Madagascar's extraordinary biodiversity: Evolution, distribution, and use

Antonelli, Alexandre; Smith, Rhian J; Perrigo, Allison L; Crottini, Angelica; Hackel, Jan; Testo, Weston; Farooq, Harith; Torres Jiménez, Maria F; Andela, Niels; Andermann, Tobias; Andriamanohera, Andotiana M; Andriambololonera, Sylvie; Bachman, Steven P; Bacon, Christine D; Baker, William J; Belluardo, Francesco; Birkinshaw, Chris; Borrell, James S; Cable, Stuart; Canales, Nataly A; Carrillo, Juan D; Clegg, Rosie; Clubbe, Colin; Cooke, Robert S C; Damasco, Gabriel; Dhanda, Sonia; Edler, Daniel; Faurby, Søren; de Lima Ferreira, Paola; Fisher, Brian L; Forest, Félix; Gardiner, Lauren M; Goodman, Steven M; Grace, Olwen M; Guedes, Thaís B; Henniges, Marie C; Hill, Rowena; Lehmann, Caroline E R; Lowry, Porter P; Marline, Lovanomenjanahary; Matos-Maraví, Pável; Moat, Justin; Neves, Beatriz; Nogueira, Matheus G C; Onstein, Renske E; Papadopulos, Alexander S T; Perez-Escobar, Oscar A; Phelps, Leanne N; Phillipson, Peter B; Pironon, Samuel; Przelomska, Natalia A S; Rabarimanarivo, Marina; Rabehevitra, David; Raharimampionona, Jeannie; Rajaonah, Mamy Tiana; Rajaonary, Fano; Rajaovelona, Landy R; Rakotoarinivo, Mijoro; Rakotoarisoa, Amédée A; Rakotoarisoa, Solofo E; Rakotomalala, Herizo N; Rakotonasolo, Franck; Ralaiveloarisoa, Berthe A; Ramirez-Herranz, Myriam; Randriamamonjy, Jean Emmanuel N; Randriamboavonjy, Tianjanahary; Randrianasolo, Vonona; Rasolohery, Andriambolantsoa; Ratsifandrihamanana, Anitry N; Ravololomanana, Noro; Razafiniary, Velosoa; Razanajatovo, Henintsoa; Razanatsoa, Estelle; Rivers, Malin; Sayol, Ferran; Silvestro, Daniele; Vorontsova, Maria S; Walker, Kim; Walker, Barnaby E; Wilkin, Paul; Williams, Jenny; Ziegler, Thomas; Zizka, Alexander; Ralimanana, Hélène

Science

DOI:
10.1126/science.abf0869

Published: 02/12/2022

Peer reviewed version

Science
AAAS

Supplementary Materials for

Madagascar's extraordinary biodiversity: Threats and opportunities

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Materials and Methods

These Supplementary Materials contain details of the data compilation and analyses conducted under each relevant section of the main paper. While as much information as possible is provided here, some of the datasets are too large to present, and these are available in an associated Zenodo repository (*135*). The datasets not presented here are listed below under the sections they link to. All methods are described in detail, and code is available upon request in cases where it is not directly linked below.

1. IUCN threat categories for plants and animals from Madagascar

Extinction risk categories were extracted from the IUCN Red List of Threatened Species (*19*), with the addition of the global trees dataset from the *Red List of Trees of Madagascar (5)*. Since IUCN only reports extinct species after 1500 CE, we complemented this list with known anthropogenically extinct animal species that occurred during the Late Pleistocene and Holocene periods, before 1500 CE (see associated Zenodo repository (*135*)). No anthropogenic plant extinctions are known from before 1500 CE. The final list includes the main groups of animals and plants native to Madagascar. Animal groups included: mammals (N=231 species), birds (N=209), reptiles (N=340), amphibians (N=296), freshwater fish (N=164), arthropods (N=374), and mollusks (N=67). Plants include asterids (N=1105 species), rosids (N=1704), other eudicots (N=81), magnoliids (N=225), monocots (N=822), gymnosperms (N=6), and ferns and lycophytes (N=33).

Repository file:

Title	*Filename*	*Description*
List of anthropogenic extinctions before 1500 CE	extinct_animals_madagascar.csv	Comma-separated table of all known anthropogenic extinctions before 1500 CE in Madagascar.

2. Approximation of IUCN categories for non-assessed plants from Madagascar

At present, approximately one third of plant species occurring in Madagascar have an assessment published on the IUCN Red List of Threatened Species (www.iucn.org). To increase the representation of the Malagasy flora in our analyses, we used a Bayesian Neural Network (BNN), following (*136*) and (*20*), to estimate the conservation status and threats for species that are so far not evaluated. We trained our BNN on existing conservation assessments from the IUCN Red List, using species-level predictors calculated from occurrence records combined with data on climate, topography, biomes, forest cover, human footprint, and sampling bias.

2.1. <u>Data compilation</u>

<u>Species checklists.</u> We used a checklist of plant species native to Madagascar from the Catalogue of the Vascular Plants of Madagascar (Madagascar Catalogue) from March, 2021(*137*). At the time of download, the Madagascar Catalogue listed 11,919 species of plants from 1,722 genera in 251 families. We used the taxonomic backbone and binomial names from this checklist as a base to obtain occurrence records and merge them with data on IUCN Red List categories and plant use. All scripts for record cleaning and predictor preparation are available in our Zenodo repository (*135*). **Occurrence data.** We obtained publicly available georeferenced occurrence records for all species from the Madagascar Catalogue checklist. Occurrence records from public databases can be error-prone (*138, 139*). Therefore, we followed a conservative approach of only using records from a validated data source. This approach included records from iNaturalist Research-grade Observations (*140*) and records based on specimens from the Missouri Botanical Garden (*141*), both obtained from www.gbif.org. We limited the search to vascular plant ("Tracheophyta") records from Madagascar with geographic coordinates associated, and only used records of presence (Occurrence status = present). We then added another batch of records from the Kew Madagascar Conservation Centre unpublished database. We obtained a total of 277,411 occurrence records for 13,229 taxa. We further increased the input data quality by applying geographic filters to remove common errors caused by automated georeferencing procedures. These filters comprised: i) Retaining only records inside Madagascar's bounding-box (longitude between 42 and 54 degrees W and latitude between 30 to 10 degrees South); ii) Removing records with an individual count of 0; and iii) Using the CoordinateCleaner R package (*142*) to remove records falling on the coordinates of Antananarivo (the capital), the centroid of Madagascar or its provinces, or the location of registered biodiversity institutions. After geographic filtering, we only retained records for species binomial names listed in the Madagascar Catalogue CPM checklist. This process left us with 187,141 records from 9,960 species for further analyses. Presence-only occurrence records compiled from specimens collected in the field are often subject to sampling bias, for example because easily accessible areas are overrepresented (*143, 144*). We generated two features quantifying the average bias at collection locations for each species to account for this effect. We used the sampbias method (*145*) to obtain the median sampling bias at the occurrence locality for each species and the range (0.05–0.95 quantiles) of bias values across occurrence records for each species. **Species-level features.** We obtained species-level features by combining occurrence records with different publicly available environmental datasets (as well as separate data on plant use, see below) and calculating summary statistics on all records for each species. We generated 57 features as input for the BNN (see Table S1 for a summary and our Zenodo repository (*135*) for the feature input data and the R-scripts we used for data generation, see "Scripts and data to predict IUCN and threat status" under Species checklists). To improve model convergence, we normalized all features to a similar range, using procedures specific to each feature-type (Table S1). During normalization, we ignored missing values ("NAs"), which may result from a lack of data in the environmental layers (e.g., some may contain lakes, others may not) or imprecision in the occurrence records (e.g., coordinate values within lakes). **Geographic features.** We generated two sets of geographic features to account for potential changes in the ranges of species since collection began: one set using all available records, and another solely using records collected since 2000. See Table S1 for the full list of geographic features used, and details of their normalization. The IUCN Red List assessment metrics Area of Occupancy (AOO) and Extent of Occurrence (EOO) were calculated using the package rCAT (*146*, *147*). We extracted the elevation at the locality of each collection record in our dataset from a global elevation model (*148*) to obtain the median elevation value and the elevational range (0.05 -0.95 quantile) for each species. We normalized via division by 600. We used a spatially explicit, global biome scheme (*149*) to classify each species as present in a biome if at least 5% of the species' records occurred in this biome (see (*150*) for more information on the 5% threshold). We used a binary feature on presence/absence for each biome with at least one species present. The resulting five binary features were: "Tropical & Subtropical Moist Broadleaf Forests", "Tropical & Subtropical Dry Broadleaf Forests", "Montane Grasslands & Shrublands", "Deserts & Xeric Shrublands", and "Mangroves". We extracted climate conditions from publicly available climate data (*148*) at each occurrence record in our database. See Table S1 for a full list of climate-based features and their normalization. **Environmental data.** We obtained data on Madagascar's protected areas (PAs) from the World Database of Protected Areas, modified as detailed below. We used these data to calculate three features for each species: i) the fraction of occurrence records in IUCN category I or II PAs (strictly protected); ii) the fraction of occurrence records IUCN categories III-VI (protected); and iii) the fraction of occurrence records outside PAs. We extracted human footprint from spatially explicit estimates of human impact across Madagascar (*151*) for each species' occurrence records. We calculated eight features from this human footprint, including the fraction of species' occurrence in four impact categories (quantiles from low impact to high impact) for two time-points (1993 and 2009) each. We used spatially explicit forest cover data for Madagascar from (*38*) (https://bioscenemada.cirad.fr/maps/) to calculate the per-species-fraction of occurrence records in cells with forest cover in 1973 and 2014, yielding two features. **Plant uses.** We obtained information on known uses of Malagasy plant species for 1,591 species from a currently compiled global plant use database (*152*). We generated binary features of plants used as animal food, fuel, human food, building materials, medicine, and in social uses. We also used the number of use-types for each species, divided by 10, as another feature. **Training labels from IUCN.** We downloaded all global IUCN Red List assessments for species native to Madagascar, covering a total of 4,500 species (*19*) and added 151 assessments for tree species, obtained from Botanic Gardens Conservation International, which had not been uploaded to the IUCN Red List at the time but have since been added. We retained only species assessed under version 3.1 of the IUCN criteria (*4*), and excluded species labeled as Extinct in the Wild (EW) or Extinct (EX). We included species assessed as Data Deficient (DD) in the pool of species for which we predicted the conservation status. **Final dataset.** Our final dataset consisted of 9,960 species (83.5% of the known native species from Madagascar) for which we could obtain usable occurrence records and hence prepare features for model training and prediction. Of these species, 4,073 (40.9%) had global conservation assessments available while 5,887 (59.1%) were unlabeled. We used the species with assessments to train the BNN (training data) and the unlabeled species to predict conservation status and major threats. We used a total of 57 features for training and prediction.

2.2. Predicting IUCN categories

We used a BNN to predict the IUCN Red List category of the 5,887 unlabeled species for which we could extract features. We reserved 10% of the 4,073 species with assessments as a test set and trained our BNN on the remaining 90%. We used the BNN implementation described in (*153*) (https://github.com/dsilvestro/npBNN), with one hidden layer comprising 20 nodes plus an additional bias node (20 x (57+1) weights) and a parametric ReLU activation function (*154*) with an estimated coefficient shared across all nodes. The output layer of the BNN included 5 nodes (20 x 5 weights) transformed into the parameters of a categorical distribution using the softMax function. We performed Monte Carlo cross-validation by repeating the analyses five times using different random seeds and different train/test splits. For each BNN, we used Gibbs sampling to draw 50 million MCMC samples of the network weights, which we thinned to 5,000 posterior samples. After assessing the performance of the trained BNNs on the test sets (see below), we combined the posterior weights from the 5 replicates to perform predictions for the unlabeled species.

2.3. Assessing the performance of the BNN

We quantified the performance of our BNN predictions in different ways. We first computed the cross-validation test accuracy, which averaged 66.9% across replicates (range: 65–68.2%). Second, we measured the accuracy of our BNN after removing predictions for species where the mean posterior probability of the most likely category fell below a threshold. In practice, this threshold would be used to prevent an IUCN Red List category being predicted for a species when confidence in the prediction is low. We found that applying a threshold of 0.808 to the mean posterior probability of the most likely category resulted in 90% classification accuracy. We used this as the threshold in our "conservative" approach to predicting the IUCN Red List category for unlabeled species. Third, we assessed how accurately the trained BNN could recover the observed number of species in each IUCN Red List category in the test set. We predicted the posterior category probabilities for the species in our test set using each of the 5,000 posterior samples of our network weights. We then used these posterior category probabilities to draw samples from the respective categorical distributions. This procedure resulted in 5,000 predicted IUCN Red List categories for each species in the test set. We counted membership of these categories for every round of samples, yielding 5,000 estimates for the number of species in each category. We calculated the mean absolute percentage error of these estimates from the observed counts in the test set. We found the mean absolute percentage errors per category to be lower than 0.1 (CR: 0.082, EN: 0.014, VU: 0.056, NT: 0.035, LC: 0.032) and with small variability across replicates (standard deviations: 0.04, 0.005, 0.024, 0.024, 0.018).

2.4. IUCN predictions using the BNN

Under our conservative threshold of 0.808, we were able to classify 975 species (18.2% of the unlabeled species) with high confidence. Of these, 39 were classified as CR, 254 as EN, and 681 as LC. The full output of the BNN classification, including the mean posterior probabilities for each class and each species are provided in our Zenodo repository (*135*). We aggregated these predictions to estimate the number of species in each IUCN Red List category across all unlabeled plants (5,887 species) as well as within large plant groups: asterids (1,948 spp), eudicots (248), ferns & lycophytes (377), magnoliids (80), monocots (1,256), and rosids (1,444). The results of these estimates are shown in Table S2.

2.5. Feature importance

We used permutation feature importance to measure each feature's effect on the prediction accuracy of our trained BNN. In this approach, a model's change in performance is measured after randomly shuffling a feature's values repeatedly. Random shuffling effectively mutes the features' information content. We measured the change in performance as the mean decrease in accuracy of predictions (delta accuracy) - a larger delta accuracy indicates a more important feature. In our implementation, we defined blocks of similar features (Table S3), which we shuffled jointly to determine the impact of the whole block on the prediction accuracy. We calculated the feature importance using the complete set of labeled species (training + test set). We found that current geography was the most important feature block (delta accuracy = 0.26). The climatic features (delta accuracy = 0.14) and geographic features incorporating the last 20 years (delta accuracy = 0.11) were the next most important blocks. We calculated another feature importance for the species in our test set with high confidence predictions (mean posterior probability of the most likely class greater than the conservative threshold of 0.808, see above). For these high confidence species, we found similarly high feature importance of the current geography feature block (delta accuracy = 0.24), followed by the past geography feature block (delta accuracy = 0.10), and the anthropogenic utilization feature block (delta accuracy = 0.05).

Repository files:

Title	*Filename*	*Description*
Scripts and data to predict IUCN and threat status	predicting_species_IUCN_status.zip	Zipped archive containing data, scripts and an Rstudio project to: (1) prepare features for using IUCNN v1.0 to predict the conservation status for Not Evaluated species (01_feature_preparation); (2) predict species IUCN status assessment using neural networks (02_predicting_species_IUCN_status); (3) predict species' threat status using neural networks (03_predicting_species_threats)
Bayesian Neural Network Threat Status predictions	threat_predictions_iucnn.txt	Tab-separated table with results of the conservation status prediction from a Bayesian Neural Network for 5,887 species of vascular plants from Madagascar. Values are the mean posterior probabilities for each IUCN Red List category

3. Threats and prediction of threats

We compiled threat categories, as defined by the IUCN (*37*), for terrestrial and freshwater vertebrates (1,332 species with IUCN assessments) and plants (3,381 species with IUCN assessments). As above, we only considered species assessed under version 3.1 of the IUCN criteria. We then used a Bayesian neural network analysis to predict the threats for an additional 5,887 unassessed plant species. We predicted threats at the broadest available level (level 1) and lumped threat categories listed for only a small number of species into the category "Other". The categories that we lumped comprise: "Climate change and severe weather", "Geological events", "Human intrusions and disturbance", "Invasive and other problematic species genes and diseases", "Other options", "Pollution", and "Transportation service corridors".

Of the unassessed species, more than 70% were predicted to be threatened by threat categories 1, 2, 4, with less than 10% potentially affected by one or more of the other threats. A summary of the results is presented in Table S4, and more detail on which taxa predictions were applied to can be found in our Zenodo repository (*135*). We used neural networks optimized through the Python library Tensorflow (v. 2.4; tensorflow.org) to predict the causes of threat as defined by the IUCN Red List. We used a multi-label binary classifier, as species often have more than one identified threat. The BNN architecture included 3 hidden layers with 60, 60, and 20 nodes, respectively, using a bias node at each layer and a tanh activation function. The output layer included 6 nodes (i.e., the six potential causes of threat) with a sigmoid activation function. After splitting the labeled data into training (80%), validation (10%), and test (10%), we trained the model using the validation loss to determine the optimal number of epochs, with the 'patience' parameter set to 5'.

We evaluated the reliability of our predictions on the test set by computing: i) the test accuracy for each threat; ii) the frequency of true positives (i.e., correctly predicting a threat); and iii) the frequency of false positives (i.e., erroneously predicting a threat). These summary statistics computed on the test set are reported in Table S5.

Repository file:

Title	*Filename*	*Description*
Observed and predicted threats	observed_and_predicted_threats.csv	Comma-separated table with the number of species with each listed threat, as defined by the IUCN or predicted by our model, across taxonomic groups.

4. Protected area database and shapefile

Attributes of Madagascar's terrestrial protected areas (PAs) and areas assessed for potential protection, and the associated spatial data, were compiled and manually reconciled using datasets from the Madagascar Protected Area System (SAPM), Directorate for the National System of Protected Areas (DSAP) (*155*), UNEP-WCMC/IUCN Protected Planet (*73*) and Alliance for Zero Extinction (*156*), Critical Ecosystem Partnership Fund (*157*), S. Goodman (*70, 72*), Key Biodiversity Areas (*74*), and personal knowledge. We follow (*72*) as closely as possible, except for areas with status updates in (*70*) and areas not treated. PAs designated as orphan sites are those that have been "abandoned by the former manager and [are] under the direction of the Ministère de l'Environnement et du Développement Durable (MEDD)" (*70*). They were scored from the dataset in (*70*), most recently updated in November 2020.

Data on PAs scored from (*72*) include visitation rates between 2012-2016; vegetation cover in 1996, 2006, and 2016; fires detected within PAs, and within a 5km radius of these in 2006 and 2016, and the corresponding changes in vegetation cover and the number of fires; state of knowledge of animal groups; and year of first botanical collections and collection density. Anthropogenic pressures reported by managers for each PA included vegetation cutting, hunting and illegal fishing, agriculture, grazing, wildfires, mining, collection of secondary forest products, and were manually scored as 0, 1, or N/A for missing data. An assessment was made of the infrastructure (camp sites, accommodation availability, offices, amenities, and research facilities) at each PA site that would enable or inhibit biologist access: data was sourced from each chapter in (*72*), from the information found under 'Infrastructure'. This information was assessed on the basis of the relative size of each area in hectares, and locality maps found in each of the PA sections, as well as the overview maps found in (*158*), particularly page 42. The assessment resulted in a grading system on whether the area was judged to have: No (0); Low (1); Medium (2); or High (3) levels of relative infrastructure/access, including for research.

A synthesized shapefile for terrestrial PAs is provided in our Zenodo repository (*135*). The terrestrial dataset is clipped to land using the Madagascar shapefile (*159*). Marine areas were removed by filtering for only PAs made up of more than 20% land. We calculated the area of each PA from the polygons using a Behrmann projection ("AREA"). The year of protection ("YEAR_PROT"), is set to the year when it was first protected, if that value was present ("year_old"). If this value was missing, we set the year of protection to the year when the PA was established in its current form, if that value was present ("SG2018year"), or to the year when the area was designated according to the WDPA database ("STATUS_YR").

We also provide a web application for interactive exploration of the PAs, vegetation and topography, available at https://www.mapequation.org/madagascar/.

Repository files:

Title	*Filename*	*Description*
Protected Area Shapefile	madagascar_terrestrial_protected_areas.zip	ESRI Shapefile for the synthesized protected areas of Madagascar, including Key Biodiversity Areas and attributes.
Protected Area Data	madagascar_terrestrial_protected_areas.csv	Comma-separated values matching the data within the Protected Area Shapefile except the shapes.
Protected Area Data Sources	madagascar_protected_areas_sources.csv	Comma-separated table with comments and sources for columns in the protected area data in the csv and shapefile

5. Assessment of progress against international targets and the percentage of taxa occurring in at least one PA

In order to assess the extent of land protection in Madagascar, we intersected the polygons of the PAs assembled in this study, with polygons of Madagascar as a whole (*159*). We calculated the proportion under protection for each PA class, (including KBAs, retrieved from (*74*)). We also intersected the PAs with the vegetation types delineated in this paper (see Fig. 5 and above) to evaluate the percentage of each vegetation type under protection.

We calculated the proportion of each vegetation type under protection for each polygon as well as for the entire country. The percentage of each existing vegetation type currently within a PA is shown in Table S6. We also used IUCN (*19*), inferred and author-curated ranges of native vertebrates (amphibians = 364, freshwater fish = 87, reptiles = 418, mammals = 221, birds = 203) and plants (*160*) to calculate the percentage of species with known distributions that overlap with the current protected area network and which taxa are not covered by any PA. We did the same for native threatened species. Only species from mainland Madagascar, Nosy Boraha, and Nosy Be were used. All analyses were performed in python version 3.6 and R version 4.0.0. A list of threatened vertebrate species with ranges that do not overlap with the existing PA network is provided in Table S7, but there are many more species yet to be assessed that may be threatened – see above and our Zenodo repository for more information (*135*). The ranges of all birds overlapped with at least one PA, this was also true when we filtered the analysis to only include resident and breeding areas (seasonality = 1 or 2 in the birdlife shapefiles http://datazone.birdlife.org/species/spcdistPOS).

Repository file:

Title	*Filename*	*Description*
Catalogue of the vascular plants of Madagascar	catalogue_of_vascular_plants_of_madagascar.csv	Comma-separated table with comprehensive taxonomic database of plants of Madagascar, from the "Catalogue of the Plants of Madagascar" project. Date of download, 12 May 2022.

6. Trends in anthropogenic pressures in PAs

We surveyed three potential proxies of anthropogenic impact across Madagascar's protected area network (see Table S8):

i) Annual burned area was averaged from 2006–2016 to produce mean burned area (*161*) and rescaled to 5 arc minutes. Mean burned area itself is not an indicator of human influence, as fire is a complex product of vegetation-climate-human interactions (*162*) and mean burned area naturally varies among ecosystem types (*163*). Across the tropics, temporal trends in fire are primarily a product of antecedent rainfall due to the strong control exerted by rainfall on the continuity and availability of fuel to burn, and any potential anthropogenic signal must be parsed from the dominant rainfall trend (*164*). In high-rainfall regions with litter-based fuels, such as that typified by forests, periods of increased fire tend to be associated with drought and below-average rainfall (*165*). In these environments, human actions can increase fire through opening up canopies, facilitating curing of fuel and the spread of fire. In contrast, in seasonally dry ecosystems with grassy ground layers, such as grasslands and savannas, drought tends to reduce fire, as there is little fuel available to burn; increasing human impacts here are associated with declines in fire, as the fragmentation of landscapes reduces fire spread (*166*). Hence, increases or decreases in fire cannot be universally associated with anthropogenic impacts and must be viewed through an ecological lens (*162*). For *post hoc* comparison, we identified pixels with significant trends in burned area (2006–2016) that could not be explained by antecedent precipitation (*104*). Significant pixels ($p < 0.05$) indicated the t-value of burned area trends could not be explained by precipitation from the previous one or two years combined, whereas zero values indicated pixels with no evidence of burned area throughout the study period. NA values indicated pixels without a significant trend or where a significant trend could be attributed to antecedent rainfall.

ii) Harmonized global night-time lights were analyzed from the period 1992–2018 (*167*). Night-time lights are an indicator of the distribution of human settlement and activity, and enable monitoring of aspects of human activity within PA boundaries (e.g., expansion or intensification, such as electrification of settlements) (*167*). We retained intensity values >8 following (*168*) and assessed changes in total night-time light intensity within PAs by comparing averages of the first three and last three years of the study period.

iii) Changes in forest cover were assessed using the published national forest cover maps of (*38*), for the years 1990 and 2017, to achieve moderate consistency with the periods available for burned area and night-time lights. Forest loss may have multiple causes, and detection accuracy may vary by biome, but has been used as an indicator of human pressure in multiple previous conservation assessments in Madagascar (*38*, *77*, *169*). We treated areas of no forest as zero in the baseline map. We then subtracted 2017 forest cover from a 1990 baseline and scaled 0-100 to identify proportional forest loss in each cell. We emphasize that interpretation of variables such as fire pressure may differ between biomes. We report the most frequently recorded biome for each PA based on (*106*).

7. *Ex situ* analyses

We matched the list of plant species native to Madagascar from the Catalogue of the Vascular Plants of Madagascar (*160*) to records held in BGCI's PlantSearch database (*10*). Matches were made on the species binomial; infraspecific ranks and cultivars were ignored. In addition, we added known *ex situ* collections not currently stored in PlantSearch (Jardin Botanique Educatif and Parc Ivoloina). For each species, we recorded the presence or absence of a species in an *ex situ* collection (including both living collection and seed bank collections). The dataset is provided in our Zenodo repository (*135*).

We used the curated list of native Malagasy terrestrial and freshwater vertebrates in our Zenodo repository (*135*) to search for all vertebrate species globally held in zoos and the species that had successfully reproduced in the last 12 months based on collection information from ZIMS (Zoological Information Management Software, https://zims.species360.org) database. This search was performed in February 2021. The dataset is provided in our Zenodo repository (*135*).

Repository files:

Title	*Filename*	*Description*
Ex situ collections of plants	ex_situ_plants.csv	Comma-separated table with numbers of *ex situ* conserved plant species, per family, from BGCI's PlantSearch database and collections of Jardin Botanique Educatif and Parc Ivoloina.

Ex situ collections of vertebrates	ex_situ_vertebrates.csv	Comma-separated table with the list of extant native Malagasy vertebrates with information on their presence in at least one international zoo holding and whether they have been bred successfully over the last 12 months. Data from the Zoological Information Management (ZIM) Software performed in February 2021.

8. Summary of software used

IUCN analysis. We prepared all analyses in R (*170*), and used the tidyverse v1.3.0 (*171*), tibble v3.0.5 (*172*), dplyr v1.0.3 (*173*), tidyr v1.1.2 (*174*), readr v1.4.0 (*175*), and ggplot2 v3.3.3 ((*176*), pg 2) packages for data wrangling and visualization; the ncdf4 v1.17 ((*177*), pg 4), sp v1.4-5 (*178*), sf v0.9-7 (*179*), raster v3.4-5 (*180*), rnaturalearth v0.1.0 (*181*), rnaturalearthdata v0.1.0 (*182*), and stars v0.4-3 (*183*) packages for spatial analyses; CoordinateCleaner v2.0-18 (*142*) for cleaning geo-referenced occurrence records, IUCNN v0.9.3 (*20*, *136*) to generate the geographic, climatic, and biome features; sampbias v1.0.4 (*145*) to calculate the bias features; and taxize v0.9.99 (*184*), lcvplants v1.1.1, and LCVP v1.0.4 (*185*) to test the effect of alternative taxonomic scrubbing on the results. **Protected Areas.** NumPy v1.21.0 (*186*), Pandas v1.3.0 (*187*), GeoPandas v0.9.0 (*188*), Rasterio v1.2.6 (*189*), xarray v0.18.2 (*190*), rioxarray v0.4.3 (*191*), GDAL v3.3.1 (*192*), Matplotlib v3.4.2 (*193*), Seaborn v0.11.1(*194*).

Supplementary figure

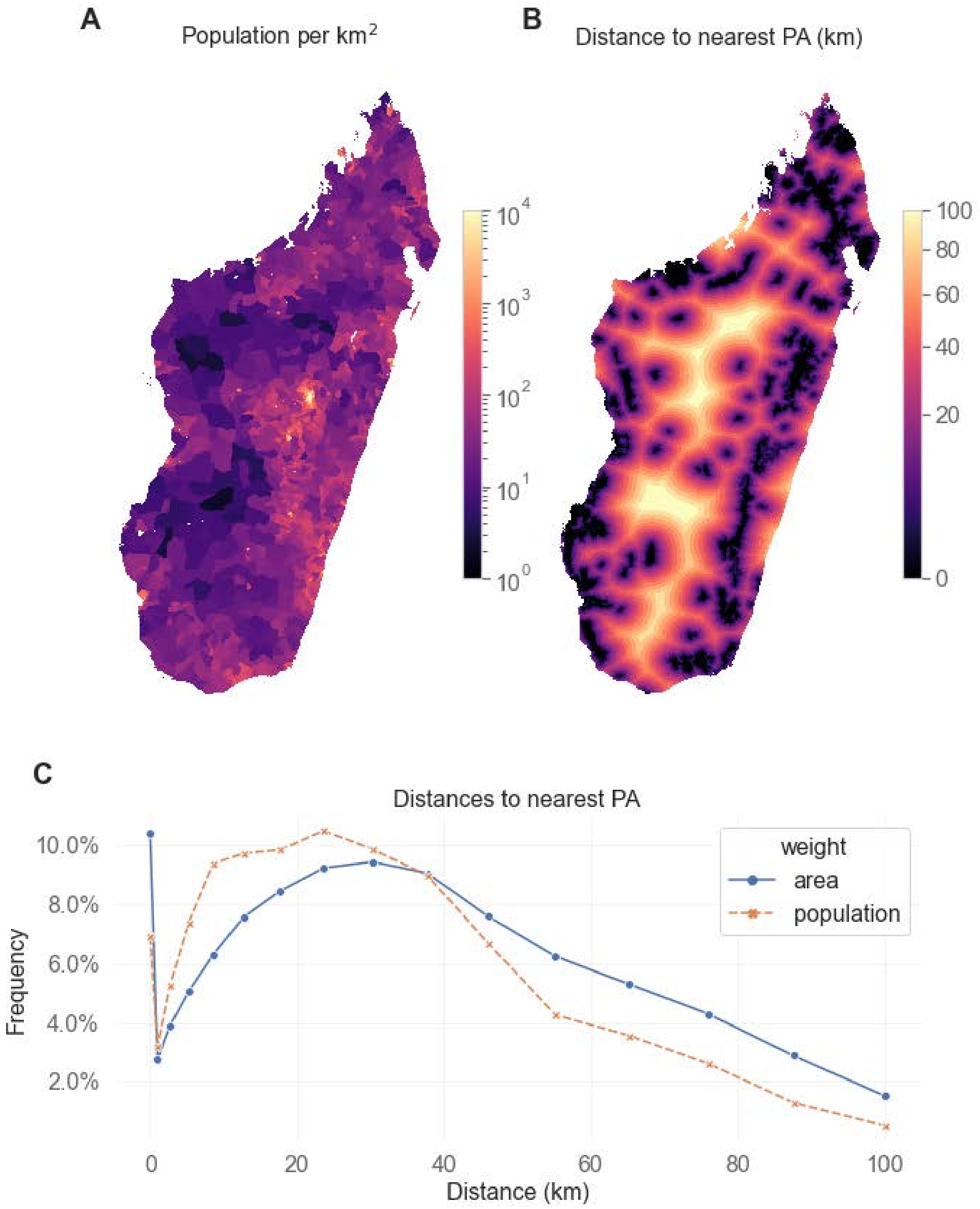

Fig. S1. Distribution of Malagasy population in relation to protected areas (PAs). (A) Population density (*102*). (B) Distance to nearest PA calculated using buffer shapes of increasing distance around each PA, from 1km to 100km. (C) Frequency distribution of distances to nearest PA, weighted by area (constant) and by population, showing that the population is non-randomly distributed towards PAs.

Supplementary Tables

Table S1. A summary of the features used for predicting species conservation status and threats. Feature = Feature name. ID = Feature ID. Cat = category. Norm = normalization. Source = Data Source.

Feature	ID	Description	Cat.	Type	Norm.	Source
Median bias	bias_median	The median bias value extracted for occurrence records of this species from a projected bias grid from sampbias	sampling bias	fraction	x / 100	https://github.com/azizka/sampbias
Bias range	bias_range	The range of bias value extracted for occurrence records of this species from a projected bias grid from sampbias. Range is the .95-.05 quantile.	sampling bias	continuous	x / 100	https://github.com/azizka/sampbias
Tropical & Subtropical Moist Broadleaf Forests	biome_1	Are at least 5% of the species records present in this biome?	biome	binary	none	https://www.worldwildlife.org/biome-categories/terrestrial-ecoregions
Montane Grasslands & Shrublands	biome_10	Are at least 5% of the species records present in this biome?	biome	binary	none	https://www.worldwildlife.org/biome-categories/terrestrial-ecoregions
Deserts & Xeric Shrublands	biome_13	Are at least 5% of the species records present in this biome?	biome	binary	none	https://www.worldwildlife.org/biome-categories/terrestrial-ecoregions
Mangroves	biome_14	Are at least 5% of the species records present in this biome?	biome	binary	none	https://www.worldwildlife.org/biome-categories/terrestrial-ecoregions
Tropical & Subtropical Dry Broadleaf Forests	biome_2	Are at least 5% of the species records present in this biome?	biome	binary	none	https://www.worldwildlife.org/biome-categories/terrestrial-ecoregions
Annual Mean Temperature	clim_bio1	The median value of this bioclimatic layer for the occurrence records of a species. Records with NA values removed	climate	continuous	x / 15	https://www.worldclim.org

Mean Temperature of Coldest Quarter	clim_bio11	The median value of this bioclimatic layer for the occurrence records of a species. Records with NA values removed	climate	continuous	x / 15	https://www.worldclim.org
Annual Precipitation	clim_bio12	The median value of this bioclimatic layer for the occurrence records of a species. Records with NA values removed	climate	continuous	log10(1 + x)	https://www.worldclim.org
Precipitation Seasonality (Coefficient of Variation)	clim_bio15	The median value of this bioclimatic layer for the occurrence records of a species. Records with NA values removed	climate	continuous	log10(1 + x)	https://www.worldclim.org
Precipitation of Driest Quarter	clim_bio17	The median value of this bioclimatic layer for the occurrence records of a species. Records with NA values removed	climate	continuous	log10(1 + x)	https://www.worldclim.org
Temperature Seasonality (standard deviation ×100)	clim_bio4	The median value of this bioclimatic layer for the occurrence records of a species. Records with NA values removed	climate	continuous	log10(1 + x)	https://www.worldclim.org
Range of Annual Mean Temperature	clim_range_bio1	The range of value of this bioclimatic layer for the occurrence records of a species. Records with NA values removed. Range is the .95-.05 quantile.	climate	continuous	x / 15	https://www.worldclim.org
Range of Mean Temperature of Coldest Quarter	clim_range_bio11	The range of value of this bioclimatic layer for the occurrence records of a species. Records with NA values removed. Range is the .95-.05 quantile.	climate	continuous	x / 15	https://www.worldclim.org
Range of Annual Precipitation	clim_range_bio12	The range of value of this bioclimatic layer for the occurrence records of a species. Records with NA values removed. Range is the .95-.05 quantile.	climate	continuous	log10(1 + x)	https://www.worldclim.org
Range of Precipitation Seasonality	clim_range_bio15	The range of value of this bioclimatic layer for the occurrence records of a species. Records with NA	climate	continuous	log10(1 + x)	https://www.worldclim.org

(Coefficient of Variation)		values removed. Range is the .95-.05 quantile.				
Range of Precipitation of Driest Quarter	clim_range_bio17	The range of value of this bioclimatic layer for the occurrence records of a species. Records with NA values removed. Range is the .95-.05 quantile.	climate	continuous	log10(1 + x)	https://www.worldclim.org
Range of Temperature Seasonality (standard deviation ×100)	clim_range_bio4	The range of value of this bioclimatic layer for the occurrence records of a species. Records with NA values removed. Range is the .95-.05 quantile.	climate	continuous	log10(1 + x)	https://www.worldclim.org
Median elevation	elevation_median	The median value of elevation for the occurrence records of a species. Records with NA values removed	elevation	continuous	x / 600	https://www.worldclim.org
Elevational range	elevation_range	The range of value of elevation for the occurrence records of a species. Records with NA values removed. Range is the .95-.05 quantile.	elevation	continuous	x / 600	https://www.worldclim.org
Fraction forest cover 1973	forest_frac_1973	The fraction of records of this species in forested grid cells in 1973	forest cover	fraction	none	https://bioscenemada.cirad.fr/maps/
Fraction forest cover 2014	forest_frac_2014	The fraction of records of this species in forested grid cells in 2014	forest cover	fraction	none	https://bioscenemada.cirad.fr/maps/
Area of Occupancy	geo_aoo	The area of occupancy. Calculated by rCAT	geographic	continuous	log10(1 + x)	Calculated from the GBIF records
Extent of Occurrence	geo_eoo	The extent of occurrence. Calculated by rCAT. For species with less than 3 records set to AOO	geographic	continuous	log10(1 + x)	Calculated from the GBIF records
Latitudinal range	geo_lat_range	The latitudinal range (.95 quantile - .05 quantile).	geographic	continuous	log10(1 + x)	Calculated from the GBIF records
Longitudinal range	geo_lon_range	The longitudinal range (.95 quantile - .05 quantile).	geographic	continuous	log10(1 + x)	Calculated from the GBIF records
Mean latitude	geo_mean_lat	The mean latitude of all records of this species	geographic	continuous	x / 90	Calculated from the GBIF records

Mean longitude	geo_mean_lon	The mean longitude of all records of this species	geographic	continuous	x / 180	Calculated from the GBIF records
Number of occurrences	geo_tot_occ	The total number of occurrences available for this species	geographic	continuous	log10(1 + x)	Calculated from the GBIF records
Number of geographically unique occurrences	geo_uni_occ	The number of geographically unique records available for this species	geographic	continuous	log10(1 + x)	Calculated from the GBIF records
Area of Occupancy	geo20_aoo	The area of occupancy. Calculated by rCAT, using occurrence records collected since the year 2000.	geographic	continuous	log10(1 + x)	Calculated from the GBIF records
Extent of Occurrence	geo20_eoo	The extent of occurrence. Calculated by rCAT, using occurrence records collected since the year 2000. For species with less than 3 records set to AOO	geographic	continuous	log10(1 + x)	Calculated from the GBIF records
Latitudinal range	geo20_lat_range	The latitudinal range (.95 quantile - .05 quantile), calculated using occurrence records collected since the year 2000.	geographic	continuous	log10(1 + x)	Calculated from the GBIF records
Longitudinal range	geo20_lon_range	The longitudinal range (.95 quantile - .05 quantile), calculated using occurrence records collected since the year 2000.	geographic	continuous	log10(1 + x)	Calculated from the GBIF records
Mean latitude	geo20_mean_lat	The mean latitude of all records of this species, calculated using occurrence records collected since the year 2000.	geographic	continuous	x / 90	Calculated from the GBIF records
Mean longitude	geo20_mean_lon	The mean longitude of all records of this species, calculated using occurrence records collected since the year 2000.	geographic	continuous	x / 180	Calculated from the GBIF records
Number of occurrences	geo20_tot_occ	The total number of occurrences available for this species, calculated	geographic	continuous	log10(1 + x)	Calculated from the GBIF records

		using occurrence records collected since the year 2000.				
Number of geographically unique occurrences	geo20_uni_occ	The number of geographically unique records available for this species, calculated using occurrence records collected since the year 2000.	geographic	continuous	log10(1 + x)	Calculated from the GBIF records
Human footprint year 1993 lowest impact	humanfootprint_1993_1	The fraction of records in areas of the lowest category of human footprint in the year 1993. Footprint was categorized so that categories represent roughly quantiles.	human footprint	fraction	none	https://wcshumanfootprint.org/
Human footprint year 1993 intermediate impact 1	humanfootprint_1993_2	The fraction of records in areas of the second lowest category of human footprint in the year 1993. Footprint was categorized so that categories represent roughly quantiles.	human footprint	fraction	none	https://wcshumanfootprint.org/
Human footprint year 1993 intermediate impact 2	humanfootprint_1993_3	The fraction of records in areas of the second highest category of human footprint in the year 1993. Footprint was categorized so that categories represent roughly quantiles.	human footprint	fraction	none	https://wcshumanfootprint.org/
Human footprint year 1993 highest impact	humanfootprint_1993_4	The fraction of records in areas of the highest category of human footprint in the year 1993. Footprint was categorized so that categories represent roughly quantiles.	human footprint	fraction	none	https://wcshumanfootprint.org/
Human footprint year 2009 lowest impact	humanfootprint_2009_1	The fraction of records in areas of the lowest category of human footprint in the year 2009. Footprint was categorized so that categories	human footprint	fraction	none	https://wcshumanfootprint.org/

		represent roughly quantiles.				
Human footprint year 2009 intermediate impact 1	humanfootprint_2009_2	The fraction of records in areas of the second lowest category of human footprint in the year 2009. Footprint was categorized so that categories represent roughly quantiles.	human footprint	fraction	none	https://wcshumanfootprint.org/
Human footprint year 2009 intermediate impact 2	humanfootprint_2009_3	The fraction of records in areas of the second highest category of human footprint in the year 2009. Footprint was categorized so that categories represent roughly quantiles.	human footprint	fraction	none	https://wcshumanfootprint.org/
Human footprint year 2009 highest impact	humanfootprint_2009_4	The fraction of records in areas of the highest category of human footprint in the year 2009. Footprint was categorized so that categories represent roughly quantiles.	human footprint	fraction	none	https://wcshumanfootprint.org/
Not protected	pa_notprotected	The fraction of records of this species outside protected area	protected area	fraction	none	https://www.protectedplanet.net/en/thematic-areas/wdpa
Protected	pa_protected	The fraction of records of this species in protected area, IUCN categories III-VI or not specified	protected area	fraction	none	https://www.protectedplanet.net/en/thematic-areas/wdpa
Strictly protected	pa_strictlyprotected	The fraction of records of this species in strictly protected areas, IUCN categories I + II	protected area	fraction	none	https://www.protectedplanet.net/en/thematic-areas/wdpa
Use Animal food	use_AnimalFood	Is this species used for this use type? Yes/no	plant use	binary	none	https://knb.ecoinformatics.org/view/doi:10.5063/F1CV4G34
Use fuel	use_Fuels	Is this species used for this use type? Yes/no	plant use	binary	none	https://knb.ecoinformatics.org/view/doi:10.5063/F1CV4G34
Use human food	use_HumanFood	Is this species used for this use type? Yes/no	plant use	binary	none	https://knb.ecoinformatics.org/view

						/doi:10.5063/F1CV4G34
Use material	use_Materials	Is this species used for this use type? Yes/no	plant use	binary	none	https://knb.ecoinformatics.org/view/doi:10.5063/F1CV4G34
Use medicine	use_Medicines	Is this species used for this use type? Yes/no	plant use	binary	none	https://knb.ecoinformatics.org/view/doi:10.5063/F1CV4G34
Social uses	use_SocialUses	Is this species used for this use type? Yes/no	plant use	binary	none	https://knb.ecoinformatics.org/view/doi:10.5063/F1CV4G34
Total number of uses	use_Totals	The total number of uses recorded for this species. Count, max 10.	plant use	count	x / 10	https://knb.ecoinformatics.org/view/doi:10.5063/F1CV4G34

Table S2. Predicted number of species in IUCN Red List assessment classes for major groups of vascular plants. 95% credible intervals are shown in square brackets.

Status	All plants (5353)	Asterids (1948)	Eudicots (248)	Ferns & lycophytes (372)	Magnoliids (80)	Monocots (1256)	Rosids (1444)
CR	988 [903, 1067]	337 [300, 370]	41 [30, 49]	62 [48, 74]	16 [11, 21]	266 [235, 294]	267 [236, 293]
EN	1749 [1647, 1849]	657 [610, 698]	77 [64, 88]	126 [107, 144]	27 [20, 33]	395 [355, 430]	466 [430, 500]
VU	193 [147, 234]	76 [54, 95]	8 [2, 13]	15 [7, 24]	3 [0, 5]	41 [27, 56]	50 [32, 65]
NT	869 [773, 959]	342 [296, 385]	39 [28, 49]	64 [49, 79]	13 [7, 18]	181 [148, 212]	231 [199, 261]
LC	1555 [1463, 1644]	536 [495, 572]	83 [71, 93]	110 [90, 128]	21 [15, 26]	374 [340, 404]	430 [398, 461]

Table S3. The defined feature-blocks ranked by decreasing feature importance. Feature importance is measured as the mean decrease in accuracy (delta accuracy) when values in a given feature block are randomly shuffled. The mean and standard deviation (std) were determined over 100 permutation replicates

Feature block	Prediction type	Delta accuracy (mean)	Delta accuracy (std)
Geographic	conservative	0.2384	0.0109
Geographic, last 20years	conservative	0.1003	0.0064
Plant use	conservative	0.0549	0.0058
Climate	conservative	0.0457	0.0063
Bias	conservative	0.0003	0.0005
Human footprint	conservative	0.0001	0.0002
Deforestation	conservative	0	0.0001
Biome	conservative	0	0
Elevation	conservative	0	0
Protected area	conservative	0	0
Geographic	naive	0.2608	0.0062
Climate	naive	0.1391	0.0059
Geographic, last 20 years	naive	0.1078	0.0045
Plant use	naive	0.0426	0.0032
Human footprint	naive	0.018	0.0035
Bias	naive	0.012	0.003
Deforestation	naive	0.0073	0.0025
Elevation	naive	0.0062	0.0022
Biome	naive	0.0051	0.0025
Protected area	naive	0.0035	0.0025

Table S4. Threats to Malagasy biodiversity. The number of species with each listed threat, as defined by the IUCN (vertebrates) or predicted by our model (plants), across taxonomic groups.

Higher taxonomic group	Taxonomic group	Threat	No. species with threat listed	Total species	% of species with threat listed
Plants	Asterids	Agriculture	2822	3204	88.1
Plants	Asterids	Energy/mining	554	3204	17.3
Plants	Asterids	Other	118	3204	3.7
Plants	Asterids	Overexploitation	2750	3204	85.8

Plants	Asterids	System modifications	2270	3204	70.8
Plants	Asterids	Urban development	63	3204	2
Plants	Ferns	Agriculture	404	415	97.3
Plants	Ferns	Energy/mining	35	415	8.4
Plants	Ferns	Other	2	415	0.5
Plants	Ferns	Overexploitation	392	415	94.5
Plants	Ferns	System modifications	286	415	68.9
Plants	Ferns	Urban development	0	415	0
Plants	Gymnosperms	Agriculture	6	6	100
Plants	Gymnosperms	Energy/mining	1	6	16.7
Plants	Gymnosperms	Other	0	6	0
Plants	Gymnosperms	Overexploitation	4	6	66.7
Plants	Gymnosperms	System modifications	5	6	83.3
Plants	Gymnosperms	Urban development	0	6	0
Plants	Magnoliids	Agriculture	252	283	89
Plants	Magnoliids	Energy/mining	82	283	29
Plants	Magnoliids	Other	13	283	4.6
Plants	Magnoliids	Overexploitation	276	283	97.5
Plants	Magnoliids	System modifications	180	283	63.6
Plants	Magnoliids	Urban development	8	283	2.8
Plants	Monocots	Agriculture	1594	1835	86.9
Plants	Monocots	Energy/mining	342	1835	18.6
Plants	Monocots	Other	98	1835	5.3
Plants	Monocots	Overexploitation	1516	1835	82.6
Plants	Monocots	System modifications	1132	1835	61.7
Plants	Monocots	Urban development	44	1835	2.4
Plants	NA	Agriculture	8134	9268	87.8
Plants	NA	Energy/mining	1770	9268	19.1
Plants	NA	Other	387	9268	4.2
Plants	NA	Overexploitation	8069	9268	87.1
Plants	NA	System modifications	6388	9268	68.9
Plants	NA	Urban development	279	9268	3.0
Plants	Other Eudicots	Agriculture	354	390	90.8

Plants	Other Eudicots	Energy/mining	55	390	14.1
Plants	Other Eudicots	Other	23	390	5.9
Plants	Other Eudicots	Overexploitation	319	390	81.8
Plants	Other Eudicots	System modifications	315	390	80.8
Plants	Other Eudicots	Urban development	15	390	3.8
Plants	Rosids	Agriculture	2702	3135	86.2
Plants	Rosids	Energy/mining	701	3135	22.4
Plants	Rosids	Other	133	3135	4.2
Plants	Rosids	Overexploitation	2812	3135	89.7
Plants	Rosids	System modifications	2200	3135	70.2
Plants	Rosids	Urban development	149	3135	4.8
Vertebrates	Ray-finned fishes	Agriculture	10	203	4.9
Vertebrates	Ray-finned fishes	Invasives/disease	53	203	26.1
Vertebrates	Ray-finned fishes	Other	25	203	12.3
Vertebrates	Ray-finned fishes	Overexploitation	90	203	44.3
Vertebrates	Ray-finned fishes	System modifications	29	203	14.3
Vertebrates	Ray-finned fishes	Urban development	7	203	3.4
Vertebrates	Amphibians	Agriculture	261	308	84.7
Vertebrates	Amphibians	Energy/mining	29	308	9.4
Vertebrates	Amphibians	Invasives/disease	243	308	78.9
Vertebrates	Amphibians	Other	26	308	8.4
Vertebrates	Amphibians	Overexploitation	258	308	83.8
Vertebrates	Amphibians	System modifications	104	308	33.8
Vertebrates	Amphibians	Urban development	201	308	65.3
Vertebrates	Birds	Agriculture	56	219	25.6
Vertebrates	Birds	Energy/mining	6	219	2.7
Vertebrates	Birds	Invasives/disease	34	219	15.5
Vertebrates	Birds	Other	53	219	24.2
Vertebrates	Birds	Overexploitation	70	219	32.0
Vertebrates	Birds	System modifications	24	219	11.0
Vertebrates	Birds	Urban development	5	219	2.3

Vertebrates	Mammals	Agriculture	162	221	73.3
Vertebrates	Mammals	Energy/mining	34	221	15.4
Vertebrates	Mammals	Invasives/disease	20	221	9.0
Vertebrates	Mammals	Other	18	221	8.1
Vertebrates	Mammals	Overexploitation	138	221	62.4
Vertebrates	Mammals	System modifications	74	221	33.5
Vertebrates	Mammals	Urban development	6	221	2.7
Vertebrates	NA	Agriculture	757	1332	56.8
Vertebrates	NA	Energy/mining	114	1332	8.6
Vertebrates	NA	Invasives/disease	360	1332	27
Vertebrates	NA	Other	146	1332	11.0
Vertebrates	NA	Overexploitation	827	1332	62.1
Vertebrates	NA	System modifications	309	1332	23.2
Vertebrates	NA	Urban development	241	1332	18.1
Vertebrates	Reptiles	Agriculture	268	381	70.3
Vertebrates	Reptiles	Energy/mining	45	381	11.8
Vertebrates	Reptiles	Invasives/disease	10	381	2.6
Vertebrates	Reptiles	Other	24	381	6.3
Vertebrates	Reptiles	Overexploitation	271	381	71.1
Vertebrates	Reptiles	System modifications	78	381	20.5
Vertebrates	Reptiles	Urban development	22	381	5.8

Table S5. Summary statistics describing the performance of the multi-label predictions of species threats.

Tests	threat 1	threat 2	threat 3	threat 4	threat 5	threat 6
Test accuracy	0.74	0.837	0.734	0.666	0.917	0.92
True positive	0.972	0.972	0.321	0.845	0.034	0.036
False positive	0.24	0.139	0.053	0.243	0	0

Table S6. Percentage of each existing vegetation type currently within a protected area. Degraded vegetation types were reclassified to their primary vegetation type. See also text and Table S1 above, and Fig. 5.

Vegetation type	Percent within protected area
Mangroves	29.4%
Spiny forest	21.5%
Humid forest	18.5%
Tapia	17.9%
Dry forest	13.3%
Subhumid forest	5.7%
Grassland-woodland mosaic	1.8%

Table S7. Threatened vertebrates with ranges not overlapping with the current PA network.

Group	IUCN-assessed threatened species with no range overlap with the PA network
Amphibians	*Gephyromantis mafy*
Mammals	*Lepilemur grewcockorum*
Mammals	*Lepilemur septentrionalis*
Mammals	*Microcebus marohita*
Reptiles	*Calumma capuroni*
Reptiles	*Calumma vohibola*
Reptiles	*Lygodactylus ornatus*
Reptiles	*Paracontias minimus*
Reptiles	*Phelsuma masohoala*
Reptiles	*Phelsuma pronki*
Reptiles	*Xenotyphlops grandidieri*

Table S8. Trends in stable night lights, proportion of forest cover and fire for Malagasy protected areas (PAs). Values are provided at 1km resolution for night lights and forest loss, and 5km for fire trends. Minimum and maximum values within PAs are reported. For forest cover, we report loss, and exclude areas of potential recent gain. NA values denote no data, i.e., no baseline forest cover, and no significant trend in fire. The three potential proxies are not implicitly equivalent.

Protected area name	Predominant biome	Change in stable night lights 1992-2018 (min-max)	Proportion forest loss 1990-2017 (min-max)	Trend in fire 2006-2016 (min-max)
Lake Tsarasaotra	Humid forest	1.23 (0.82-1.6)	NA (-)	0 (0-0)
Lake Sofia	Grassland-woodland mosaic	0 (0-0)	NA (-)	NA (-)
Ambatofotsy (Anosibe An'Ala) NPA	Humid forest	0 (0-0)	16.51 (2.34-44.91)	NA (-)
Ankorabe (Antadonkomby)	Grassland-woodland mosaic	0 (0-0)	NA (-)	NA (-)
Analalava Foulpointe NPA	Humid forest	0 (0-0)	3.75 (3.35-4.15)	NA (-)
Analalava	Dry forest	0 (0-0)	NA (-)	0 (0-0)
Ambararata Londa	Dry forest	0 (0-0)	2.37 (0-19.56)	0.2 (0-1.7)
Ambatotsirongorongo NPA	Humid forest	0 (0-0)	8.29 (0.78-22.26)	0 (0-0)
Ambohidray NPA	Humid forest	0 (0-0)	6.91 (0.33-23.8)	NA (-)
Ambohijanahary Special Réserve	Humid forest	0 (0-0)	4.06 (0-30.05)	NA (-)
Angavo Androy NPA	Spiny forest	0 (0-0)	1.37 (0-19.19)	0 (0-0)
Bemarivo Special Réserve	Dry forest	0 (0-0)	9.59 (0-48.82)	0 (0-0)
Bongolava Classified Forest (Marosely) NPA	Dry forest	0 (0-0)	6.8 (0-41.63)	-1.73 (-5.74-3.81)
Kasijy Special Réserve	Dry forest	0 (0-0)	1.11 (0-15.7)	-2.29 (-2.29--2.29)
Maningoza Special Réserve	Dry forest	0 (0-0)	5.51 (0-21.9)	-2.51 (-2.51--2.51)
Ranobe PK32 NPA	Spiny forest	0 (0-0)	36.71 (0-95.2)	0.95 (-2.24-3.74)
Tampoketsa-Analamaintso Special Réserve	Humid forest	0 (0-0)	3.96 (0-33.78)	2.86 (2.72-2.97)
Mahavavy-Kinkony wetlands NPA	Dry forest	0 (0-0)	8.04 (0-65.51)	0.04 (-2.99-2.39)
Mangoky Ihotry	Dry forest	0 (0-0)	10.61 (0-84.53)	-0.28 (-4.15-2.77)

Tsitongambarika NPA	Humid forest	0 (0-0)	14.71 (0-70.3)	-0.03 (-1.35-0)
Torotorofotsy Wetlands	Humid forest	0.75 (0-4.98)	24.58 (0.15-67.37)	NA (-)
Beanka NPA	Dry forest	0 (0-0)	0.39 (0-5.66)	0 (0-0)
Sahafina Forest (Anivorano-Brickaville) NPA	Humid forest	0 (0-0)	0.9 (0-10.05)	0 (0-0)
Corridor Ankeniheny Zahamena	Humid forest	0 (0-0)	10.21 (0-90.43)	1.47 (0-4.53)
Ambositra-Vondrozo Corridor NPA (COFAV)	Humid forest	0 (0-0)	10.52 (0-73.63)	0 (-2.71-2.36)
Antoetra NPA	Humid forest	0 (0-0)	4.44 (0.15-13.51)	0 (0-0)
Bombetoka Belemboka	Dry forest	0 (0-0)	2.76 (0-25.02)	-1.31 (-3.87-0)
Ambondrombe (Belo sur Tsiribihana) NPA	Dry forest	0 (0-0)	21.99 (1.21-66.35)	NA (-)
Lake Alaotra NPA	Grassland-woodland mosaic	0 (0-0)	0 (0-0)	0 (0-0)
Nosivolo wetland NPA	Humid forest	0 (0-0)	13.81 (0-36.62)	0 (0-0)
Avenue of the Baobabs NPA	Grassland-woodland mosaic	0 (0-0)	NA (-)	2.87 (2.81-2.91)
Anjozorobe-Angavo-Tsinjoarivo Corridor	Humid forest	0 (0-0)	24.33 (0-80.48)	5.03 (3.58-5.27)
Loky Manambato NPA	Humid forest	0 (0-0)	2.11 (0-34.43)	0.21 (0-3.15)
Menabe Antimena	Dry forest	0 (0-0)	11.31 (0-92.87)	0.74 (-2.32-3.3)
Maromizaha	Humid forest	0 (0-0)	22.17 (0.15-74.03)	3.03 (3.03-3.03)
Tsinjoriake-Andatobo MPA	Spiny forest	0 (0-0)	2.55 (0-13.67)	0 (0-0)
Ampanganandehibe-Behasina	Grassland-woodland mosaic	0 (0-0)	0.08 (0.08-0.08)	NA (-)
Nosy Antsoha	-	NA (NA-NA)	NA (-)	NA (-)
Analalava-Analabe-Betanantanana (Ambatosoratra) NPA	Humid forest	0 (0-0)	5.58 (1.02-12.89)	NA (-)
Mahialambo NPA	Grassland-woodland mosaic	0 (0-0)	NA (-)	NA (-)
Mangabe-Ranomena-Sahasarotra NPA	Humid forest	0 (0-0)	37.57 (0.34-89.23)	2.51 (2.51-2.51)
Agnalazaha	Humid forest	0 (0-0)	17.56 (0.31-66.32)	0 (0-0)
Ampasindava	Dry forest	0 (0-0)	23.67 (0-91.48)	0 (0-0)
Alandraza Analavelo	Humid forest	0 (0-0)	0.46 (0-3.76)	-2.52 (-2.52--2.52)
Galoko Kalobinono	Dry forest	0 (0-0)	23.01 (0-71.65)	0.36 (0-2.4)

Makirovana-Ambatobiribiry Complex NPA	Humid forest	0 (0-0)	12.12 (4.12-24.2)	NA (-)
Massif d'Ibity NPA	Grassland-woodland mosaic	0 (0-0)	NA (-)	NA (-)
Oronjia NPA	Dry forest	0 (0-0)	3.06 (0-6.47)	0 (0-0)
Pointe à Larrée NPA	Grassland-woodland mosaic	0 (0-0)	9.61 (1.92-18.38)	0 (0-0)
Vohidava Betsimalao	Spiny forest	0 (0-0)	1.47 (0-13.47)	0 (0-0)
Site Bioculturel d'Antrema	Dry forest	0 (0-0)	2.47 (0-21.68)	-1.05 (-2.52-0)
Ambatovaky Special Réserve	Humid forest	0 (0-0)	9.28 (0-56.41)	0.15 (0-2.69)
Ambohitantely Special Réserve	Humid forest	0 (0-0)	1.95 (0-10.06)	NA (-)
Analamazaotra	Humid forest	0 (0-0)	2.71 (0.46-8.41)	NA (-)
Analamerana Special Réserve	Dry forest	0 (0-0)	1.97 (0-36.46)	0.38 (0-2.4)
Andranomena Special Réserve	Dry forest	0 (0-0)	11.18 (0-51.27)	0.04 (0-2.65)
Andringitra National Park	Humid forest	0 (0-0)	0.7 (0-20.21)	0 (0-0)
South Anjanaharibe Special Réserve and extension	Humid forest	0 (0-0)	1.59 (0-23.34)	0 (0-0)
Ankarafantsika	Dry forest	0 (0-0)	12.79 (0-88.28)	0.48 (-1.42-3.03)
Ankarana Special Réserve	Dry forest	0.02 (0-1.68)	1.5 (0-21.49)	0 (0-0)
Baly Bay National Park	Dry forest	0 (0-0)	2.05 (0-49.1)	0 (0-0)
Tsingy de Bemaraha National Park and Strict Nature Réserve	Dry forest	0 (0-0)	1.09 (0-28.52)	-0.97 (-2.65-1.39)
Betampona Strict Nature Réserve	Humid forest	0 (0-0)	1.08 (0-3.71)	0 (0-0)
Beza Mahafaly Special Réserve	Spiny forest	0 (0-0)	9.89 (0-43.51)	0 (0-0)
Bora Special Réserve	Dry forest	0 (0-0)	18.33 (2.18-59.04)	2.52 (2.52-2.52)
Cape Sainte Marie Special Réserve and extension	Spiny forest	0 (0-0)	NA (-)	0 (0-0)
Sahamalaza-Radama Islands National Marine Park	Dry forest	0 (0-0)	3.29 (0-14.1)	0 (0-0)
Isalo National Park	Tapia	0.21 (0-2.69)	0.13 (0-8.45)	-1.05 (-2.78-0)
Kalambatrika Special Réserve	Humid forest	0 (0-0)	0.31 (0-6.24)	-2.28 (-4.41--0.24)

Kirindy Mite National Park and extension	Dry forest	0 (0-0)	15.74 (0-92.47)	0.05 (0-2.85)
Lokobe Strict Nature Réserve	Dry forest	0 (0-0)	0.99 (0-6.1)	0 (0-0)
Mananara-North National Park	Humid forest	0 (0-0)	3.28 (0.01-21.19)	0 (0-0)
Mangerivola Special Réserve	Humid forest	0 (0-0)	4.29 (0-37.49)	3.17 (3.17-3.17)
Manombo Special Réserve	Humid forest	0 (0-0)	10.73 (0-40.65)	0 (0-0)
Manongarivo Special Réserve and extension	Humid forest	0 (0-0)	9.51 (0-64.85)	0 (0-0)
Mantadia National Park and Analamazaotra Special Réserve	Humid forest	0 (0-0)	5.24 (0-55.35)	NA (-)
Marojejy National Park	Humid forest	0 (0-0)	1.45 (0-20.61)	0 (0-0)
Fandriana-Marolambo Forest Corridor NPA (COFAM)	Humid forest	0 (0-0)	10.08 (0-67.25)	-0.22 (-2.42-0)
Marotandrano Special Réserve	Humid forest	0 (0-0)	7.38 (0-65.63)	-2.92 (-2.92--2.92)
Masoala National Park	Humid forest	0 (0-0)	2.17 (0-44.9)	0 (0-0)
Midongy South National Park	Humid forest	0 (0-0)	10.23 (0-74.17)	0.26 (0-2.92)
Mikea NPA	Spiny forest	0 (0-0)	15.72 (0-94.21)	0.05 (0-2.61)
Montagne d'Ambre National Park and Special Réserve	Humid forest	0 (0-0)	2.8 (0-35.42)	0.16 (0-2.27)
Nosy Mangabe Special Réserve	Humid forest	0 (0-0)	0 (0-0)	0 (0-0)
Pic d'Ivohibe Special Réserve	Humid forest	0 (0-0)	0.45 (0-4.18)	NA (-)
Ranomafana National Park and extension	Humid forest	0 (0-0)	3.63 (0-37.14)	0.56 (0-2.33)
Tsaratanana Strict Nature Réserve and extension	Humid forest	0 (0-0)	9.44 (0-73.44)	0.65 (0-2.81)
Tsimanampetsotse National Park and extension	Spiny forest	0 (0-0)	6.89 (0-85.08)	0 (0-0)
Tsingy de Namoroka National Park	Dry forest	0 (0-0)	2 (0-26.15)	0.5 (0-2.41)
Zahamena National Park and Strict Réserve	Humid forest	0 (0-0)	1.22 (0-32.81)	2.89 (2.51-4.53)
Zombitse-Vohibasia National Park and extension	Subhumid forest	0 (0-0)	5.09 (0-87.97)	0.79 (-1.28-2.82)
Ambatoatsinanana	Humid forest	0 (0-0)	2.44 (0.08-9.86)	NA (-)
Petriky	Humid forest	0 (0-0)	0.73 (0.02-1.47)	0 (0-0)

Mandena NPA	Humid forest	3.57 (3.17-4.07)	1.31 (0.41-2.79)	0 (0-0)
Massif d'Itremo NPA	Grassland-woodland mosaic	0.27 (0-2.38)	0 (0-0)	2.59 (2.35-2.85)
Montagne des Francais NPA	Dry forest	0 (0-0)	5.44 (0.2-16)	0 (0-0)
Tsimembo-Manambolomaty-Bemamba Complex NPA	Dry forest	0 (0-0)	9.58 (0-78.97)	0.18 (-2.65-2.71)
Mandrozo	Dry forest	0 (0-0)	7.03 (0-29.56)	0 (0-0)
Bemanevika (Ankaizina wetlands) NPA	Humid forest	0 (0-0)	3.86 (0-31.87)	-2.44 (-2.44--2.44)
Mahimborondro	Humid forest	0 (0-0)	2.24 (0-29.46)	0 (0-0)
Manjakatompo-Ankaratra Massif NPA	Humid forest	0 (0-0)	15.41 (0-44.17)	2.12 (0-3.34)
Andreba NPA	Humid forest	0 (0-0)	0.85 (0.3-1.24)	0 (0-0)
Makira Natural Park	Humid forest	0 (0-0)	3.31 (0-42.81)	0 (0-0)
Ankodida NPA	Spiny forest	0 (0-0)	2.89 (0-17.08)	0 (0-0)
COMATSA Nord	Humid forest	0 (0-0)	5.6 (0-59.56)	0.08 (0-2.71)
COMATSA Sud	Humid forest	0 (0-0)	3.46 (0-66.83)	0 (0-0)
Ifotaky Complex NPA	Spiny forest	0 (0-0)	3.11 (0-25.54)	0 (0-0)
Ambanitazana (Antsiranana)	Humid forest	0 (0-0)	37.45 (26.53-46.55)	NA (-)
Ambato-Boeny	Dry forest	0 (0-0)	38.14 (5.01-80.7)	2.63 (2.63-2.63)
Ambatofinandrahana	Grassland-woodland mosaic	0.03 (0-1.95)	NA (-)	-2.68 (-3.26--2.31)
Ambereny	Dry forest	0 (0-0)	5.15 (0-48.1)	0 (0-0)
Ambondrobe (Vohemar)	Humid forest	0 (0-0)	4.39 (0-19.91)	0 (0-0)
Anena (Beloha)	Spiny forest	0 (0-0)	7.98 (0.03-55.03)	0 (0-0)
Angodoka-Ambakoa (Besalampy)	Dry forest	0 (0-0)	20.43 (0.38-76.82)	0 (0-0)
Ankafina (Ambohimasoa)	Humid forest	0 (0-0)	NA (-)	NA (-)
Ankarabolava-Agnakatriky	Humid forest	0 (0-0)	14 (14-14)	0 (0-0)
Antanifotsy Nord (Diana)	Dry forest	0 (0-0)	2.66 (0-7.89)	NA (-)
Antanifotsy Sud (Diana)	Dry forest	0 (0-0)	1.58 (0.06-5.38)	0 (0-0)
Loza Bay	Mangroves	0 (0-0)	1.53 (0-15.41)	-1.11 (-2.66-2.96)
Belalanda	Grassland-woodland mosaic	0 (0-0)	NA (-)	0 (0-0)
Bobakindro (Salafaina)	Humid forest	0 (0-0)	8.81 (0.68-18.69)	NA (-)
Cap Saint-André	Dry forest	0 (0-0)	6.6 (0-43.65)	0 (0-0)
Mahajamba Bay - Anjavavy Complex	Dry forest	0 (0-0)	8.04 (0-72.87)	-0.47 (-5.54-4.58)

Fanambana (Vohemar)	Dry forest	0 (0-0)	18.97 (0.72-52.4)	NA (-)
Onive Classified Forest	Humid forest	0 (0-0)	12.5 (0-81.13)	0 (0-0)
Sainte Marie Island (Ambohidena)	Humid forest	0 (0-0)	9.63 (0.23-35.61)	0 (0-0)
Ilevika (Matsaborilava)	Dry forest	0 (0-0)	41.07 (24.76-49.3)	2.35 (2.32-2.39)
Lake Andrapongy and Anjingo River	Dry forest	0 (0-0)	5.95 (0-41.22)	0.37 (-2.54-2.32)
Lake Itasy	Grassland-woodland mosaic	0 (0-0)	NA (-)	0 (0-0)
Lake Tseny	Dry forest	0 (0-0)	2.94 (0.25-7.51)	NA (-)
Lakes Anony and Erombo	Grassland-woodland mosaic	0 (0-0)	3.84 (0-26.02)	0 (0-0)
Mahatsara (Mahambo Foulpointe)	Humid forest	0 (0-0)	7.47 (4.54-13.25)	NA (-)
Makay	Subhumid forest	0 (0-0)	7.55 (0.72-27.14)	-0.21 (-1.19-0)
Mandraka	Humid forest	0 (0-0)	26.97 (7.75-52.08)	NA (-)
Nankinana (Ambodibonara-Masomeloka)	Humid forest	0 (0-0)	1.51 (0-17.22)	NA (-)
Ambakoana/Analabe NPA	Humid forest	0 (0-0)	NA (-)	NA (-)
Ambohipiraka NPA	Dry forest	0 (0-0)	17.36 (7.11-24.92)	NA (-)
Ankafobe NPA	Humid forest	1.78 (1.74-1.83)	NA (-)	NA (-)
Mahafaly Plateau Forest Complex NPA	Spiny forest	0 (0-0)	34.37 (0.02-86.4)	0 (0-0)
Nosy Be Crater NPA	Dry forest	0 (0-0)	3.38 (0-51.07)	0 (0-0)
Fierenana NPA	Humid forest	0 (0-0)	4.94 (0.01-45.84)	0 (0-0)
Vohibola Classified Forest NPA	Humid forest	0 (0-0)	17.6 (1.99-48.14)	NA (-)
Port-Bergé wetlands NPA	Dry forest	0.01 (0-1.63)	13.24 (0-70.44)	3.04 (2.72-3.21)
Nosy Varika	Humid forest	0 (0-0)	2.16 (0-8.93)	0 (0-0)
North Pangalane	Humid forest	0 (0-0)	10.23 (0-43.06)	0 (0-0)
Anja Community Réserve	Humid forest	0 (0-0)	1.73 (0-3.47)	NA (-)
Ankavia-Ankavanana River (Antalaha)	Humid forest	0 (0-0)	6.45 (3.21-11.72)	0 (0-0)
Antaimbalana-Andranofotsy River (Maroantsetra)	Humid forest	0 (0-0)	2.75 (0.24-8.19)	0 (0-0)
Bemarivo River	Humid forest	0 (0-0)	NA (-)	0 (0-0)
Maevarano River	Dry forest	0 (0-0)	3.73 (0.03-13.16)	0 (0-0)
Mahanara River	Humid forest	0 (0-0)	3.27 (0.03-8.23)	0 (0-0)

Mananjary River	Humid forest	0 (0-0)	NA (-)	0 (0-0)
Mangarahara-Amboaboa River	Humid forest	0 (0-0)	NA (-)	2.16 (1.48-2.53)
Sambava River	Humid forest	0 (0-0)	1.92 (1.92-1.92)	0 (0-0)
Sofia River	Dry forest	0 (0-0)	3.23 (0-16.92)	3.15 (3.15-3.15)
Ivoloina River	Humid forest	0 (0-0)	NA (-)	0 (0-0)
Mananara South River	Grassland-woodland mosaic	0 (0-0)	NA (-)	NA (-)
Mangoro-Rianila Rivers	Humid forest	0 (0-0)	5.43 (0-43.39)	1.25 (0-3.67)
Namorona-Faraony Rivers	Humid forest	0 (0-0)	0 (0-0)	0 (0-0)
Sahafary (Andranomena Antsiranana)	Dry forest	0 (0-0)	0.56 (0-1.77)	2.47 (2.14-2.55)
Angavokely Forest Station	Humid forest	0 (0-0)	13.88 (2.09-25.66)	0 (0-0)
Anjiamangirana Forest Station	Dry forest	0 (0-0)	19.89 (0.67-57.96)	NA (-)
Tarzanville (Moramanga)	Humid forest	0 (0-0)	17.59 (10.7-22.38)	NA (-)
Tsinjoarivo	Dry forest	0 (0-0)	0.8 (0-5.05)	-2.89 (-3.05--2.77)
Ambavanankarana Wetland	Mangroves	0 (0-0)	2.06 (0-31.13)	0 (0-0)
Ambila-Lemaintso Wetland	Humid forest	0 (0-0)	34.54 (7.21-56.31)	NA (-)
Ankobohobo Wetland	Mangroves	0 (0-0)	6.04 (0-26.08)	0 (0-0)
Maevatanana-Ambato-Boeny Wetlands	Grassland-woodland mosaic	0 (0-0)	9.46 (0.79-37.78)	-2.07 (-2.95-0)
Ampombofofo	Dry forest	0 (0-0)	1.55 (0-9.04)	0 (0-0)
Andrafiamena NAP	Dry forest	0 (0-0)	9.42 (0-58.35)	0.7 (-3.52-2.97)
Vohipaho Complex NPA	Humid forest	0 (0-0)	30.93 (8.29-58.82)	0 (0-0)
Analamay-Mantadia Forest Corridor NPA (CFAM)	Humid forest	0 (0-0)	8.42 (0-32.98)	NA (-)
Andohahela	Spiny forest	0 (0-0)	2.22 (0.14-5.41)	NA (-)
Andravory (Andrafainkona)	Humid forest	0 (0-0)	9.58 (0-37.95)	NA (-)
Beampingaratsy	Humid forest	0 (0-0)	12.53 (0-75.65)	0.1 (0-2.29)
Cap d'Ambre	Humid forest	0 (0-0)	7.73 (0-36.59)	0 (0-0)
Efatsy (Farafangana)	Humid forest	0 (0-0)	40.44 (4.27-86.36)	0 (0-0)
Sud-Ouest Ifotaky + Behara-Tranomaro	Spiny forest	0 (0-0)	5.21 (0-53.82)	0 (0-0)
Kianjavato NPA	Humid forest	0 (0-0)	16.74 (0-37.28)	0 (0-0)
Lake Andranomalaza	Mangroves	0 (0-0)	0.65 (0-1.79)	0 (0-0)
Lake Sahaka-Analabe NPA	Humid forest	0 (0-0)	1.58 (1.12-2.04)	0 (0-0)

Mangoky river	Grassland-woodland mosaic	0 (0-0)	4.8 (0-33.05)	1.86 (-3.51-2.59)
Mangoky-Ankazoabo Complex NPA	Subhumid forest	0 (0-0)	4.81 (0-38.59)	-0.72 (-3.66-2.37)
Menabe Central Corridor NPA	Dry forest	0 (0-0)	31.81 (0-98.2)	0.44 (0-3.31)
Menarandra Forest/Vohindefo NPA	Spiny forest	0 (0-0)	18.59 (0-80.08)	0 (0-0)
Vohidefo	Spiny forest	0 (0-0)	8.27 (0.04-36.96)	0 (0-0)
Rigny Bay Complex	Dry forest	0 (0-0)	1.18 (0-11.87)	0 (0-0)
Amoron'i Onilahy and Onilahy River NPA	Spiny forest	0 (0-0)	28.07 (0-94.74)	-0.06 (-2.74-0)
Saint Augustin Forest	Spiny forest	0 (0-0)	15.89 (0.11-57.65)	0 (0-0)
Seven Lakes NPA	Spiny forest	0 (0-0)	8.51 (0.07-33.97)	0 (0-0)
Sorata	Humid forest	0 (0-0)	7.54 (0-50.93)	NA (-)
Southwestern Coastal Wetlands and Nosy Manitse Future MPA	Spiny forest	0 (0-0)	3.99 (0-26.85)	0 (0-0)
Tambohorano wetland NPA	Dry forest	0 (0-0)	7.39 (0-39.74)	0 (0-0)
Vohibe-Ambalabe (Vatomandry) NPA	Humid forest	0 (0-0)	36.32 (16.88-55.76)	NA (-)
Vondrozo Classified Forest NPA	Humid forest	0 (0-0)	7.84 (0-52.97)	0.14 (0-1.85)
West Itampolo - Mahafaly	Spiny forest	0 (0-0)	0.05 (0-1.59)	0 (0-0)
Zafimaniry Classified Forest NPA	Humid forest	0 (0-0)	11.59 (0.23-43.86)	NA (-)
Mamela Honko	Spiny forest	0 (0-0)	0.66 (0-2.74)	0 (0-0)
Ambalibe Menabe	Dry forest	0 (0-0)	24.93 (0-85.01)	2.44 (-1.02-3.86)