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INCREASING ISOLATION OF PROTECTED AREAS IN TROPICAL FORESTS OVER THE PAST TWENTY YEARS

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Abstract. Protected areas are one of the cornerstones for conserving the world's remaining biodiversity, most of which occurs in tropical forests. We use multiple sources of satellite data to estimate the extent of forest habitat and loss over the last 20 years within and surrounding 198 of the most highly protected areas (IUCN status 1 and 2) located throughout the world's tropical forests. In the early 1980s, surrounding habitat in the 50-km unprotected or less highly protected ''buffers'' enhanced the protected areas' effective size and their capacity to conserve richness of forest-obligate species above the hypothetical case of complete isolation. However, in nearly 70% of the surrounding buffers, the area of forest habitat declined during the last 20 years, while 25% experienced declines within their administrative boundaries. The loss of habitat occurred in all tropical regions, but protected areas in South and Southeast Asia were most severely affected because of relatively low surrounding forest habitat in the early 1980s and high subsequent loss, particularly in dry tropical forests. The future ability of protected areas to maintain current species richness depends on integrating reserve management within the land use dynamics of their larger regional settings.

Key words: biodiversity; deforestation; isolation; land use change; protected areas; remote sensing; satellite data; tropical forest.

INTRODUCTION

Tropical forests are a primary conservation focus because (1) they contain about two-thirds of the world's plant and animal species (Raven 1980) and (2) they are currently under threat from logging (see Plate 1), clearing for agriculture, and other types of land use change. Protected areas are central to conservation strategies designed to safeguard remaining habitats and species. Forest habitat outside the established administrative boundaries augments a protected area's capacity to conserve species richness for several reasons: larger population sizes decrease risks of extinction (Pimm et al. 1988); animal species can access critical habitats outside reserve boundaries (Hansen and Rotella 2002); and exposure to edge effects and human pressures such as invasive species, fire, and hunting is reduced (Woodroffe and Ginsberg 1998, Brashares et al. 2001, Brooks et al. 2002, Laurance et al. 2002). Empirical studies have established the positive relationship that often exists between habitat area and species richness (Brooks et al. 1997, Pimm and Raven 2000). Habitat loss surrounding protected areas therefore could reduce their conservation capacity, even if habitat is maintained within their administrative boundaries (Hansen and Rotella 2001; Hansen et al., *in press*).

In this study, we use multiple sources of satellite data to examine the extent of existing forest habitat and loss in the last two decades throughout the world's moist and dry tropical forests. We quantify the current extent and loss of forest habitat both within and surrounding 198 protected areas with the highest protection status (totaling 163 and 35 areas in moist and dry tropical forest, respectively) over the past 20 years. We assess implications for the future capacity of these areas to conserve species richness. Spatially explicit information on forest cover conversion throughout the tropics has not previously been available to identify locations of most rapid change, beyond satellite analysis in selected locations (Skole and Tucker 1993, Achard et al. 2002) and assessments aggregated at the national scale (FAO 2000). This lack of comprehensive spatial information has precluded pinpointing where forest conversion is eroding the ability of protected areas to maintain biodiversity and developing compensatory conservation strategies.

DATA AND METHODS

Our previously published satellite analyses (DeFries et al. 2002, Hansen et al. 2003; Hansen and DeFries, *in press*) provide the basis for determining forest extent and loss within and surrounding a sample of protected areas over the last 20 years. Here we assess the effect

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PLATE 1. Logging in the state of Mato Gosso, Brazil. Photo credit: R. DeFries.

of the observed changes in forest extent on the capacity of these protected areas to conserve species richness. The data and methods for carrying out the analysis are as follows.

Selection of sample of protected areas

The sample includes 198 protected areas located throughout moist and dry tropical and subtropical forests (see the Appendix). The sample includes protected areas that are particularly important for conservation, based on their high degree of protection status, relatively large size, and the presence of intact forest in the early 1980s within their administrative boundaries.

Specifically, we use the following criteria to determine which protected areas to include in the study: (1) those located in moist or dry tropical and subtropical forests, as delineated by Olson et al. (2001); (2) those with a high protection status of 1a (strict nature reserve), 1b (wilderness area), or 2 (national park), as defined by the International Union for the Conservation of Nature (IUCN 1994); (3) those with reserve boundaries delineated in the World Database on Protected Areas developed by United Nations Environment Program (UNEP) World Conservation Monitoring Center (WCMC) in collaboration with the IUCN World Commission on Protected Areas (*available online*);[7] (4) reserve size >25 600 ha to cover at least four pixels in the coarse-resolution satellite data (see satellite data methods); and (5) forest cover >60% in the protected area in the early 1980s.

Application of the first three criteria yielded 468 reserves and the fourth and fifth criteria yielded the final sample of 198 reserves (163 in moist and 35 in dry forests). Note that the database from which the sample was derived does not include all highly protected areas, only those with delineated boundaries.

Satellite analysis for determining current extent and changes in forest habitat

We derive the area of forest habitat from the Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Continuous Fields (VCF) product (Hansen et al. 2003). The VCF product depicts the percentage of tree cover at a 500-m resolution using a supervised regression tree algorithm and training data derived from high-resolution Landsat data applied to seven bands of MODIS data acquired October 2000–December 2001. The product depicts tree cover at the peak of the growing season. Using a definition of forest as >80% tree canopy cover, we calculate the percentage of forest cover within each 500-m pixel. This percentage provides the subpixel area within each 500-m pixel containing forest cover. The percentage multiplied by the area of the pixel (500 $\times$ 500 m) provides an estimate of the forest cover within the pixel. The VCF data set is publicly available online through the University of Maryland Global Land Cover Facility;[8] it is also distributed as a MODIS Land product.

To identify locations with loss of forest habitat over the last two decades, we use high-resolution Landsat

[7] ⟨http://www.unep-wcmc.org/protected_areas/⟩

[8] ⟨glcf.umiacs.umd.edu⟩

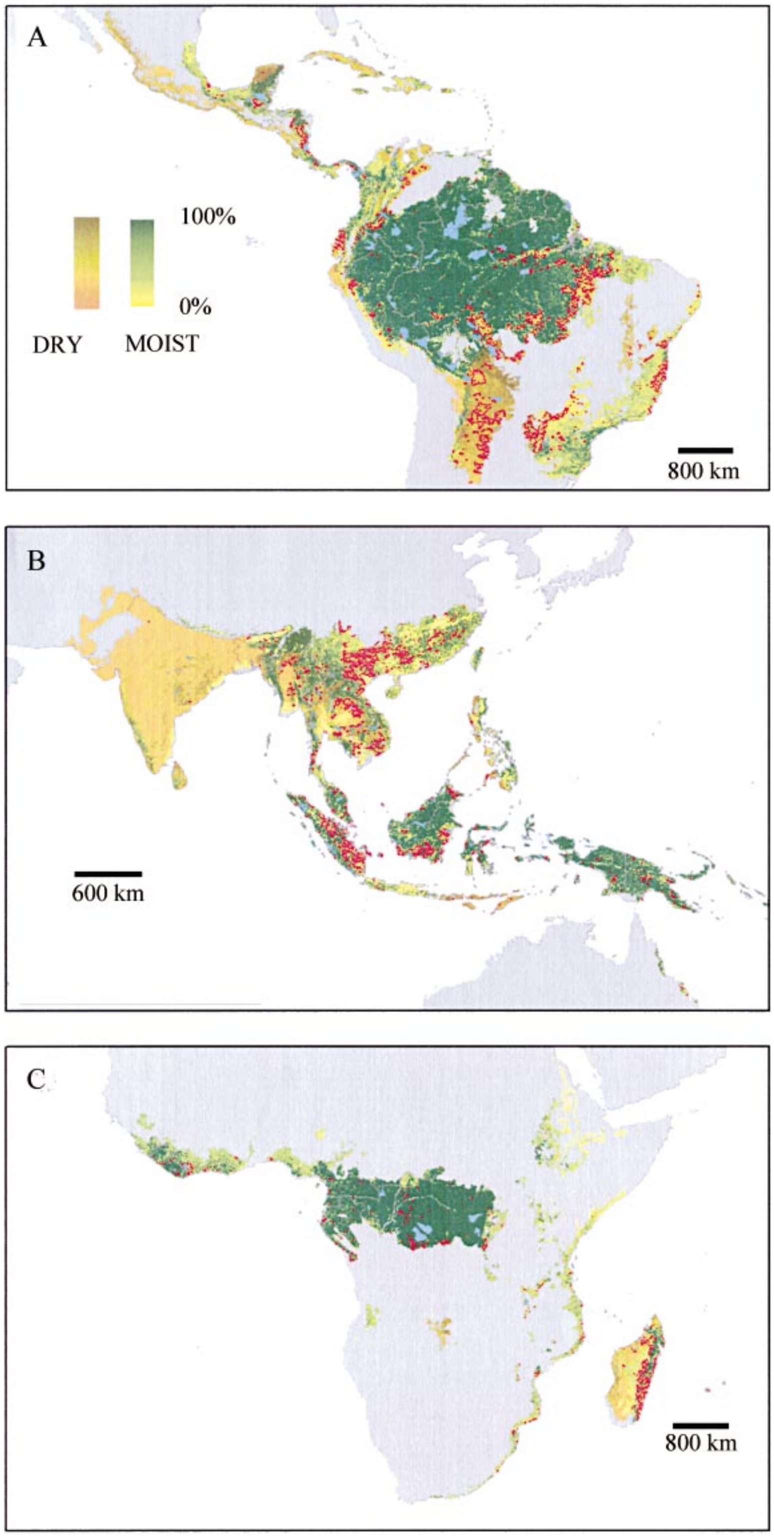

FIG. 1. Percent cover of forest estimated from 500-m MODIS data acquired October 2000–December 2001 in moist tropical and subtropical forest (yellow to green color bar) and dry tropical and subtropical forest (tan to olive color bar) as delineated by Olson et al. (2001) in Latin America (top), South and Southeast Asia (middle), and Africa (bottom). Locations of decline in forest cover between the early 1980s and 2001 are outlined in red. Protected areas included in this study are shown in blue.

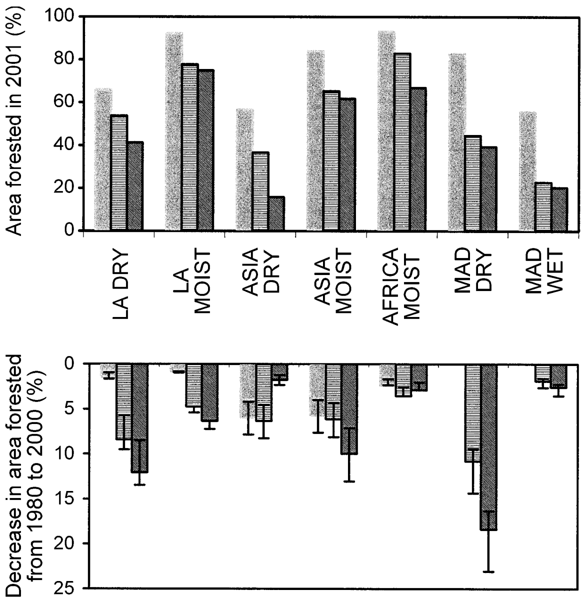

FIG. 2. (Top) Estimated percentage area forested in the year 2001 within the administrative boundaries of the protected areas (gray), within the 50-km buffer of the protected area (horizontal stripe), and within total ecoregion (diagonal stripe). (Bottom) The estimated decrease in percentage of area forested from the early 1980s to 2000. Abbreviations (with total habitat area as delineated by Olson et al. [2000] in millions of square kilometers in parentheses) are: LA DRY, Latin American Dry Forests (1.8); LA MOIST, Latin American Moist Forests (9.2); ASIA DRY, South and Southeast Asia Dry Forests (3.7); ASIA MOIST, South and Southeast Asia Moist Forests (6.0); AFRICA MOIST, African Moist Forests (3.3); MAD DRY, Madagascar Dry Forests (0.3); MAD WET, Madagascar Moist Forests (0.3). Error bars represent the range of estimates for decrease in forest cover based on correction factors for calibrating AVHRR and Landsat-derived estimates (see DeFries et al. 2002).

analyses in locations where they are available, combined with the coarser resolution Advanced Very High Resolution Radiometer (AVHRR) Pathfinder Land data from 1982 to 2000 as published in DeFries et al. (2002) and Hansen and DeFries (*in press*). The AVHRR data are the only globally comprehensive satellite observations available for a time series spanning the last two decades. The procedure estimates subpixel percent cover of trees for each year in the time series, using regression tree analysis with multitemporal metrics derived from monthly values of the five AVHRR spectral bands and the Normalized Difference Vegetation Index and training data (61 222 pixels) derived from high-resolution Landsat data. Training data represent percent cover of trees in locations where change is unlikely to have occurred in the 18-year time interval. We use these data where change has not occurred to distinguish ''noise'' from actual change. We label a grid cell as ''change'' if the difference in percent cover of trees exceeds a threshold corresponding to two standard deviations from the mean difference between time periods for the training-site locations (~14%). To minimize noise and obtain a representative annual change value, we derive estimates for three 5-year intervals (1982–1987, 1988–1992, and 1992–1999) by using the median change value for the interval. We use the difference between the first and second interval to represent changes in the 1980s and the difference between the second and third interval to represent 1990s. The standard error (standard deviation of residuals) as compared with training data for the three 5-year intervals is 11.03% and 10% to 20% compared with field observations (Hansen et al. 2002).

Because the coarse 8-km AVHRR resolution probably underestimates changes in percent cover, we use a correction factor based on Landsat analyses as relevant as possible to each region, ranging from 1.5 in Latin America, where clearing generally occurs in large, contiguous patches, to 3.7 in Africa, where clearing occurs on a much finer scale. The correction factors are determined by correlating forest loss derived from high-resolution (30 m) Landsat data with the AVHRR estimates (see DeFries et al. [2002] for Landsat data sets and correction factors). We adjust the area of change in the AVHRR-derived percent cover of trees (the product of the difference in percent cover of trees and the pixel area) by the correction factor to estimate changes in area of forest cover.

Determination of forest cover loss within and surrounding protected areas and implications for capacity to conserve species richness

For each protected area in the sample, we estimate the percent cover of forest for 2001 using the MODIS Vegetation Continuous Fields within the boundaries of the protected areas, within a periphery of the protected area, and within the entire ecoregion. We use the AVHRR data calibrated with Landsat analyses to estimate the change in percent cover of forest since the early 1980s. We report here results from the surrounding area as 50 km from the perimeter of the protected area, an arbitrary but reasonable distance to capture ecological interactions between the protected area and its surroundings. We carried out identical analyses for distances of 25, 75, and 100 and found similar values for percent cover of forest and changes over the last 20 years as we detected for the 50-km buffer.

We illustrate the possible implications of the loss of forest cover within and surrounding the protected areas for one protected area by calculating the species richness capacity (SRC) for the early 1980s and 2001 relative to the species richness capacity assuming fully intact forest. The species–area relationship states that $S = cA^z$, where S is species richness, A is area, and c and z are constants (Rosenzweig 1995). The relative capacity of the reserve to conserve species richness is then $(A_{it} + A_{st}/A_{ii} + A_{si})^z$, where A_{it} and A_{st} represent area of habitat inside and surrounding the protected area, respectively, at time t, and A_{ii} and A_{si} represent the areas for fully intact habitat (Brooks et al. 1999).

TABLE 1. Estimated mean forest area as a percentage of total area inside the administrative boundaries and in the surrounding 50-km buffer for protected areas in the sample for the early 1980s and 2001.

Region	No. and size protected areas		No. with forest loss		Mean forest area (%)			
					Inside		50-km buffer	
	Total no. sampled	Mean size (km^2)	Inside	50-km buffer	Early 1980s	2001	Early 1980s	2001
Latin America								
Moist	78	4089 (5636)	18	47	88.0 (9.9)	86.9* (10.3)	79.7 (17.7)	74.9** (18.9)
Dry	7	4179 (5505)	2	6	62.4 (24.2)	62.0 (24.2)	56.8 (22.9)	51.5 (18.4)
South and SE Asia								
Moist	70	1565 (2082)	18	52	82.3 (11.6)	79.6** (12.6)	69.0 (19.2)	63.6** (19.0)
Dry	25	762 (480)	6	12	60.5 (17.5)	55.1† (13.4)	42.3 (17.8)	36.6* (15.2)
Central Africa								
Moist	12	5940 (10 069)	5	10	85.5 (17.2)	83.6 (20.0)	79.8 (24.5)	76.2† (27.2)
Dry	1	1500	0	0				
Madagascar								
Moist	3	659 (151)	0	3	85.7 (10.7)	85.7 (10.7)	57.6 (18.5)	45.0* (18.7)
Dry	2	1063 (647)	0	1	55.9 (0.9)	55.9 (0.9)	24.8 (0.2)	21.9 (3.9)
All								
Moist	163	3078 (5102)	41	112	85.3 (11.5)	83.5** (12.6)	74.7 (19.5)	69.6** (20.5)
Dry	35	1484 (2722)	8	19	60.5 (17.9)	56.6† (15.4)	44.4 (19.4)	39.1** (16.7)

Notes: Standard deviations are shown in parentheses. Results of two-tailed paired *t* tests for the difference in mean forest area between the two dates are indicated by symbols (†, *) in the ''2001'' columns.
† $P < 0.10$; * $P \leq 0.05$; ** $P \leq 0.01$.

We define this quantity as the species richness capacity (SRC) for the analysis presented here. Because there is a time lag between loss of habitat and species extinction, reductions in SRC reflect local extinctions that may have already occurred, as well as the loss of capacity to maintain species richness in the future (Pimm and Raven 2000). Two hypothetical extremes bound a protected area's SRC: fully intact forest cover within the protected area and its surroundings (SRC = 1), and fully eroded forest cover in the surrounding area where the SRC value depends on the size of the protected area and the current forest cover within the boundaries. Most protected areas fall between these extremes.

The value for *z* varies depending on characteristics such as habitat condition, taxa of interest, degree of isolation, and spatial scale (Rosenzweig 1995, Veech 2000, Hubbell 2001). In keeping with previous studies of fragmented tropical landscapes, we use a *z* value of 0.25 as a best estimate (Pimm and Raven 2000, Brooks et al. 2002) with lower and upper bounds of 0.15 and 0.40, respectively, based on the general range found in empirical studies (Hubbell 2001). The method to estimate SRC assumes that all area within and surrounding the protected areas would be suitable forest habitat if intact, a reasonable assumption because only those protected areas located within moist and dry tropical and subtropical forested ecoregions are included in the study. It also assumes that all non-forest habitat is completely unsuitable for forest-dwelling species, which is challenged by other studies (Ricketts et al. 2001, Horner-Devine et al. 2003).

RESULTS AND DISCUSSION

Our analysis indicates that the percentage of forested area in 2001, relative to the total area of ecoregions within each respective continent and forest type, as delineated by Olson et al. (2001), varies from ~16% in dry forests of South and Southeast Asia to 74% in Latin American moist forests (Figs. 1 and 2). Within the protected areas included in the sample, the percentage of forest cover is substantially higher, as expected, ranging from 55% to 92%. 50-km buffers surrounding protected areas are intermediate between the two, possibly reflecting the remoteness of protected areas, less intense land use surrounding them, or, in some cases, managed land use in designated buffer areas.

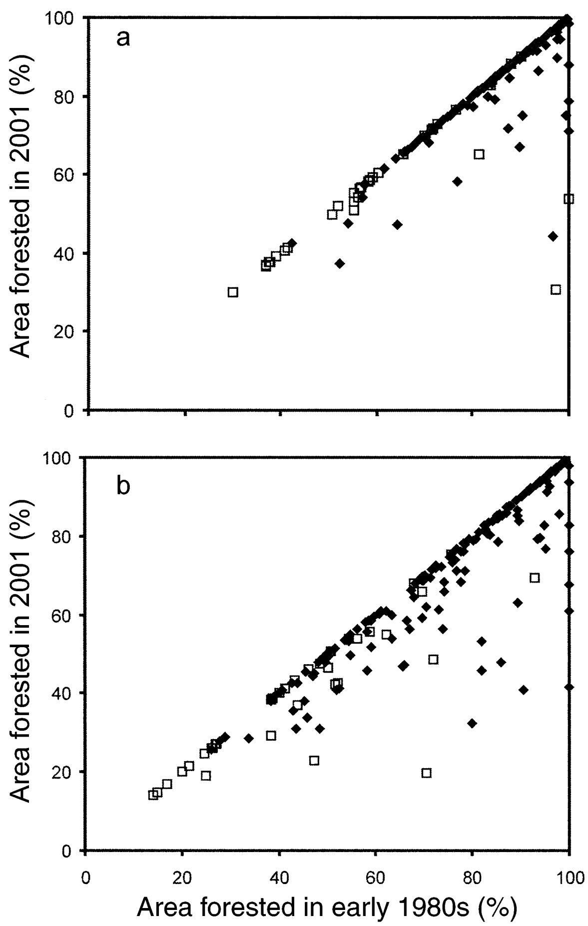

FIG. 3. Estimated percentage of area forested relative to fully intact forest habitat (a) within the administrative boundary of protected area and (b) within the surrounding 50-km buffer, for the early 1980s and 2001 for 198 protected areas in the sample. Solid diamonds represent protected areas in tropical and subtropical moist forest, and open squares represent protected areas in dry forest.

Of all the continents and forest types, dry forests of Latin America and Madagascar experienced the greatest decreases over the last 20 years in percentage of area forested (relative to total habitat area): 12% (0.22×10^6 km^2 decrease) and 18% (0.06×10^6 km^2 decrease), respectively (Fig. 2). In terms of absolute loss of forest habitat, however, the greatest loss occurred in moist forests of Latin America (0.58×10^6 km^2) and South and Southeast Asia (0.60×10^6 km^2).

Within the administrative boundaries of protected areas, loss of forest cover occurred in 25% of those located in moist forest and 23% in dry forests (Table 1). Of these, 9% declined by more than 5% forest area. Our result indicating no or little loss of habitat for the majority of protected areas is in keeping with the questionnaire-based conclusion of Bruner et al. (2001) that protection is generally effective in protected areas. There are, however, exceptions where substantial loss of habitat inside administrative boundaries has occurred (Fig. 3 and Appendix). Loss of forest cover within the protected areas was greatest (mean of ~5%) in dry forests of South and Southeast Asia, where the protected areas are relatively small. Moreover, the percent cover of forest in this region was relatively low in the early 1980s, averaging 60.5% within administrative boundaries of protected areas and 42.3% in the surrounding 50 km.

In the periphery surrounding the protected areas in our sample, our analysis suggests that loss of forest habitat was considerable in the last 20 years (Fig. 3 and Appendix). Of protected areas, 69% in moist tropical forests and 54% in dry forests experienced a decline in forest habitat within 50 km of their periphery, with 28% and 29%, respectively, declining by more than 5% of the forest area. Moist forests of Madagascar suffered the greatest loss in the 50 km surrounding the protected areas, although there were only a small number of forests in the sample (Table 1). The average values mask substantial differences among individual protected areas. For example, between the early 1980s and 2001, the percent cover of forest in the surrounding 50 km periphery declined from 91% to 41% in San Rafael, Paraguay, and from 80% to 33% in Way Kambas in Sumatra, Indonesia.

One approach to assessing the consequences of the loss of forest habitat surrounding protected areas is to measure the loss of capacity to conserve species richness, calculated from the empirical species–area relationship as described under *Data and methods*. This approach suggests that, ~20 years ago, the presence of forest habitat outside the administrative boundaries of most protected areas enhanced their species richness capacity beyond the forest habitat within the boundaries alone. Despite little or no loss of forest habitat within their administrative boundaries over the past 20 years, reduction in forest habitat surrounding protected areas has reduced their capacity to conserve species richness. An example from Pacaás Novos, a protected area established in 1979 in the southwest of the Amazonian state of Rondônia, Brazil, illustrates the general phenomenon (Fig. 4). The satellite analysis indicates >93% forest cover both inside the protected area and in the surrounding 50 km in the early 1980s. Between then and 2001, the forest cover remained relatively stable within the administrative boundaries, declining by only 2%. Forest cover in the surrounding 50 km area, however, declined by 37%. Based on the species–area relationship, capacity to conserve species richness in the early 1980s was 99% of the fully intact case for Pacaás Novos (Fig. 4). By 2001, the decline in forest habitat in the surrounding area reduced the SRC to 94%. In the hypothetical case of complete isolation of Pacaás Novos in the future, the SRC would decrease to 65%. Such a severe decline is not likely to occur in reality, but is used here to illustrate the extreme case of complete isolation.

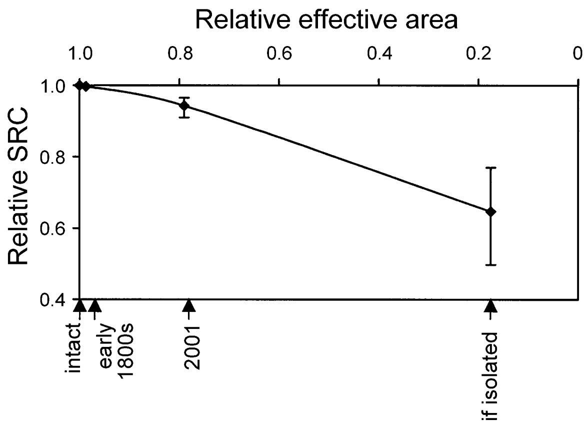

FIG. 4. Species richness capacity (SRC) for Pacaás Novos protected area in Rondônia, Brazil, for the early 1980s, 2001, and a hypothetical case of complete loss of surrounding habitat as a function of relative effective area (area of forest cover relative to fully intact forest habitat within protected area and surrounding 50-km buffer). Error bars represent the range of estimates using low (0.15) and high (0.50) *z* values. The midpoint uses a *z* value of 0.15.

The species–area approach for estimating the consequences of declining forest area surrounding protected areas is used here to illustrate, rather than to precisely quantify, the consequences for all protected areas in the sample. None of the protected areas, or their surrounding peripheries, can realistically be considered as isolated islands. The inherent assumption that species richness is not supported in areas outside fully forested habitat is questionable (Ricketts et al. 2001, Horner-Devine et al. 2003). Moreover, our sample includes protected areas with varying sizes and ecological characteristics. In some, migrations and dispersal between the protected area and the periphery may be crucial to the maintenance of species richness, whereas in others these processes may be less important. The loss of forest habitat surrounding protected areas throughout much of the tropics, as documented in this paper, illustrates the need to improve understanding of these interactions between protected areas and their surrounding areas.

The approach used here to assess the loss of forest habitat in and around tropical protected areas has several limitations. The satellite analyses of changes in forest cover are likely to underestimate the true loss in conservation capacity. First, they do not account for hunting, foraging, and other human pressures that contribute to species loss beyond that associated with loss of habitat area. Second, the satellite analysis cannot distinguish between native forests and forest plantations that are unsuitable for many species; therefore it potentially overestimates the area of forest habitat. Finally, the coarse resolution of the satellite data may not detect habitat degradation occurring in small patches due to factors such as selective logging (Nepstad et al. 1999). For these reasons, our estimates are conservative. On the other hand, the presence of surrounding land use practices that are conducive to conserving species richness, despite loss of forest habitat (Hughes et al. 2002), could enhance conservation capacity beyond the values reported in this analysis.

CONCLUSION

Over the last 20 years, >68% of protected areas in our sample of 198 relatively large, highly protected areas experienced loss of forest cover within a 50-km periphery of their administrative boundaries, in both moist and dry tropical forests. Substantially fewer (~25%) experienced loss of forest habitat within their administrative boundaries. Forest habitat surrounding the administrative boundaries of the protected areas enhances their capacity to conserve species richness by increasing their effective size and maintaining ecological processes that depend on interactions between the protected area and the surroundings. Because forest habitat is likely to continue to decline in the future, the loss of effective, as opposed to administrative, area heightens the imperative to manage protected areas within the land use dynamics of their larger regional setting (Margules and Pressey 2000). Options include promoting alternative livelihoods such as ecotourism for human populations in proximity to protected areas (Newmark et al. 1994), establishing networks of reserves connected by protected corridors and buffer zones to maintain critical elements of the landscape (Laidlaw 2000), and developing pricing and compensation mechanisms to value the ecosystem services provided by land in proximity to protected areas (Daily 1997). The loss of conservation capacity in the protected areas also underscores the critical conservation value of the remaining large tracts of tropical wilderness areas (Myers et al. 2000, Wilson 2002).

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APPENDIX

Tables showing protected areas included in the study are available in ESA's Electronic Data Archive: *Ecological Archives* A015-001-A1.