

(Euphorbiaceae) and members of the family Myristicaceae. The forest is dense, multi-stratified, and distinctly rich in woody trees (Figure 7). The understory is generally open especially on slopes and ridge tops, and composed of monocots, ferns, and young woody trees. The middle strata range from fairly clear to closed; this aspect depends on the vegetation height and the density of shrubs and young trees. In some areas, particularly in low-lying topographic settings, the canopy can form a nearly

Figure 8. Portions of the zone around Camp 1 at 450 m are composed of secondary habitat and degraded formations that are dominated by plants such as *Aframomum angustifolium* (Zingiberaceae) in the foreground and bamboos (Poaceae) in the middle section of the photo. The disturbance factors that gave rise to such habitat include landslides, most likely the result of periods of heavy rainfall associated with tropical depressions and cyclones, or anthropogenic forest clearing decades ago for swidden agricultural purposes. These zones are often surrounded by relatively intact forest, such as on the hills in the back portion of the image. Such areas had partially regenerated into secondary forests over the 25 years between the 1996 and 2021 inventories of the zone. (Photo by Voahangy Soarimalala.)

100% cover, reaches between 25 to 35 m in height, and consists of large trees and tall palm trees; lianas are also present. The dominant tree taxa, often with prominent buttresses, tall and straight trunks, and individual crowns that can exceed 20 m in diameter, include *Canarium* spp. (Burseraceae), *Cryptocarya* spp. (Lauraceae), and *Sloanea rhodanta* (Elaeocarpaceae). Epiphytes are also observed on both rocks and trees, and include ferns, orchids, and Piperaceae, but this feature is less pronounced at this site as compared to higher portions of the massif.

The vegetation formation in the Camp 1 zone is notably sensitive to subtle phenomenon associated with climatic factors, landslides or anthropogenic pressures, which result in changes to forest structure and floristic composition, including the local colonization and proliferation of pioneer, exotic, and invasive species. It was not uncommon to observe in place and from satellite images scattered spots of secondary and degraded formations in this elevational zone, characterized by native and non-endemic taxa such as *Aframomum angustifolium*, introduced planted species including *Musa acuminata*, invasive species such as *Lantana camara* (Verbenaceae), and some endemic species such as *Perrierbambus madagascariensis* (Poaceae) (Figure 8).

775 m (Camp 2 or Camp Marojejya, Marojejia, and Marojejyia)

Our camp site was within what is today MNP's Camp Marojejya and adjacent to the Ambavaomby River, a tributary that joins the Manantenina River a short distance below and just after the dramatic Cascade Andampimbazaha. On the other side of the Manantenina River valley and directly across from the camp is the Ambatotsondrona Massif (Figure 9). It takes about 1 hour to walk from Camp 1 to Camp 2.

The forest below Camp 2 and within the transect zone shows some indications of past human disturbance, including, as compared to the 450 m zone, more advanced regenerating secondary forest and distinctly less bamboo and *Afromomum*. The forest above Camp 2 and within the elevational transect zone seems to be largely intact and along the summit trail the topography rises abruptly. Starting at about 800 m is the transition zone from lowland to medium altitude moist evergreen forests (= lower montane forest or lower montane rainforest of some authors) and this formation is most evident in areas with steep topography.

The section of the forest above Camp 2 and along the trail leading to Camp 3 is characterized by

Figure 9. View from Camp 2 (Camp Marojejya) towards the Ambatotsondrona Massif (summit at 1261 m). The forest at the foot of the summit has a non-continuous canopy, which is presumably associated with natural landslides and perhaps with former areas of swidden agriculture on the less steep slopes. (Photo by Erik Patel.)

Figure 10. Above Camp 2 at about 800 m is the transition zone between lowland to medium altitude moist evergreen forests and characterized by emergent trees that exceed 30 m in height and with distinctly vertical trunks, notable epiphyte loads, and a relatively open understory. (Photo by Voahangy Soarimalala.)

Figure 11. The habitat below Camp 2 is largely lowland moist evergreen forest resting on shallow soils and certain areas with exposed bedrock, giving rise to a more diminutive forest stature than the zone above Camp 2. (Photo by Jacquis Tahianarivony.)

Figure 12. *Takhtajania perrieri* is known from four sites in northern Madagascar, including the Parc National de Marojejy. This species first named in the early 20th-century from Manongarivo was rediscovered in 1994 in Anjanaharibe-Sud and then subsequently a few other sites in northern Madagascar. The individual shown here is in fruit and was found on a ridge above Camp 2. (Photo by Jacquis Tahianarivony.)

a dense medium altitude moist evergreen forest with deep soils (Figure 10). Below Camp 2 the formation is largely lowland moist evergreen forest resting on shallow soils and with considerable exposed bedrock or close to the surface (Figure 11). In general, the forests in the Camp 2 transect zone are dense, tall, and multi-layered. The undergrowth is light to dense, marked by the presence and abundance of *Pandanus* (Pandanaceae) and *Cyathea* (Cyatheaceae). The undergrowth is richer in ferns, *Impatiens* (Balsaminaceae), and Cyperaceae, as compared to the area around Camp 1. The middle forest strata are dense and composed of shrubs, *Cyathea* tree ferns and palms, including *Marojejya insignis* (Arecaceae). The upper stratum reaches 15 to 25 m, is largely closed to closed canopy, and made up of large trees and lianas. The emergent trees exceed 30 m in height and are characterized by a dbh greater than 80 cm and distinctly vertical trunks, particularly in low-lying areas or on slopes. Compared to Camp 1, the forest of Camp 2 is marked by the considerable increase in the frequency and diversity of parasitic plants. Epiphytes are also rich and diverse, the most common of which are from the families Aspleniaceae, Orchidaceae, Piperaceae, and Pteridaceae, indicating an important level of humidity. The impacts of passing cyclones are evident around Camp 2, such as along the trail leading towards the stand of *Takhtajania* (Winteraceae) (Figure 12), and vegetation changes include the opening of the canopy, a distinct change in forest structure, an abundance of tree falls, and a local increase in climbing bamboos, Cyperaceae, and vining shrubs, sometimes making access difficult.

1300 m (Camp 3 or Camp Simpona)

The camp site where the team was installed is known today as Camp Simpona, which was very close to the 1996 site known as Antranohofa. This site or a nearby area is Humbert's (1955a) locality known as Andilana and that of Griveaud (1960) designated as Andasy II. The area around our Camp 3, particularly below, is in a forested valley, and here the watershed shifts from the Manantenina River to the southern draining Andranomifotatra River. Below Camp 3 is a lookout platform known as Point de Vue that provides an extraordinary view of the lower lying formations largely to the east and the higher massifs to the north, as well as a portion of Marojejy's higher cliffs (Figure 13). There were few signs of human disturbance in the 1500 m transect zone, with the exception of the construction of the camp and occasional cut trees of *Ivodea* spp. (Rutaceae, *bilahy*), the bark of which is used in the fabrication of a local alcoholic beverage (*betsa-betsa*).

Figure 13. Photo from the Point de Vue, below Camp 3, towards the east and showing the extensive forest, mostly on the slopes draining into the Manantenina River, as well as a view of the Ambatotsondrona Massif (1261 m). The partially cleared distant hills outside the Parc National de Marojejy are evident. (Photo by Inaki Relanzon.)

Figure 14. The habitat around Camp 3 at 1300 m is medium altitude moist evergreen forest and this formation shows important local differences based on topography. Shown here is forest habitat on a ridge, which is shorter in stature and with a more open canopy than in valleys. (Photo by Jacquis Tahianarivony.)

The trail connecting Camp 2 to Camp 3 offers an excellent opportunity to appreciate the transition between the lowland to medium altitude moist evergreen forest formations. This transition can be highlighted by differences in several indicators, such as the increasing abundance of bryophytes, lower canopy height, reduction of biovolume, and tree architecture having more twisted trunks and fewer trees with massive buttressed roots. Around Camp 3, the dominant formation is medium altitude moist evergreen forest with mosses and lichens. The canopy height is between 10 to 20 m and this aspect and vegetation density vary based on the nature of the substrate and topography. The tallest trees occur in lower-lying areas and on mid-slopes, while the ridges are covered by fairly low forest with an open canopy (Figure 14). The general characteristics of the local formation are defined by dense undergrowth and rich plant diversity. Among the typical families are Acanthaceae, Balsaminaceae, Bignoniaceae, Orchidaceae, Pandanaceae, and a variety of ferns, as well as Melastomataceae. The middle strata are open to slightly closed, and shelter shrubs and young trees. The upper stratum is largely closed to distinctly closed, thus filtering and reducing light intensity penetrating into the middle and lower vertical portions of the forest and promoting the proliferation of mosses and lichens on tree trunks and the substrate. The soil is often covered by dense herbaceous plants such as ferns and with pronounced leaf litter and organic material. The vegetation at lower-lying topographic levels is rich in trees many distinctly more branching - notably different from the formations on ridges and crests, where trees are more twisted - and do not exceed 50 cm in dbh. Parasitic plants are increasingly common in this elevational zone, namely *Bakerella* (Loranthaceae) and *Viscum* (Santalaceae), but epiphytes remain dominant. The vegetation has several adaptations to the local environment, in particular occasion strong winds and severe climatic fluctuations. Portions of the forest opened up by heavy winds are dominated by genera that install spontaneously, such as *Scleria* (Cyperaceae), *Nastus* and *Sokinochloa* (Poaceae), *Senecio* (Asteraceae), and different shrubs.

1550 m (Camp 4)

As mentioned above, this site and the trail leading to Camp 4 were created during the 1996 inventory to provide access to an intermediate elevational transect zone between Camp 3 and Camp 5. Griveaud's (1960) 1600 m site, which he referred to as Ambodifiakarana, is in the general vicinity of our Camp 4, but probably along the main summit trail. Our Camp 4 is about 1.5 hours walk from Camp 3 and accessible via a path of about 520 m leading from the summital trail and the bifurcation is about midway between Camp 3 and Camp 5. The zone in the protected valley around the camp, which drains into the Andranomifotatra River, and making up a good portion of the transect zone, is for the most part the upper limit of medium altitude moist evergreen forest, classically referred to as upper montane forest, elfin forest or mossy forest. With increasing elevation, the vegetation and ground loads of moss and epiphytes within the transect zone are distinctly denser. Above the camp and mostly on exposed ridges is a transition to more sclerophyllous vegetation, with distinctly lower tree stature, heavier epiphyte loads, and plants sculpted by exposure to wind.

The rugged relief, relatively cool average temperatures, often stiff winds, and edaphic conditions give rise to an ecological situation where the tallest tree formations occur in valleys, low-lying areas, and on low slopes (Figure 15). On the higher slopes and ridge tops this formation is replaced by montane ericoid thickets. Nevertheless, the vegetation formation that dominates this site is dense upper portion of medium altitude moist evergreen forest and is distinctly stratified. The canopy can exceed 16 m in height and emergent trees reach up to 22 m. The canopy height decreases considerably with increased elevation and reaches up to 4 m at the level of the ridges and summits. The tallest vegetation in the transect zone is around Camp 4, characterized by a diverse understory, the middle strata being dense, and with a partially closed to closed canopy. The largest trees can reach 70 cm dbh. Mosses and bryophytes envelop the trunks of trees and line the ground to form a notably thick and spongy layer (Figure 16). On the high slopes, ridges, and crests, dense to very dense vegetation can be found, which in certain areas is largely impenetrable. At this elevational level, the dominant vegetation includes *Kalanchoe* (Crassulaceae), Melastomataceae, Orchidaceae, and Piperaceae, as well as epiphytic ferns. Lianas are less diversified as compared to lower elevational zones. Indeed, the characteristics of the vegetation are similar to those of Camp 3 and present the same processes of regeneration after damage by strong storm winds.

Figure 15. At the level of Camp 4, found at 1550 m, the steep topographic variation, relatively cool temperatures, often brisk wind, and soil conditions result in local conditions were the tallest forest, classified as the upper portion of medium altitude moist evergreen forest, is in valley bottoms. This formation has a diverse understory and largely closed canopy. (Photo by Jacquis Tahianarivony.)

Photo 16. Another aspect of the habitat at Camp 4, found at 1550 m, is the development of mosses and bryophytes that envelop tree trunks and branches, as well as heavy epiphytic plant loads. (Photo by Jacquis Tahianarivony.)

1880 m (Camp 5)

This camping site was just above tree line and in a zone with a water source that is presumably one of the headwaters of the Andranomifotatra River. The site was 1.5 to 2 hours walk from Camp 4 and

Figure 17. The area around Camp 5, which is shown in the middle of the image, at 1880 m is a mosaic of montane ericoid thicket, montane grassland, and zones with exposed rock. This is the zone that forms the source of at least one portion of the Andranomifotatra River. (Photo by Jacquis Tahianarivony.)

Figure 18. The montane grasslands above forest line and in the vicinity of Camp 5 tended to occur in areas with shallow soils and with small shrubs and a range of different plants generally less than 1 m in height. (Photo by Jacquis Tahianarivony.)

Figure 19. A vegetation formation above forest line and in the vicinity of Camp 5 is montane ericoid thicket, which tends to be in areas with some ground water and shallow soils. As shown here along the trail leading to the summit, in some areas the vegetation can be dense. (Photo by Eric Mathieu.)

a relatively short distance to the summit. Griveaud's (1960) camp known as Matsabory that he placed at 2030 m was probably closer to the summital zone.

The landscape is made up of a mosaic of natural habitats ranging from montane ericoid thicket (= low ericoid bush) to montane grasslands. Just below the camp was the upper limit of a sclerophyllous forest formation. Camp 5 was located in the middle of a montane grassland, not exceeding 0.5 m in height, consisting mainly of grasses and Cyperaceae (Figure 17). The grassland had patches of small shrubs, rarely exceeding 1 m in height and dominated by members of the families Araliaceae, Asteraceae, Ericaceae, Myrtaceae, Monimiaceae, and Rutaceae (Figure 18). The montane ericoid thickets tend to occur near stream banks and in areas with shallow soils and ranging from dense to very dense vegetation not surpassing 6 m in height (Figure 19). These thickets are dominated by the families Araliaceae, Asteraceae, Lauraceae, Monimiaceae, Myrtaceae, and Primulaceae and with no pronounced vertical stratification and woody vegetation dbh less than 20 cm. In the zone between 1800 m and the physical summit at 2130 m, there are temporarily flooded areas and such areas form the sources of numerous headwaters of different watersheds, including the Androranga, Lokoho, and Sambava rivers.

Geology and soils

The geology of the Marojejy Massif is complex and the following text is adapted from Crowley and Sparks

(2018). The local geology is primarily made up of charnockitic granite from the Terminal Proterozoic to early Cambrian Ambalavao Kiangara-Maevarano Igneous Suite (Roig *et al*., 2012). Alternating bands of older rocks from the Bemarivo Domain can be found throughout the western and southern portions of the massif.

Following Armstrong and McGroddy (2018), the most common soils on and around the massif are Haplic Cambisols, which are at the earliest stage of development and are generally found on slopes and in areas where disturbance has reset the soil development timeline. In addition, Haplic Ferralsols also occur, and these are highly weathered, acidic soils with reduced capacity to retain essential cations (e.g. calcium and magnesium), and relatively high in iron and aluminum. The iron oxides found in these soils give them their characteristic reddish color. The third most common soil at the site is Vitric Andosol, which is the result of past volcanic activity. These soils are relatively young, show little development, and close to the surface compose a horizon rich in vitreous materials.

Meteorology

The generalities presented here on the climate of Marojejy are derived from Rakotondrafara *et al*. (2018). Temperature records used by these authors are from 1985 to 2014 and from MODIS (Moderate Resolution Imaging Spectroradiometer) satellite data with a resolution of 0.1° (approximately 11 km), as well as 22 weather stations on the island. Precipitation data from the same period are divided into 10-day periods (decadal), and derived from the TAMSAT (Tropical Applications Meteorology using SATellite) satellite with the same resolution mentioned above. It is important to underline that these analyses use a single point towards the lower elevations of the eastern side of the massif, and the derived data do not necessarily reflect the meteorological aspects at higher elevations and along the drier western portion.

The massif and surrounding areas are dominated by the humid climate of the north, with average annual rainfall being 1654 mm, of which 64% falls between November and April. Between 1985 and 2014, dry episodes of up to 20 days occurred at the height of the rainy season, and rainy season precipitation during this period increased by about 0.2% annually, or around 50 mm. Towards the end of this 30-year period, the rainy season tended to end 10 days earlier, as compared to the mid and late 1980s.

On average, the daily temperature varies between 14.0°C and 22.7°C. The cold season falls between June and August, with temperatures dropping to 8°C. The warm season tends to be between December and February, although peak temperatures over 28.9°C were recorded between September and November. From 1985 to 2014, there was no significant change in the average minimum daily temperature, while the average maximum temperature increased by 1.1°C. This increase should be considered of significance and potentially related to local patterns of climatic change in the greater Marojejy region.

During the 2021 mission to Marojejy, a simple weather station was installed at each of the five camps, consisting of a rain gauge place in an open area without overhead vegetational cover and a minimum-maximum thermometer installed under vegetation and out of direct sunlight. At dawn each day, data were recorded from each of these devices and the rain gauge was emptied and the temperature indices of the thermometer returned to "zero." The descriptive statistics for the weather data during the period the group inhabited each camp site in 1996 and 2021 are presented in Table 2.

A comparison of the site weather data from 1996 and 2021, based on readings during the same calendar periods and separated by 25 years, show some differences that might have influenced the sampling of different vertebrate groups (Table 2). For example, in 1996 at the 450 m site, average maximum temperature was distinctly lower and average rainfall was higher than in 2021. At the 750 m site, the meteorological data between the two transects are largely similar. At the 1300 m site, some contrasts are worth noting: the average minimum temperature in 1996 was lower than in 2021, while the inverse was the case for average maximum temperature, and in 2021 there was more precipitation during the course of a 24-hour period with cumulative totals up to 59 mm. At the 1550 m site in 1996, there was distinctly heavier rain as compared to 2021, including a 24-hour period with 84 mm of precipitation. At the last site (1880 m), the average temperature patterns were largely in parallel between the two periods of inventory, although it was slightly wetter in 2021 than in 1996. In another contribution herein (Marline *et al*., 2023), details are presented on weather stations placed along the elevational transect and covering the period from 2014 to 2020.

Table 2. Summary of minimum and maximum temperatures during the 1996 and 2021 expeditions to Marojejy. The 1996 data are taken from Goodman (2000b) and the 2021 data based on unpublished field data gathered by Fandresena Rakotoarimalala, Fifaliantsoa Rasolobera, and Voahangy Soarimalala.

Measured dates within each transect	Temperature (°C)[1]		
	Minimum	Maximum	Rainfall (mm)[2]
450 m			
4-14 October 1996	10, 13-17 14.7 ± 1.10	10, 17-23 20.1 ± 1.87	8, 2.0-40.0 10.6 ± 12.68
2-11 October 2021	9, 12-16 14.6 ± 1.23	9, 22-27 25.2 ± 1.48	6, 0.3-4.0 1.5 ± 1.56
750 m			
15-23 October 1996	10, 13-18 15.9 ± 1.58	10, 19-27 23.2 ± 2.14	7, 1.0-27.5 12.2 ± 10.76
12-20 October 2021	9, 12-15 14.1 ± 0.93	9, 21-25 21.9 ± 1.36	9, 0.1-27.5 11.1 ± 10.66
1325 m			
24 October-3 November 1996	9, 10-13 11.4 ± 0.83	9, 19-23 21.3 ± 1.56	5, 1.0-23.0 8.0 ± 7.8
21-29 October 2021	9, 12-15 13.6 ± 1.24	9, 18-20 19.2 ± 0.97	5, 4.0-59 15.8 ± 24.33
1550 m[3]			
4-13 November 1996	9, 9-13 11.0 ± 1.40	9, 15-18 16.5 ± 1.17	6, 0.5-45.0 11.0 ± 15-84
30 October-6 November 2021	9, 11-14 12.3 ± 1.00	9, 18-18 18.0 ± 0.00	6, 0.5-15.3 7.1 ± 6.67
1875 m			
14-20 November 1996	7, 8-13 9.9 ± 1.64	7, 18-23 21.0 ± 1.69	5, 0.5-1.0 0.6 ± 0.2
7-15 November 2021	8, 9-12 10.5 ± 1.07	8, 20-24 21.9 ± 1.25	7, 0.5-9.0 3.3 ± 3.10

[1] Data are presented as number of records, range (minimum-maximum), mean, and ± standard deviation.
[2] Data are presented as number of 24-hour periods (days) at a given site with rain, range (minimum-maximum), mean, and ± standard deviation. Hence, 24 hour periods without rainfall are not considered in these summary statistics.
[3] Reported in Goodman (2000b) as 1625 m and based on new GPS recordings from 2021 the correct elevation is 1550 m.

Future monitoring

On the basis of data on the plants and animals present along a transect comprising over 1400 m of vertical elevation of five different sites on the eastern slopes of Marojejy in 1996, ranging from lowland forest to above forest line, and a repeated inventory in 2021 of the same sites and with parallel field techniques, it is possible to examine changes that have taken place over the course of nearly 25 years. The associated information and comparisons between the two inventories provide important insight into possible vicissitudes that could be related to anthropogenic pressures such as forest degradation and hunting, broad-scale patterns of climate shifts (specifically broad patterns of human-induced changes) or stochastic aspects of sampling procedures. As shown in another analysis presented herein based on satellite image interpretation of the Manantenina River valley, where the lower portions of the 1996 and 2021 transect surveys were conducted, this is a zone of the park that has had reduced anthropogenic pressure between 1996 and 2022 (Tahinarivony, 2023b, herein). In many of the contributions presented in this monograph, specifically animal groups surveyed both in 1996 and 2021, differences between the results from each survey period are discussed.

An analysis conducted based on Landsat 5, 7, and 8 images of Marojejy and obtained between 1996 and 2016 and with a precision of 1 pixel (approximately an area of 30 x 30 m) (Rabenandrasana *et al*., 2018), shows little change at a relatively course level in forest cover in the protected area during this period (Table 3). It is important to mention at a finer scale, particularly the removal of precious hardwood trees for which the park has been the subject of such exploitation (Patel, 2007; Schuurman & Lowry, 2009), is not visible in the Rabenandrasana *et al*. (2018) analyses. During the 2021 inventory of the site and in particular in the lower elevational zones, signs of relatively recent selective exploitation of hardwoods were found. For the most part such areas were off the main Mandena-summit trail and the resulting canopy openings at a scale of less than 30 x 30 m.

As mentioned earlier, data from the 1996 and 2021 elevational transects that encompassed a

Table 3. Measures of natural forest loss from 1996 to 2006 and from 2006 to 2016 in different natural formations at Marojejy. Data derived from Goodman *et al*. (2018a) and Rabenandrasana *et al*. (2018).

Habitat type	Forest cover (ha) in 1996	Forest cover (ha) in 2006	Forest loss (ha) between 1996-2006 (% loss)	Forest cover (ha) in 2016	Forest loss (ha) between 2006-2016 (% loss)
Moist evergreen forest	50,412	49,808	604 (1.2%)	49,566	242 (0.5%)
Total	**50,412**	**49,808**	**604 (1.2%)**	**49,566**	**242 (0.5%)**

notable ecological gradient - where variables such as shifts in temperature, humidity, and rainfall change in a continuous manner - provide the means to understand the ecology and biogeography of a variety of organisms, and possible change across 25 years, whether natural or anthropogenic. In order to follow the evolution of the biota of the Marojejy Massif, one of the most important protected areas on the island with regards to Malagasy natural patrimony, we strongly recommend that in a regular periodic manner, say every 10 years, a parallel transect inventory be conducted, paying close attention to the same methodologies and calendar periods used in 1996 and 2021, to document patterns of change through time.

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Appendix 1

Participants in the project

Excluding local people that took part in the 2021 elevational transect of Marojejy, a total of 12 field-workers were involved, as well as a number of people that collaborated and helped with the analyses and manuscript preparation. The addresses of all of the scientists are given below.

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