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Developing Conservation Priorities Based on Forest Type, Condition, and Threats in a Poorly Known Ecoregion: Sulawesi, Indonesia

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ABSTRACT

The island of Sulawesi is the largest in Indonesian Wallacea, one of the most important ecoregions in SE Asia and globally. Here, we generate a comprehensive and detailed map of forest type, its condition, and some of its threats, which highlights key forest conservation areas, pinpoints frontlines within them, and provides the basis for the development of more specific objectives. We relied upon a variety of techniques to generate five main descriptors of forest quality: condition, its level of endangerment, its landscape setting, its simulated fate given a simple model of forest change, and its overall size. Using the results of this analysis, we assessed the existing protected areas (PA), recognized by the Indonesian government, and a conservation portfolio (CP) generated by a recently completed Ecoregional Conservation Assessment (ECA). Our map of conservation priorities is congruent with previous conservation activities, although several priority areas were identified outside of the current PA system and should be the focus of strategic protected area development. Our ranking system is simple, transparent, and flexible. Its modular construction will allow local managers to choose among available proxy measures and to add their own conservation values according to specific priorities and desired outcomes. We envision this analysis as the foundation upon which more specific conservation strategies, based upon detailed biotic information as it becomes available, can be developed.

Key words: ecoregional conservation assessment; environmental diversity; SE Asia; Wallacea.

THE GLOBAL MAP OF BIOTIC ENDEMISM AND DIVERSITY has been well established (Myers *et al.* 2000, Olson & Dinerstein 2002, Lamoreux *et al.* 2006). Despite the controversy surrounding different approaches (Jepson & Whittaker 2002, Brummitt & Lughadha 2003, Myers & Mittermeier 2003), the more practical and pressing conservation issues lie within each of these regions, not among them. Local resource managers ultimately feel their conservation area is important, whether or not it ranks in the top 200 sites, and all have limited resources and time. They need detailed strategies and maps with clear geographic foci (Harris *et al.* 2005). Unfortunately, the application of global techniques is not feasible at more fine-scaled geographic scales (Ferrier 2002, Cowling *et al.* 2004), particularly for tropical forests, because our knowledge of insular patterns of endemism and diversity is much less reliable (Reddy & Davalos 2003, Higgins *et al.* 2004, Kuper *et al.* 2006). Even for well-known groups, the processes generating these patterns require a detailed historical perspective (Graham *et al.* 2006) and our ability to distinguish between the assumed generative mechanism of *in situ* diversification and other mechanisms may be weak (Bridle *et al.* 2004). The use of biodiversity proxies in these situations is necessary for the development of immediate and effective conservation strategies (Margules *et al.* 2002, Reyers *et al.* 2002, Pressey 2004). Here, we produce a conservation base map, focused on forest cover and type, to develop a modular and effective ranking system for the development of strategies at both the ecoregional and landscape scales for the globally important island of Sulawesi, Indonesia. Sulawesi forms the center of the SE Asian ecoregion of Wallacea. The dynamic continent of SE Asia critically needs coordinated and strategic development of conservation plans, due to unprecedented habitat loss, globally high levels of endemism, and a projected extinction crisis, due largely to human-mediated disturbance of existing forests (Sodhi *et al.* 2004).

The island of Sulawesi has been highlighted as a globally important conservation area, across a range of evaluation criteria (Dinerstein & Wikramanayake 1993, Olson & Dinerstein 2002, Rodrigues *et al.* 2004, Shi *et al.* 2005, Wilson *et al.* 2006). This status is a result of its long history as a large oceanic island (Hall & Holloway 1998, Wilson & Moss 1999), position at the biogeographic crossroads between East Asia and Australasia (Wallace 1869, Whitmore 1982), and complex geology (Hamilton 1979), including the largest mafic outcrops in the world (Proctor 2003). These processes have resulted in high levels of endemism, particularly of the fauna, at both the continental and local scales (Olson *et al.* 2001, Evans *et al.* 2003, Eken *et al.* 2004, Orme *et al.* 2005). A recent survey of plant species richness and endemism across Malesia, using the National Herbarium of the Netherlands collections data base (Roos *et al.* 2004), indicated that Sulawesi was intermediate for these measures. This mediocrity is actually remarkable for several reasons. Firstly, collection rates on the island are among the lowest in Indonesia and taxonomic study has been limited, with most experts reporting large numbers of undescribed species (Coode 1994, Hopkins 1998, Kleijn & van Donkelaar 2001). Additionally, its

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historical isolation from the Sunda Shelf islands through the Quaternary Period (Whitmore 1987, Voris 2000, Bird *et al.* 2005) prevented the continental enrichment experienced by Borneo, Sumatra, and Java. Finally, its strange geography, with four narrow arms radiating from a small central area, has placed strong geographic constraints on local population size. With a land area of 179,380 km^2, no location is more than 100 km from the coast. It is a large island without an 'interior.'

Our map focuses on five major aspects of current forest type and human settlement patterns: forest canopy condition, forest type and its endangerment, forest status based on its landscape setting, a numerical simulation of forest fate given observed trends, and the overall size of the site. We have excluded the use of biotic information in the development of this map for one main reason: the inherent difference in data quality between remotely sensed and collection-based information. Collection histories and the resulting distribution of species can be biased by a number of factors (Reddy & Davalos 2003). Reported biodiversity hotspots can become self-fulfilling, due to ease of logistics, connections made in museums, and team expeditions. To illustrate this bias in the data for Sulawesi, we present an analysis of the collection history of plants, based upon the complete collection data base from the National Herbarium of the Netherlands, and its effect on interpretations of species diversity. Unfortunately, our knowledge will not be sufficiently improved in the near future without a major and expensive effort (Pressey 2004), which is unlikely to occur. The use of 'indicator' groups could solve this shortcoming, but the particular value of a specific indicator group for the rest of the biota seems to depend heavily upon the biological and historical idiosyncrasies of the group or ecoregion (Lawton *et al.* 1998, Meijaard & Nijman 2003, Schulze *et al.* 2004), making this approach somewhat circular and unduly focused on a single objective.

Additionally, preliminary analyses of available species distribution data for the majority of groups found on Sulawesi, such as butterflies and amphibians, suggested that collection density and history were insufficient to capture meaningful patterns across the entire ecoregion. Observations of species occurrences, particularly of rare taxa, are mostly based on relatively brief collection trips and not on geographically exhaustive searches. This limitation makes the interpretation of these maps difficult: are the collection data representative of the 'optimal' habitat for the species or the 'optimal' collecting locations for scientists? These data also contain large areas of missing data. How to incorporate this type of uncertainty into our analysis was unclear. Remotely sensed data are geographically complete and can be directly and strategically ground-truthed. Several of the chosen environmental proxies have been shown to capture many aspects of a region's biodiversity (Gould 2000, Ferrier 2002, Reyers *et al.* 2002, Lombard *et al.* 2003, Kati *et al.* 2004, Oliver *et al.* 2004). Additionally, this list of parameters explicitly incorporates several aspects of forest vulnerability, such as topographic slope and forest margins (Kinnaird *et al.* 2003, Wilson *et al.* 2005, Soares-Filho *et al.* 2006). These proxies are also related to general patterns of species distribution at the regional and landscape levels (Duivenvoorden 1995, Webb & Peart 2000, Pitman *et al.* 2001, Cannon & Leighton 2004), unlike the extremely broad parameters used in a critique of the environmental diversity approach (Araujo *et al.* 2001). Among birds in central Sulawesi, the most important aspect of the overall landscape that seemed to impact diversity was the diversity and quality of forest (Waltert *et al.* 2004, Sodhi *et al.* 2005).

In most studies utilizing environmental proxies, each factor was analyzed separately in order to determine the 'best' method. Here, we adopt a more pragmatic approach, acknowledging that most conservation issues are multivariate, and construct a modular ranking system, in which each of these proxies is analyzed separately, but a final cumulative rank is used to identify conservation priorities. The modularity of the system would allow conservationists to take any subset of these rankings and derive their own specific set of rankings. Using this approach, we assess the existing system of protected areas (PA) and the conservation portfolio (CP) generated by the Steering Committee of the Ecoregional Conservation Assessment recently coordinated by The Nature Conservancy (see Appendix S1). The CP is a map of conservation sites, identified using a knowledge-based process of compiling and assessing data from a wide variety of sources and allowing expert opinion to strongly influence the decision. By exploiting the expert knowledge embodied in these two sets of conservation areas, we can ensure sufficient complementarity of sites (Justus & Sarkar 2002). This cumulative rank should minimize the effect of biases introduced by any one proxy while the modularity of the system will allow local managers and conservation biologists to identify and develop their own ranking system based upon specific expected outcomes or objectives.

METHODS

DATA LAYERS.—We compiled remotely sensed data for the entire island of Sulawesi from a number of different sources. All data were thoroughly checked and verified against other existing and complementary data sets. A Digital Elevation Model (DEM) was generated from data selected within a sufficient area of interest to capture the entire ecoregion and downloaded from the Shuttle Radar Topography Mission website (http://srtm.usgs.gov/). These data have a standard 90-m resolution. Data describing soil types were digitized from maps produced by the Indonesian government's Pusat Penelitian Geologi (Geology Research Center) in Bandung, Indonesia (Energy and Natural Resources Department). Human population and road density patterns were generated from the national census performed by the Indonesian government in 2000 by the Biro Pusat Statistik (Central Bureau of Statistics, Jakarta). The data for roads required an additional phase of manual correction using satellite imagery. These corrections were primarily made by Agus Salim. Finally, Landsat images were downloaded from the Global Land Cover Facility (http://glcf.umiacs.umd.edu/index.shtml). Because of the unusual shape of the island, a composite of 32 separate satellite images had to be analyzed. A detailed list of images is provided in a supplementary table (see Appendix S2). These images were captured over a 4-yr period (1999–2002) with the vast majority of them taken in 2000–2001. Because one region of the island was covered in clouds in all available images prior to the loss of instrumentation on the LANDSAT satellite, we purchased a Level 1Geometrically corrected (L1G) gap-filled Scan Line Corrector (SLC)-off product taken in 2004 from the United States Geological Survey and used it to complete these clouded areas. Most of the images were captured in the months of July and August and very few through October to February. Registered images were first projected into UTM zone 51S using ArcGIS v.9.1 (Copyright 1999–2005 ESRI). Copies of these images can be provided upon request.

The collections data of the National Herbarium of the Netherlands in Leiden for the entire ecoregion were georeferenced as extensively as possible, using searches of place names and collection information. Of the 15,612 records in this data base, adequate geographic information was available to determine the location to the county or kecamatan level for 12,314 records. We examined the geographic distribution of these collection records and the simple relationship between the number of collections and the plant species diversity in the 15 different biogeographic regions of the island recognized in the ECA.

FOREST CONDITION.—A 4-wk field survey, covering 17 different conservation sites scattered across the island, was performed by C. H. Cannon and J. R. Harting. A brief description of this survey is provided as supplementary information (Appendix S3). Both automated and supervised classification of scenes using multivariate tools available in ERDAS v. 8.5 software (Leica Geosystems Geospatial Imaging, LLC, Norcross, GA, U.S.A.) indicated that an automated procedure was unfeasible because of the inherent variability across such a large array of satellite images and forest types. Several data transformations, including NDVI and Tasseled Cap (Crist & Cicone 1984), were applied to scenes to aid in classification; however, the most reliable result across all 32 scenes turned out to be simply 'forest' and 'nonforest.' Using the initial results of an unsupervised classification of each separate image, we generated a single mosaic map of forest condition by visually verifying and reclassifying pixels. During this reclassification, performed by CHC and JRH, various aspects of the spectral bands, DEM, and visible signs of human activity were used to break the 'forest/nonforest' classes into five distinct classes of forest condition. The manual classification was performed at 1:100,000 resolution on 90-m detail satellite images. This type of interactive and knowledge-based classification (Thenkabail 1999) was necessary in this study because of the great complexity involved with analyzing a large number of separate satellite images across an extremely variable topographic surface.

'Old-growth' areas exhibited an unbroken and even canopy layer with no obvious human-mediated disturbance patterns. 'Good' condition areas exhibited a forest canopy unbroken by large clearings with only scattered signs of human activity. 'Fair' condition areas possessed a mostly intact canopy with obvious signs of human activity. 'Poor' condition areas were highly fragmented, largely dominated by human activity but with scattered forest remnants present. 'Converted' areas were dominated completely by human land-use patterns, including urban and agricultural landscapes. These areas could normally be easily distinguished by the sharp angularity of margins and textures in the images. This last category is quite broad and lumps a large amount of variation together, including plantation forestry. We chose to use this single class because the focus of our study was on natural forest types, not human altered landscapes. Final vector data sets outlining forest condition blocks from each Landsat scene were mosaicked and cleaned of any overlapping polygons using topology tools in ArcGIS v. 9.1. In subsequent discussion, 'good forest cover' includes both Old Growth and Good forest conditions and is referred to as 'Great to Good' (G2G) forest. 'Poor forest cover' refers to both Poor and Converted forests (P2C).

FOREST TYPE.—To identify major forest types, we combined an elevational model with four distinct soil classes. Our elevational model was based on field experience and an analysis of the Leiden plant collection data base. The elevational data for each species occurrence were first plotted in a frequency distribution and examined for natural breaks, both in diversity and in composition. Using the results from this exercise, we chose to distinguish among three different forest types ('Lowland': 0–400 m asl; 'Hill': 400–850 m asl; 'Upland': 850–1500 m asl) where most other broad scale studies only identify two (Olson *et al.* 2001). A major transition in total number of species and taxonomic composition was identified at 400 m asl. This transition in plant species composition indicated a substantial difference in habitat quality from the perspective of the animal populations dependent on them. The results of this analysis are presented in a supplemental analysis (Appendix S4). We also recognized two more traditional higher elevational limits, 'Montane':1500–2500 m asl and 'Tropalpine': > 2500 m asl.

The geological history of the island of Sulawesi (Hamilton 1979) has created a very complicated and diverse set of soil conditions, which varies sharply across the island in a heterogeneous environmental setting. While the geological map contained a great deal of detail, we chose to lump many soil classes into an intermediate class, which contains soils derived from sedimentary to metamorphic rocks, on young volcanic to older, more leached sites. In comparison to the other three soil types recognized: limestone, mafic, and alluvium, little evidence has been found for the effect of intermediate types on local tree distribution. The intersection of these five elevation and four soil classes generated 15 forest types with sufficiently large areas for analysis. Insignificant amounts of alluvial soils are present in the upper three elevation zones and were excluded. Additionally, the total area of tropalpine forests was too small in relation to other forest types to warrant distinguishing among its soils. Three special forest types (mangrove, wetland, and karst) were also recognized, primarily through remote-sensing techniques and verified as distinct species assemblages both in field surveys and distribution analyses. To identify endangered forest types, we calculated a simple percentage of G2G forest remaining and the total land area in each type. Forest types were then simply ranked from those with the lowest percentage of G2G forest (most endangered) to those with the highest (least endangered).

FOREST STATUS.—Separate regressions were performed for forest condition against all available landscape parameters. Significant results were obtained for the following six factors: elevation, slope, proximity to coast, rainfall, human population density, and road density (Appendix S5). These results agree well with other studies (Lawrence & Foster 2002, Kinnaird *et al.* 2003, Etter *et al.* 2006, Soares-Filho *et al.* 2006). Human activity is naturally concentrated in basins and ravines, leaving steeper slopes undisturbed. Rainfall is probably associated with good condition forest because of enhanced productivity and thus recovery rates of wetter sites (Lawrence & Foster 2002). Because of the unusual shape of Sulawesi, the island has no 'heart' and much of the land area is accessible from the coast by boat. On an island with low road densities, this coastal effect can have a major negative impact by making otherwise inaccessible sites available to conversion and exploitation.

For these six landscape factors, a composite raster for the entire island at a resolution of 1 km^2 was scored on a scale from 1 to 5 by its quintile position in the separate distributions of each landscape parameter, with the value 1 being associated with G2G forest and the value 5 being associated with poor forest and open areas. 'Landscape setting' was then simply the summation of these six parameters for each pixel. Forest condition was correlated with this summation of landscape parameters in a nonlinear fashion (Fig. 1). To minimize the possible effects of spatial autocorrelation in the regression model between landscape setting and forest condition, the regression analysis was performed on a random subsample of pixels from the 1-km^2 resolution rasters. Sampling intensity was 18 percent and the pixels were chosen equally from each cell of a 66-km^2 hexagonal grid to ensure equal distribution of the random sample across the island. The total number of pixels in the 1-km^2 resolution raster was 179,380 to cover the land area. The regression analysis was performed on 32,662 pixels. The equation below is the best-fitting line for this relationship, where x is the landscape setting value. The R^2 for this regression was 0.42 and F-ratio of 11,690 ($P < 0.01$). There was little difference in the equation between the random subsample and the complete sample.

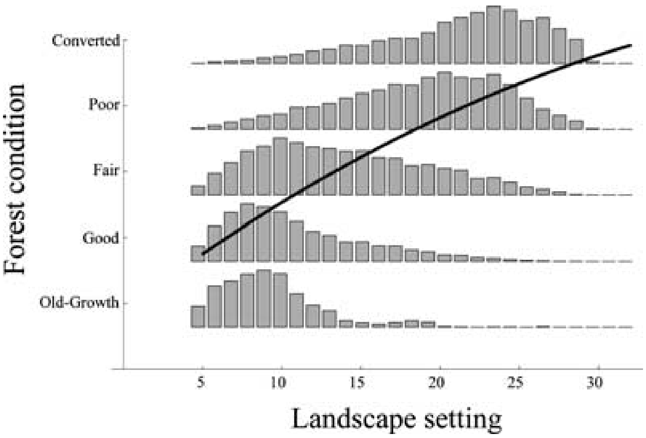

FIGURE 1. Relationship of forest condition with its landscape setting on the island of Sulawesi, Indonesia. 'Landscape setting' is the cumulative score for each of six environmental parameters, each highly correlated with forest condition (see Methods). Each bar chart represents the frequency distribution of the landscape setting for each category of forest condition. The regression line illustrates the best-fitting relationship between forest condition and its landscape setting. The distributions and regression analysis were based upon 18 percent coverage of pixels obtained in a stratified random fashion by using the hexagonal grid to control for spatial autocorrelation (see Methods).

$$\text{Forest condition} = 0.92 + 0.18x + -0.0015x^2.$$

Forest status was then calculated as the residual of current condition to the condition predicted by this equation and its landscape setting. Given these residuals, two types of forest status can be recognized. Positive status was assigned to pixels with forest in better condition than would be predicted given the above equation and its landscape setting as defined above. In other words, if the residual of the equation lie in the direction of good condition, the site could be considered to be in better condition than expected. Negative status was then assigned to those sites in worse condition than expected. Separating these two categories for forest status seems useful as they indicate different conservation values. Those managers interested in protected high-quality wilderness areas can focus on positive status sites while restoration and reconciliation scientists may choose to focus on negative status sites.

FOREST CHANGE SIMULATION.—A forest cover change analysis was conducted for five widely separated locations across Sulawesi (Harting & Cannon 2005). Sites for this analysis were determined by the availability of older Landsat TM scenes (acquisition dates 1988–1991), cloudless areas, and representation of the vegetation types on the island. Forest condition for older scenes was determined as described above after co-registering with newer scenes. Change was then determined as a transition from one class to another in proportion to its representation in the site of interest. The resulting probabilities from this change analysis were then used as one aspect of a computer simulation of forest change. Because this change analysis involved a relatively small amount of total area and total range of variation in landscape and setting for the ecoregion, two additional major aspects used in the computer simulation involved landscape setting, as described above under 'Forest Status' and the condition of the surrounding forest. The simulation was performed on the initial condition raster with a resolution of 1 km^2 per pixel. All pixels were used in the simulation.

The simulation involved an iterative process where the probability of change in forest condition was calculated for each pixel in the forest condition raster. Iterations of the simulation first calculated the probable change of each pixel across the entire raster with subsequent iterations based upon each new raster. The probability that forest condition would change from one condition to another was based upon two separate calculations: one based upon the condition of the forest surrounding each pixel (neighborhood effect) and each pixel's landscape setting (global proclivity). The underlying landscape parameters were not allowed to change during the iterative process, which is one shortcoming of the simulation because certain aspects of the landscape, such a human population and road density should be expected to vary. The simulation was written by CHC using Mathematica 5.1 (Wolfram, Inc., Champaign, IL, U.S.A.) and can be provided upon request.

The probability of a change in forest condition due to the neighborhood effect was determined simply by comparing the condition of the focal pixel with the average forest condition of its eight surrounding pixels. If the forest condition of the focal pixel differed from the average condition of its neighborhood then a change in forest condition, in the direction of the difference, would be proposed. For example, if forest condition in the focal pixel was 'Good' while all surrounding pixels were 'Converted,' the probability is quite high that forest condition would decline in the focal pixel (Kinnaird *et al.* 2003). The probability of a change in forest condition due to global proclivity was determined by comparing the condition of the focal pixel with its expected condition from the nonlinear regression used above to determine Forest Status. A Monte Carlo process, based upon the probability density function of the observed in the expected distribution of forest conditions given the landscape setting, was used to determine whether a change in forest condition should be proposed or not. If the forest condition of the focal pixel matched its expected condition, then obviously no change would be proposed, but if the observed forest condition was substantially different than the mean forest condition for the given landscape setting, then a change in forest condition would be likely.

The neighborhood and global proclivity effects were calculated separately and then the proposed changes were added together equally, resulting in a final proposal of forest change for the focal pixel. If the proposed change from each of these two effects was equal but in opposing direction, then the final proposal would be no change. After a final proposal for forest change was calculated from the landscape and neighborhood settings, a second Monte Carlo process was used to determine if the proposed change was allowable, given the observed rates of change in the forest change analysis described in the first paragraph under this section. For example, if the final proposal for forest change was from Converted to Old-Growth, this change was very rarely observed (Harting & Cannon 2005) and would only rarely be allowed but if the final proposal was from Good to Poor condition, which was a common observation, it would almost always be allowed. Ten iterations were performed at which point the rate of forest change appeared to reach stationarity, where little forest change occurred and primarily involved a relatively small subset of areas that converted back and forth. This effect has been noted in other simulation studies (Luijten 2003) and is due to the static nature of the underlying landscape parameters. It does indicate the current rate of deforestation and decline in forest

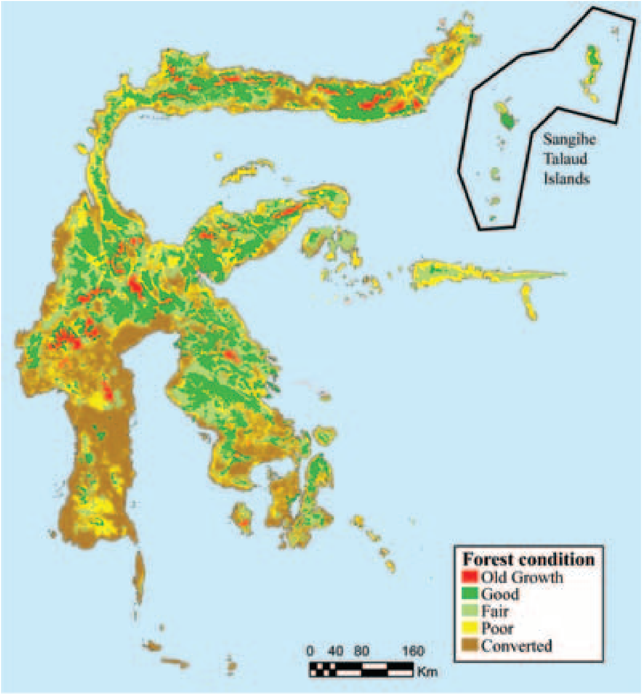

FIGURE 2. Forest condition on the island of Sulawesi. A composite of 32 Landsat images was manually classified based upon both visual inspection and the results from several remote-sensing techniques. The 'converted' class includes all sites that are completely dominated by human activity, including urban areas and regions of intensive agriculture and plantations. The Sangihe Talaud island chain has been moved down next to the northern arm within the black border. Its actual position, in relation to the main island, is shown in Fig. 6. This convention is followed in the Figures 2–5.

TABLE 1. *Major forest types on the island of Sulawesi and their relative condition.* ***Total*** *land area is given for each forest type in both absolute and relative amounts across the entire ecoregion. Good condition forested areas are given for each forest type in absolute amounts and the percentage of that forest type which is in* ***G2G*** *condition. Poor condition and converted areas are given for each forest type in absolute amounts and the percentage of that forest type which is in* ***P2C*** *condition. Types are arranged in ascending order of G2G percentage.*

	Total		G2G		P2C	
Forest type	ha	(%)	Ha	(%)	Ha	(%)
Wetlands	568,643	3	1823	0	546,987	96
Lowland alluvium	1,512,201	8	44,749	3	1,425,199	94
Mangrove	76,264	0	3464	5	72,418	95
Hill alluvium	39,919	0	4172	10	31,618	79
Lowland limestone	1,199,129	6	135,479	11	845,300	70
Lowland intermediate	5,712,661	31	720,636	13	3,929,842	69
Lowland mafic	537,446	3	181,925	34	189,122	35
Hill limestone	583,432	3	207,296	36	163,123	28
Hill intermediate	3,124,860	17	1,215,776	39	1,034,489	33
Upland intermediate	2,450,343	13	1,227,408	50	715,023	29
Karst	149,996	1	82,290	55	12,073	8
Hill mafic	650,385	3	392,164	60	71,917	11
Upland limestone	353,074	2	218,175	62	54,143	15
Montane intermediate	1,055,281	6	732,346	69	150,012	14
Tropalpine	161,767	1	125,711	78	15,325	9
Upland mafic	311,061	2	245,540	79	13,423	4
Montane limestone	65,647	0	57,260	87	2096	3
Montane mafic	73,155	0	66,889	91	969	1
Total	**18,625,264**		**5,663,104**	**30**	**9,273,077**	**50**

condition will probably slow, without any conservation activity, as easily convertible and accessible areas are exhausted. The difference in forest condition between the original raster and the tenth iteration was used to calculate the simulated forest change for each pixel.

RANKING SYSTEM.—The average values for the CPs and PAs were then calculated for each of the environmental proxy categories: forest condition, positive and negative forest status, simulated change in forest condition, endangered types, and total area. CP and PA were analyzed separately. Each site was then ranked for each category, using the following criteria. Sites with better forest condition were ranked more highly than sites with poor forest condition. Higher positive or negative status was given a higher rank, as were larger areas. Sites with a higher score for endangered types and higher probability of decline in forest condition, given the computer simulation, were ranked more highly than sites with lower scores and lower probability for decline in condition.

A cumulative rank was then given to each CP and PA simply by adding these separate ranks together. Sites with a low cumulative score thus rank more highly than sites with a high cumulative score. A range of weighting systems was explored, giving each category up to three times the value of the others, but the order of the top 20 sites remained stable across these weighting schemes.

HEXAGONAL ASSESSMENT GRID.—To refine the analysis of priority conservation sites, we produced a 66-km^2 hexagonal grid for the entire island and intersected this with the CP and PA sites. These grid elements were not confined to the sites, but could also include border areas, thus incorporating a form of buffer zone into the analysis. The ranking procedure described above was then performed on each hexagonal grid unit. The number of top ranking grids recognized in the results was determined by the overall size of the site. The largest sites were given five high ranking grids while the smallest were only allowed one, with a categorical distribution of grids provided for intermediate-sized sites.

RESULTS

Across the ecoregion, almost one third (30%) was covered by G2G forest (Fig. 2; Table 1) while one half (50%) was in poor condition or had been converted into intensive human land use (P2C). A strong positive correlation exists between forest condition and elevation, as

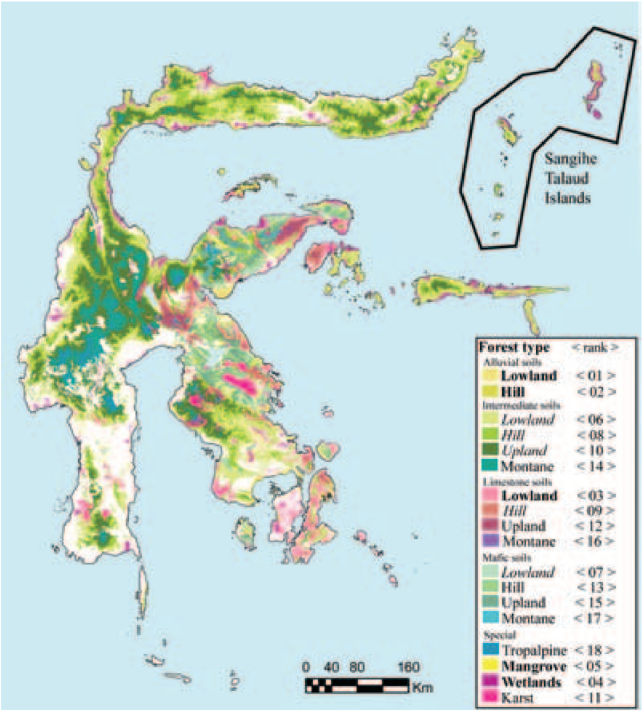

FIGURE 3. Major forest types and their distribution on the island of Sulawesi. Converted areas, from the previous map, are shown in white. The legend groups the forest types by soil. The bold-faced types are the most endangered habitats on the island while the italicized are moderately endangered. < rank > in the legend refers to the forest type's level of endangerment, from highest to lowest (see Table S1).

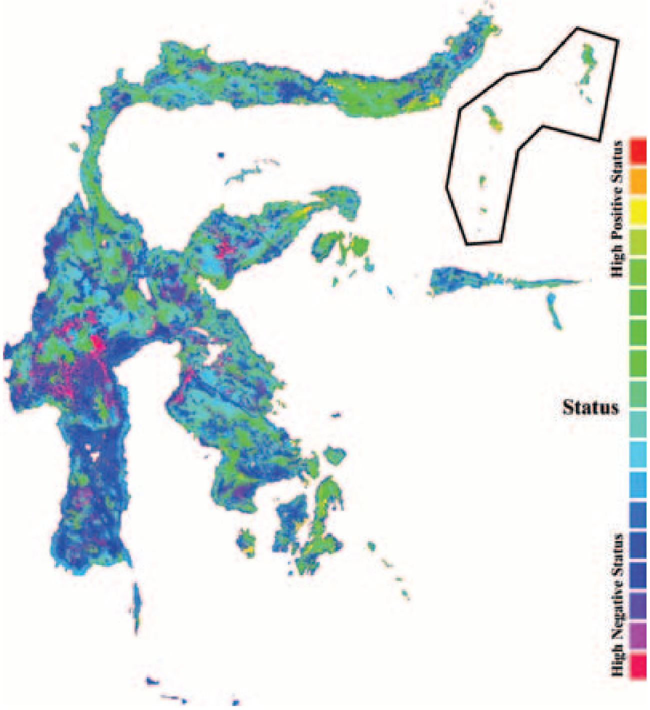

FIGURE 4. Forest status on the island of Sulawesi. The color-coding indicates the residual values of current forest condition, given the relationship between forest condition and a composite score based upon seven landscape parameters found to be highly correlated with forest condition (see Methods and Appendix S4). 'High positive status' indicates sites that are in better condition than expected and 'High negative status' indicates sites that are in worse condition than expected.

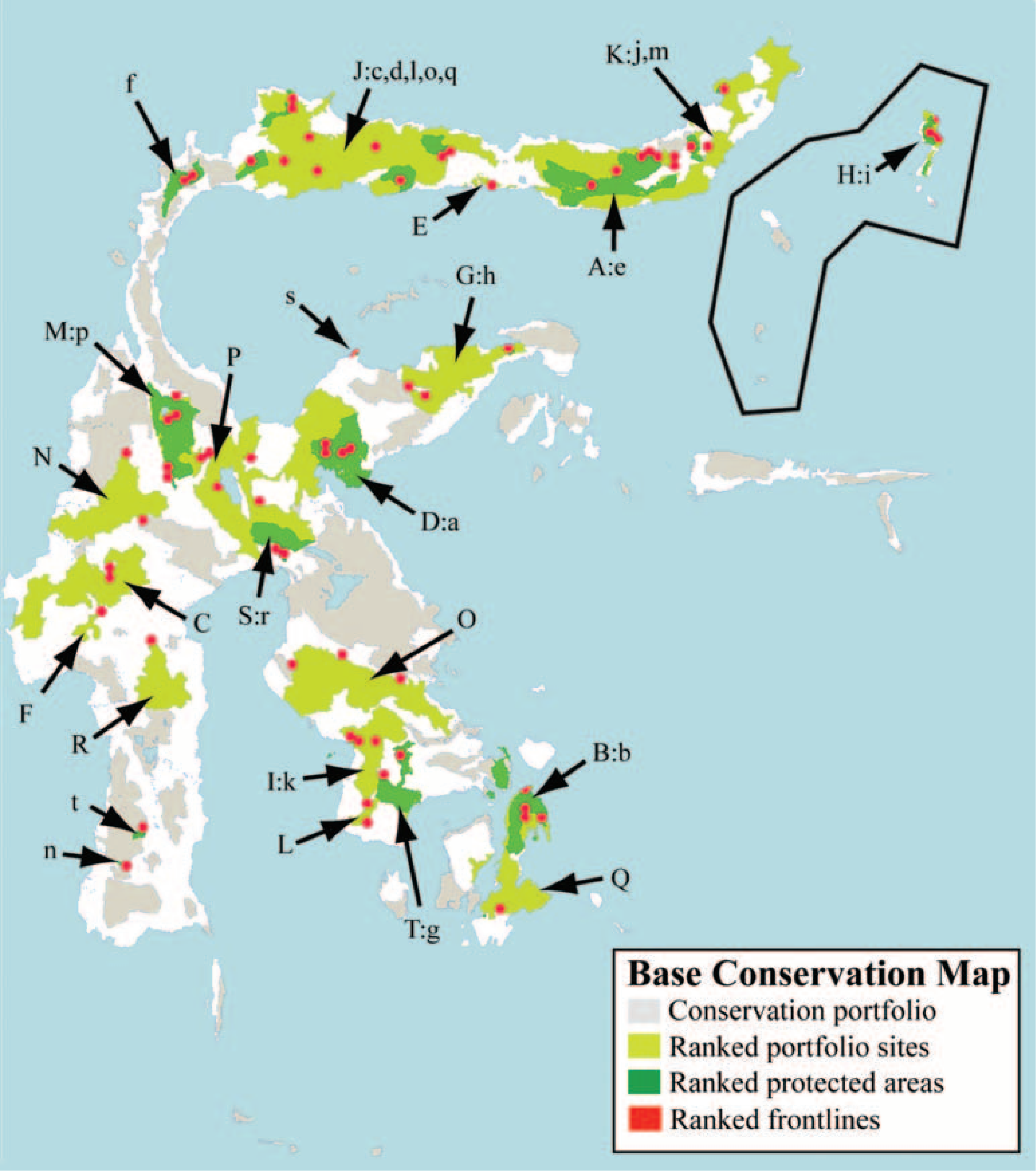

FIGURE 5. Map of high conservation values on the island of Sulawesi. The top 20 ranking protected areas and conservation portfolio elements are shown, including the top-ranking conservation frontlines within each site. The complete conservation portfolio is shown in gray and includes the light CP sites. The labels match those in Tables 2 and 3. Complete names and details of CPs and PAs are given in Supplementary Material.

little over 20 percent of lowland forests remain in G2G condition while 70 percent of upland forests above 1500 m elevation are intact. Soil type and geology also had a strong effect on forest condition. Only 3 percent of G2G forests on rich alluvial soils remain while forests on mafic soils were generally in the best condition at every elevation (Table 1). The top two endangered forest types were alluvial sites below 850 m elevation while lowland forest on limestone ranked third (Fig. 3). These patterns closely follow soil fertility and site accessibility trends, with lowland alluvium converting easily into productive agricultural land while marginal upland forests on

TABLE 2. *Top 20 existing protected areas on the island of Sulawesi ranked by forest condition, negative and positive forest status, simulated change, endangered forest types, and overall size. Forest status ranges from −1 to 1 but absolute values are given under both positive and negative columns. Code refers to Figure 5. The numbers in parentheses represent the rank of each proxy measure for each PA. The italicized row, without a code, represents the unprotected areas on the island. The top 10 sites in each category are in bold-faced type. See Methods for detailed description of ranking system.*

Protected area name	Total rank	code	Forest condition	Positive status	Negative status	Simulated change	Forest type	Size (Kha)
Cagar Alam Morowali	82	a	2.55 (14)	0.43 (24)	**0.42 (08)**	−0.08 (22)	**09.7 (10)**	**199 (04)**
Suaka Margasatwa North Buton	95	b	2.51 (13)	**1.33 (09)**	0.06 (37)	−0.04 (27)	**13.3 (04)**	**142 (05)**
Suaka Margasatwa Nantu	97	c	**2.08 (05)**	0.84 (14)	0.07 (32)	−0.01 (30)	**12.0 (05)**	034 (11)
Cagar Alam Doku	98	d	**1.99 (02)**	0.77 (16)	0.09 (29)	−0.02 (29)	**10.3 (08)**	020 (14)
Taman Nasional Bogani-Nani Wartabone	101	e	**1.88 (01)**	1.13 (13)	0.05 (38)	0.01 (40)	**10.6 (07)**	**277 (02)**
Cagar Alam Gunung Sojoli	103	f	2.74 (19)	0.34 (32)	**0.44 (07)**	−0.18 (17)	06.4 (20)	**063 (08)**
Taman Nasional Rawa Aopa Watumohai	104	g	3.50 (31)	0.64 (18)	0.36 (12)	−0.19 (14)	05.7 (23)	**108 (06)**
Suaka Margasatwa Lombuyan I-II	105	h	2.63 (16)	**1.56 (06)**	0.14 (22)	−0.07 (24)	**09.8 (09)**	003 (28)
North and South Karakeleng	107	i	**2.12 (08)**	**1.65 (04)**	0.01 (40)	0.02 (41)	**18.6 (02)**	029 (12)
Cagar Alam Gunung Ambang	107	j	2.85 (21)	0.58 (19)	0.32 (14)	−0.12 (19)	07.5 (19)	019 (15)
Taman Wisata Alam Tirta Rimba	108	k	3.04 (22)	1.18 (11)	0.16 (21)	−0.14 (18)	09.0 (12)	005 (24)
Cagar Alam Panua	110	l	2.77 (20)	0.58 (20)	0.12 (25)	−0.10 (21)	08.7 (15)	**049 (09)**
Suaka Margasatwa Gunung Manembo-nembo	111	m	2.46 (12)	**1.73 (03)**	0.06 (34)	−0.18 (16)	04.2 (25)	007 (21)
Cagar Alam Bantimurung	114	n	**2.23 (09)**	**1.44 (07)**	0.09 (27)	0.00 (35)	**10.7 (06)**	002 (30)
Not Protected	*114*		*3.48 (30)*	*0.35 (31)*	***0.40 (10)***	*−0.19 (15)*	*03.4 (27)*	***16K (01)***
Cagar Alam Tinombala	118	o	**2.05 (03)**	0.46 (21)	0.10 (26)	0.02 (42)	08.4 (16)	**035 (10)**
Taman Nasional Lore Lindu	118	p	**2.08 (06)**	0.71 (17)	0.08 (31)	0.03 (44)	08.2 (17)	**208 (03)**
Suaka Margasatwa Pinjam / Tanjung Mantop	118	q	2.42 (11)	**1.78 (02)**	0.14 (23)	0.05 (46)	**16.7 (03)**	002 (33)
Cagar Alam Pegungunan Faruhumpenai	120	r	2.56 (15)	0.37 (29)	0.25 (17)	−0.03 (28)	04.8 (24)	**094 (07)**
Cagar Alam Tanjung Api	121	s	**2.10 (07)**	**2.03 (01)**	0.00 (46)	0.00 (35)	**23.8 (01)**	002 (31)
Taman Wisata Alam Lejja	127	t	2.64 (17)	0.39 (26)	0.13 (24)	−0.11 (20)	06.2 (21)	008 (19)

poor soils are avoided. The heavily populated southwestern arm is almost entirely converted into intensive agriculture and urban areas. Mangroves and wetlands are critically endangered with less than 5 percent and 1 percent undisturbed, respectively. The smaller island archipelagos have little forest cover. Montane and tropalpine forests were not considered to be endangered, with a substantial majority of these sites across the island still in G2G condition.

The nonlinearity of the relationship between forest condition and composite landscape score (Fig. 1) indicates that most G2G forest is concentrated on a relatively small range of landscapes and the co-occurrence of relatively few vulnerabilities at a site are correlated with a rapid decline in condition, although there is considerable variation. Unfortunately, this variation in forest status is largely negative: very few ‘old-growth’ sites have more than half the possible composite landscape setting score and none have the maximum while a much larger proportion of ‘converted’ sites have a low composite landscape score and some even have the minimum (Fig. 1). The forest status map (Fig. 4) illustrates the difference between the two distinct categories of ‘positive’ and ‘negative’ status. Positive status is concentrated in G2G areas adjacent to large population centers or near the coastline. These areas are also associated with existing PAs, indicating that these areas do perform a protective function (Curran *et al.* 2004). The importance of these PA for supporting bird diversity on the island has been clearly demonstrated (Lee *et al.*, in press).

The simulated forecast for forest change indicate that the rate of forest conversion should slow down substantially in the near future, as most sites that are easily converted have already met this fate. Future large-scale conversion, if it occurs, will probably be of a different nature, in which marginal gains and specialized techniques are pursued. The majority of the forecasted conversion occurs in the southwestern arm, where disturbance has already been quite heavy and much of the remaining forest is fragmented and vulnerable to conversion. Once the forest conversion slows down, the simulation reaches a stationarity where slightly more forest appears to be recovering than declining. This result should be expected because it uses static estimators for highly variable landscape parameters like human population, extraction activity, and road densities. No accurate trend data are available for the ecoregion for these parameters and a simultaneous forecast analysis for these landscape parameters has not yet been attempted.

The top 20 sites for the existing PAs and CPs (Fig. 5; Tables 2 and 3; see Tables S1 and S2 for a complete list of these sites) generated by our modular ranking system include major sites in all of the biogeographic regions, without designing this objective into our approach. This added complementarity of the top ranking

TABLE 3. *Top 20 conservation portfolio sites on the island of Sulawesi ranked by forest condition, negative and positive forest status, simulated change, endangered forest types, and overall size. Forest status ranges from −1 to 1 but absolute values are given under both positive and negative columns. Code refers to Figure 5. The numbers in parentheses represent the rank of each proxy measure for each CP. The italicized row, without a code, represents the areas not included in the portfolio. The top 10 sites in each category are in bold-faced type. See Methods for a detailed description of ranking system*

Conservation portfolio site name	Total rank	Code	Forest condition	Positive status	Negative status	Simulated change	Forest types	Size (Kha)
Taman Nasional Bogani Nani–Wartabone & environs	165	A	**2.08 (05)**	1.14 (13)	0.06 (67)	0.00 (68)	**11.1 (08)**	**659 (04)**
Wakuru, Ereke, and Cagar Alam Kakenawe	166	B	2.92 (32)	1.15 (12)	0.11 (55)	−0.15 (43)	**11.9 (07)**	218 (17)
Western Sulawesi Highlands	177	C	**2.02 (02)**	0.65 (38)	0.18 (40)	−0.03 (62)	06.0 (28)	**398 (07)**
Cagar Alam Morowali and environs	178	D	2.45 (17)	0.51 (47)	0.28 (31)	−0.04 (58)	08.5 (19)	**456 (06)**
Boloyohuto	190	E	**2.35 (10)**	**1.80 (05)**	0.03 (75)	−0.17 (38)	**13.1 (05)**	016 (57)
Panna	190	F	2.43 (15)	0.90 (23)	0.46 (14)	−0.21 (34)	00.2 (58)	031 (46)
Balingara and Lombuyan Mts.	191	G	**2.35 (09)**	0.77 (28)	0.12 (52)	−0.01 (66)	06.4 (26)	**318 (10)**
North and South Karakelang	193	H	2.36 (12)	**1.57 (07)**	0.04 (70)	−0.03 (61)	**16.9 (04)**	047 (39)
Kolaka	196	I	2.61 (23)	0.87 (26)	0.09 (59)	−0.03 (60)	**10.2 (10)**	213 (18)
Polahi-Marissa Forest Complex	198	J	2.43 (16)	0.56 (45)	0.11 (56)	−0.02 (63)	08.7 (16)	**1K (02)**
Northern Tip of Sulut	198	K	3.37 (51)	0.62 (41)	0.20 (35)	−0.32 (19)	03.6 (40)	280 (12)
Poleang	204	L	2.85 (31)	0.76 (30)	0.19 (38)	−0.15 (42)	09.4 (15)	026 (48)
Taman Nasional Lore Lindu and environs	205	M	**2.19 (06)**	0.68 (36)	0.13 (50)	0.02 (79)	08.1 (20)	252 (14)
Sungai Budong-Budong	206	N	2.55 (19)	0.34 (61)	0.26 (32)	−0.06 (54)	05.8 (31)	**325 (09)**
Mengkoka Tangkele Boke Abuki	207	O	2.35 (11)	0.45 (50)	0.11 (54)	0.00 (76)	10.1 (11)	**501 (05)**
West Poso	207	P	2.73 (29)	0.51 (48)	0.38 (20)	−0.08 (52)	03.5 (43)	244 (15)
Lambusango Lasalimo	212	Q	3.21 (45)	0.91 (22)	0.16 (45)	−0.11 (48)	06.0 (29)	122 (23)
Taman Wisata Alam Nanggala III	214	R	3.08 (40)	0.43 (52)	0.36 (23)	−0.30 (22)	00.2 (57)	176 (20)
Faruhumpenai and East Poso region	215	S	2.72 (28)	0.39 (54)	0.19 (39)	−0.11 (47)	05.1 (36)	314 (11)
Taman Nasional Rawa Aopa Watumohai	219	T	3.56 (59)	0.61 (42)	0.37 (22)	−0.20 (36)	05.3 (35)	116 (25)
Area not in portfolio	*240*		*4.20 (75)*	*0.14 (77)*	***0.59 (07)***	*−0.30 (24)*	*05.6 (56)*	***8K (01)***

sites was probably due to the advantageous starting point of the PA, chosen by the Indonesian government to adequately represent the biotic diversity on the island, and the CP, generated by the ECA. Additionally, sites with a wide range of total land areas were determined to be a high priority, for example the tiny PA Tanjung Api (Fig. 5s), which contains an extremely isolated and threatened island of lowland forest in remarkably good condition. Other small PAs are embedded within low-ranking, poor quality CPs (Figs. 5n, t), representing tiny and highly threatened islands of valuable forest. Most CP sites contain at least one small PA within them, although in several instances the relative areas differ dramatically. In the southeastern arm, a large CP site (Fig. 5I) contains a tiny recreation park (k), both independently making the list. Large areas of important habitat are without federal government protection, particularly in the western central highlands (Fig. 5C, F, N, R). The upland areas in the southeast (O) is the single largest high-ranking but unprotected CP.

The hexagonal grid within these high-ranking sites seems to have done an effective and intuitive job of identifying the conservation frontlines, through the more detailed ranking of the individual ranking of the grid cells (hexgrids) and choosing those with the highest rank (Fig. 5, red hexagons). Again, without having built the objective into the ranking system, most high-ranking hexgrids lie at the frontier between conservation sites and neighboring human population centers, roads, and disturbed areas. These highlighted frontier regions represent critical access points for disturbance to particularly valuable and vulnerable habitat. Remarkably, several examples from the Lore Lindu National Park (Fig. 5M, p) match the exact locations of previous and current land disputes (Acciaioli 2004), indicating that landscape parameters can be good predictors for future land conflicts (Wessels *et al.* 1999). On the other hand, within the large CP site of the Polahi-Marissa forest complex (Fig. 5J), most of the frontlines are vital battlegrounds deep within the proposed conservation area, created by logging activities in the largest areas of remaining lowland and hill forest on the island.

Three ranking categories were particularly important in valuing these different conservation sites: forest condition, presence of endangered forest types, and overall size (Tables 2 and 3). Top 10 ranking sites for these three categories were likely to be among the top 20 but the rankings across these categories are only highly correlated in a few examples. Positive forest status was a relatively strong indicator as well, particularly for the PA, which is reassuring and makes intuitive sense because these areas have been under active protection and should be in better condition than their landscape setting might suggest. Conversely, the highest ranking protected

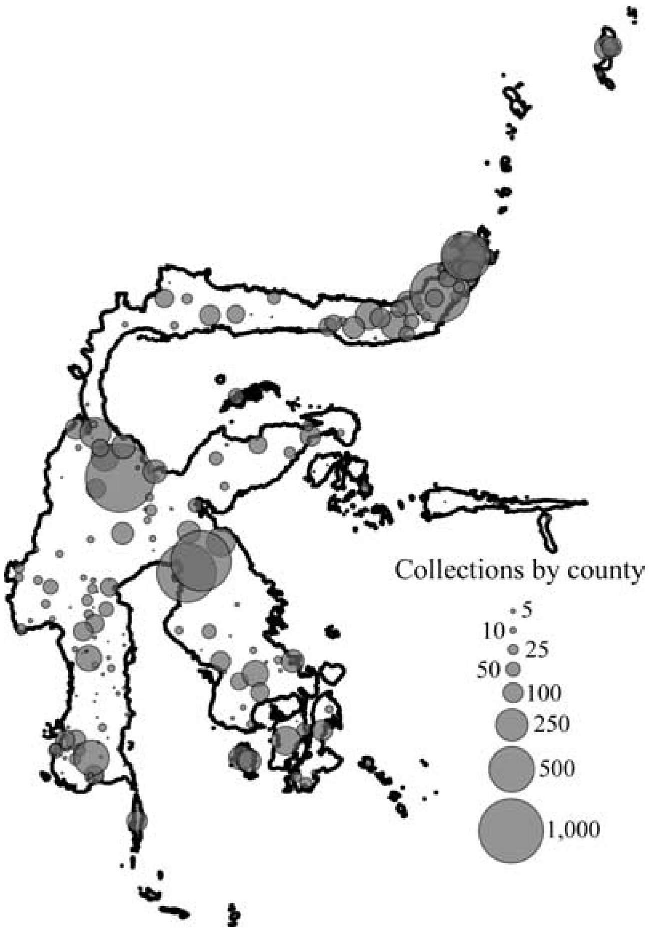

FIGURE 6. The geographic distribution of plant collections on the island of Sulawesi. The number of plant collections in the data base of the National Herbarium of the Netherlands (Leiden) was counted for each kecamatan or county. The diameter of the circles centered upon each county indicates the number of collections that have been made in each county.

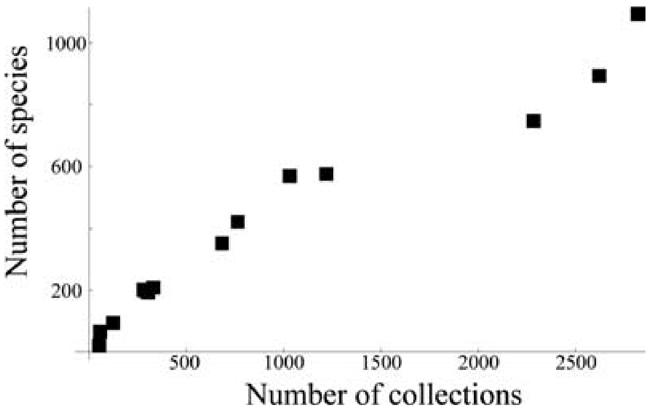

FIGURE 7. The relationship between plant collection density and species diversity on the island of Sulawesi. Each black square represents a major biogeographic region.

area, Morowali (Fig. 5a), was among the highest ranking forest of negative status, indicating that this area needs immediate and positive action to prevent further decline. The highly ranked sites of forecasted forest decline played little part in either composite ranking, indicating that the majority of the immediate and most probable change is still likely to occur outside of the CP and PA sites. This bias was partially built into the selection strategy for the CP. The fact that areas outside the current PA system were ranked 14th in our list indicates that several of the existing elements of this system are not performing well.

The geographic distribution of plant collections from the National Herbarium of the Netherlands is clearly focused on three small portions of the ecoregion: the northeastern arm, the environs of Lore Lindu National Park, and the Soroako INCO mining complex (Fig. 6). Several large regions of the island are known from a very small number of collections, particularly the western highlands and coastal areas, the western and middle portions of the northern arm, and the central southeastern arm. This geographic bias in collection history obviously has a direct effect on the observed species diversity measures, as collection density by biogeographic region has a linear relationship with number of unique species observed (Fig. 7). There is no relationship between the size of an area and plant species diversity or collection history.

DISCUSSION

The conservation of natural resources and ecosystems in the tropics is an inherently multivariate issue, particularly in poorly known and rapidly changing ecoregions like Sulawesi. We feel that no single strategy for developing priorities can supply appropriate results for all conservation objectives in all locations. Additionally, we feel that all conservation organizations should not join together under the exact same agenda but should each pursue their own agenda, in collaboration and cooperation with other groups. In this way, efforts will be diversified. Our map of important conservation frontiers on the island of Sulawesi, including the detailed geographic locations of major frontlines within these sites, provides an immediate and pragmatic tool for developing a wide variety of strategies. Our map is based upon transparent reasoning, involves a wide range of remotely sensed parameters and models, and allows each site and frontline to be categorized according to specific aspects of its landscape setting and forest cover status. Using our results as a base map, any conservation organization can readily target those areas that supply the best set of objectives for their own specific conservation values, whether it is to conserve habitat or prevent extinction of a particular group of organisms.

Overall, the rankings of the CP and existing PA sites were largely congruent with current conservation activities on the island, including Wildlife Conservation Society's longterm activities in the Bogani-Nani Wartabone National Park, Operation Wallacea's extensive training and research activities on Buton Island, and The Nature Conservancy's presence in Lore Lindu National Park. Our top 20 CP sites also point toward important areas to be actively incorporated into the federal protection system, particularly in the western highlands and southeastern hill forests. Because our ranking system is modular and can be weighted according to different conservation objectives, natural resource managers and policy makers can easily examine the individual rankings of this hexgrid system and identify different sets of frontlines, based upon more specific knowledge and objectives (rankings for hexgrids for all sites are available upon request).

This analysis was performed without reference to the biotic composition of these conservation sites. A heated debate recently occurred in the literature about this issue (Brooks *et al.* 2004, Cowling *et al.* 2004) but in many cases, it is a moot topic because the data are simply not available, nor are they likely to become available in the near future. Museum and herbarium collection records and reports of human hunting-gathering activity should be used cautiously because of the geographic biases inherent in the distribution of these data, as is apparent in the Leiden plant collection records for the ecoregion (Fig. 6). Given our current state of knowledge, these data should probably be used primarily to design future and more objective sampling regimes (Waltert *et al.* 2004). Heavily weighting biotic endemism or species richness, particularly when reliable data are only available for higher trophic level organisms, likely skew conservation priorities away from more fundamental aspects of the landscape, like overall forest integrity, its proclivity to change, and the endangerment of poorly sampled and understood forest types. Additionally, placing such emphasis on species richness and endemism can lead to a distortion of species concepts (Chaitra *et al.* 2004). Our results capture many of the conservation objectives central to most conservation organizations (Groves *et al.* 2002, Redford *et al.* 2003), without explicitly incorporating them into the design of the ranking system. In the future, the modular and flexible nature of this ranking system can easily be adapted to reliable biotic data as they become available. For example, some particularly charismatic or endangered members of an ecoregion, such as the maleo (*Macrocephalon maleo*) or anoa (*Bubalus depressicornis* and *B. quarlesi*), warrant their own category within this ranking system and this can easily be added by mapping these specific conservation priorities (Burton & Hedges 2005) and generating a new combined ranking, for that species in particular.

Using a relatively simple and transparent approach, we have produced a detailed map of the important conservation frontiers in a poorly known, but globally important ecoregion, using detailed analyses of readily available GIS data. Additionally, the critical frontlines in each one of these important sites were located in great geographic detail. This map can be used at all administrative levels, from the federal policy maker choosing future areas to incorporate into the national PA system down to the provincial and even local manager monitoring development and extraction activities. The separate categories within the total rank can be used by each of these decision makers to categorize the conservation importance of each conflict and specific strategies for each conservation site can be developed. This type of multifaceted understanding should provide conservation strategists a sound footing in the identifying the social, economic, and political drivers of land-use change in and around important high conservation value areas.

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SUPPLEMENTARY MATERIAL

The following supplementary material is available for this article online at: www.blackwell-synergy.com/toc/btp.

Appendix S1 The Nature Conservancy's Ecoregional Conservation Assessment.

Appendix S2 Position and date of satellite image acquisition.

Appendix S3 Detailed description of a 4-wk field survey, covering 17 different conservation sites scattered across the island of Sulawesi.

Appendix S4 Elevational zonation of plant species.

Appendix S5 Regression analysis for modeling forest status based upon landscape parameters.

Table S1 *Conservation rankings of Protected Areas (PA) on Sulawesi.*

Table S2 *Conservation rankings of Conservation Portfolio (CP) on Sulawesi.*

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