Deforestation Trends in a Tropical Landscape and Implications for Endangered Large Mammals

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Abstract: *The remarkable large-mammal fauna of the Indonesian island of Sumatra is one of the most endangered on Earth and is threatened by rampant deforestation. We used remote sensing and biological surveys to study the effects of deforestation on populations of endangered large mammals in a Sumatran landscape. We measured forest loss and created a predictive model of deforestation for Bukit Barisan Selatan National Park and an unprotected buffer area based on satellite images between 1985 and 1999. We used automatic cameras to determine the distribution and relative abundance of tigers (*Panthera tigris sumatrae*), elephants (*Elephas maximus*), rhinoceros (*Dicerorhinus sumatrensis*), and tapirs (*Tapir indicus*). Between 1985 and 1999, forest loss within the park averaged 2% per year. A total of 661 km^2 of forest disappeared inside the park, and 318 km^2 were lost in a 10-km buffer, eliminating forest outside the park. Lowland forest disappeared faster than hill/montane forest (by a factor of 6) and forests on gentle slopes disappeared faster than forests on steep slopes (by a factor of 16). Most forest conversion resulted from agricultural development, leading to predictions that by 2010 70% of the park will be in agriculture and that by 2036 lowland forest habitat will be eliminated. Camera-trap data indicated avoidance of forest boundaries by tigers, rhinoceroses (up to 2 km), and elephants (up to 3 km). Classification of forest into core and peripheral forest based on mammal distribution suggests that, by 2010, core forest area for tigers and rhinoceros will be fragmented and reduced to 20% of remaining forest. Core forest area for elephants will be reduced to 0.5% of remaining forest. Halting forest loss has proven one of the most difficult and complex problems faced by Indonesia's conservation agencies today and will require a mix of enforcement, wise land-use strategies, increased education, capacity to manage, and new financing mechanisms.*

Tendencias de Deforestación en un Paisaje Tropical y Sus Implicancias para Mamíferos Grandes en Peligro

Resumen: *La asombrosa fauna de mamíferos grandes de la isla indonesa de Sumatra es una de las más en peligro de extinción sobre la Tierra y esta amenazada por una deforestación incontrolable. Utilizamos percepción remota y prospecciones biológicas para estudiar los impactos de la deforestación sobre las poblaciones de mamíferos grandes en peligro en un paisaje de Sumatra. Medimos la pérdida de bosques y creamos un modelo predictivo de la deforestación para el Parque Nacional Bukit Barisan Selatan y para un área de amortiguamiento no protegida con base en imágenes de satélite entre 1985 y 1999. Utilizamos cámaras automáticas para determinar la distribución y la abundancia relativa de tigres (*Panthera tigris sumatrae*), elefantes (*Elephas maximus*), rinocerontes (*Dicerorhinus Sumatrensis*), y tapires (*Tapir indicus*). Entre 1985 y 1999 la pérdida de bosques dentro del parque promedió 2%/año. Un total de 661 km^2 de bosque desaparecieron dentro del parque, y se perdieron 318 km^2 en una zona de amortiguamiento de 10 km, eliminándose bosques fuera del parque. El bosque en tierras bajas desapareció más rápido que el bosque de lomerío o montano (por un factor de 6) y bosques en lomeríos suaves desaparecieron más rápido que el bosque en pendientes pronunciadas (por un factor de 16). La mayor conversión de bosque resultó del desarrollo agrícola, llevando a predicciones de que en 2010 el 70% del parque será agrícola y que en 2036 el hábitat para*

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bosque de tierras bajas habrá sido eliminado. Datos de cámaras automáticas indicaron la evasión de linderos de bosques por tigres, rinocerontes (hasta 2 km) y elefantes (hasta 3 km). La clasificación del bosque en bosque núcleo y periférico sugiere que para 2010, el bosque núcleo para tigres y rinocerontes estará fragmentado y reducido a 20% de bosque remanente. El bosque núcleo para elefantes estará reducido a 0.5% del bosque remanente. Detener la pérdida de bosques es uno de los problemas más difíciles y complejos que enfrentan las agencias indonesas de conservación y requerirá de una combinación de fuerza pública, estrategias de uso de suelo inteligentes, mayor educación, capacidad administrativa y nuevos mecanismos de financiamiento.

Introduction

Deforestation of tropical forests constitutes one of the greatest threats to biodiversity and the conservation of nature in the ongoing Sixth Extinction. One of the many responses of conservation biologists to this threat has been the development of an array of tools for measuring and monitoring deforestation, many of which use remotely sensed data from aircraft or satellite-mounted sensors (Asia Pacific Systems Engineering 2001; Saatchi et al. 2001; Sánchez-Azofeifa et al. 2001; Steininger et al. 2001). These remotely sensed data, however, tell only part of the story. Loss of tropical forest habitat through deforestation has many consequences that cannot be measured from satellite sensors (Turner et al. 2001), in particular the effects of deforestation on wildlife. Therefore, approaches that link remotely sensed estimates of forest loss with biological surveys on the ground are critical as conservation biologists seek to understand and prevent deforestation.

Indonesia provides one particularly pertinent example of the devastating effects of massive deforestation. Indonesia is one of the most biodiversity-rich and ecologically complex nations in the world. Although covering only 1.3% of the globe, the Indonesian archipelago accounts for nearly 10% of the world's remaining tropical forest (BAPPENAS 1993), making it second only to Brazil in forest area and the amount of biodiversity it harbors. Despite the country's extensive system of protected areas and production forests (forests available for logging), an abundance of detailed land-use plans, and enormous amounts of donor assistance, Indonesia's forest cover has declined dramatically in the past decade (Jepson et al. 2001; Whitten et al. 2001). Holmes (2002) reports that 20 million ha of Indonesia's forests have been lost since 1989, at an average annual deforestation rate of 1.7 million ha. Although 57 million ha of forest remain on the three main islands of Sumatra, Kalimantan, and Sulawesi, only 15% of this is lowland, nonswampy forest, which supports the highest biodiversity (MacKinnon 1997; Whitten et al. 2000, 2001).

Sumatra, Indonesia's second-largest island, is experiencing the most rapid deforestation in the archipelago (Holmes 2002). Over the last 12 years, the island has lost an estimated 6.7 million ha of forest, representing a 29% loss of forest cover, and Holmes (2002) predicts that Sumatra's nonswampy lowland forest will be gone by 2005. Loss of Sumatra's lowland forests, particularly those designated as protected areas, puts a large number of mammal populations at risk. Characteristic of its high levels of biodiversity, Sumatra has more mammal species (201) than any other Indonesian island, many of which are dependent on lowland forest ecosystems (Payne et al. 1985; Nowak 1991). The island is unusual in supporting populations of most of Asia's large mammals, including Sumatran rhinoceros (*Dicerorhinus sumatrensis*), elephants (*Elephas maximus*), Malayan tapir (*Tapir indicus*), serow (*Capricornis sumatraensis*), orangutans (*Pongo pygmaeus*), and gibbons (*Hylobates* spp.). Sumatra also has a large community of carnivores, including the Asiatic dhole (*Cuon alpinus*), the sun bear (*Helarctos malayanus*), and eight species of felids, most notably the endemic Sumatran tiger (*Panthera tigris sumatrae*). Several of these species exist in extremely small populations outside Indonesia (i.e., rhinoceros and elephant in peninsular and Bornean Malaysia and Indochina) or have been driven to extinction elsewhere in Indonesia (tigers on Java and Bali), underscoring the importance of Sumatra in biodiversity conservation.

The dramatic loss of Sumatra's forest cover is attributed to a variety of factors, including logging (legal and illegal), development of estate crops (primarily oil palm and pulpwood plantations), conversion to agriculture (by opportunistic settlers and those arriving through Indonesia's official transmigration program), and forest fires (Sunderlin 1999; Barber & Schweithelm 2000; Whitten et al. 2000; Barr 2001; Robertson & van Schaik 2001; Holmes 2002). The amount of forest loss attributable to each of these actions and the complicating effects of the Asian financial crisis are highly contested, are often political, and may vary across the island (Sunderlin 1999; Robertson & van Schaik 2001). What is certain, however, is that extinction of Sumatra's lowland forests will result in a landscape dominated by agriculture and scrubland with isolated patches of forest on inaccessible steep slopes. In such a landscape, the survival of Sumatra's large-mammal fauna will be in serious jeopardy.

We documented the extent of deforestation in and around the Bukit Barisan Selatan National Park (BBSNP) from 1985 to 1999 and projected possible deforestation through 2010, based on rates and distribution of forest loss determined over the previous 15 years. We compared these rates to island-wide estimates of forest loss and placed them in the context of social and political events in Indonesia over the last two decades. We then examined how these patterns of deforestation may influence core habitat availability for four large mammal species: Sumatran elephants, Sumatran tigers, Sumatran rhinoceros, and Malay tapirs. We chose landscape species (Sanderson et al. 2002) because all are large bodied and wide ranging and tend to occur naturally at low population densities (with the possible exception of elephants), characteristics that may increase a species' vulnerability to habitat loss (Terborgh & Winter 1980; Diamond 1984). All four species are listed under Appendix 1 of the Convention on International Trade in Endangered Species, all prefer lowland forest habitats, and all are protected by Indonesian law (Peraturan Pemerintah no. 7 1999). Finally, these species are considered charismatic and are being used by the Indonesian government and international donors as flagship species to promote conservation of Sumatran landscapes. Although our study focuses on one particularly dire example of tropical deforestation, we believe that our methods and results are generally applicable to the conservation biology of landscapes under severe threat.

Methods

Study Area

The BBSNP is the third-largest protected area (3568 km^2) on the Indonesian island of Sumatra. Located in southwest Sumatra (lat. 4°31′–5°57′S, long. 103°34′–104°43′E), the park extends 150 km along the Barisan Mountains and spans the provinces of Lampung and Bengkulu. The BBSNP contains some of the largest tracts of lowland forest remaining on Sumatra and is the major watershed for southwest Sumatra (Food and Agriculture Organization 1981). The park is bordered by villages, agriculture, and plantation forestry. The park's long shape results in 700 km of borders. Poaching and encroachment for logging and agriculture are rife. Despite these problems, the BBSNP remains an important refuge for Sumatra's mammals, including Sumatran tigers, Asian elephants, Sumatran rhinoceroses, and Malay tapirs (Food and Agriculture Organization 1981; O'Brien & Kinnaird 1996). The park is also home to the endemic Sumatra short-eared rabbit (*Nesolagus netscheri*) and Sumatran Peacock-Pheasant (*Polyplectron chalcurum*).

Patterns of Deforestation

We acquired Landsat Thematic Mapper (1985–1997) and Enhanced Thematic Mapper Plus (1999) images over the BBSNP for 1985, 1989, 1994, 1997, and 1999. Images were georeferenced to 1:50,000 topographic maps from the Topography Division of the Indonesian Army and checked with global positioning systems in the field. All data were projected to the Universal Transverse Mercator (UTM) projection, Zone 48 south. The spatial precision of georeferenced images was approximately 110 m with respect to maps and field measurements and within 30 m (one pixel) between different images. The extent of the study area was defined as the extent of the 1994 image (the most limiting satellite coverage) and covered 70% of the park (2338 km^2). We also examined 2430 km^2 in a 10-km buffer surrounding the park.

Images were displayed in 5–4–3 band combinations and manually interpreted through on-screen digitization. Six land-cover types were distinguishable on the images: forest, agricultural areas, burned areas, grasslands, village enclaves, and unknown, nonforested types. The time series of images was interpreted as a temporal progression of land-use change, with forest cover at each time point used as the base forest cover for the next time point. Classification accuracy of the 1999 image was assessed through comparison with independent on-the-ground surveys at 140 points surrounding cameras. Vegetation data on tree cover, understory foliage density, and presence of plant species indicative of disturbance (e.g., bamboo [Poaceae] and wild ginger [Zingiberaceae]) were used to develop a discriminate function analysis (DFA) to distinguish forest plots from nonforested plots. Comparison of DFA plot results with image classification indicated an 80% accuracy of image classification for nonforested plots. We assumed that classification accuracy for earlier images was approximately the same.

A 50-m digital elevation model derived from digitized topographic contours was used to calculate slope and elevation classes. Elevation was categorized into four classes: 0–500, 501–1000, 1001–1500, and 1500–2000 m. Slope was categorized into six classes: 0–10, 11–20, 21–30, 31–40, 41–50, and >50°. We defined forest below 500 m elevation as lowland forest and above 500 m as hill/montane forest.

Rates of Deforestation

Rates of forest loss were calculated as the slope of the regression line (area of forest lost between image years) for a given elevation/slope class. Using these slopes (rate of loss), we calculated time to extinction for each elevation/slope class by solving the regression equation when forest area equaled zero (0 = 1985 forest area − regression slope * years to extinction). We then subtracted 16 years to estimate years to extinction from 2001. We calculated the probability of losing forest for each elevation/slope class and created a matrix of probabilities of forest loss for combined elevations and slopes. Because road networks are known to affect deforestation, we assessed deforestation patterns in relation to distance from roads and settlements.

Predicting Future Deforestation

To examine patterns of future deforestation, we developed a predictive model based on observed rates and patterns of deforestation described in the forest-loss probability matrix. We applied probabilities of forest loss to predicted remaining forest for each year through 2010. Beginning with the 1999 image, we allowed deforestation to proceed from the outside edge of the forest block inward for each combination of slope and elevation class. For each year, we determined the number of cells in a slope and elevation class available for deforestation. A cell was considered "available" for deforestation if it (1) had forest the previous year, (2) was on the edge of the forest block, and (3) was in the appropriate slope and elevation class. If the number of available cells was less than the predicted rate of deforestation, then all available cells were removed. We then selected a new set of available cells based on the same criteria but from the new edge of the forest block. This iterative process continued until the number of available cells was less than the predicted rate of deforestation, in which case cells were randomly selected to match the predicted rate. If at any point no cells were available, then the model skipped to the next slope and elevation class. Slope and elevation classes were processed first within an elevation class, then by slope class, proceeding from shallow slopes to steep slopes, then working from low-lying areas to higher elevations. Thus, low-lying, flat areas were "deforested" before high, steep areas within a given year. When a given year was completed, the resulting landscape was used as input for the next year's cycle of deforestation.

Image processing and geographic analysis were completed with ERDAS Imagine (version 8.4, from ERDAS, Atlanta, Georgia), Arcview 3.2 and ARC/INFO 7.2 (Environmental Systems Research Institute, Redlands, California), and a series of PERL scripts (PERL Institute, Mountain View, California).

Wildlife Sampling

We sampled large mammals from October 1998 to June 2000 with automatic cameras (CamTrak South, Watkinsville, Georgia) equipped with passive infrared motion sensors. Cameras were also equipped with data packs that stamped each photograph with time and day of exposure. Cameras were dispersed in 20-km^2 sampling blocks at approximately 10-km intervals for the length of the park. Blocks were oriented from the edge of the park boundary to the center. Within each block we assigned one camera per square kilometer to random UTM coordinates. Cameras were operated 24 hours per day for approximately 30 days for each block. Number of trap days was defined as the number of 24-hour periods a camera was operating in the forest and was calculated from the time a camera was mounted until it was retrieved or until the last frame of film was exposed. We identified each photographed animal to species, recorded the time and date of photo, and rated each photo as a dependent or independent event. We defined independent events as (1) consecutive photographs of different individuals of the same or different species, (2) consecutive photographs of individuals of the same species taken more than 0.5 hours apart, or (3) nonconsecutive photos of individuals of the same species. We have found that the number of trap days required to obtain an independent photograph for a species is strongly related to independent estimates of density (T.O. and M.K., unpublished data: trap days/photo $= 106.8 - 59.8 \times$ Ln[density], $r^2 = 0.79$); therefore, we used numbers of photographs as a reliable index of species abundance.

We measured distances between cameras and the 1999 forest boundaries and then examined the distribution of tiger, elephant, rhinoceros, and tapir abundance indices relative to forest boundaries by comparing observed and expected distributions of independent photographs. Expected distributions were calculated as proportional to camera distribution. For example, if 20% of all cameras were placed within 1 km of the forest boundary, we expected 20% of all photographs for a species to be made within this zone. Next, we calculated the residuals between observed and expected photo captures and looked for natural breaks in the distribution of residuals with Jenk's optimization method to calculate the goodness of variance fit (GVF; Dent 1996). The GVF identifies optimal breaks in data categories when alternative data classifications are used on the same set of numerical data. Once we identified natural breaks for species, we tested for "avoidance" of forest boundaries with a two-sample chi-squre goodness of fit (above and below natural break). For species whose distributions were shifted away from forest boundaries, we created internal buffers of 2 and 3 km and calculated the peripheral forest area avoided by a species. We defined the remaining forest as a species' core forest area. We measured degree and extent of fragmentation for each species core forest area over time. We repeated this analysis for 1985, 1989, 1994, 1997, 1999, 2005, and 2010, assuming the same edge-avoidance behavior as measured in 1999.

Results

Patterns and Rates of Deforestation

In 1985, 2228 km^2 of the landscape examined was forested (53.8%), and most of this was within the BBSNP

(84%). Within park boundaries, 54% of the land was lowland forest and 26% was hill/montane forest (Table 1). Most of the forest outside the park in the 10-km buffer had already been lost, with only 10% lowland forest and 5% hill/montane forest remaining (Table 1). Comparison of images between 1985 and 1999 showed a loss of 661 km^2 of forest inside the BBSNP, a loss of 318 km^2 in the buffer, and a decline in forest cover from 80% to 52% inside the park and from 15% to 1.6% outside the park. By 1999, lowland forest had decreased by 27% and hill/montane forest by 53% in the BBSNP. In the buffer zone there was almost total extirpation of lowland forest (<1% remaining) and a 75% reduction in hill/montane forest by 1999.

Between 1985 and 1999, deforestation in the BBSNP averaged 2.0%/year. The slowest rates occurred from 1989 to 1994 (1.58%/year), and the highest rates occurred from 1994 to 1997 (3.1%/year). Deforestation rates varied by elevation and slope (Fig. 1). Lowland forest disappeared at a rate of 25 km^2/year, compared with 3.9 km^2/year in hill/montane forest. On relatively flat slopes (0–20°), forest loss averaged 16.5 km^2/year but dropped to 0.8 km^2/year on the steepest slopes (>40°). Deforestation patterns did not vary with distance from roads or settlements.

The limited forest area of the buffer zone experienced lower rates of forest loss, ranging from 15 km^2/year to 0.7 km^2/year in lowland and hill/montane forest, respectively. Deforestation by slope also varied in the buffer zone, from 9.5 km^2/year on slopes of ≤10° and declining to 0.5 km^2/year on slopes of >40°. Although deforestation rates were lower in the buffer zone than in the park, the net effect was greater because the buffer contained a smaller forest area in 1985.

As expected, deforestation resulted in a dynamic pattern of fragmentation of remaining forest areas. Within the BBSNP, fragmentation increased from 1985 to 1997 and then began to decrease as fragments in the 1–2 km^2 range were completely eliminated. Increasing fragmentation was also reflected in a continuous rise over time in the creation of small isolates between 1 ha and 1 km^2. Between 1985 and 1999, the size of the main forest block declined from 1774.5 km^2 to 1136.4 km^2, a 36% reduction in area. The main forest block is expected to be only 692.8 km^2 by 2010, an additional 25% decline in area. Patterns of fragmentation differed in the buffer zone, where the initial forest areas were already small (maximum size = 131.1 km^2) and highly fragmented. The number of fragments >1 km^2 in size declined steadily over time, and the area of the largest fragment decreased by 86%. Numbers of small fragments initially increased but after 1987 began to steadily decline because they were removed entirely from the landscape. By 1999 less than half the initial (1985) forest patches remained in the buffer zone.

Image analysis indicates that the majority of forest

Table 1. Area (km^2) and percentage (in parentheses) of Bukit Barisan Selatan National Park (BBSNP) within study area and of a 10-km buffer surrounding BBSNP in each land-use class at each point in time.

	1985		*1989*		*1994*		*1997*		*1999*	
Land-use class	*BBSNP*	*buffer*	*BBSNP*	*buffer*	*BBSNP*	*buffer*	*BBSNP*	*buffer*	*BBSNP*	*buffer*
Lowland forest[a]	1272 (54)	232 (10)	1140 (49)	99 (4)	1102 (47)	40 (2)	970 (42)	22 (1)	929 (40)	8 (0)
Hill/montane forest[b]	598 (26)	125 (5)	568 (24)	58 (2)	404 (17)	42 (2)	322 (14)	36 (2)	281 (12)	31 (1)
Burn	—	—	8 (<1)	0.04 (0)	—	—	92 (4)	2 (0)	4 (<1)	—
Grasslands	8 (<1)	—	8 (<1)	—	8 (<1)	—	8 (<1)	—	8 (<1)	—
Unknown, nonforest	8 (<1)	1 (0)	0.08 (<1)	0.14 (0)	—	0.31 (0)	14 (1)	3 (0)	97 (4)	2 (0)
Enclave village areas	—	12 (<1)	0.05 (<1)	41 (2)	9 (<1)	57 (2)	10 (<1)	57 (2)	12 (<1)	58 (2)
Agriculture	459 (20)	1970 (84)	613 (26)	2142 (92)	813 (35)	2201 (94)	918 (39)	2220 (95)	1005 (43)	2241 (96)

[a] *Defined as forest cover < 500 m elevation.*
[b] *Defined as forest cover > 500 m elevation.*

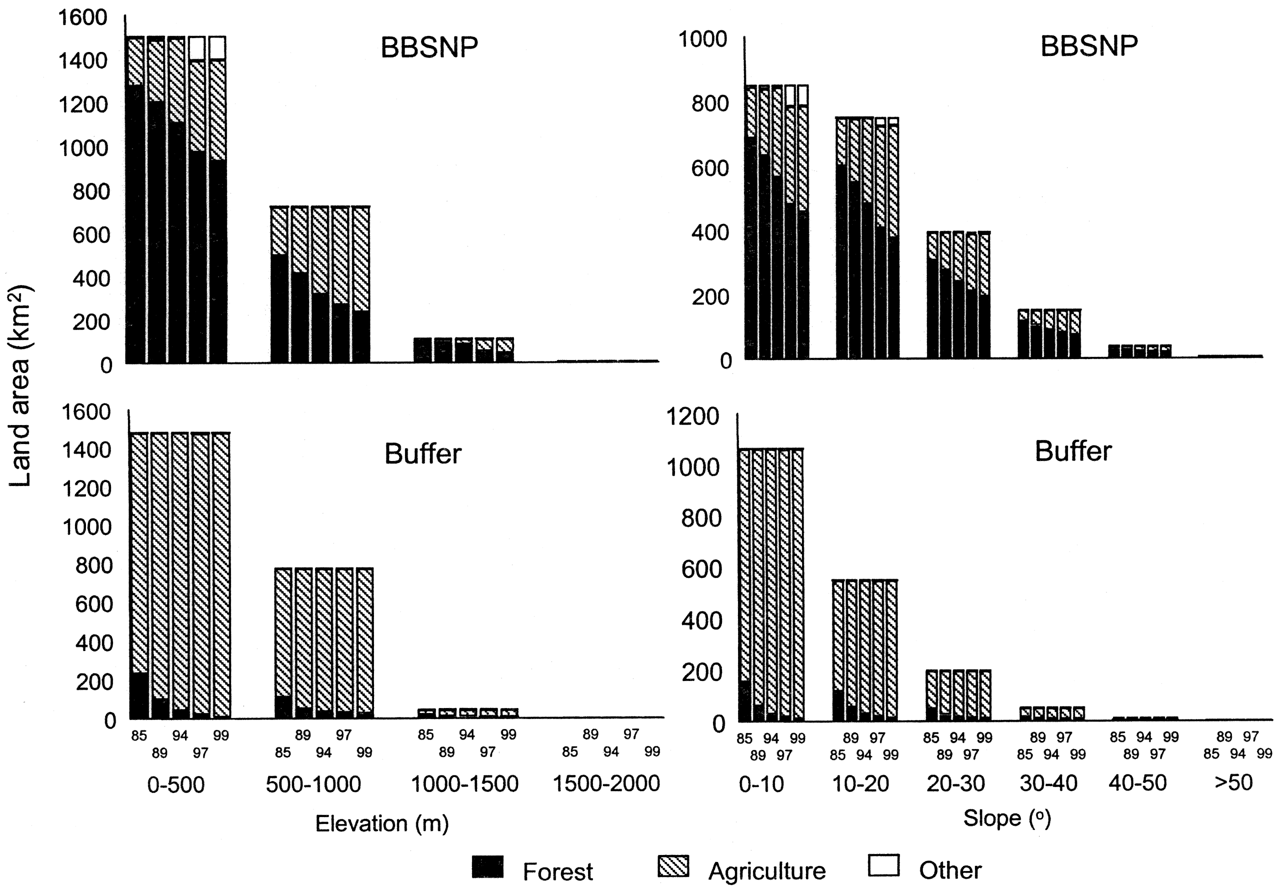


Figure 1. Area of land (km^2) classified as forest, agriculture, or other by elevation and slope classes and by year for Bukit Barisan Selatan National Park (BBSNP) and a 10-km buffer.

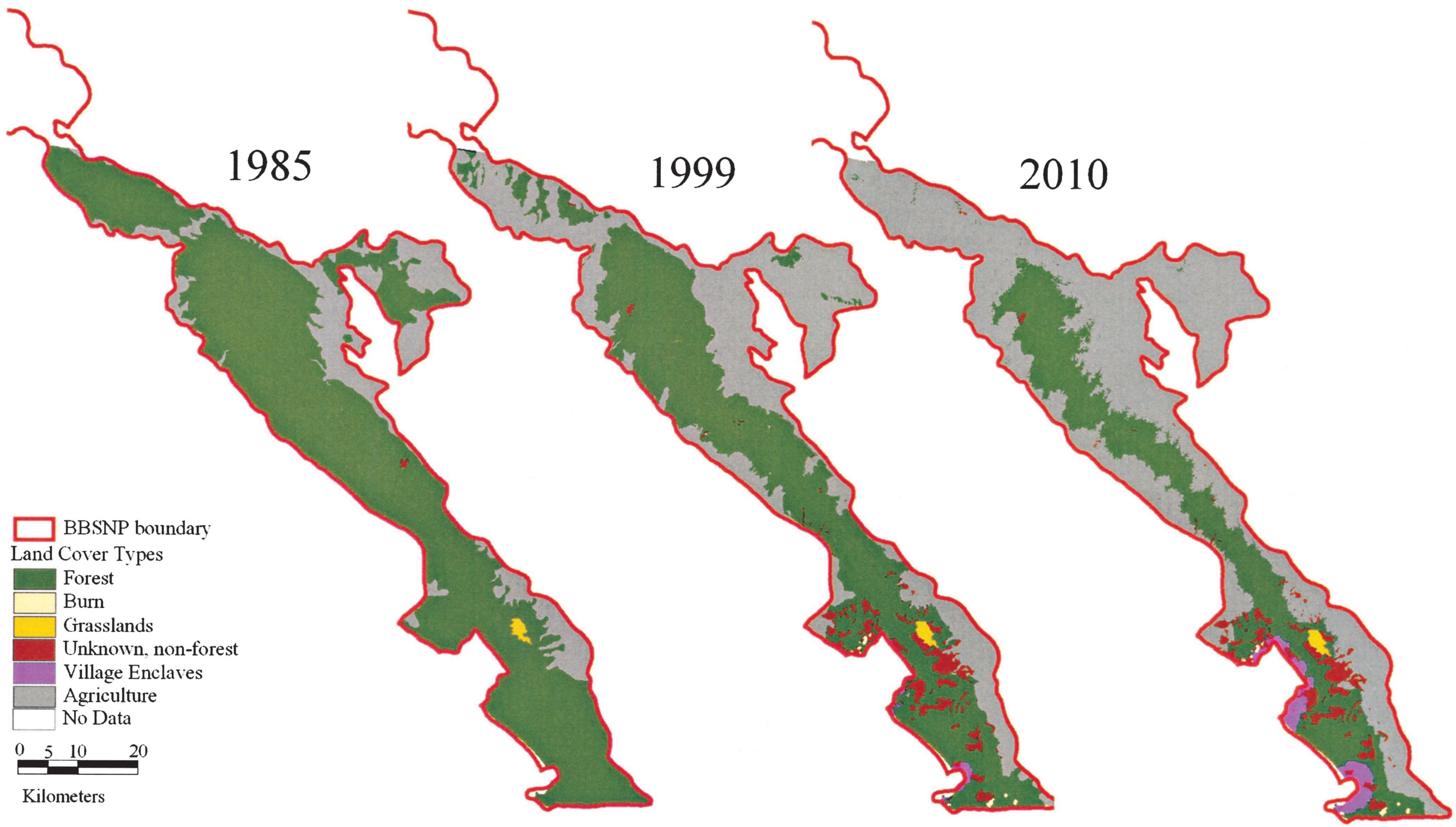
conversion resulted from agricultural development inside and outside the park (Table 1; Fig. 2). The area of land classified as agriculture more than doubled inside the BBSNP and increased by 12% in the buffer zone. Land classified as unknown/nonforested and burned land increased fourfold inside the park, but this change was relatively minor in terms of lost forest area (5%). Unknown/nonforested and burned land classifications remained relatively unchanged outside the park (<0.1%).

Time to Extinction of Forest Habitats

By 2010 our model predicted that 70% of the BBSNP will be agricultural lands or village enclaves (Table 2; Fig. 2). Lowland forests will have declined to 28%, and hill/montane forests will account for 2% of the BBSNP land cover, a cumulative area of little over 700 km^2 in forest. Extrapolation of 1985–1999 deforestation trends for forests at elevations of ≤500 m (Fig. 1) indicated elimination of lowland forest habitat within the BBSNP by 2036, assuming that all lowland forest disappears at the same rate over time. The actual extinction time may be slightly delayed, however, if interior lowland forest valleys persist due to isolation.

Effects on Wildlife

During 4967 trap days in 140 km^2 (seven blocks) of park, we recorded 10 independent photographs of rhinoceros, 14 of tigers, 43 of elephants, and 64 of tapir. Given the park's shape and the 10-km length of sample blocks, camera distribution was clumped 2–3 km from the forest edge. Tigers and rhinoceros were photographed more than twice as often (per camera) at ≥2 km from the forest edge than at closer distances. Elephants were photographed slightly more often in the interior (1.4 times), and tapir were photographed at approximately equal rates near and far from the forest edge. Jenk's optimization method located natural breaks in the distribution of expected deviations from the observed distribution and indicated that species tended to avoid forest edges (Fig. 3). Natural breaks in tiger and rhinoceros distributions occurred at 2 km inside the forest, and breaks for elephant and tapirs occurred at 3 km. Differences were statistically significant for elephants



	1985	1999	2010
Area of Lowland Forest (km²):	1272.7	928.9	654.1
Area of Total Forest (km²):	1871.1	1209.2	707.4
Percentage of BBSNP with Forest Cover (%):	80	52	30
Area of Core Forest for Tigers and Rhinos (km²):	955.3	524.7	148.2
Area of Core Forest for Elephants (km²):	56.0	13.6	0.3

Figure 2. Land-use classifications for Bukit Barisan Selatan National Park (BBSNP) by year and forest-cover summary statistics.

Table 2. Predicted area and percentage of forest cover within Bukit Barisan Selatan National Park for 2005 and 2010.

	2005		*2010*	
Forest class	*area (km^2)*	*%*	*area (km^2)*	*%*
Lowland forest	778.9	33	654.1	28
Hill/montane forest	114.9	6	53.4	2
Nonforest	1414.1	60	1630.6	70

($\chi^2_1 = 11.94, p < 0.001$), tigers showed a trend toward significance ($\chi^2_1 = 3.03, p = 0.08$), and rhinoceros and tapirs showed no significant differences ($p > 0.1$). Results for rhinoceros, however, may be an artifact of small sample size. The distribution of rhinoceros footprints recorded by antipoaching units show a clustering in the park's interior (Hutabarat et al. 2001).

Application of 2- and 3-km internal buffers to forest areas identified the amount of core forest available for elephants, tigers, and rhinoceros from 1985 to 1999 and the expected amount of core forest remaining in 2010 (Fig. 4). A 2-km internal buffer resulted in a core forest area of 52% of the total forest in 1985 and 44% by 1999 (Table 3). After 1999 the situation deteriorated rapidly, and projected core forest area for tigers and rhinoceros in 2010 was only 22% of remaining forest (152.2 km^2 in nine fragments). Applying 2-km buffers demonstrates a loss of small, core forest fragments between 1985 and 1999, and reductions in the size of main forest blocks. By 2010, fragmentation increased again, and maximum fragment size declined to only 52.8 km^2 (Table 3). As expected, a 3-km internal buffer pointed to a more rapid loss of core forest. Core forest area was reduced to 34% of total forest area in 1985, distributed in one small and one large fragment. By 1999, fragmentation increased and core forest area was 266.1 km^2 (22% of remaining forest area). By 2010, core forest was only 0.5% of the remaining forest, a mere 36.2 km^2 distributed in five fragments, with two fragments of >1 km^2 in size. For both 2- and 3-km buffers, the largest remaining core forest areas expected to exist in 2010 were in the southern portion of the park.

In summary, forest loss and fragmentation in and around the BBSNP between 1985 and 1999 has resulted

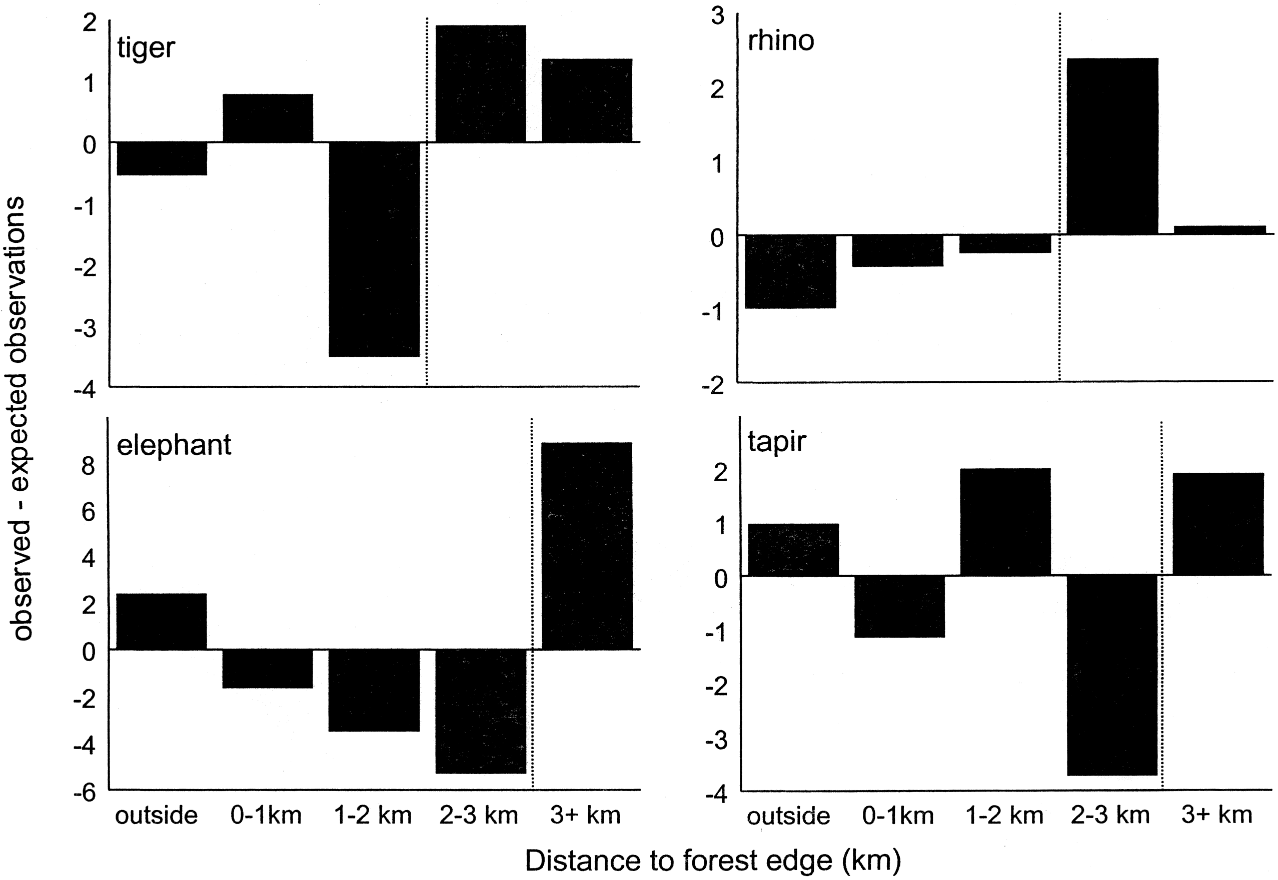


Figure 3. Distributions of deviation from expected number of photographs for four mammal species by distance to forest edge. Dashed lines show natural breaks in the distributions based on Jenk's optimization method (Dent 1996).

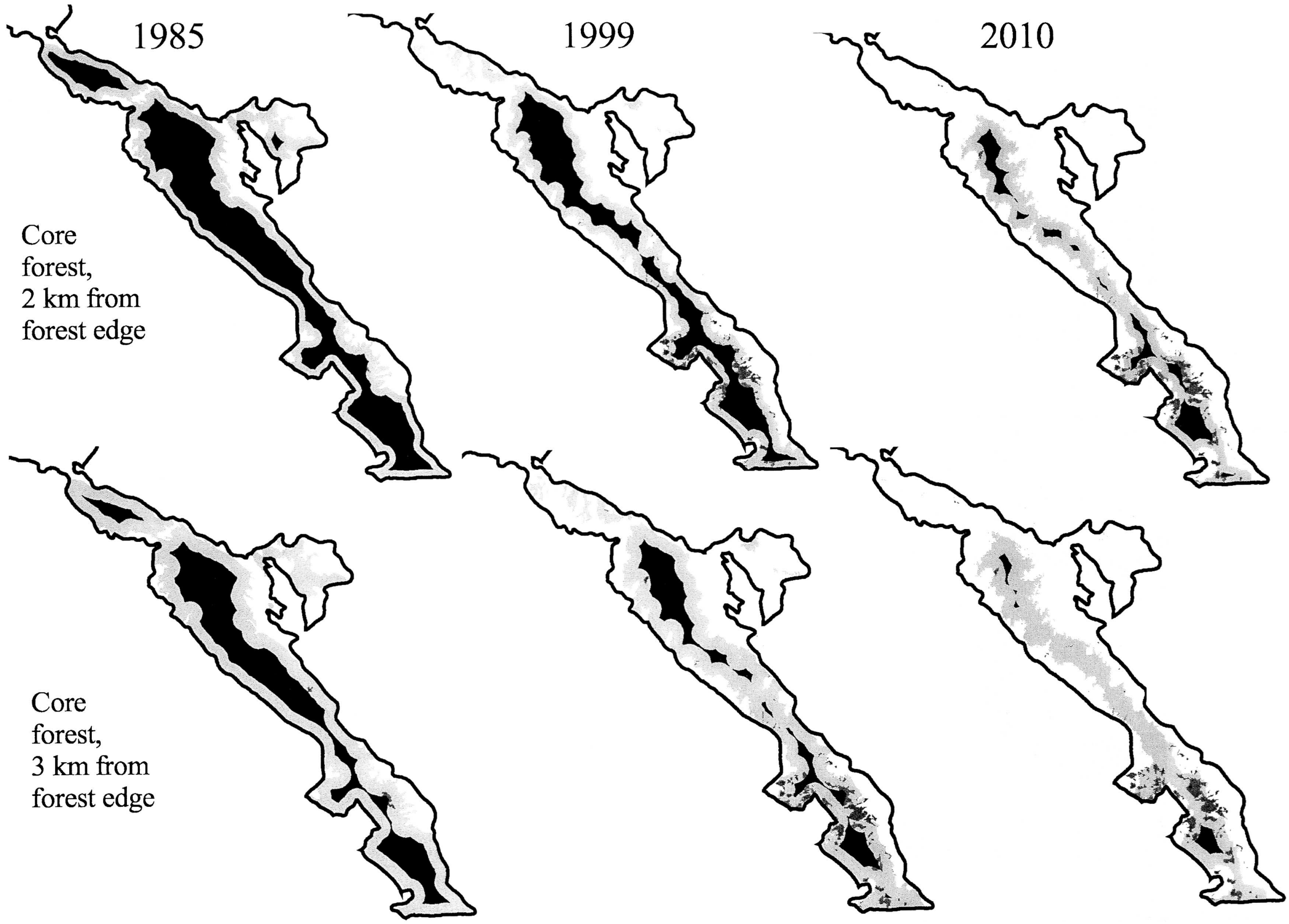


Figure 4. Forest boundaries and distribution of core forest areas after application of 2- and 3-km internal buffers for 1985, 1999, and 2010 (shading: grey, peripheral forest; black, core forest).

in near-total loss of forest in the 10-km buffer adjacent to the park and a 28% reduction in forest cover inside the park boundary through conversion to agriculture and expansion of village enclaves. Predictions of future forest fragmentation resulted in a 60% reduction in the size of the largest forest block by 2010, a decline in the number of forest blocks of >1 km^2, and an increase in forest fragments of <1 km^2. The situation was more dramatic for large mammals that preferentially use interior forest area. By 2010, core forest area for tigers and rhinoceroses (>2 km from forest edge) was reduced to 20% of total forest area and became increasingly fragmented. Core forest area for elephants (>3 km from forest edge) was reduced to 0.5% of remaining forest area and occurred primarily in the southern portion of the park.

Discussion

Holmes (2002) reports that "Conservation of the species-rich lowland forests of Indonesia has reached the crisis stage." This appraisal of the state of tropical forests has been repeated by conservationists worldwide (van Schaik et al. 1999; Myers et al. 2000; Jepson et al. 2001; Whitten et al. 2001) and is certainly applicable to the Sumatran landscape we considered. Our results indicate that forests are being lost at an alarming rate in southern Sumatra, even within ostensibly protected areas. Projections of future deforestation are not encouraging: by 2036, lowland forest will be eliminated from the BBSNP. Although this scenario is more optimistic than the one Holmes (2002) predicted for Sumatra overall, the results are nonetheless shocking, and managers should not be complacent.

Underlying Causes of Forest Loss in BBSNP

Several factors contribute to the alarming rates of deforestation of the BBSNP, but agricultural encroachment is the most important. Between 1994 and 1997, international market conditions and the Asian monetary crisis favored expansion of coffee and pepper plantations (Sunderlin 1999). During this time, the BBSNP experienced the greatest conversion of forest; by 1999, over

Table 3. Area of core forest and number and size range of core forest fragments > 1 km² in Bukit Barisan Selatan National Park by year for 2- and 3-km internal buffers.

Year	*Total area (km^2)*	*No. fragments ≥1 km^2*	*Size range (km^2)*
2-km internal buffer (tigers and rhinos)			
1985	963.6	3	6.1–881.2
1989	823.3	2	1.0–767.9
1994	654.3	2	0.1–642.3
1997	589.8	1	589.8
1999	532.2	2	245.8–286.5
2005	335.3	4	5.9–150.2
2010	152.2	9	1.4–52.8
3-km internal buffer (elephants)			
1985	632.7	2	33.3–599.4
1989	494.8	2	0.1–480.7
1994	365.2	4	1.6–255.4
1997	314.9	5	1.6–203.6
1999	266.1	5	2.9–163.2
2005	136.6	5	0.1–84.3
2010	36.2	5	9.0–25.4

43% of the BBSNP was classified as agricultural land. Land clearing was carried out by villagers living on the boundaries of the park, new immigrants displaced by the economic crisis, and urban investors engaged in speculative land clearing (M.K. and T.O., unpublished data).

Illegal logging contributes to deforestation in the BBSNP but is more difficult to measure. Clear-cutting is often conducted in conjunction with agricultural land clearing, and selective logging is difficult to detect with remote sensing based on Landsat data because the canopy is disturbed but generally left intact. Timber theft is especially difficult to control because of the pervasive networks involved (McCarthy 2000; Jepson et al. 2001), which often include participation of the military and police (Barber & Talbott 2001). Although illegal logging was prevalent in Lampung province prior to the economic crisis, these activities increased substantially after 1996, reportedly to the point where local timber supplies were exhausted (Elmhirst et al. 1998). Fortunately, there are no large sawmills or pulp and paper mills in Lampung Province, and as a result the park does not suffer the same levels of illegal logging reported elsewhere on Sumatra (McCarthy 2000; Barr 2001).

Forest loss due to wildfire occurs on an annual basis when farmers burn their lands adjacent to forest boundaries and when campfires set by poachers spread (Kinnaird & O'Brien 1998). The effects of wildfires, however, are most pronounced during El Niño Southern Oscillation (ENSO) events. Normally, lowland rainforests are resistant to burning because of high humidity, frequent rainfall, and rapid decomposition of leaf litter and fallen wood (Whitmore 1984). During ENSO events, a prolonged dry season results in an accumulation of combustible litter on the forest floor, increasing vulnerability to and severity of wildfire. Fires in BBSNP forest habitats have been shown to adversely affect regeneration, increase the likelihood of invasion by exotic plants, reduce primary productivity and wildlife diversity, and increase the likelihood and severity of future fires (Kinnaird & O'Brien 1998; Barber & Schweithelm 2000; Sunarto 2000).

Contrary to many findings (Hafner 1990; Forman & Alexander 1998; Wilkie et al. 2000), proximity to roads did not influence deforestation in the BBSNP. This lack of association between roads and deforestation occurs because there are only two short roads in the park (<20 kms total), and deforestation around the oldest road occurred prior to 1985. The widespread distribution of deforestation (Fig. 2) confirms that access to the park is not limited to roads.

Implications of Forest Loss for Endangered Mammals

The BBSNP has become a model for many other protected areas in the world, where the general trend is toward isolation. Given the current rates of deforestation and without immediate action, the demise of Sumatra's tigers, rhinoceros, and elephants within the BBSNP landscape is almost certain.

Habitat loss for large forest mammals is disproportional to and faster than simple forest loss when these species tend to avoid forest boundaries. We interpret the tendency of tigers, elephants, and rhinoceros to occur in the forest interior as avoidance of human activities that reduce cover and increase disturbance (including hunting) at the forest edge and in the peripheral forest. Griffiths and van Schaik (1993) found that large mammals in northern Sumatra, including elephants and tigers, moved away from areas of high human activity. Barnes et al. (1997) and Theuerkauf et al. (2001) found that elephant density in Gabon and elephant activity in the Ivory Coast decreased with proximity to roads and forestry operations. Finally, Woodroffe and Ginsberg (1998) and Revilla et al. (2001) found a decrease in survivorship for carnivores and other mammals as a result of interactions with humans on park edges. For multiple reasons, peripheral forests of the BBSNP are degraded habitat for the large mammals we studied, and these species are at greater risk when using these areas.

Elephants, tigers, and rhinoceros have large range requirements that include high-quality habitat composed of core forest. Using approximate home-range requirements for female tigers (50–80 km^2: Franklin et al. 1999; Karanth & Stith 1999), elephant families (60–170 km^2: Olivier 1978; Sukumar 1989), and rhinoceros (50–60 km^2: Hutabarat et al. 2001), we estimate that the BBSNP currently provides core forest for 6–10 female tigers, 8–10 rhinoceroses and 1–2 elephant families. By 2010 the largest core forest fragments will encompass home ranges for a maximum of 1 tiger, 1 rhinoceros, and no elephant families. Tigers, rhinoceros and elephants may continue to survive in suboptimal ranges composed of mixed core and peripheral forest, but the quality of these suboptimal ranges will vary with the proportion of core forest within the range. Animals living in an area with a low percentage of core forest will be at higher risk of mortality, so animals will probably attempt to monopolize as much core forest as possible. Assuming that suboptimal ranges are centered on single, core-forest fragments, and given the size distribution of remnant, core-forest fragments in 2010, home ranges may contain from 2% to 97% core forest for tigers and rhinoeros and 2% to 87% core forest for elephants. In summary, not only are populations being reduced by loss of forest habitat, but most of the surviving large mammals will spend a higher percentage of time in an unfriendly matrix with increased risk of mortality. Already, most human-elephant conflict takes place in the central portion of the park, where almost all the forest is classified as peripheral (Kinnaird et al. 2001).

Outlook for the Future

Loss of forest has proven one of the most difficult and complex problems for Indonesia's conservation agencies since the downfall of President Suharto in 1996, and to date there is no solution (Sunderlin 1999; Barber & Talbott 2001; Jepson et al. 2001). Currently, the inability to protect the country's forest resources is caused by economic collapse, corruption, and unstable governments (Jepson et al. 2001; Robertson & van Schaik 2001). Historically, however, forest loss has been the result of perverse incentives for forest destruction, unwise land-use strategies, unregulated expansion of oil palm plantations and pulp and paper mills, and a simple lack of education and capacity to manage (Whitten et al. 2000; Barr 2001; Jepson et al. 2001). The fact that the Department of Nature Conservation lies under the Ministry of Forestry only complicates policy development. The Ministry is responsible for generating revenue through forest exploitation, which creates internal conflicts.

If we are to conserve large-mammal populations in tropical landscapes, such as those in the BBSNP, we must take immediate and dramatic action. Management must concentrate on conserving the remaining forest habitat within the park and reducing the threats to large mammals in peripheral forest areas. For the BBSNP, managing human activities inside and outside the park will be crucial to mitigating threats (Revilla et al. 2001). Enforcement of existing laws prohibiting hunting of wildlife and timber theft within the park would reduce harassment of mammals, decrease the risk of fire, and reduce other forms of habitat deterioration. Managers may also need to consider restoration of lost or heavily disturbed forest and of the forest edge. Laurance (1999) has stressed that it is not enough to conserve isolated, fragmented reserves and that the intervening matrix must also be protected, reforested, and possibly reconfigured. Simulation models show that 58% less habitat may be required for species persistence if the habitat matrix is converted from low to high quality (Fahrig 2001). If park managers work to improve the quality of the peripheral forest matrix, the risks of mortality for wide-ranging mammals would decline and the amount of friendly habitat would more than double.

Given the current nature of park management on Sumatra, the best short-term hope may lie in increasing participation by communities and nongovernmental organizations in management decisions. Local and international nongovernmental organizations are taking increasing responsibility for monitoring (Wildlife Conservation Society), conducting antipoaching patrols (Wildlife Conservation Society and International Rhino Foundation), and engaging local communities (Wildlife Conservation Society and World Wide Fund for Nature). However, increased reliance on private conservation organizations seems unlikely to constitute a long-term solution unless the government grants management authority to these organizations.

Indonesia's decentralization and regional autonomy programs may provide an unexpected opportunity for conservation because local communities have a vested interest in their natural resources (Tarrant 2001; Wyckoff-Baird et al. 2001) and may develop a proprietary interest in the park. A less hostile attitude toward large mammals and an appreciation of the indirect benefits that humans derive from the park would do much to reduce threats inside and outside the park.

Help is needed in the form of increased funding and improved management. Financial support garnered through debt-for-nature swaps targeted at protected areas are widely claimed to hold great promise for conserving forests in countries such as Indonesia (van Schaik & Kramer 1999; World Bank 2001). World Heritage status for Indonesian protected areas may also open new sources of funding. Even with increased financial support, however, the government must still address corruption, theft, legal uncertainty (both prosecutorial and judicial), and bureaucratic inertia. Unless Indonesia quickly develops a system of good governance and wise management driven by a civil and just society, there is little hope for the future of Sumatra's forests, tigers, rhinoceros, and elephants.

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Literature Cited

Asia Pacific Systems Engineering (APSE). 2001. QuickMap. Jakarta, Indonesia. Available from http://www.environmentalmapping.com (accessed November 2001).

BAPPENAS. (National Development Planning Agency, Indonesia). 1993. Biodiversity action plan for Indonesia. BAPPENAS, Jakarta, Indonesia.

Barber, C. V., and J. Schweithelm. 2000. Trail by fire. World Resources Institute, Washington, D.C.

Barber, C. V., and K. Talbott. 2001. The chainsaw and the gun: the role of the military in deforesting Indonesia. Center for International Forestry, Bogor, Indonesia. Available from http://www.cgiar.org/cifor (accessed November 2001).

Barnes, R. F. W., K. Beardsley, F. Michelmore, K. L. Barnes, M. P. T. Alers, and A. Blom. 1997. Estimating forest elephant numbers with dung counts and a geographic information system. Journal of Wildlife Management **61:**1384–1393.

Barr, C. 2001. Profits on paper: the political-economy of fiber, finance, and debt in Indonesia's pulp and paper industries. Pages 60–99 in C. Barr, editor. Banking on sustainability: structural adjustment and forestry reform in post-Suharto Indonesia. Center for International Forestry and World Wildlife Fund–International, Macroeconomics Program Office, Washington, D.C.

Dent, B. D. 1996. Cartography: thematic map design. 4th edition. W.C. Brown/McGraw Hill, Dubuque, Iowa.

Diamond, J. M. 1984. "Normal" extinctions of isolated populations. Pages 193–246 in M. H. Nitecki, editor. Extinctions. University of Chicago Press, Chicago.

Elmhirst, B., Hermalia, and Yulianti. 1998. "Krismon" and "Kemarau": a downward sustainability spiral in a North Lampung Translok settlement. Pages 106–121 in M. van Noordwijk and H. de Foresta, editors. Agroforestry in landscapes under pressure: Lampung research planning trip, 17–21 June 1998. International Center for Research in Agroforestry, Bogor, Indonesia.

Fahrig, L. 2001. How much habitat is enough? Biological Conservation **100:**65–74.

Food and Agriculture Organization (FAO). 1981. Barisan Selatan Game Reserve management plan, 1982–1987. Field report. FAO, Bogor, Indonesia.

Franklin, N. Bastoni, Sriyanto, D. Siswomartono, J. Manansang, and R. Tilson. 1999. Last of the Indonesian tigers: a cause for optimism. Pages 130–147 in J. Seidensticker, S. Christie, P. Jackson, editors. Riding the tiger: tiger conservation in human-dominated landscapes. Cambridge University Press, Cambridge, United Kingdom.

Forman, R. T. T., and L. E. Alexander. 1998. Roads and their major ecological effects. Annual Review of Ecology and Systematics **29:**207–231.

Griffiths, M., and C. van Schaik. 1993. The impact of human traffic on the abundance and activity periods of Sumatran rainforest wildlife. Conservation Biology **7:**623–626.

Hafner, J. 1990. Forces and policy issues affecting forest use in northeast Thailand 1900–1985. Pages 69–94 in M. Poffenberger, editor. Keepers of the forest: land management alternatives in Southeast Asia. Kumarian Press, West Hartford, Connecticut.

Holmes, D. A. 2002. The predicted extinction of lowland forests in Indonesia. Pages 7–13 in E. Wickramanayake, E. Dinerstein, C. J. Loucks, D. M. Olson, J. Morrison, J. Lamoreux, M. McKnight, and P. Hedao, editors. Terrestrial ecoregions of the Indo-Pacific: a conservation assessment. Island Press, Washington, D.C.

Hutabarat, A. A., D. D. Subrata, and N. J. van Strien. 2001. Indonesia Rhino Conservation Program [IRCP] 2000 annual report and summary of relevant data. IRCP, Bogor, Indonesia.

Jepson, P., J. K. Jarvie, K. MacKinnon, and K. A. Monk. 2001. Decentralization and illegal logging spell the end for Indonesia's lowland forests. Science **292:**859–861.

Karanth, K. U., and B. M. Stith. 1999. Prey depletion as a critical determinant of tiger population viability. Pages 100–113 in J. Seidensticker, S. Christie, and P. Jackson, editors. Riding the tiger: tiger conservation in human-dominated landscapes. Cambridge University Press, Cambridge, United Kingdom.

Kinnaird, M. F., and T. G. O'Brien. 1998. Ecological effects of wildfire on lowland rainforest in Sumatra. Conservation Biology **12:**954–956.

Kinnaird, M. F., S. Hedges, M. Tyson, and A. Sitompul. 2001. Conservation assessment for Sumatran elephants in Lampung Province, Sumatra, Indonesia. Interim report: year two. U.S. Fish and Wildlife Service, Arlington, Virginia.

Laurance, W. F. 1999. Introduction and synthesis. Biological Conservation **91:**101–107.

MacKinnon, K. 1997. The ecological foundations of biodiversity protection. Pages 36–63 in R. Kramer, C. van Schaik, and J. Johnson, editors. The last stand. Oxford University Press, Oxford, United Kingdom.

McCarthy, J. F. 2000. 'Wild logging': the rise and fall of logging networks and biodiversity conservation projects on Sumatra's rainforest frontier. Occasional paper 31. Center for International Forestry Research, Bogor, Indonesia.

Myers, N., R. A. Mittermeier, C. G. Mittermeier, G. A. B. da Fonseca, and J. Kent. 2000. Biodiversity hotspots for conservation priorities. Nature **403:**853–858.

Nowak, R. M. 1991. Walker's mammals of the world. 5th edition. The Johns Hopkins University Press, Baltimore, Maryland.

O'Brien, T. G., and M. F. Kinnaird. 1996. Birds and mammals of the Bukit Barisan Selatan National Park, Sumatra. Indonesia. Oryx **30:**207–217.

Olivier, R. C. D. 1978. On the ecology of the Asian elephant. Ph.D. dissertation. University of Cambridge, Cambridge, United Kingdom.

Payne, J., C. M. Francis, and K. Phillips. 1985. A field guide to the mammals of Borneo. The Sabah Society, Sabah, Malaysia.

Revilla, E., F. Palomares, and M. Dilibes. 2001. Edge-core effects and the effectiveness of traditional reserves in conservation: Eurasian badgers in Doñana National Park. Conservation Biology **15:**148–158.

Robertson, J. M. Y., and C. P. van Schaik. 2001. Causal factors underlying the dramatic decline of the Sumatran orang-utan. Oryx **35:**26–38.

Saatchi, S., D. Agosti, K. Alger, J. Delabie, and J. Musinsky. 2001. Examining fragmentation and loss of primary forest in the southern Bahian Atlantic Forest of Brazil with radar imagery. Conservation Biology **15:**867–875.

Sánchez-Azofeifa, G. A., R. C. Harris, and D. L. Skole. 2001. Deforestation in Costa Rica: a quantitative analysis using remote sensing imagery. Biotropica **33:**378–384.

Sanderson, E. W., K. H. Redford, A. Vedder, P. B. Coppolillo, and S. E. Ward. 2002. A conceptual model for conservation planning based on landscape species requirements. Landscape and Urban Planning **58:**41–56.

Steininger, M. K., C. J. Tucker, P. Ersts, T. J. Killeen, Z. Villegas, and S. B. Hecht. 2001. Clearance and fragmentation of tropical deciduous forest in the Tierras Bajas, Santa Cruz, Bolivia. Conservation Biology **15:**856–866.

Sukumar, R. 1989. The Asian elephant: ecology and management. Cambridge University Press, Cambridge, United Kingdom.

Sunarto. 2000. Survival of plant communities and dynamics of forest ecosystem in response to fire: a long-term study from Sumatra. (need degree) thesis. University of East Anglia, Norwich, United Kingdom.

Sunderlin, W. D. 1999. The effects of economic crisis and political change on Indonesia's forest sector, 1997–99. Center for International Forestry, Bogor, Indonesia. Available from http://www.cgiar.org/ cifor (accessed 15 November 1999).

Tarrant, J. 2001. Big-bang decentralization. Quarterly newsletter 3. Natural Resources Management Program, Jakarta, Indonesia.

Terborgh, J., and B. Winter. 1980. Some causes of extinction. Pages 119–33 in M. E. Soulé and B. A. Wilcox, editors. Conservation biology: an evolutionary-ecological perspective. Sinauer Associates, Sunderland, Massachusetts.

Theuerkauf, J., H. Ellenberg, W. E. Waitkuwait, and M. Mühlenberg. 2001. Forest elephant distribution and habitat use in the Bossematié Forest Reserve, Ivory Coast. Pachyderm **30:**37–43.

Turner, W., E. J. Sterling, and A. C. Janetos. 2001. Contributions of remote sensing to biodiversity conservation: a NASA approach. Conservation Biology **15:**832–834.

van Schaik, C. P., and R. A. Kramer. 1999. Toward a new protection paradigm. Pages 212–230 in R. Kramer, C. van Schaik, and J. Johnson, editors. The last stand. Oxford University Press, Oxford, United Kingdom.

van Schaik, C. P., J. Terborgh, and B. Dugelby. 1999. The silent crisis: the state of rain forest nature preserves. Pages 64–89 in R. Kramer, C. van Schaik, and J. Johnson, editors. Last stand: protected areas & the defense of tropical biodiversity. Oxford University Press, Oxford, United Kingdom.

Whitmore, T. 1984. Tropical rainforests of the Far East. 2nd edition. Oxford University Press, Oxford, United Kingdom.

Whitten, T., S. J. Damanik, J. Anwar, and N. Hisyam. 2000. The ecology of Sumatra. 2nd edition. Periplus Editions, Singapore.

Whitten, T., D. Holmes, and K. MacKinnon. 2001. Conservation biology: a displacement behavior for academia? Conservation Biology **15:**1–3.

Wilkie, D., E. Shaw, F. Rotberg, G. Morelli, and P. Auzel. 2000. Roads, development and conservation in the Congo basin. Conservation Biology **14:**1614–1622.

Woodroffe, R., and J. R. Ginsberg. 1998. Edge effects and the extinction of populations inside protected areas. Science **280:**2126–2128.

World Bank. 2001. Indonesia: environment and natural resource management in a time of transition. World Bank, Washington, D.C.

Wyckoff-Baird, B., A. Kaus, C. A. Christen, and M. Keck. 2001. Shifting the power: decentralization and biodiversity conservation. Biodiversity Support Program, Washington, D.C.