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Prioritizing key biodiversity areas in Madagascar by including data on human pressure and ecosystem services

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ABSTRACT

Establishment of protected area networks to protect species and habitats has been one of the most effective conservation tools used around the world. On this premise Madagascar is planning to triple its protected areas by 2012. Recent studies have addressed the design of this new network in order to optimize biodiversity conservation. However, given the limited time, available resources and looming imminent threats both to biodiversity and to ecosystem services, we argue that we need to prioritize this process by including human related factors. We developed a framework and three composite indices, incorporating human related threats, ecosystem services and biological measures, which we used to identify priorities within the developing protected area network of Madagascar. In particular, we examined data on human population, roads, agricultural suitability and fire prevalence, alongside measures of hydrological and biological importance. Sixteen key biodiversity sites, which were not formally gazetted in the first round of designation, emerged as especially important for both biodiversity and ecosystem services. Two of these unprotected sites contain endemic frog species under imminent threat of extinction. Six of the sites we highlighted were subject to high-human pressure, while we detected limited human activity in the other ten. Our framework is computationally straight-forward and applicable to other regions of the world, and could be applied alongside community and stakeholder consultation.

1. Introduction

Warnings of a global biodiversity crisis dominate contemporary conservation science literature (Mace et al., 2000; Pimm and Raven, 2000; Schipper et al., 2008). Available funds for conservation are insufficient relative to the scale of the crisis, making the prioritization of globally important sites a critical challenge for conservationists (Brooks et al., 2006). The funding crisis is particularly acute in the tropics, where high concentrations of biodiversity are threatened by human activities and population pressure (Carwardine et al., 2008).

In response, numerous frameworks for prioritising worldwide conservation effort have been developed (Brooks et al., 2006), including Biodiversity Hotspots, the Global 200 and key biodiversity areas (KBAs) (Myers et al., 2000; Olson and Dinerstein, 2002; IUCN, 2007; Langhammer et al., 2007). The majority of these methods use criteria based on ecological irreplaceability or vulnerability to extinction, in order to select sites of highest conservation priority. However, none of these frameworks has been universally adopted by the conservation community and all are constrained by the gaps and biases in species distribution and threat status data (Myers et al., 2000; Novacek and Cleland, 2001). In addition, global frameworks remain difficult to apply at a national scale, leaving many nations without the means to assess, plan or implement conservation where it is needed most (Eken et al., 2004).

Protected areas remain the chief mechanism for ensuring the long-term persistence of biodiversity (Margules and Pressey, 2000), with an expanding role in the issues of sustainable development and human welfare (Naughton-Treves et al., 2005). The effectiveness of a protected area may be greatly influenced by the social, political and economic context in which it operates (O'Connor et al., 2003). Where these factors have been ignored in protected area establishment, conservation efforts are often impeded and local livelihoods adversely affected (Cernea and Schmidt-Soltau, 2003). However, despite the recognised need to explicitly consider socioeconomic factors at an early stage in protected area establishment (Robinson, 2006), the tools for identifying conservation priorities continue to be dominated by biological criteria alone (see e.g. Kremen et al., 2008).

The inclusion of national or regional socioeconomic factors can substantially alter the areas identified as conservation priorities compared to assessments based solely on biological criteria (Moran et al., 1997; O'Connor et al., 2003). The socioeconomic criteria used to date have usually focused on institutional capacity

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and governance (Angelstam et al., 2003) and indices of potential return-on-investment (O'Connor et al., 2003). A measure of ecosystem services, which are increasingly being recognised as powerful motivations for conservation, has been proposed as an important criterion within holistic conservation assessments (Balvanera et al., 2001). Indeed, such services undoubtedly have significant economic value and substantial benefits for human well-being (Millennium Ecosystem Assessment, 2005). However, progress toward an accepted methodology for incorporating ecosystem services into conservation assessments has been limited (Egoh et al., 2007) or conducted only at global scales (Turner et al., 2007). To address this, we have conducted an assessment of conservation priorities on a national scale that integrates multiple biological and socioeconomic criteria together with the provision of ecosystem services, in this case multiple use hydrological services.

As an illustrative case study we have applied this methodology to Madagascar, which has been consistently identified as a global conservation priority (Myers et al., 2000; Robinson, 2006) due to the high levels of endemism and species richness (Ganzhorn et al., 2001). Madagascar is subject to threat from intense human pressure, with some authorities estimating that as much as 85–90% of primary vegetation has already been lost through deforestation, fire and conversion to agriculture (Myers et al., 2000; McConnell, 2002; Kull, 2004). Added to this, severe soil degradation and erosion continue to act on a landscape already degraded over very long timescales (Bakoariniaina et al., 2006; Vågen et al., 2006). The human context of these losses is severe poverty, political instability and rapid population growth (2.7% $year^{-1}$) (Department of Economic and Social Affairs Population Division, 2009), which together has increased the demand upon, and vulnerability of, natural resources and biodiversity. In response, a programme known as the "Durban Vision" is underway to expand the Malagasy protected area network (Système des Aires Protégées de Madagascar – SAPM) to cover 10% of the country (Terborgh, 2004). Gathering sufficient funding to designate and manage the entire suite of potential sites is likely to be a challenge, and conservation in Madagascar, like much of the developing world, is already seriously under-funded, given its global importance (Carwardine et al., 2008). Further threats to Madagascar's protected areas are caused by recurrent political problems such as those experienced in 2002 and 2009: unstable government is no friend of biodiversity conservation (Glew and Hudson, 2007). Consequently it is necessary to identify those sites which represent the best investment in terms of their biological importance, ecosystem services and the likelihood of effective protection. Similar decisions are being made across the world (Knight et al., 2007).

In this study we devised a method for assessing relative conservation priorities within a given set of potential sites identified initially on biological grounds (i.e. as KBAs), and we applied this to Madagascar, employing three composite indices, namely; human pressure, hydrological services, and additional measures of biological importance. Our goals were to appraise these sites according to their relative conservation importance, indicators of human pressure and their value as providers of hydrological services; and via a series of priority scenarios, to demonstrate the value of a multifactor approach when granting protection and allocating resources.

2. Materials and methods

Key biodiversity areas (KBAs) have already been identified in Madagascar as sites of global importance for conservation, based on the presence of globally significant populations or congregations of threatened or restricted range species (Langhammer et al., 2007). In total, 170 KBAs have been identified in Madagascar, of which 126 are terrestrial sites. Of these, 56 terrestrial KBAs were already included in the Malagasy protected area network (Table S1); for this study, we focused on the 70 remaining terrestrial KBAs, which were not gazetted, provisionally protected or officially identified for protection at the end of 2007. We refer to these 70 sites here as "unprotected KBAs". They range in size from less than 2 km^2 to nearly 3000 km^2, with the majority covering less than 100 km^2. Within these 'unprotected KBAs' are sites which are under preliminary consideration for formal protected status, some of which are already the subject of a moratorium against mining or forestry operations; and this is, on the ground, a rapidly evolving situation. For the purposes of our analysis this group of 70 can be taken as a group of KBAs which for various reasons have not been given formal protected status in earlier rounds of consideration.

We collated data to derive our indices from international and Malagasy sources (see Table 1 for full citations of data sources), and analysed them in a Geographic Information System (ArcGIS 9.2: ESRI). We drew together baseline data, consisting of polygon features of administrative boundaries, the SAPM (Protected Area System of Madagascar) and the Malagasy KBAs. The 70 individual unprotected KBAs were initially scored in appropriate units for each variable assessed, and subsequently assigned a ranking for each of three composite indices, based on these scores (rank scores ranged from 1 to 70, where 70 indicated the highest scoring site for each analysis) (Tables S2 and S3). Protected KBAs were also assessed, for comparison (attributes of protected KBAs are listed in Table S4). The use of ranked scores facilitated the rapid identification of areas of highest conservation priority and was used in preference to more sophisticated optimisation and complimentary techniques, which require expertise and resources frequently unavailable to developing nations, such as Marxan (Possingham et al., 1999) or Zonation (Moilanen, 2007), which have been applied successfully to problems related to reserve selection and prioritisation in recent years. Although it is possible to include other variables in Marxan, for example, the use of these tools has to date been predominately biologically driven although there is recognition of the need to incorporate non-biological data in priority-setting (MPA News, 2004; Kremen et al., 2008).

To make conservation planning viable, decision-makers need to address specific stakeholder concerns or community and cultural interests—a process that in Madagascar has been ongoing for some time. Therefore, to aid incorporation of non-biological factors into strategic conservation planning which could then be subject to wider consultation and scrutiny among stakeholders, our results are presented as a series of 'priority scenarios'. These priority scenarios enable policy makers to identify those sites of highest conservation importance within the context of human activities—highlighting sites subject to the highest levels of human pressure and those where conservation benefits may be more easily achieved.

2.1. Biological importance

The suite of Malagasy sites in our case study was selected initially on biological criteria (as KBAs). We additionally assessed the biological importance of the unprotected KBAs using a composite of three measures, namely extinction risk, connectivity and taxonomic overlap. Unprotected KBAs were primarily sorted by extinction risk, and secondarily by connectivity score. Within the resulting categories, sites were ordered by taxonomic overlap score. Thus, an overall rank order of biological importance was produced for the set of 70 sites.

Risk of imminent extinctions occurring within a KBA was assessed using data from the Alliance for Zero Extinction (AZE) which identifies sites representing the last stronghold of a highly threatened species (point features: Ricketts et al., 2005). All KBAs which contain or overlap with AZE sites were scored as areas of

Table 1
Data sources.

	Subject	Data name	Extent	Format (resolution[a])	Source, date
Baseline	Country outline	Madagascar administrative boundaries level one	Madagascar	Polygon Feature	SAHIMS (2004)[b]
	Existing protected areas	Protected area system of Madagascar (SAPM)	Madagascar	Polygon features	ANGAP and SAPM (2007)
	Biological conservation priorities	Key biodiversity areas of Madagascar	Madagascar	Polygon features	Conservation International Madagascar (2007)
	Deforestation	Change in natural forest cover in Madagascar 1990–2005	Madagascar	Raster grid (0.03 km)	Conservation International and IRG (2007)
	Vegetation type	Madagascar vegetation map	Madagascar	Raster grid (0.03 km)	Vegetation Mapping Project (2001)
Human pressure	Population density	Landscan Global Population Database	Africa subset	Raster grid (0.80–0.90 km)	ORNL (2006)
	Road density	Madagascar roads	Madagascar	Line features	SAHIMS (2006)[b]
	Fire prevalence	Fires detected in Madagascar 2003–2007 from MODIS satellite images	Madagascar	Point features (derived from grid 0.80–0.90 km)	NASA and UMD (2007) and Justice et al. (2002)
	Agricultural suitability	Suitability for rain-fed crops	Global	Raster grid (9.00 km)	Fischer et al. (2002) (GAEZ)[c]
Ecosystem services	Hydrological services	Hydrological importance of KBAs for: (a) drinking water and (b) irrigating rice paddies	Madagascar	Raster grid (0.50 km)	Wendland et al. (2009)
Biological importance	Imminent extinctions	AZE sites of the world	Global	Point features	Ricketts et al. (2005)
	Taxonomic overlap	Overlap of modelled occurrence of six taxonomic groups (ants, butterflies, frogs, geckos, lemurs and plants)	Madagascar	Raster grid (30-arc sec grid)	Kremen et al. (2008)

Abbreviations: GAEZ, Global Agro-Ecological Zones Assessment; ORNL, Oak Ridge National Laboratory; SAHIMS, Southern Africa Human-development Information Management Network (United Nations initiative); UMD FIRMS, University of Maryland Fire Information for Resource Management System.

[a] Resolution is given for raster and grid datasets only.

[b] Obtained by SAHIMS in the years indicated, but originally created and published by: country outline – World Food Programme's Vulnerability Analysis and Mapping (WFP VAM) Unit; roads – Malagasy Conseil National de Secours.

[c] While this data was published in 2002 as part of the GAEZ, it was derived from data produced by several sources at different dates—including climate, soil, elevation and land cover.

highest biological importance. The connectivity of each unprotected KBA to existing protected areas or potential protected areas (other unprotected KBAs) was assessed, although any estimate will be limited by variability between taxa. KBAs within 500 m of an existing protected area were scored as highly connected (after Maschinski and Wright, 2006) while those within 500 m of another KBA classed as moderately connected. The 500 m threshold allowed for the potential to connect protected areas with habitat corridors, and for possible imprecision in the underlying boundary data. It does not, however, take account of matrix effects on connectivity, which may be considerable (Laurance, 2008). Scores for taxonomic overlap were derived for KBAs from a recently published assessment of biological conservation priorities in Madagascar: Kremen et al. (2008) used the reserve algorithm, Zonation (Moilanen, 2007) to model the distribution of 2315 species from six taxonomic groups (see Table 1) at high resolution (30 arc second or $\sim$0.86 km^2 grid). A central component of their study is the scoring of grid cells according to congruence between the six taxonomic groups modelled. We extracted this measure of taxonomic overlap for all grid cells within the boundaries of unprotected KBAs, and took the mean score to give a ranked measure of priority for each site.

To provide context to the measures of biological importance, we estimated changes in natural forest cover between 1990 and 2005 for each of the KBA sites in our study. We reclassified forest cover change data derived from LandSat imagery (Raster grid, 0.03 km: Conservation International and IRG, 2007) to identify grid cells containing natural forests in 1990 and in 2005, from which the percentage change in forested area within the boundaries of each site was estimated for the 15-year period. This gives some long-term context and enables analysis of deforestation rates together with measures of human population and activities. Note that those sites classified as protected KBAs have mostly only recently gained formal protection (2005–2007).

2.2. Human pressure

To assess the anthropogenic pressures affecting unprotected KBAs, we developed a composite 'human pressure index', comprising four indicators for which reliable, relatively high-resolution contemporary data were available (Table 1 and Table S2). Together, these indicators represent anthropogenic pressures that affect biodiversity worldwide (namely human population, roads and agriculture) and a more country-specific challenge which nonetheless is widespread in many parts of the world (prevalence of fire). In this way, our method may be applied elsewhere and adapted as appropriate to country-specific issues and data availability. For measures of population, roads and fires, a 2 km buffer zone around each KBA was included in the analyses, to account for the influence of nearby anthropogenic activities upon biodiversity. Buffers of this size reflect evidence found for the relationship between deforestation rates and proximity to settlements in Madagascar (McConnell et al., 2004). While such pressures may also originate from greater distances (Smith et al., 1997), buffers much larger than 2 km would obscure the specific characteristics of many smaller sites, and cause significant overlap between KBAs. No buffer was applied to the agricultural suitability analysis, since this measure concerned the value, and vulnerability, of land specifically within KBA boundaries. Differences in each measure between the groups of protected and unprotected KBAs were identified using Mann–Whitney U tests; ($n = 126$ for all: 56 for protected KBAs and 70 for unprotected KBAs) (see also Figs. S1–S4).

We extracted population counts for Madagascar from the global LandScan 2006 dataset (raster grid, population counts modelled to 0.80–0.90 km resolution), a revised edition of the data used in previous assessments such as Gorenflo and Brandon (2006). The data represent the best approximation available for the current situation, interpolated from the most recent census data (1993),

Table 2
Reclassification of data from the Global Agro-Ecological Assessment (GAEZ) into the categories used in this study to measure agricultural suitability in key biodiversity areas (KBAs). Adapted from Fischer et al. (2002).

GAEZ Agricultural suitability classification		New agricultural suitability classification	
Category	Suitability index (SI)	Category	Score
Unsuitable Water	0 0	Unsuitable	0
Very marginal Marginal Forests	$0 < SI \leq 5$ $5 < SI \leq 25$ $SI \leq 25$	Marginal	1
Moderate Forests	$25 < SI \leq 40$ $SI > 25$	Moderate	2
Medium Good	$40 < SI \leq 55$ $55 < SI \leq 70$	Good	3
High Very High	$70 < SI \leq 85$ $SI > 85$	High	4

using an algorithm based upon indicators such as land cover, night time lights and proximity to roads (Oak Ridge National Laboratory, 2006). From these data, population density was calculated for each KBA. While population data alone can be misleading, when considered in conjunction with human activities (as in our index) the output can provide an important indicator of both the risk to biodiversity as well as potential impacts upon humans resulting from conservation.

Accelerated rates of land degradation and species extinction are often facilitated by the expansion of roads into wild areas (for overview see Spellerberg, 2002), although the precise role of roads in deforestation in Madagascar is difficult to quantify with certainty (Casse et al., 2004). Data describing the national road network were used to estimate 'road density', as the total length of all recorded roads within each KBA, normalised by area (linear km of road km^{-2}). Our analysis of road density as a human pressure on KBAs was limited to those roads recorded in the available data, which excluded smaller roads and tracks; thus our estimates should be considered conservative.

The role of fire remains a complex and highly contentious issue in Madagascar (Kull, 2004) but is recognised as a threat to biodiversity (Ganzhorn et al., 2001). We estimated fire prevalence from fires detected by the University of Maryland's Fire Information for Resource Management System (FIRMS). The data were generated from satellite images as point features representing those grid cells (0.80–0.90 km) in which at least one fire was detected during the study year (NASA and UMD, 2007; Justice et al., 2002). For each KBA, annual fire prevalence was calculated from 2003 to 2007, as the number of fires detected in each year, normalised by area. Mean annual fire prevalence was then taken for this 5-year period. Although this measure gives no indication of the burned extent from each fire nor distinguishes between natural fires and those related to shifting agricultural practices (which are widespread in Madagascar), it represents the most accurate data available for use in this assessment.

The drive for agricultural expansion presents a major threat worldwide to biodiversity and is often a source of conflict between conservation and local people (O'Connell-Rodwell et al., 2000). The suitability of land within KBAs for cultivation was estimated using information produced by the Global Agro-Ecological Zone (GAEZ) assessment, based on a range of data describing climate, soils and terrain (Raster grid, 9.00 km: Fischer et al., 2002). The GAEZ index was reclassified to rank agricultural suitability on a scale of 0 (unsuitable) to 4 (highly suitable) (Table 2).

Assessment of auto-correlation between the descriptive variables was conducted with Spearman's Rank. In two cases we found a weak positive relationship (Spearman's Rank Correlations ($n = 70$)) between population and road densities for unprotected KBAs ($rs = 0.386$, $P < 0.01$), and between fire density and agricultural suitability ($rs = 0.297$, $P < 0.05$). Overall, there was very limited correlation between results for the four indicators across the 70 unprotected sites. This validated the inclusion of all four in the composite human pressure score, since no single indicator provided an adequate surrogate for any other. For each of the four variables, the 70 unprotected KBAs were ranked and the mean rank score taken. From this, KBAs were assigned an overall human pressure score, where a maximum of 70 indicated the highest level of human pressure (Table S3 and Fig S5C).

2.3. Hydrological services

While ecosystem services are widely recognised as an important driver for conservation (see Section 1), quantitative data remain scarce. For poor nations such as Madagascar, maintaining the benefits of ecosystem services may be a more realistic motive for conservation than the protection of nature for nature's sake (Armsworth et al., 2007). However, accepted methods for including a full range of ecosystem services in conservation assessments are still lacking and datasets with national coverage of ecosystem services are few and far between (Balvanera et al., 2001). For Madagascar however, we were able to use the results of an assessment of hydrological importance conducted by Wendland et al. (2009) (raster grid, 0.5 km) to incorporate this vital ecosystem service into our analysis. We derived mean scores from these data for each unprotected KBA, for two hydrological ecosystem services: one weighted according to the provision of drinking water to downstream populations, and the other for irrigation of rice paddies. These two measures were combined to produce an index of relative hydrological importance.

2.4. Scenario analysis

We brought together the biological, human pressure, and hydrological rankings and considered the composite result within four priority scenarios of practical application to conservation planning. This approach intends to facilitate multifactor conservation planning in which measures of both threat and importance can be considered simultaneously. Rather than producing a single composite measure of priority, our three independent indices were retained, and KBAs grouped according to the combination of conservation importance and human pressure measures derived for each site (Table S5). These scenarios were designed to assist conservation planners in identifying and prioritising those sites of greatest biological and/or hydrological importance in which human pressure is especially high (indicating vulnerable areas in urgent need of protection) or especially low (facilitating equally important, but potentially easier conservation). The thresholds for each scenario were based on categorisation of the ranked KBAs according to five equal groups (from 'Very High' to 'Very Low'), an approach that is readily adaptable according to the number of sites, available funding and conservation policy.

2.5. Sensitivity analysis

Given that some errors are inevitable, and often hard to quantify in remotely sensed datasets, we conducted a sensitivity analysis to assess the robustness of our findings. We identified two forms of error which had the potential to affect the human pressure index. The first, a systematic bias during data collection would result in all data points in a given dataset being either over- or under-estimated.

Table 3
Mean change in human pressure index rank position as a result of data manipulation. Error was introduced to all four-component variables (population density, fire, agricultural suitability and road density) at randomly selected KBAs.

Frequency of modification (*n*)	Error magnitude (percentage of standard deviation)		
	1%	5%	10%
1% (1)	1.2	2.0	3.4
5% (4)	1.1	1.5	3.5
10% (7)	1.2	2.1	4.0

As this form of instrumentation error is assumed to affect all points equally, the ranked order of KBAs is unaffected. The second form of error, mis-registration of values affecting some data points but not others, has the potential to affect a ranked index. Consequently, we tested the sensitivity of the human pressure index to such errors, through systematically manipulating the underlying datasets. We examined whether randomly introducing error of different magnitudes (1, 5 and 10% of standard deviation of the mean of the dataset) to an increasing proportion of sites resulted in substantial changes to the findings. Errors were introduced to randomly selected sites, affecting all four components of the human pressure index (Table 3). Ten runs of each error simulation were conducted and the mean change in human pressure score for modified points was recorded. The index was found to be robust to the introduction of errors, low levels of manipulation having negligible effects on the overall index.

3. Results

3.1. Human pressure

In 70% of all 126 terrestrial KBAs, the population density was estimated at less than 20 people km^{-2}, below the national average of 32 people km^{-2} (Fig. S1). Median population density was higher in unprotected KBAs (14.7 people km^{-2}) than protected KBAs (9.7 people km^{-2}), but not significantly so ($U = 1592$; ns). Gorenflo and Brandon (2006) suggest that biodiversity can be negatively affected by densities as low as 10 people km^{-2}. More than half of unprotected KBAs exceeded this threshold.

Within both categories of KBAs, road density was above the national average of 0.12 linear km km^{-2} (Fig. S2). Median road density was slightly higher in unprotected sites (0.21 linear km km^{-2}) than protected sites (0.17 linear km km^{-2}), but not significantly ($U = 1769$; ns).

Between 2003 and 2007, the number of fires detected in Madagascar varied per year from ca. 40,000 to over 70,000; or 0.10 fires km^{-2} $year^{-1}$ on average (Fig. S3). Fires were widespread, but most prevalent in the central highlands and the more arid western regions. Fires were detected in all but two KBAs during the 5-year period. Median fire density was higher in unprotected KBAs (0.06 fires km^{-2} $year^{-1}$) than in protected KBAs (0.04 fires km^{-2} $year^{-1}$), but not significantly ($U = 1717$; ns).

Madagascar had a national average of 2.15 on our scale for agricultural suitability (moderate to good suitability), derived from the GAEZ assessment. The majority of KBAs were rated lower, with most only marginally or moderately suitable for agriculture (Fig. S4). Median agricultural suitability was significantly higher among unprotected sites (1.9 compared to 1.4 for protected KBAs) ($U = 54.0$; $P < 0.01$), indicating a greater threat to those areas which remain unprotected.

When the individual components were drawn together into a single index, many of the smallest unprotected KBAs were subject to high human pressure; six sites that scored 60 or more (out of 70) were among the 15 smallest sites analysed (all covering less than 12 km^2) (Table S3). This negative relationship with site size was strongest for the population density component of the human pressure analysis (Spearman's Rank Correlation, $rs = -0.539$, $n = 70$, $P < 0.01$). For the composite human pressure score, the relationship was weaker, but still significant ($rs = -0.337$, $n = 70$, $P < 0.01$).

3.2. Biological importance

We showed that 59% of unprotected KBAs were not connected to the existing SAPM network or to other KBAs. Larger sites were better connected: the median size for maximum connectivity was over 500 km^2, compared to just 25 km^2 for minimum connectivity. Not one site less than 20 km^2 in size was adjacent to a SAPM site or other KBA. Sites with minimum connectivity were, on average, subject to more human pressure (mean score 39 out of 70, compared to 27 among other unprotected KBAs), but not significantly (Mann–Whitney $U = 447.5$, $n = 70$, ns). Higher connectivity was found among KBAs containing humid forests: these represented 17 out of 23 sites with maximum connectivity. In contrast, not one unprotected KBA dominated by littoral forest was connected to the SAPM; the same was true for all but one site dominated by western dry forests.

For taxonomic overlap, only 25% of unprotected KBAs scored more than 3.0 out of 6.0, of which all but two were dominated by humid forests, including many larger sites with high connectivity. Taxonomic overlap was highest in the humid forests of Tsaratanana-Marojejy (5.2 out of 6.0), one of the largest unprotected KBAs (2111 km^2) and sharing boundaries with an existing protected area. Human pressure was found to be very low in this site (scoring just 2 out of 70).

Overall, sites of highest composite biological importance were spread throughout eastern and northern Madagascar and most were dominated by humid forests (Fig. S5A). Among the ten most biologically important sites human pressure scores varied considerably, but were not especially high (ranging from 2 to 39 out of 70). Notably, agricultural suitability was particularly low within all but one of these sites (less than 1.8 out of 4.0).

In 1990, natural forest was detected in all but two areas categorised here as unprotected KBAs. The majority of KBAs (79.0%) had lost less than 10.0% of their natural forest cover between 1990 and 2005, just below the national average of 11.8%. Median forest loss was higher in unprotected KBAs (4.1%) than those KBAs which were recently afforded protection (2.5%) but these differences were not significant (Mann–Whitney U test, $U = 1742.5$, n (protected KBAs) = 56, n (unprotected KBAs) = 68, ns; two unprotected sites with no forest in 1990 were excluded). Deforestation rates were higher among more densely populated sites (median 12.1% deforestation for upper quartile KBAs ordered by population density; median 4.0% or below for all other quartiles), but no significant correlation was identified between deforestation rates and population density (Spearman's Rank Correlation, $rs = 0.142$, $n = 68$, ns).

3.3. Hydrological services

The majority of unprotected KBAs produced relatively low scores for hydrological importance (of a possible 200, the top score was 77 and 80% of sites scored 20 or less) (Table S3, S5 and Fig. S5B). To indicate the relative hydrological importance of unprotected KBAs, the sites were ranked, with the most important assigned a rank score of 70 (Manjakatompo-Ankaratra Massif). Among the 10 most hydrologically important unprotected KBAs, site size varied considerably (from 22 to 2111 km^2), but all except one were dominated by humid forests. Human pressure scores varied considerably among these 10 KBAs, including sites that represented both ends of the spectrum (scores ranged from 2 to 66 out of 70).

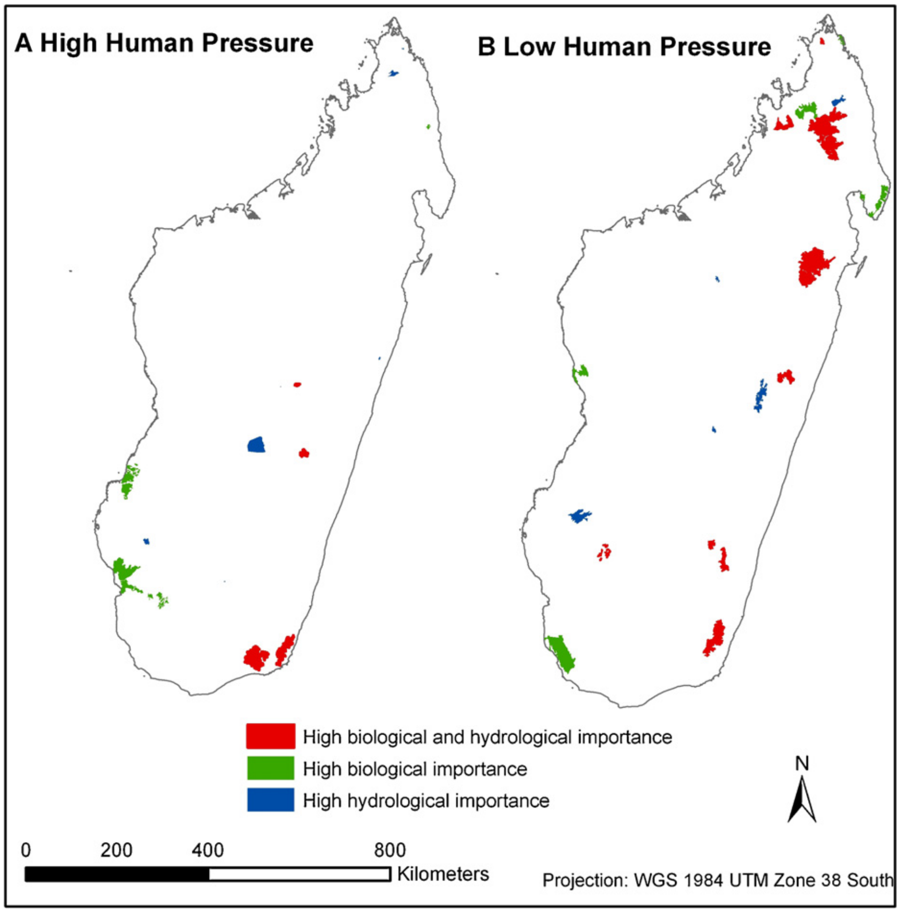

Fig. 1. Priority scenarios for unprotected key biodiversity areas of highest biological and hydrological importance. (A) High-human pressure; (B) Low-human pressure. Small sites are difficult to distinguish, please also refer to Table S5.

3.4. Combined assessments

We found a negative correlation (Spearman's Rank) between human pressure and biological importance ($rs = -0.340$, $n = 70$, $P < 0.01$): a weak relationship nonetheless indicating that more valuable sites may lie in less pressured areas. There was no significant relationship between human pressure and hydrological importance ($rs = -0.220$, $n = 70$, ns), but a positive correlation was found between biological and hydrological importance ($rs = 0.358$, $n = 70$, $P < 0.01$), suggesting that sites of great ecological importance may also be of economic value for providing an essential ecosystem service to humans.

When we ordered KBAs by human pressure and analysed them according to five equal groups (designated here: very high, high, medium, low, and very low), the median rank score for hydrological importance increased with decreasing human pressure (very high = 26.5, high = 31.5, medium = 43.0, low = 43.5 and very low = 44.0). A similar, but less distinct pattern was shown for biological importance (very high = 28.0, high = 33.5, medium = 20.5, low = 45.5 and very low = 43.5).

To facilitate the use of our methods in conservation planning the sites were split into two priority scenarios, according to the human pressure index: A – 'high pressure' (those scoring medium, high or very high) and B – 'low pressure' (those scoring low or very low). Overall, we found similar numbers of unprotected KBAs in both 'high pressure' (A) (Fig. 1A) and 'low pressure' (B) scenarios (Fig. 1B; Table S5). Sixteen KBAs emerged as top priorities for protection; these sites were either subject to high, or very low-human pressure, but were all important for both biological and hydrological criteria. In both cases, these results highlighted opportunities to conserve areas of ecological and socioeconomic importance, but for which conflicts with human activities may be more, or less likely to occur.

4. Discussion

By integrating biological, socioeconomic and ecosystem service data, this study revealed insights into the importance and suitability of potential sites for conservation. The study confirmed that expansion of the protected area network in Madagascar is urgently needed, not just to conserve biodiversity, but to maintain the ecosystem services that people depend on. While the 'Durban Vision' aims to protect 10% of Madagascar's land surface as soon as possible (see Section 1), the establishment of new protected areas will take time. The rate at which the network of protected sites can expand will be affected by the availability of funding, resources and staff capacity, among other things.

The priority scenarios to which the 70 unprotected KBAs were assigned were categorized according to differing levels of importance (for biodiversity and ecosystem services) within the context of human pressure. Our scenario analysis opens the way for a two-pronged approach to site selection: resources can be directed towards the more immediately vulnerable sites subject to high-human pressure, while 'easier' targets of similar importance but limited human activity may be protected with fewer hurdles. In each case, the conservation of areas providing important hydrological services is of clear benefit to local people: a win–win approach is then possible. In developing countries these benefits are urgently needed; Madagascar is just one example with 55.5% of children under 5 years old showing stunted growth linked to water-borne disease and poor nutrition, while globally 178 million children are

Table 4
Priority key biodiversity areas (KBAs) in Madagascar (see also Table S4).

KBA	Rank score		
	Human	Biological	Hydrological
A. HIGH biological & hydrological importance, subject to HIGH human pressure			
Antoetra	66.0	57.0	63.0
Ifotaka complex	39.0	61.0	59.0
Manjakatompo-Ankaratra Massif	32.0	69.0	70.0
Tsitongambarika classified forest and surrounding areas	30.5	62.0	60.0
Vohibola classifed forest	41.0	55.0	65.0
Zafimaniry classified forest	62.0	58.0	64.0
B. HIGH biological & hydrological importance, subject to LOW human pressure			
Andringitra-Pic d'Ivohibe	13.5	56.0	55.0
Anjanaharibe Sud-Marojejy	5.0	66.0	69.0
Ankeniheny-Lakato	22.0	67.0	62.0
Bidia-Bezavona classified forest	18.0	48.0	57.0
Manongarivo	15.5	64.0	54.0
Midongy Sud-Anosy Mountains-Andohaela Parcel I	6.0	70.0	67.0
Montagne d'Ambre	24.0	59.0	43.0
Tsaratanana-Marojejy	2.0	68.0	68.0
Vondrozo classified forest and surrounding areas	10.0	49.0	53.0
Zombitse-Vohibasia National Park surrounding areas	28.0	47.0	48.0

stunted (Black et al., 2008). It is encouraging that for the 16 KBAs found to be of high importance for both biological criteria and ecosystem services, more are found in areas of low-human pressure (10 sites) than high-human pressure (6 sites) (Fig. 1 and Table 4). Protection of the area covered by this group would correspond to almost one fifth of the total Durban Vision SAPM target, and would be mutually beneficial to biodiversity and Malagasy people. It is of note that five of these sites have been granted protected status in the last 2 years and the others are now moving towards formal protection.

The biological importance analysis highlighted the KBAs that may represent the most worthwhile investments for conservation; protection of these sites may prevent imminent extinctions, increase connectivity within the SAPM and maximise representation of different taxonomic groups. We noted that two unprotected KBAs contained AZE sites, Manjakatompo-Ankarata Massif and the Midongy Sud-Anosy Mountains, both dominated by humid forests. These sites represented the most urgent priorities, as their protection could prevent the imminent extinctions of three endemic frog species, namely *Boophis williamsi* and *Mantidactylus pauliani* in the Ankaratra Massif, and *Anodonthyla rouxae* in the Anosy Mountains (Alliance for Zero Extinction, 2007a,b). Moreover, their mountainous terrain and range of environmental conditions could make them potential refugia for surviving endemics during rapid climate change (Hewitt, 2004). While the Manjakatompo-Ankarata Massif KBA covered just 40 km^2 and was more than 70 km from the nearest protected area, the Midongy Sud-Anosy Mountains site was more than 1000 km^2 in size and connected to two existing national parks, with the potential to link the two.

The lack of connectivity between the current SAPM and many unprotected KBAs, particularly of the under-represented littoral forests and western dry forests, both of which contain high degrees of endemism but have been historically neglected (Consiglio et al., 2006; Ganzhorn et al., 2001; Kremen et al., 2008), highlights habitat fragmentation as a major challenge to Malagasy conservation and the viability of the future SAPM. This problem was emphasised by the higher human pressure scores found in many small sites, especially regarding population and road density. This issue is of particular importance considering the highly endemic and fragmented Malagasy biodiversity, as the long-term persistence of species is less likely in isolated sites which are also vulnerable to human activities (Fahrig, 2003).

Our relatively optimistic findings relating to deforestation from 1990 to 2005 are supported by recently released data indicating that rates of deforestation in protected areas (as opposed to KBAs at various stages of protection) are as low as 0.12% per year against a rate of 0.65% per year in unprotected forests (MEFT, USAID and Conservation International, 2009). Any optimism is tempered by the likelihood that forests in many sites were already depleted and degraded by 1990 (Green and Sussman, 1990). Indeed, nearly a third of all KBAs had less than 50% forest cover in 1990, and much of the Malagasy forest resource is subject to repeated cycles of degradation and regeneration (Ingram and Dawson, 2005).

The limited congruence among human pressure variables emphasizes the complexity of the socioeconomic context to conservation, as demonstrated elsewhere (O'Connor et al., 2003; Angelstam et al., 2003). This may be explained by the different circumstances in which the four human activities are likely to operate. No single unprotected KBA demonstrated a simultaneous combination of high population, road density and agricultural suitability while experiencing consistent, concentrated burning: not one site ranked within the top 10 scores for every measure. Encouragingly, the majority of KBAs scored below the national averages for our human pressure indicators. This finding might have been expected since many sites represent the last remaining intact areas of forest. Higher median scores among unprotected KBAs for the four human pressure components compared to protected sites may indicate that the SAPM has, so far, successfully maintained lower levels of human disturbance, compared to unprotected areas, supporting the findings of Bruner et al. (2001) and Naughton-Treves et al. (2005). These results may also warn that unprotected KBAs are more vulnerable to degradation. Considering the variability within both sets of KBAs, these suggestions are made cautiously.

The methods we have applied using Madagascar as a detailed case study are potentially adaptable for use elsewhere by incorporating the relevant country-specific drivers affecting conservation. Access to good quality data such as those we have integrated here will be something of a rarity, but the method could be applied to any combination of national or local datasets which can be integrated into simple ranks, providing decision-makers with a deeper insight than when metrics are considered in isolation. This could then be effective for informing consultation with communities and stakeholders, who will be able to contribute on issues like cultural significance or potential for nature-based tourism, which may only be possible to capture on a site-by-site basis.

Human related factors, measures of pressure or value, can be of crucial importance, and if not prioritised carefully with a view to national or local considerations, can undermine efforts to address threats to biodiversity in the very areas most in need of protection. Alongside biodiversity, hydrological services and fire prevalence are important considerations for conservation planning in Madagascar, but very different ecosystem services and threat factors may be more important in other locations, and our knowledge of them will usually be imperfect (Chan et al., 2007). As reliable, high-resolution data regarding dynamic processes such as climate change and population growth become available our assessment could be enhanced to accommodate such factors.

Overall, our approach has shown the value of considering biological criteria in parallel with human drivers for conservation, through the increased insight gained regarding individual sites, within a national scale assessment. The use of a multi-parameter GIS approach in a robust and computationally straight-forward framework has much potential as a tool for informing conservation planning, particularly in the developing countries.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.landurbplan.2010.02.002.

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