Comparing Methods for Prioritising Protected Areas for Investment: A Case Study Using Madagascar’s Dry Forest Reptiles

Charlie J. Gardner1,2*, Christopher J. Raxworthy3, Kristian Metcalfe1,4,5, Achille P. Raselimanana6,7, Robert J. Smith1, Zoe G. Davies1

1 Durrell Institute of Conservation and Ecology (DICE), School of Anthropology and Conservation, University of Kent, Canterbury, Kent, United Kingdom, 2 WWF Madagascar and Western Indian Ocean Programme Office, BP 738, Antananarivo 101, Madagascar, 3 Department of Herpetology, American Museum of Natural History, New York, New York, United States of America, 4 Centre for Ecology and Conservation, University of Exeter, Penryn, Cornwall, United Kingdom, 5 Environment and Sustainability Institute, University of Exeter, Penryn Campus, Cornwall, United Kingdom, 6 Association Vahatra, BP 3972, Antananarivo 101, Madagascar, 7 Département de Biologie Animale, Faculté des Sciences, BP 906, Université d’Antananarivo, Antananarivo 101, Madagascar

* cg399@kent.ac.uk

Abstract

There are insufficient resources available to manage the world’s existing protected area portfolio effectively, so the most important sites should be prioritised in investment decision-making. Sophisticated conservation planning and assessment tools developed to identify locations for new protected areas can provide an evidence base for such prioritisations, yet decision-makers in many countries lack the institutional support and necessary capacity to use the associated software. As such, simple heuristic approaches such as species richness or number of threatened species are generally adopted to inform prioritisation decisions. However, their performance has never been tested. Using the reptile fauna of Madagascar’s dry forests as a case study, we evaluate the performance of four site prioritisation protocols used to rank the conservation value of 22 established and candidate protected areas. We compare the results to a benchmark produced by the widely-used systematic conservation planning software Zonation. The four indices scored sites on the basis of: i) species richness; ii) an index based on species’ Red List status; iii) irreplaceability (a key metric in systematic conservation planning); and, iv) a novel Conservation Value Index (CVI), which incorporates species-level information on endemism, representation in the protected area system, tolerance of habitat degradation and hunting/collection pressure. Rankings produced by the four protocols were positively correlated to the results of Zonation, particularly amongst high-scoring sites, but CVI and Irreplaceability performed better than Species Richness and the Red List Index. Given the technological capacity constraints experienced by decision-makers in the developing world, our findings suggest that heuristic metrics can represent a useful alternative to more sophisticated analyses, especially when they integrate species-specific information related to extinction risk. However, this can require access to, and understanding of, more complex species data.
Introduction

Conservation is severely under-resourced globally [1, 2], but particularly in tropical developing countries where biodiversity is concentrated [3, 4], so interventions must be prioritised to ensure maximum impact. The principal strategy for conserving biodiversity is the establishment of protected areas, which now cover almost 13% of the world’s land surface [5, 6]. However, these areas vary greatly in the value of their constituent biodiversity [7, 8], having largely been established in landscapes where opportunity costs have been lowest [9–11], rather than the most important for conservation [12, 13].

Although protected areas can successfully reduce the pressures that threaten biodiversity [10, 14–16], their performance is largely dependent on investment in active management. Thus, even modest increases in funding could substantially improve protected area effectiveness [17]. Ongoing deforestation and forest degradation in protected areas worldwide (e.g. [18–20]) suggests that there are more sites than can be financed and managed optimally in many countries, and that protected areas are under-resourced at the global level [21]. Given the huge variation in the contribution of protected areas to global biodiversity conservation [7, 8], and the fact that conservation goals are achieved most efficiently if available investment is targeted preferentially towards the most important sites [22], it follows that the optimal allocation of conservation resources will necessitate triage [23]. This does not, however, imply that low-value or underperforming protected areas should be degazetted, since even paper parks (which exist in legislation but lack any management [24]) may be somewhat effective at conserving biodiversity [17].

Decisions regarding the selection of priority areas for investment from within existing protected area networks should be evidence-based. However, such choices are almost always made by state-mandated protected area management agencies, non-governmental organisations and/or conservation funding bodies (henceforth decision-makers), actors who do not tend to make sufficient, appropriate or systematic use of scientific tools and approaches in decision-making [25–29]. Indeed, their priorities may be influenced by the (often implicit) values held by individuals and organisations [30–33], rather than rational, explicit methods, and this may lead to suboptimal results.

A range of metrics and approaches can be used to provide an evidence base for protected area prioritisation and triage, including the sophisticated software tools developed for systematic conservation planning and assessments (i.e. to inform the design of protected area portfolios where the representation and persistence of biodiversity are maximised for least cost) [34]. However, the uptake and use of such tools by decision-makers is limited by the need for specific training (which can be expensive and time-consuming), data availability, institutional support and institutional memory, since those receiving training are often moved into higher-level roles as a result [35, 36]. Even in contexts where significant investments have been made in building capacity for the use of such technological tools (such as over the last decade in Madagascar), barriers to their uptake by decision-makers remain; as a result, prioritisation decisions continue to be carried out based on simple measures such as richness of threatened species (e.g. [37, 38]).

Given that outputs from conservation planning tools are rarely applied in the context of prioritisation across existing protected area portfolios, it is important to assess the performance of the different metrics that can be, or are, used in such circumstances. In this paper, we evaluate four simple indices, including a novel Conservation Value Index (CVI), that could be used to identify priority sites for investment from a network of 22 designated and candidate protected areas in the contiguous dry regions of Madagascar. We benchmark our findings against the site ranking produced using the widely-used systematic planning software Zonation [39],
and consider the relative strengths and weaknesses of each approach, given the constraints of data availability that may hinder conservation decision-making.

**Materials and Methods**

**Study region and taxa**

Madagascar is one of the world’s top conservation priorities [40, 41]. Since 2003, it has been implementing its ‘Durban Vision’, an ambitious programme to extend the coverage of its protected area system from 1.7 million ha to 6 million ha [42, 43]. However, progress towards this goal has been hampered by the 2009–2014 political crisis, which left the country without a recognised legitimate government, leading to increased illegal wood trafficking and reduced funding for conservation [44, 45]. Prior to the Durban Vision, all Malagasy protected areas were managed by the parastatal Madagascar National Parks (MNP) and were designated as IUCN category I, II or IV, with the primary objective of conserving biodiversity [46]. In comparison, the new generation of sites is composed mainly of category III, V and VI multiple-use protected areas, managed for multiple socio-economic objectives as well as the maintenance of biodiversity, and administered by a range of actors including local community associations, non-governmental organisations (NGOs) and decentralised state authorities [47–49]. Together with the existing MNP protected areas, they form the Madagascar Protected Area System (SAPM).

The location of new protected areas has been partially informed by gap analyses and systematic conservation planning [50, 51], based purely on biodiversity data without the inclusion of cost information [43], with the aim of maximising the representation of endemic biodiversity within SAPM. Over 500 priority sites were identified, of which 93 had been granted permanent or temporary protected status by 2012 [52]. The organisation(s) responsible for each protected area, which are primarily Malagasy and international NGOs, are expected to independently source the necessary funds to ensure its long-term management. However, the Madagascar Foundation for Protected Areas and Biodiversity has been created to meet emergency shortfalls for the ‘best’ protected areas, which are characterised as such based on factors including a site’s contribution to biodiversity representation within SAPM (M. Nicoll, pers. comm.). Thus, many protected areas are essentially competing for some of their funds from the same, limited, pool of financial support. In their management plans, individual protected areas promote their importance on the basis of species richness, as well as lists of threatened and locally endemic species.

The freely available and comprehensive reptile inventory data from a range of sites in the contiguous dry regions of Madagascar make this taxonomic group a convenient case study for assessing the performance of prioritisation tools. The country’s reptile fauna is diverse, comprising almost 400 species, with 92% of these being endemic [53–55]. Many of the species are highly range restricted or micro-endemic [56, 57], and the majority are forest-dependent [55, 57, 58]; given historical deforestation trends [59], such species may depend on the effective maintenance of protected areas for their long-term survival. The dry regions of Madagascar are composed of two ‘Global 200’ priority ecoregions: the Madagascar dry forests in the west, and the Madagascar spiny desert of the south and southwest [60]. Although northern Madagascar also harbours dry forests, they are isolated from the western areas by a large band of humid forest and are excluded from this analysis due to a lack of inventory data.

**Biodiversity survey data**

We compiled a database of reptile inventories for both established and candidate protected areas in western and southern Madagascar (Fig 1; S1 Table), and supplemented these data with our own survey records (C. Raxworthy, unpublished data). All inventories used standard
protocols including pit-fall traps and refuge searches (see references in S1 Table). The database included inventories of 22 sites, comprising eight national parks, seven new protected areas and seven candidate protected areas which have been identified as priority sites for future designation (Fig 1). Species taxonomy follows Glaw and Vences [58] and subsequent revisions wherever the specific identity of split taxa is unambiguous [61–64]. The database was cleaned by removing all records of species no longer considered valid (i.e. subsequently synonymised;
n = 2), records that have not been described/identified to species level (n = 10), probable mis-
identifications (n = 5) and introduced species (n = 1).

Simple site prioritisation indices
Sites were ranked on the basis of four simple prioritisation protocols: 1) species richness, (the
number of species recorded at a site, a measure often used by decision-makers); 2) an index
derived from species Red List status [65]; 3) an irreplaceability index (a key metric in system-
atric conservation planning); and, 4) a Conservation Value Index (CVI) in which species were
scored on the basis of four attributes reflecting rarity and threat. For protocols 2, 3 and 4, scores
were assigned to individual species and the site score (SS) was then calculated as the cumulative
score of all species occurring there.

**Protocol 1 – Richness (SR).**

\[
SS_{SR} = r \quad \text{(where } r \text{ is the species richness of a site)}
\]

**Protocol 2 – Red List Index (RL).** Scores were assigned to species on the basis of their Red
List rankings from the 2011 Global Reptile Assessment for Madagascar [65], as follows: 5, Crit-
ically Endangered (CR); 4, Endangered (EN); 3, Vulnerable (VU); 2, Near Threatened (NT); 1,
Least Concern (LC). Species classified as Data Deficient (DD) (n = 9) or Not Evaluated (NE)
(n = 4) were excluded on the basis that insufficient data exist to permit evaluation.

\[
SS_{RL} = \sum RL_{species}
\]

**Protocol 3 – Irreplaceability (IR).** Using a method based on Brugière and Scholte [66],
where each species is weighted by the inverse of the number of protected areas in which it was
recorded.

\[
IR_{species} = \frac{1}{n} \quad \text{(where } n \text{ is the number of protected areas within the sample at which a species occurs)}
\]

\[
SS_{IR} = \sum IR_{species}
\]

**Protocol 4 – Conservation Value Index (CVI).** Scores were assigned to each species based
on four attributes that reflect relative rarity and threat, and thus extinction risk. Rarity was
assessed using degree of endemism (E) and representation in protected areas within the study
sample (R); for both these attributes, ‘rarer’ species score higher than widespread and well-rep-
resented species. Threat was based on hunting and collection pressure (C) and degradation tol-
erance (T), because these factors have a significant influence on the long-term viability of
Madagascar’s reptiles [55, 57]. The relative tolerance of species to habitat modification is par-
ticularly critical [55, 67–69] as most species in Madagascar are forest dependent [57], and forest
loss and degradation outside of protected areas shows no sign of reducing [59, 70]. Degradation-
tolerant species may maintain viable populations in transformed environments outside
protected areas [71–73] and so assumed lower conservation priority within the CVI. Hunting
for domestic consumption and collection for the global pet trade affect comparatively few spe-
cies, but represent the primary extinction threat to those that are targeted [55, 74, 75].

We assigned scores to each species on a five-point scale for each attribute (Table 1). For E,
we visually estimated range thresholds using distribution maps in Glaw and Vences [58].
Watershed-based biogeographical models [76] were not used to identify micro-endemic

---

**PLOS ONE | DOI:10.1371/journal.pone.0132803 July 10, 2015 5 / 18**
species because they are not a good proxy for local endemism in reptiles [77]. Instead we used 10,000 km² (approximately 2% of Madagascar’s land surface) as the threshold range size to distinguish between micro-endemics and endemic species restricted to a single bioclimatic region. 

\[ R \text{ was scored on the basis of occurrences in protected areas within this study.} \]

\[ C \text{ threat values were determined using CITES (Convention on International Trade in Endangered Species) listings and the literature on reptile declines in Madagascar.} \]

\[ T \text{ were assigned according to a review of the literature; species for which no degradation tolerance data were available (n = 24) were assumed to be degradation intolerant (i.e. given a score of 5) on the basis of the precautionary principle.} \]

Since rarity and threat are likely to interact in influencing species viability, summed rarity and threat values were multiplied to produce a CVI score (range: 4–100).

\[ CVI_{\text{species}} = (E + R) \times (C + T) \]  

(5)

\[ SS_{CVI} = \sum CVI_{\text{species}} \]  

(6)

To test the sensitivity of CVI to variation in the weighting of individual attribute scores for species, we performed sensitivity analyses in which the relative weighting of each attribute was doubled.

### Zonation

In order to produce a definitive benchmark against which to compare the site prioritisation protocols, we ran an assessment using the systematic conservation planning software Zonation v3.1 [78]. Zonation is a spatial conservation prioritisation framework which is based on conservation feature distributions defined using grid cells [39]. The underlying meta-algorithm starts from the full landscape and proceeds by iterative removal of cells (sites), at each step eliminating those which result in the smallest marginal loss in conservation value. The most important cells in the landscape are thus retained until last. Subsequently, Zonation produces a hierarchical ranking of conservation priority for each cell over the entire landscape [78]. We therefore: 

1. converted the presence-absence data for each species into a raster grid format to identify the

### Table 1. Attributes and scoring criteria used in Conservation Value Index (CVI) and Zonation assessments (E, C and T only). PA = protected area.

| Score | Rarity factors | Threat factors |
|-------|----------------|----------------|
|       | Degree of endemism (E) | Hunting and collection pressure (C) | Degradation tolerance (T) |
|       | Representation in sample PAs (R) | No known threat | Tolerant of modified or artificial habitats |
| 1     | Indigenous, non-endemic species | Recorded in 12–15 PAs (n > 75%) | N/A |
| 2     | Widespread endemic, occurring in dry and humid regions | Recorded in 8–11 PAs (45 > n < 75%) | N/A |
| 3     | Endemic to dry regions | Recorded in 4–7 PAs (20 > n < 45%) | Known threat (CITES Appendix I and II), but not likely to cause local extirpations | Tolerant of edge effects, medium-intensity degradation or secondary growth. |
| 4     | Endemic to one bioclimatic regiona | Recorded in 2–3 PAs (10 > n < 20%) | Threat known to have caused local extirpations or severe population declines | Intolerant of low-intensity degradation |
| 5     | Local endemic, range size estimated as < 10,000 km² | Recorded in only 1 PA (n < 10%) | Threat known to have caused local extirpations or severe population declines | |

\[ a \text{ Following Cornet [109]}

doi:10.1371/journal.pone.0132803.t001
distribution of each species across the landscape, with each site represented by a single cell; and, ii) used the Zonation additive-benefit function removal rule which bases selection on a cell’s weighted summed occurrence value over all species [39]. With this cell removal rule, species occurrences are considered additive, so the cell with the lowest value summed across all species will be removed at each step [78]. The result is that species rich cells tend to have a higher value than cells containing fewer species.

In order to produce the most informed ranking possible, species were weighted on the basis of endemism \( E \), hunting and collection pressure \( C \) and degradation tolerance \( T \) scores from \( CVI \), according to the formula: weighting = \( E \times (C + T) \). Representation scores were not included in the weighting as these data are incorporated in the Zonation algorithm. Since these species weightings may bias the results to be more closely correlated with those produced by \( CVI \), we also ran the Zonation analysis with all species weighted equally.

Comparison and assessment of site prioritisation indices

We evaluated the performance of each of the four prioritisation protocols by comparing the resultant site rankings with those produced by Zonation, using Spearman’s rank correlations.

Results

The final dataset contained 134 species distributed across 12 families: Boidae (3), Chamaeleonidae (14), Crocodylidae (1), Gekkonidae (36), Gerrhosauridae (8), Iguanidae (6), Lamprophidae (34), Pelomedusidae (2), Podocnemididae (1), Scincidae (24), Testudinidae (3), and Typhlopidae (2).

Species rankings

The three non-\textit{Richness} site prioritisation protocols produced species rankings that are broadly similar, but important differences emerged for certain species (Table 2). For example, two tortoises (\textit{Astrochelys radiata} and \textit{Pyxis arachnoides}) ranked in the top 10\% of species using \( CVI \) and \textit{Red List Index}, but featured in the lower 35\% of species using \textit{Irreplaceability}. Using \( CVI \), the 15 highest ranked species include four members of the order Testudines (tortoises and turtles), seven species in the family Chamaeleonidae (chameleons) and four species in the family Gekkonidae (geckos) (S2 Table).

Site rankings

Site species richness ranged from 17 in Kelifely to 72 in Ranobe PK32 (mean = 35.3, S.E. = 3.3, median = 30). The site rankings produced by the four prioritisation protocols are all strongly positively correlated with the output of Zonation (Table 3, Fig 2). In ascending order, the weakest correlation was between Zonation and \textit{Richness} (\( r_s = 0.711, p < 0.01 \)), followed by Zonation and \textit{Red List Index} (\( r_s = 0.861, p < 0.01 \)), Zonation and \textit{Irreplaceability} (\( r_s = 0.920, p < 0.01 \)), and Zonation and \textit{CVI} (\( r_s = 0.927, p < 0.01 \)). Inter-protocol ranking variability was greater for lower, rather than higher, ranked sites (the highest ranked site being number 1; Fig 2).

The high degree of association between \textit{CVI} and Zonation was not just an artefact of using a similar species weighting system in both protocols, as \( CVI \) was most strongly correlated with the outputs of Zonation when species weightings were not used (\( r_s = 0.977, p < 0.01 \)). Sensitivity analyses indicated that \textit{CVI} is relatively robust to changes in individual species attribute weightings, with correlation coefficients ranging from 0.916 to 0.932 when each of the four attribute scores were doubled (S3 Table).
Using CVI to compare sites of different protected status suggests that national parks (mean CVI = 1130.0, S.E. = 214.7, n = 8) are of greater conservation value for the reptile fauna than new protected areas (mean CVI = 942.3, S.E. = 203.4, n = 7) or candidate sites for future protection.

| Highest scoring 20 species according to CVI | CVI score | CVI rank | RL score | RL rank | IR score | IR rank |
|--------------------------------------------|-----------|----------|----------|---------|----------|---------|
| Brookesia bonsi                           | 80        | = 1      | 5        | = 1     | 1        | = 1     |
| Brookesia decaryi                         | 80        | = 1      | 4        | = 7     | 1        | = 1     |
| Brookesia exarmata                        | 80        | = 1      | 4        | = 7     | 1        | = 1     |
| Brookesia perarmata                       | 80        | = 1      | 4        | = 7     | 1        | = 1     |
| Furcifer belalandaensis                   | 80        | = 1      | 5        | = 1     | 1        | = 1     |
| Pyxis planicauda                          | 80        | = 1      | 5        | = 1     | 1        | = 1     |
| Erymnochelys madagascariensis             | 80        | = 1      | 5        | = 1     | 0.5      | = 37    |
| Furcifer nicosiai                         | 72        | = 8      | 4        | = 7     | 1        | = 1     |
| Phelsuma breviceps                        | 72        | = 8      | 3        | = 19    | 0.33     | = 59    |
| Uroplatys henkeli                         | 72        | = 8      | 3        | = 19    | 1        | = 1     |
| Furcifer rhinoceratus                     | 72        | = 8      | 3        | = 19    | 1        | = 1     |
| Astrochelys radiata                       | 70        | = 12     | 5        | = 1     | 0.17     | = 92    |
| Pyxis arachnoides                         | 70        | = 12     | 5        | = 1     | 0.17     | = 92    |
| Phelsuma borai                            | 64        | = 14     | 0        | = 122   | 0.5      | = 37    |
| Uroplatys guenterheri                     | 64        | = 14     | 4        | = 7     | 0.33     | = 59    |
| Ebenavia maintimainty                     | 60        | = 16     | 4        | = 7     | 1        | = 1     |
| Lygodactylus klemmeri                     | 60        | = 16     | 2        | = 37    | 1        | = 1     |
| Paragehya petiti                          | 60        | = 16     | 3        | = 19    | 1        | = 1     |
| Pygomeles petteri                         | 60        | = 16     | 4        | = 7     | 1        | = 1     |
| Sirenoscincus yamagishii                  | 60        | = 16     | 4        | = 7     | 1        | = 1     |

| Lowest scoring 20 species according to CVI | CVI score | CVI rank | RL score | RL rank | IR score | IR rank |
|--------------------------------------------|-----------|----------|----------|---------|----------|---------|
| Zonosaurus laticaudatus                    | 16        | = 110    | 1        | = 45    | 0.08     | = 123   |
| Oplurus cyclurus                           | 16        | = 110    | 1        | = 45    | 0.09     | = 117   |
| Oplurus cuvier                             | 16        | = 110    | 1        | = 45    | 0.2      | = 85    |
| Langaha madagascariensis                   | 16        | = 110    | 1        | = 45    | 0.13     | = 104   |
| Leioheterodon madagascariensis             | 16        | = 110    | 1        | = 45    | 0.13     | = 104   |
| Lygodactylus tuberosus                     | 14        | = 120    | 1        | = 45    | 0.25     | = 75    |
| Lygodactylus tolamyae                      | 12        | = 121    | 1        | = 45    | 0.08     | = 123   |
| Madagascarophis colubrinus                 | 12        | = 121    | 1        | = 45    | 0.08     | = 123   |
| Dromicodryas quadrilineatus                | 12        | = 121    | 1        | = 45    | 0.5      | = 37    |
| Thamnosophis lateralis                     | 12        | = 121    | 1        | = 45    | 0.33     | = 59    |
| Furcifer verrucosus                       | 10        | = 125    | 0        | = 122   | 0.09     | = 117   |
| Paroedura picta                           | 10        | = 125    | 1        | = 45    | 0.09     | = 117   |
| Furcifer lateralis                         | 8         | = 127    | 1        | = 45    | 0.1      | = 114   |
| Furcifer oustaleti                         | 8         | = 127    | 1        | = 45    | 0.09     | = 117   |
| Chalarodon madagascariensis                | 8         | = 127    | 1        | = 45    | 0.09     | = 117   |
| Trachylepis elegans                       | 6         | = 130    | 1        | = 45    | 0.07     | = 131   |
| Trachylepis gravenhorstii                  | 6         | = 130    | 1        | = 45    | 0.08     | = 123   |
| Dromicodryas bernieri                      | 6         | = 130    | 1        | = 45    | 0.07     | = 131   |
| Mimophis mahfalensis                       | 6         | = 130    | 1        | = 45    | 0.07     | = 131   |
| Hemidactylus mercatorius                   | 4         | 134      | 1        | = 45    | 0.08     | = 128   |

doi:10.1371/journal.pone.0132803.t002
This finding was consistent across all the prioritisation protocols.

Discussion

We have carried out the first evaluation of a range of well-known and new heuristic metrics which can be used to prioritise investment across a portfolio of sites. The site rankings produced by all prioritisation protocols were strongly correlated with the outputs of Zonation due to the fact that they are partially driven by species richness; since each individual species score is positive, sites scores will increase with greater numbers of recorded species. With the exception of Species Richness, all protocols were consistent in the selection of the top five ranking protected areas but showed greater variability in selecting between lower-ranking sites. This suggests that, while the most important of these sites would always be targeted to receive funding, the more marginal sites may be more difficult to reliably identify, thus making the selection...
of an appropriate prioritisation protocol of even greater importance. Despite their similarities, variation in the performance of the different protocols, when compared to the Zonation benchmark, provides insight into the suitability of each for use in the prioritisation of protected areas for investment.

Conservation assessments are intended to inform decisions, rather than provide definitive prescriptions [33, 79]. Ideally, with any prioritisation exercise, decision-makers should use a systematic approach such as Zonation whenever they have the capacity to do so or, if this is lacking, seek to develop or ‘borrow’ the necessary expertise by collaborating with research institutions [80, 81]. In addition to providing more robust assessments, Zonation can also be used for complex modelling that is beyond the scope of heuristic metrics (e.g. incorporating future climate change scenarios into planning) [82]. Where available, data reflecting species value (such as the attributes used in the CVI, population viability, or other characteristics discussed below) should be integrated into assessments in order to ensure that the evidence base is as rich and robust as possible, hence we included additional information on species threat status into our CVI protocol and benchmark assessment. It would have been best practice to have included non-biodiversity data in the assessment explicitly, for example cost information [83–85], probability of habitat loss, and the relative effectiveness [86] of the different protected area models employed in SAPM. However, such data are unavailable for Madagascar and, therefore, they were not used in this study or in the prioritisation exercise that informed the location of new protected areas within the Durban Vision expansion [43].

However, in situations where systematic conservation assessment software cannot be used, indices can provide a transparent, repeatable evidence base to inform prioritisation decision-making, thus representing an improvement on non-systematic approaches. The simplest such index is Species Richness, but this metric performed relatively poorly in our analysis, and would have identified Ranobe PK32 as the most important site for reptile conservation in our sample. All other protocols consistently rank Tsingy de Bemaraha as the most valuable site, despite it harbouring only 86% as many species as Ranobe PK32, because 28% of its reptiles are locally endemic [87]. Furthermore, Species Richness is not an accurate indicator of conservation value [88, 89] because all species are not equal. While value can be assigned to species according to a range of criteria (e.g. genotypic [90] or phenotypic [91] distinctiveness, public preferences [92],...
or ecological function [93]), we differentiated between species using parameters that reflect extinction risk as this is the most urgent issue facing conservationists [94]. Understanding the threats faced by species is critical to estimating their vulnerability and thus dependence on conservation interventions [74], yet systematic conservation planning assessments do not always incorporate such data.

The richness of threatened species is often used to inform prioritisations (e.g. [37, 38]), and the strong (0.86) positive correlation between the Red List Index and Zonation suggests this metric may be a useful proxy measure if the necessary data are available. However, the Red List Index failed to account for Data Deficient and Not Evaluated species, and thus almost 10% of species in our sample were excluded from the analysis. Additionally, since the use of such an index is dependent on the availability of full, up-to-date Red List assessments, its utility will be limited for many taxonomic groups and geographical regions, given that only 2.75% of described species had been evaluated by 2010 [33].

The concept of irreplaceability is a key metric in systematic conservation assessments, and the Irreplaceability index performed well in comparison to Zonation. However, measures of irreplaceability alone may not adequately reflect conservation value, because some species may be widespread and occur in a number of protected areas, yet remain highly threatened. For example, the tortoises Astrochelys radiata and Pyxis arachnoides were ranked low in terms of irreplaceability as both species are present in six protected areas, but they have suffered rapid, range-wide declines in population density [95, 96] that have resulted in them being classified as Critically Endangered [97]. In addition, care is needed when dealing with species that are commonly found outside the sites being considered. For example, the gecko Phelsuma modesta was recorded in only one protected area and therefore ranked high in terms of irreplaceability, although its abundance in heavily modified, non-forest habitats (e.g. urban areas [58, 98]) demonstrate that it is not dependent on the effective management of protected areas for its survival. Similar problems may arise if species occur within the study region, but only at the periphery of their range (e.g. if reptiles widespread in humid eastern Madagascar occurred at sites on the edge of the dry forest). However, in the case of the current case study, this issue is mitigated by the extremely high rates of species turnover between the humid and dry regions of Madagascar [55, 58, 99]. The problem of species that appear rare in a dataset but, in reality, are not, will afflict any richness or complementarity-based analysis. In such cases, one might consider excluding these species or, alternatively, using an explicitly target-based approach to measuring irreplaceability which sets lower targets for species deemed of minimal conservation importance by planners. Nonetheless, this risks introducing an element of subjectivity into the prioritisation exercise unless these species can be systematically identified by, for instance, using CVI.

The strongest correlation between site rankings was produced for Zonation and CVI, suggesting that the latter index could be used to inform protected area prioritisation in situations where more sophisticated analyses are not feasible. The index incorporated measures of rarity (a proxy for irreplaceability) and threat (a proxy for Red List status). As it only used inventory data, which were compiled into a database of species presence, and published literature to assign attribute scores using a simple scoring system, it can be adopted by decision-makers without the need for specific technological training. Nevertheless, the data requirements for the use of CVI are more burdensome than for Zonation and the other indices tested, which may limit its utility. Although CVI performed well in prioritising the forests of Madagascar’s dry regions for reptile conservation, additional case studies are needed to further examine its functionality. In particular, the approach may be most appropriate for dealing with a small number of pre-identified sites (e.g. prioritising across an existing protected area portfolio), rather than
for carrying out a conservation assessments which might seek to prioritise among many (i.e. hundreds or even thousands) of localities to optimise the establishment of new protected areas.

Our study was designed to investigate the performance of different protocols in prioritising amongst a portfolio of sites, and we do not intend it to serve as a definitive prioritisation of protected areas within the study region. Biases may have arisen due to the variation in survey effort undertaken at each site, which ranges over two orders of magnitude in terms of survey duration (S1 Table). However, most conservation decision-making is not only urgent but characterised by an imperfect evidence base. This is especially true given the expense of biodiversity surveys in tropical developing countries [100] and the rapidly diminishing returns from increased inventorying [101]. As such it is more prudent to make decisions based on available information and invest in action, as opposed to further data collection [102–104]. In addition, spatial patterns of reptile distributions and associated conservation value may not reflect those of other species groups, thus limiting the utility of a single-group assessment. While patterns of cross-taxon distributions are highly congruent at a global scale [105], this is not always the case at smaller scales within Madagascar [50, 77]. Thus the inclusion of data on multiple taxonomic groups would be required to provide a more robust prioritisation of investment across existing and candidate protected areas in the study region.

Despite these caveats, our results provide new insights into the relative conservation importance of candidate and existing protected areas in western and southern Madagascar. As a group, the established generation of national parks are more valuable for reptile conservation than both the Durban Vision generation of new protected areas and hitherto unprotected candidate sites; national parks comprise four of the five highest ranking sites for all protocols apart from Species Richness, and only one national park is in the bottom-ranked 30%. Two candidate sites, Nosy-Ambositra and Ankara, rank amongst the top 50% of sites using Zonation, and therefore warrant consideration for future protected area establishment. Currently, many of Madagascar’s national parks currently lack sufficient resources [52] to prevent deforestation within their boundaries [20, 70, 106]. Given the fact that management effectiveness can be improved with even modest increases in funding [17], the analyses suggest that available finances may be best invested in the existing national park system and the Durban Vision generation of new protected areas, rather than designating and managing additional new protected areas. A robust test of this question would need to factor in the relative costs and marginal conservation gains of funding the establishment of new protected areas versus the management of established sites [85], and should be considered a priority question for funders of national protected area systems worldwide.

Conclusions

The prioritisation of protected areas for investment is important if we are to maximise the effectiveness of protected area networks for biodiversity conservation. However, many conservation assessments and systematic conservation planning exercises do not contribute to the implementation of conservation action [32, 107, 108]. Given that management is limited by insufficient financial resources, it is all the more critical that available funds are targeted towards the most important sites. While sophisticated analytical tools can and should be used to inform such investment decisions, decision-makers often lack the capacity to use them, or choose not to for other reasons. Instead, they frequently rely on non-transparent, subjective processes or simple measures such as species richness or the number of threatened species. It is therefore important to understand how such metrics can perform and in what circumstances they should be used. Our analysis suggests that some heuristic indices can provide a transparent framework to support evidence-based decision-making by practitioners, although their
performance is variable and partially dependent on the amount of information required to use them. Our CVI, which incorporates measures of rarity and threat for individual species, appears to provide a useful alternative to more sophisticated systematic conservation planning tools, and emphasises the benefits of integrating species-specific data into conservation assessments.

Supporting Information

S1 Table. Sources of reptile data for the 22 sites in the dry regions of Madagascar used as a case study system to compare four different site prioritisation protocols and Zonation (NPA = new protected area established since 2003).

(S1 Table)

S2 Table. Attribute scores assigned to 134 reptile species found across 22 sites in the dry regions of Madagascar, used to calculate the conservation value index (CVI).

(S2 Table)

S3 Table. The site prioritisation rankings according to the conservation value index (CVI) protocol, following sensitivity analyses where each of individual species attribute scores were doubled.

(S3 Table)

Acknowledgments

We thank Martin Nicoll for discussions that contributed to development of the CVI, Atte Moilanen for advice on the use of Zonation, and Hugh Possingham and three anonymous reviewers who provided comments which greatly improved the manuscript.

Author Contributions

Conceived and designed the experiments: CJG CJR KM APR RJS ZGD. Performed the experiments: CJG KM. Analyzed the data: CJG KM. Contributed reagents/materials/analysis tools: CJR APR. Wrote the paper: CJG CJR KM APR RJS ZGD.

References

1. James AN, Gaston KJ, Balmford A (1999) Balancing the Earth’s accounts. Nature 401: 323–324. PMID: 16862091
2. Waldron A, Mooers AO, Miller DC, Nibbelink N, Redding D, Kuhn TS, et al. (2014) Targeting global conservation funding to limit immediate biodiversity declines. P. Natl. Acad. Sci. USA. doi: 10.1073/pnas.1221370110
3. Balmford A, Gaston KJ, Blyth S, James A, Kapos V (2003) Global variation in terrestrial conservation costs, conservation benefits, and unmet conservation needs. P. Natl. Acad. Sci. USA 100: 1046–1050.
4. Bruner AG, Gullison RE, Balmford A (2004) Financial costs and shortfalls of managing and expanding protected-area systems in developing countries. BioScience 54: 1119–1126.
5. Jenkins CN, Joppa L (2009) Expansion of the global terrestrial protected area system. Biol. Conserv. 142: 2166–2174.
6. Bertzky B, Corrigan C, Kemsey J, Kenney S, Ravilious C, Besançon C, et al. (2012) Protected planet report 2012: Tracking progress towards global targets for protected areas. Gland: IUCN and Cambridge: UNEP-WCMC. 60 p.
7. Rodrigues ASL, Andelman SJ, Bakarr MI, Boitani L, Brooks TM, Cowling RM, et al. (2004) Effectiveness of the global protected area network in representing species diversity. Nature 428: 640–643. PMID: 15071592
8. Le Saout S, Hoffmann M, Shi Y, Hughes A, Bernard C, Brooks TM, et al. (2013) Protected areas and effective biodiversity conservation. Science 342: 803–805. doi:10.1126/science.1239268 PMID: 24233709
9. Pressey RL (1994) Ad hoc reservations: Forward or backward steps in developing representative reserve systems? Conserv. Biol. 8: 662–668.
10. Joppa LN, Pfaff A (2011) Global protected area impacts. P. R. Soc. B 278: 1633–1638.
11. Barr LM, Pressey RL, Fuller RA, Segan DB, McDonald-Madden E, Possingham HP. (2011) A new way to measure the world’s protected area coverage. PLoS ONE 6: e24707 doi: 10.1371/journal.pone.0024707 PMID: 21957458
12. Brooks TM, Bakarr MI, Boucher T, da Fonseca GAB, Hilton-Taylor C, Hoekstra JM, et al. (2004) Coverage provided by the global protected-area system: is it enough? BioScience 54: 1081–1091.
13. Beresford AE, Buchanan GM, Donald PF, Butchart SHM, Fishpool LDC, Rondinini C. (2011) Poor overlap between the distribution of protected areas and globally threatened birds in Africa. Anim. Conserv. 14: 99–107.
14. Brooks TM, Wright SJ, Sheil D (2009) Evaluating the success of conservation actions in safeguarding tropical forest biodiversity. Conserv. Biol. 23: 1448–1457. doi:10.1111/j.1523-1739.2009.01334.x PMID: 20078645
15. Nelson A, Chomitz KM (2011) Effectiveness of strict vs. multiple use protected areas in reducing tropical forest fires: a global analysis using matching methods. PLoS ONE 6: e22722. doi: 10.1371/journal.pone.0022722 PMID: 21857950
16. Geldmann J, Barnes M, Coad L, Craigie ID, Hockings M, Burgess ND (2013) Effectiveness of terrestrial protected areas in reducing habitat loss and population declines. Biol. Conserv. 161: 230–238.
17. Bruner AG, Gullison RE, Rice RE, da Fonseca GAB (2001) Effectiveness of parks in protecting tropical biodiversity. Science 291: 125–128. PMID:11141563
18. Gaveau DLA, Epting J, Lyne O, Linkie M, Kanninen M, et al. (2009) Evaluating whether protected areas reduce tropical deforestation in Sumatra. J. Biogeogr. 36: 2165–2175.
19. Tang L, Shao G, Piao Z, Dai L, Jenkins MA, Wang S, et al. (2010) Forest degradation deepens around and within protected areas in East Asia. Biol. Conserv. 143: 1295–1298.
20. Allnutt TF, Asner GP, Golden CD, Powell GVN (2013) Mapping recent deforestation and forest disturbance in northeastern Madagascar. Trop. Conserv. Sci. 6: 1–15.
21. Watson JEM, Dudley N, Segan DB, Hockings M (2014) The performance and potential of protected areas. Nature 515: 67–73. doi: 10.1038/nature13947 PMID: 25373676
22. Fuller RA, McDonald-Madden E, Wilson KA, Cawardine J, Grantham HS, Watson JEM, et al. (2010) Replacing underperforming protected areas achieves better conservation outcomes. Nature 466: 365–367. doi: 10.1038/nature09180 PMID: 20592729
23. Bottrill MC, Joseph LN, Cawardine J, Bode M, Cook C, Game ET, et al. (2008) Is conservation triage just smart decision making? Trends Ecol. Evol. 23: 649–654. doi: 10.1016/j.tree.2008.07.007 PMID: 18848367
24. Brandon K, Sanderson S, Redford K (1998) Parks in peril: People, politics, and protected areas. Washington DC: Island Press. 519 p.
25. Pullin AS, Knight TM, Stone DS, Charman K (2004) Do conservation managers use scientific evidence to support their decision-making? Biol. Conserv. 119: 245–252.
26. Pullin AS, Knight TM (2005) Assessing conservation management’s evidence base: A survey of management-planner collaboration in the United Kingdom and Australia. Conserv. Biol. 19: 1899–1996.
27. Cook CN, Hockings M, Carter RW (2010) Conservation in the dark? The information used to support management decisions. Front. Ecol. Environ. 8: 181–186.
28. Cook CN, Carter RW, Fuller RA, Hockings M (2012) Managers consider multiple lines of evidence important for biodiversity management decisions. J. Environ. Manage. 113: 341–346. doi: 10.1016/j.jenvman.2012.09.002 PMID: 23062270
29. Milner-Gulland EJ, Barlow J, Cadotte MW, Hulme PE, Kerby G, Whittingham MJ (2012) Ensuring applied ecology has impact. J. Appl. Ecol. 49: 1–5.
30. Marris E (2007) What to let go. Nature 450: 152–155. PMID: 17994058
31. Wilson RS (2008) Balancing emotion and cognition: A case for decision-aiding in conservation efforts. Conserv. Biol. 22: 1452–1460. doi: 10.1111/j.1523-1739.2008.01016.x PMID: 18717697
32. Game ET, Kareiva P, Possingham HP (2013) Six common mistakes in conservation priority setting. Conserv. Biol. 27: 480–485. doi: 10.1111/cobi.12051 PMID: 23565990
33. Pullin AS, Sutherland W, Gardner T, Kapos V, Fa JE (2013) Conservation priorities: Identifying need, taking action and evaluating success. In: Macdonald DW, Willis KJ, editors. Key topics in conservation biology 2. Oxford: Wiley-Blackwell pp. 3–22.

34. Margules CR, Pressey RL (2000) Systematic conservation planning. Nature 405: 243–253. PMID: 10821285

35. Bottrill MC, Pressey RL (2012) The effectiveness and evaluation of conservation planning. Conserv. Lett. 5: 407–420.

36. Gaston KJ, Jackson SF, Nagy A, Cantú-Salazar L, Johnson M (2008) Protected areas in Europe: Principle and Practice. Ann. N.Y. Acad. Sci. 1134: 97–119. doi: 10.1196/annals.1439.006 PMID: 18566091

37. Schwitzer C, Mittermeier RA, Davies N, Johnson S, Ratsimbazafy J, Razafindramanana J et al. (2013) Lemurs of Madagascar: A strategy for their conservation 2013–2016. Gland: IUCN. 197 p.

38. Schwitzer C, Mittermeier RA, Johnson SE, Donati G, Irwin M, Peacock H, et al. (2014) Averting lemur extinctions amid Madagascar’s political crisis. Science 343: 842–843. doi: 10.1126/science.1245783 PMID: 24558147

39. Moilanen A (2007) Landscape zonation, benefit functions and target based planning: Unifying reserve selection strategies. Biol. Conserv. 134: 571–579.

40. Brooks TM, Mittermeier RA, da Fonseca GAB, Gerlach J, Hoffmann M, Lamoreux JF, et al. (2006) Global biodiversity conservation priorities. Science 313: 58–61. PMID: 16825561

41. Holt BG, Lessard JP, Borregaard MK, Fritz SA, Araújo MB, Dimitrov D, et al. (2013) An update of Wallace’s zoogeographic regions of the world. Science 339: 74–78. doi: 10.1126/science.1228282 PMID: 23258408

42. Raik D (2007) Forest management in Madagascar: An historical overview. Madag. Conserv. Dev. 2: 5–10.

43. Corson C. (2014) Conservation politics in Madagascar: The expansion of protected areas. In: Scales I, editor. Conservation and Environmental Management in Madagascar. London and New York: Routledge. pp. 193–215.

44. Butler R (04 Jan 2010) Madagascar’s political chaos threatens conservation gains. Available: http://e360.yale.edu/feature/madagascars_political_chaos_threatens_conservation_gains/2217/. Accessed 16 December 2014.

45. Randriamalahela H, Liu Z (2010) Rosewood of Madagascar: between democracy and conservation. Madag. Conserv. Dev. 5: 11–22.

46. Randrianandianina BN, Andriamahaly LR, Harisoa FM, Nicoll ME (2003) The role of protected areas in the management of the island’s biodiversity. In: Goodman SM, Benstead JP, editors. The natural history of Madagascar. Chicago: University of Chicago Press. pp. 1429–1432.

47. Gardner CJ (2011) IUCN management categories fail to represent new, multiple-use protected areas in Madagascar. Oryx 45: 336–346.

48. Gardner CJ, Nicoll ME, Mbohoahy T, Olesen KLL, Ratsifandrihamanana AN, Ratsirarson J, et al. (2013) Protected areas for conservation and poverty alleviation: experiences from Madagascar. J. Appl. Ecol. 50: 1289–1294.

49. Virah-Sawmy M, Gardner CJ, Ratsifandrihamanana AN (2014) The Durban Vision in practice: Experiences of the participatory governance of Madagascar’s new protected areas. In: Scales I, editor. Conservation and Environmental Management in Madagascar. London and New York: Routledge. pp. 216–251.

50. Kremen C, Cameron A, Moilanen A, Phillips SJ, Thomas CD, Beentje H, et al. (2008) Aligning conservation priorities across taxa in Madagascar with high-resolution planning tools. Science 320: 222–226. doi: 10.1126/science.1155193 PMID: 18403708

51. Rasoavahiny L, Andrianarisoa M, Razafimpanahanana A, Ratsifandrihamanana AN (2008) Conducting an ecological gap analysis for the new Madagascar protected area system. Parks 17: 12–21.

52. AGRECO (2012) Analyse des coûts et sources de financement du système des aires protégées de Madagascar (Octobre 2010 –Janvier 2012). Antananarivo: AGRECO. 100 pp.

53. Goodman SM, Benstead JP (2005) Updated estimates of biotic diversity and endemism for Madagascar. Oryx 39: 73–77.

54. Nagy ZT, Sonet G, Glaw F, Vences M (2012) First large-scale DNA barcoding assessment of reptiles in the biodiversity hotspot of Madagascar, based on newly designed COI primers. PLoS ONE 7: e34506. doi: 10.1371/journal.pone.0034506 PMID: 22479636
55. Jenkins RKB, Tognelli MF, Bowles P, Cox N, Brown JL, Chan L, et al. (2014) Extinction risks and the conservation of Madagascar's reptiles. PLoS ONE 9: e100173. doi: 10.1371/journal.pone.0100173 PMID: 25111137
56. Vences M, Wollenberg KC, Vieltes DR, Lees DC (2009) Madagascar as a model region of species diversification. Trends Ecol. Evol. 24: 456–465. doi: 10.1016/j.tree.2009.03.011 PMID: 19500874
57. Raxworthy CJ (2003) Introduction to the reptiles. In: Goodman SM, Benstead JP, editors. The natural history of Madagascar. Chicago: University of Chicago Press. pp. 934–949.
58. Glaw F, Vences M (2007) A field guide to the amphibians and reptiles of Madagascar. 3rd edn. Köln: Vences and Glaw Verlag. 495 p.
59. Harper GJ, Steininger MK, Tucker CJ, Juhn D, Hawkins F (2007) Fifty years of deforestation and forest fragmentation in Madagascar. Environ. Conserv. 34: 325–333.
60. Olson D, Dinerstein E (1998) The Global 200: A representation approach to conserving the world's biologically valuable ecoregions. Conserv. Biol. 12: 502–515.
61. Köhler G, Diethert HH, Nussbaum R, Raxworthy CJ (2009) A revision of the fish scale geckos, genus Geckolepis Grandidier (Squamata, Gekkonidae) from Madagascar and the Comoros. Herpetologica 65: 419–435.
62. Raxworthy CJ, Ingram CM, Rabibisoa N, Pearson RG (2007) Applications of ecological niche modeling for species delimitation: A review and empirical evaluation using day geckos (Phelsuma) from Madagascar. Syst. Biol. 56: 907–923. PMID: 18066927
63. Cadle JE, Ineich I (2008) Nomenclatural status of the Malagasy snake genus Bibilava Glaw, Nagy, Franzen, and Vences, 2007: Resurrection of Thamnophis Jan and designation of a lectotype for Leptophis lateralis Duméril, and Bibron, and Duméril (Serpentes: Colubridae). Herpetol. Rev. 39: 285–288.
64. Nagy ZT, Glaw F, Vences M (2010) Systematics of the snake genera Stenophis and Lycodryas from Madagascar and the Comoros. Zool. Scr. 39: 426–435.
65. IUCN (2012) IUCN Red List of Threatened Species http://www.iucnredlist.org/. Accessed 19 March 2013.
66. Brugière D, Schoile P (2013) Biodiversity gap analysis of the protected area system in poorly-documented Chad. J. Nat. Conserv. 21: 286–293.
67. Daily GC (2001) Ecological forecasts. Nature 411: 245–245. PMID: 11357107
68. Fischer J, Lindenmayer DB, Manning AD (2006) Biodiversity, ecosystem function, and resilience: Ten guiding principles for commodity production landscapes. Front. Ecol. Environ. 4: 80–86.
69. Gibbons JW, Scott DE, Ryan TJ, Buhlmann KA, Tuberville TD, Metts BS, et al. (2000) The global decline of reptiles, déjà vu amphibians. BioScience 50: 653–666.
70. ONE (Office National pour l’Environnement), DGF (Direction Générale des Forêts), FTM (Foiben-Tao- Sarinta), MNP (Madagascar National Parks), Conservation International (2013) Evolution de la couverture des forêts naturelles à Madagascar 2005–2010. Antananarivo: Office National pour l’Environnement. 48 p.
71. Harris GM, Pimm SL (2004) Bird species’ tolerance of secondary forest habitats and its effects on extinction. Conserv. Biol. 18: 1607–1616.
72. Gardner CJ (2009) A review of the impacts of anthropogenic habitat change on terrestrial biodiversity in Madagascar: Implications for the design and management of new protected areas. Malagasy Nature 2: 2–29.
73. Gardner TA, Barlow J, Chazdon R, Ewers RM, Harvey CA, Peres CA, et al. (2009) Prospects for tropical forest biodiversity in a human-modified world. Ecol. Lett. 12: 561–582. PMID: 19504750
74. Raxworthy CJ, Nussbaum RA (2000) Extinction and extinction vulnerability of amphibians and reptiles in Madagascar. Amphib. Reptile Conserv. 2: 15–23.
75. Walker RCJ, Rafelarisoa TH (2012) Distribution of radiated tortoise (Astrochelys radiata) bush meat poaching effort. Chelonian Conserv. Biol. 11: 223–226.
76. Wilné L, Goodman SM, Ganzhorn JU (2006) Biogeographic evolution of Madagascar’s microendemic biota. Science 312: 1063–1065. PMID: 16709785
77. Pearson PG, Raxworthy CJ (2009) The evolution of local endemism in Madagascar: Watershed vs. climatic gradient hypotheses evaluated by null biogeographic models. Evolution 63: 959–967. doi: 10.1111/j.1558-5646.2008.00596.x PMID: 19210532
78. Moilanen A, Meller L, Leppänen J, Pouzols FM, Arponen A, Kujala H (2012) Zonation v3.1: Spatial conservation planning framework and software. User manual. Helsinki: University of Helsinki. 287 p.
79. Knight AT, Cowling RM, Campbell BM (2006) An operational model for implementing conservation action. Conserv. Biol. 20: 408–419. PMID: 16903102
80. Smith RJ, Verissimo D, Leader-Williams N, Cowling RM, Knight AT (2009) Let the locals lead. Nature 462: 280–281. doi: 10.1038/462280a PMID: 19924192

81. Knight AT, Cowling RM, Boshoff AF, Wilson SL, Pierce SM (2011) Walking in step: Lessons for linking spatial prioritisation to implementation strategies. Biol. Conserv. 111: 202–211.

82. Veloz SD, Nur N, Salas L, Jongsoomjit D, Wood J, Stralberg D, et al. (2013) Modeling climate change impacts on tidal marsh birds: restoration and conservation planning in the face of uncertainty. Ecosphere 4: art49. doi: 10.1890/ES12-00341.1

83. Joseph LN, Maloney RF, Possingham HP (2009) Optimal allocation of resources among threatened species: A project prioritisation protocol. Conserv. Biol. 23: 328–338. doi: 10.1111/j.1523-1739.2008.01124.x PMID: 19183202

84. Cowardine J, Wilson KA, Hajkowicz SA, Smith RJ, Klein CJ, Watts M, et al. (2010) Conservation planning when costs are uncertain. Conserv. Biol. 24: 1529–1537. doi: 10.1111/j.1523-1739.2010.01535.x PMID: 20561000

85. Auerbach NA, Tulloch AIT, Possingham HP (2014) Informed actions: where to cost effectively manage multiple threats to species to maximise return on investment. Ecol. Appl. 24: 1357–1373.

86. Nelson A, Comitz KM (2011) Effectiveness of strict vs. multiple use protected areas in reducing tropical forest fires: a global analysis using matching methods. PLoS ONE 6: e22722. doi: 10.1371/journal.pone.0022722

87. Bora P, Randrianantoandro JC, Randrianavelona R, Hantalalaina EF, Andriantsimanalafy RR, Rakotondravony D, et al. (2010) Amphibians and reptiles of the Tsingy de Bemaraha Plateau, Western Madagascar: Checklist, biogeography and conservation. Herpetol. Conserv. Biol. 5: 111–125.

88. Rey Benayas JM, de la Montaña E (2003) Identifying areas of high-value vertebrate diversity for strengthening conservation. Biol. Conserv. 114: 357–370.

89. Barlow J, Gardner TA, Araujo IS, Avila-Pires TC, Bonaldo AB, Costa JE, et al. (2007) Quantifying the biodiversity value of tropical primary, secondary, and plantation forests. P. Natl. Acad. Sci. USA 104: 18555–18560.

90. Diniz JAF (2004) Phylogenetic diversity and conservation priorities under distinct models of phenotypic evolution. Conserv. Biol. 18: 698–704.

91. Owens IPF, Bennett PM (2000) Quantifying biodiversity: A phenotypic perspective. Conserv. Biol. 14: 1014–1022.

92. Smith RJ, Veríssimo D, Isaac NJB, Jones KE (2012) Identifying Cinderella species: Uncovering mammals with conservation flagship appeal. Conserv. Lett. 5: 205–212.

93. Scheiner SM (2012) A metric of biodiversity that integrates abundance, phylogeny, and function. Oikos 121: 1191–1202.

94. Brooks T, da Fonseca GAB, Rodrigues ASL (2004) Species, data, and conservation planning. Conserv. Biol. 18: 1682–1688.

95. Leutertiz TEJ, Lamb T, Limberaza JC (2005) Distribution, status, and conservation of radiated tortoises (Geochelone radiata) in Madagascar. Biol. Conserv. 124: 451–461.

96. Walker RCJ, Gardner CJ, Rafelariarisoa TH, Smith I, Razafimanatsoa R, Louis Jr EE (2013) Conservation of the Madagascar spider tortoise (Pyxis arachnoides) amid changing land use policy: Assessing the spatial coincidence of relict populations with protected areas and mining concessions. In: Castellano CM, Rhodin AGJ, Ogle M, Mittermeier RA, Randriamahazo H, Hudson H, et al., editors. Turtles on the brink in Madagascar: Proceedings of two workshops on the status, conservation, and biology of Malagasy tortoises and freshwater turtles. Chelon. Res. Monogr. 6: 135–145.

97. van Dijk PP, Leutertiz TEJ, Rhodin AGJ, Mittermeier RA, Randriamahazo H (2013) Turtles on the brink in Madagascar: An IUCN red listing assessment workshop. In: Castellano CM, Rhodin AGJ, Ogle M, Mittermeier RA, Randriamahazo H, Hudson H, et al., editors. Turtles on the brink in Madagascar: Proceedings of two workshops on the status, conservation, and biology of Malagasy tortoises and freshwater turtles. Chelon. Res. Monogr. 6: 33–36.

98. Gardner C, Jasper L (2009) The urban herpetofauna of Toliara, southwest Madagascar. Herpetol. Notes 2: 239–242.

99. Rakotondravony HA, Goodman SM (2011) Rapid herpetofaunal surveys within five isolated forests on sedimentary rock in western Madagascar. Herpetol. Conserv. Biol. 6: 297–311.

100. Gardner TA, Barlow J, Araujo IS, Ávila-Pires TC, Bonaldo AB, Costa JE, et al. (2008) The cost-effectiveness of biodiversity surveys in tropical forests. Ecol. Lett. 11: 139–150. PMID: 18031554

101. Grantham HS, Moilanen A, Wilson KA, Pressey RL, Rebelo TG, Possingham HP (2008) Diminishing return on investment for biodiversity data in conservation planning. Conserv. Lett. 1: 190–198.

102. Soulé M (1985) What is conservation biology? BioScience 35: 727–734.
103. Cowling RM, Knight AT, Privett SDJ, Sharma G (2010) Invest in opportunity, not inventory of hotspots. Conserv. Biol. 24: 633–635. doi: 10.1111/j.1523-1739.2009.01342.x PMID: 19843127

104. Knight AT, Bode M, Fuller RA, Grantham HS, Possingham HP, Watson JEM, et al. (2010) Barometer of life: more action, not more data. Science 329: 141–141. doi: 10.1126/science.329.5988.141-a PMID: 20616250

105. Lamoreux JF, Morrison JC, Ricketts TH, Olson DM, Dinerstein E, McKnight MW, et al. (2006) Global tests of biodiversity concordance and the importance of endemism. Nature 440: 212–214. PMID: 16382239

106. Whitehurst AS, Sexton JO, Dollar L (2009) Land cover change in western Madagascar’s dry deciduous forests: a comparison of forest changes in and around Kirindy Mite National Park. Oryx 43: 275–283.

107. Knight AT, Cowling RM (2010) Trading-off ‘knowing’ versus ‘doing’ for effective conservation planning. In: Leader-Williams N, Adams WM, Smith RJ, editors. Trade-offs in conservation: deciding what to save. Oxford: Blackwell Publishing. pp. 275–291.

108. Knight AT, Cowling RM, Rouget M, Balmford A, Lombard AT, Campbell BM (2008) Knowing but not doing: Selecting priority conservation areas and the research-implementation gap. Conserv. Biol. 22: 610–617. doi: 10.1111/j.1523-1739.2008.00914.x PMID: 18477033

109. Cornet A (1974) Essai de cartographie bioclimatique à Madagascar. Paris: Orstrom. 28 p.