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Fragmentation of Asia's remaining wildlands: implications for Asian elephant conservation

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Abstract

Habitat loss and fragmentation are main causes for Asian elephant population declines. We mapped wildlands – large, unfragmented and undeveloped areas – asking: (1) Where are the largest wildlands that constitute elephant habitats? (2) What proportion of these wildlands is protected? (3) What is their potential for elephant conservation? Our study demonstrates that wildlands constitute only 51% of the Asian elephant range. Myanmar has the largest wildland (~170,000 km^2), followed by Thailand and India. In Principal Components Analysis (PCA), the first two components explained 73% of the variation in fragmentation among ranges. We identified three fragmentation clusters from the PCA. Cluster A contains large ranges with unfragmented wildlands; cluster B includes ranges with well-developed transportation networks and large human populations; and cluster C contains ranges with severely fragmented wildlands. In cluster A, we identified four ranges with elephant populations >1000 animals: ARYO, MYUC, BNMH and BITE. Together with ranges that support >1000 elephants in cluster B, these A ranges have great potential for long-term elephant conservation. We propose that fragmentation clusters and population size can be used to identify different elephant monitoring and management zones.

INTRODUCTION

Wild populations of Asian elephant (*Elephas maximus*) are declining and are currently estimated at 25,000–50,000 elephants (Santiapillai & Jackson, 1990; Sukumar, 1990). These estimates represent educated guesses compiled by elephant specialists (Sukumar, 1989; Santiapillai & Jackson, 1990; Dawson, 1993).

The main reason for the Asian elephant's decline is dramatic habitat loss due to habitat fragmentation, expanding human populations and growing resource demands (Sukumar, 1989). Once found throughout much of Asia, elephant populations are now restricted to small and isolated habitat fragments dispersed across 13 countries (Sukumar, 1989; Santiapillai & Jackson, 1990). Growing rural populations, agricultural land conversion and deforestation have blocked traditional migration routes and pushed elephants into ever-shrinking habitat islands. Pocketed elephants with reduced access to resources increasingly take to crop raiding (Sukumar & Gadgil, 1988; Sukumar, 1991; Santiapillai & Ramono, 1993; Williams, Johnsingh & Krausman, 2001), and face almost certain extermination by local villagers.

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Little is know about how much unfragmented habitat remains inside the species' geographic range. This information is essential for long-term elephant conservation, because elephants depend on entire landscapes rather than a few habitat patches. Modern mapping technology provides the spatial analysis tools and data needed to determine how much habitat remains for endangered species (McShea *et al.*, 1999; Rappole, King & Leimgruber, 2000) and how much has been affected by development (Liu *et al.*, 2001). We have used Geographic Information Systems (GIS) in combination with satellite data and other digital maps to answer three questions: (1) Where in Asia are the largest unfragmented wildlands that constitute elephant habitats? (2) What proportion of these unfragmented wildlands is protected? (3) What potential do these unfragmented wildlands offer for long-term conservation of elephant populations?

METHODS

Mapping definitions

We define wildlands as large areas of natural vegetation unaffected by habitat fragmentation over time periods long enough that natural ecological processes (e.g., natural regeneration) determine ecosystem structure, composition and functions. Wildlands must be large enough to support viable populations of naturally occurring species. They must also be large enough so that natural disturbances do not reduce their area below the minimum required to maintain viable populations (Pickett & Thompson, 1978).

To map wildlands for Asian elephant conservation, we combined global land-cover data with development data, under the following assumptions:

(a) Long-term elephant conservation requires large wildlands (Sukumar, 1989). All major natural vegetation types (e.g., forest, shrubland/savanna, grassland) are potentially wildlands and can be mapped using satellite data.
(b) Elephants live in a variety of wildland habitats, including grasslands, shrublands/savannas and forests (McKay, 1973; Seidensticker, 1984).
(c) Irrigated grasslands are under intensive agricultural use and thus are not wildlands.
(d) Frequent fires are an indicator of increased human activity. Because of differences in natural fire regimes, we expect no fires in some ecosystems (most tropical forests), and a few fires each year in others (grasslands, shrublands, savannas). Even in fire-adapted systems, fire frequencies should not exceed one or two a year.
(e) Roads and transportation network structures are indicators of human development and fragment wildlands.
(f) The smaller and more fragmented a wildland area, the less suitable it is for elephants. Areas smaller than the minimal home range reported for an Asian elephant herd are not likely to support elephant populations in the long term.

Data sources and mapping

Based on our mapping assumptions we combined data layers from eight different sources to create two products: (1) a map delineating remaining unfragmented wildlands inside and outside elephant ranges; (2) a map showing current protection status of these wildlands (Table 1; Fig. 1). Each hierarchical mapping step corresponded to one or several of our assumptions. Details on mapping procedures and data sources are listed in Appendix 1.

(a) *Extracting potential wildlands.* We used the 1 km resolution Global Land Cover Characterization (GLCC) map to extract potential wildlands (Appendix 1(a)). We created three wildland categories by reducing the original GLCC land-cover classes into: forest, shrubland/savanna and grassland (Appendix 2, Fig. 1).
(b) *Removing irrigated grasslands from wildlands.* Distinguishing grasslands from croplands using satellite imagery is difficult because of similarities in spectral reflectances. We used global irrigation data to exclude areas with >0% irrigation from our grassland category, assuming these areas are agricultural.

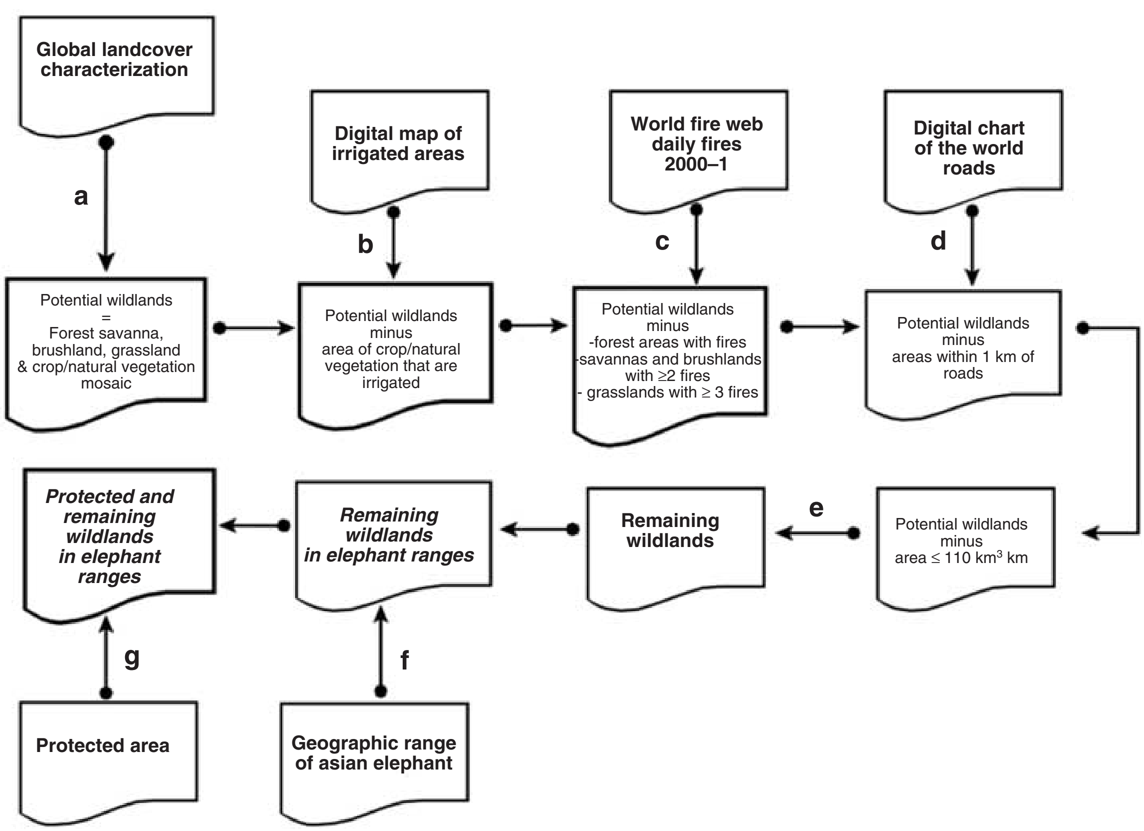

Fig. 1. Flowchart of data analysis for mapping remaining wildlands in elephant ranges and determining protection status of wildlands. Letters correspond to analysis steps described in the methods section.

Table 1. Data used for regional analysis of remaining wildlands in the Asian elephant's geographic range

Data set	Title	Scale/resolution	Source	Comments
Land cover	Global Land Cover Characterization (GLCC)	1 km^2	USGS EROS DAAC <http://edcdaac.usgs.gov/glcc/glcc.html>	Land-cover maps produced from Advanced Very High Resolution Radiometer (AVHRR) satellite imagery from 1992/1993 (Loveland, Estes & Scepan, 1999)
Percent irrigated area	A digital global map of irrigated areas	30′ x 30′	Center for Environmental Systems Research <http://www.usf.uni-kassel.de/usf/mitarbeit/homepages/doell/research9.htm>	A coarse-resolution map based on many heterogeneous sources describing the percent area within each cell that is equipped for irrigation (Döll & Siebert, 1999).
Transportation network	The Digital Chart of the World (DCW)	1:1,000,000	ESRI, 1993	A vector data set based on navigational charts. We combined data on roads, railways, pipelines and powerline corridors into a transportation network layer.
Daily fire location	Global Fire Product, Daily Fire Positions	1.2 km^2	World Fire Web <http://www.gvm.sai.jrc.it/fire/gfp/doc/gfp.htm>	The data set represents daily fire detections derived from 1 km resolution AVHRR satellite data (Dwyer, Grégoire & Malingreau, 1998). We compiled all daily fires between 5/1/00 and 4/30/02 into a cumulative fire raster file. Raster values represent the number of fires detected for each cell during the year.
Elephant geographic range	The Asian Elephant: Ecology and Management; IUCN Asian Elephant Action Plan	1:1,000,000	Sukumar, 1989; Santiapillai & Jackson, 1990	We digitized the hardcopy maps from each source.
Protected areas	IUCN/WCMC Protected Areas Database	1:1,000,000	WCMC, 1997	We utilized all protected areas in the IUCN categories I–V.
Population	LandScan 2001 Global Population Database	30″x 30″	Oak Ridge National Laboratory <http://www.orn	LandScan uses census counts and geographic features to estimate the population density of workplaces andtransportation corridors in addition to residential locations (Dobson *et al.*, 2000; Bhaduri *et al.*, 2002).
Elevation	GTOPO30	1 km^2	l.gov/gist/> USGS EROS <http://edcdaac.usgs.gov/gtopo30/gtopo30.html>	GTOPO30 was developed in 1996 from eight different data sources through a collaborative project lead by the US Geological Survey's EROS Data Center (EDC) <http://edcdaac.usgs.gov/gtopo30/README.html#h37> Techniques used during development varied with sources (for examples see: Bliss & Olsen, 1996; Gesch & Larson, 1996).

(c) *Removing areas with frequent fires.* We removed areas with frequent fires from wildlands, using a fire index based on fire regimes of different ecosystems (Appendix 1(b)). We compiled daily fire data for Asia in a 1 km resolution raster map. Each 1 km raster cell was assigned the number of fires occurring in the cell between 1 May 2000 and 30 April 2001. We then removed all wildland cells that were: (1) forest with any fires; (2) shrubland/savanna with ≥2 fires; or (3) grassland ≥3 fires.

(d) *Removing areas accessible by transportation networks.* Roads are detrimental to Asian elephants, because they frequently accelerate forest destruction, poaching and other illegal activities (Bryant, Nielsen & Tangley, 1997). We excluded all wildlands within 1 km of transportation networks.

(e) *Minimum wildland area to support elephants.* Data on wild elephant populations indicate that a single maternal herd can occupy a minimum space of ~110 km^2 (Sukumar, 1989: 105–115 km^2; Desai, 1991: 111 km^2). We excluded all wildlands below this minimum, because we deemed them unlikely to support elephants even over the short term (Appendix 1(d)).

(f) *Wildland inside elephant ranges.* Based on published elephant ranges (Sukumar, 1989; Santiapillai &

Jackson, 1990), we further reduced our wildlands by excluding areas outside ranges or above 2500 m elevation.

(g) *Wildland protection status inside elephant ranges.* We used a digital protected areas map (World Conservation Monitoring Centre, 1997) to assess how much of the remaining wildland in elephant ranges is protected.

Quantifying wildland fragmentation

For each range country we calculated elephant range area, remaining wildland inside ranges, and percent protected wildland inside ranges. We also summarized wildland information by elephant range irrespective of country boundaries by calculating number of remaining patches, total patch area and mean patch area. Given the coarseness of published range maps, we sometimes had difficulties in precisely matching elephant ranges with other layers. To compensate, we also calculated the total area of the largest wildland in the vicinity of a range. For this index a precise geographic match was not required. However, if there were few wildlands inside a range, there were also few unfragmented wildlands in the vicinity.

Determining fragmentation patterns

To identify variables that best explain variation in fragmentation across the Asian elephant's geographic range, we applied Principal Components Analysis (PCA) (Systat, 2000). We included the following variables: range area, number of patches, average patch area, total patch area, and area for the largest wildland patch in the range's vicinity. Increases in human population density and transportation network density cause habitat loss and fragmentation and we added these variables to the analysis. Mean population density was calculated based on Landscan 2001, a global database on human populations (Table 1). Transportation network density was determined by dividing the length of roads, railroads, powerlines and pipelines by the range's area.

PCA results indicated two distinct fragmentation gradients and we used K-means clustering to identify fragmentation clusters along these gradients. To investigate relationships between fragmentation clusters and elephant populations, we assigned each elephant range to a population category: category 1: small populations <1000 elephants, and category 2: large populations ≥1000 elephants. This classification was based on published estimates (Santiapillai & Jackson, 1990; Santiapillai, 1997). We used Fisher's exact test to check for significant associations between fragmentation and elephant population categories.

RESULTS

Only 51% of the Asian elephant's geographic range can be considered wildland (Fig. 2). Agriculture, irrigation, fires and roads affect all other range areas. Of these wildlands, only 16% are under legal protection.

Myanmar has the largest amount of remaining wildland in elephant ranges (Table 2; Fig. 3). These ranges have more wildland area than the combined ranges of Thailand and India, the countries ranking second and third. Thailand has the most protected wildlands, followed by Myanmar. However, if relative protection is considered (i.e., percent wildland protected), Myanmar is at the bottom of the list along with Nepal and China, while Thailand and Sri Lanka have the highest degree of protection.

PCA results demonstrate general trends in fragmentation and development (Table 3). Together, the first two principal components explain 73% of the variation among 59 elephant ranges. Component 1 (46% variation) separated highly fragmented ranges from ranges with extensive, unfragmented wildlands. It had strong correlations with range area, total wildland patch area average wildland patch area and area of the largest wildland patch in range vicinity. Component 2 (27% variation) was primarily a function of transportation network and mean population densities. It separated ranges with substantial development and human population densities from other ranges. It also had a stronger correlation with number of wildland patches than component 1, indicating that patchiness increases with development and human population.

Table 2. Area (km^2) of remaining wildlands inside Asian elephant geographic ranges

Country	Geographic range	Remaining wildlands	Protected wildlands	
Bangladesh	11,425	2,886	452	(16%)
Bhutan	3323	1,232	350	(28%)
Cambodia	55,382	20,088	6927	(34%)
China	41,390	31,910	2216	(7%)
India	151,309	46,880	5547	(12%)
Indonesia	30,750	19,709	3396	(17%)
Laos	53,611	42,747	8318	(19%)
Malaysia	57,237	29,106	4512	(16%)
Myanmar	288,990	168,461	11,215	(7%)
Nepal	2195	88	0	(0%)
Sri Lanka	27,816	4,102	1664	(41%)
Thailand	95,914	47,864	21,694	(45%)
Vietnam	53,765	31,909	5485	(17%)

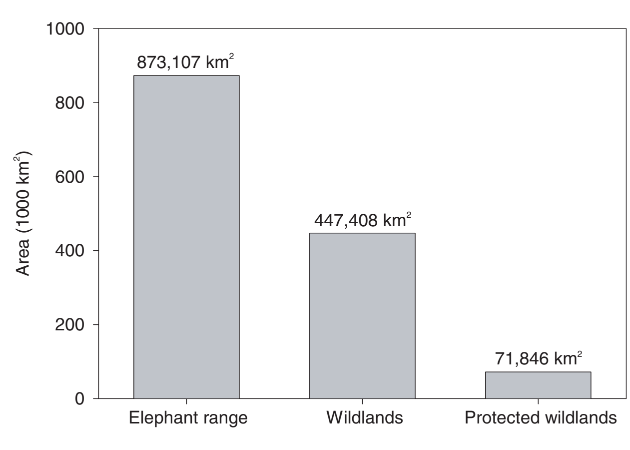

Fig. 2. Area of remaining and protected wildlands inside the geographic range of the Asian elephant.

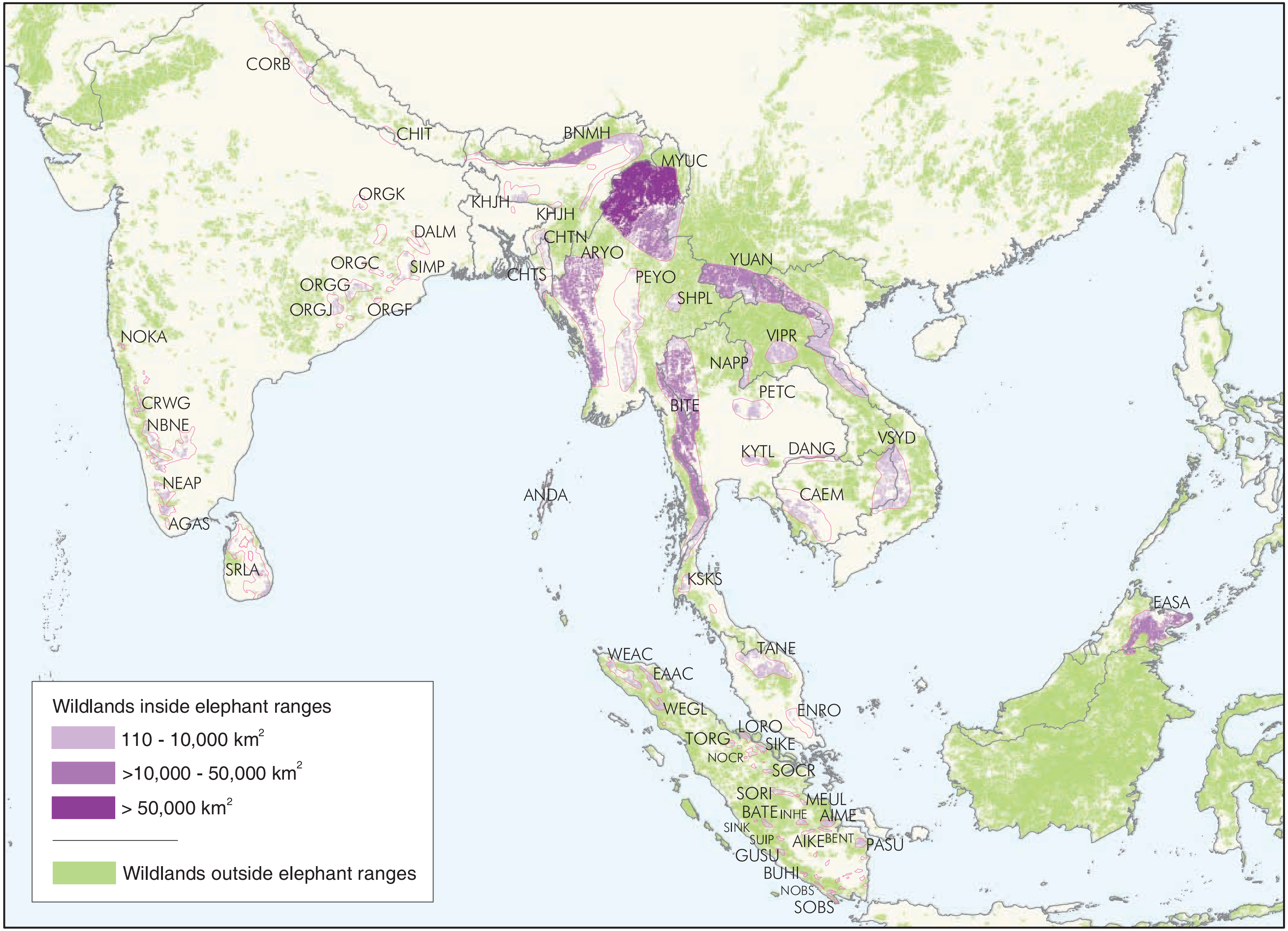

Fig. 3. Remaining unfragmented wildlands inside and outside the geographic range of the Asian elephant.

Table 3. Loadings for wildland fragmentation and development variables measured inside the geographic range of the Asian elephant. Loadings were calculated for the first two axes in Principal Components Analysis (PCA).

	Loadings	
Variable	Principal component 1	Principal component 2
Range area	0.938	0.258
Total wildland patch area	0.923	0.173
Average wildland patch area	0.805	–0.126
Area of largest wildland patch in range vicinity	0.664	–0.119
Number of wildland patches	0.460	0.609
Mean population density	–0.293	0.782
Transportation network density	–0.313	0.871

Table 4. Cross-tabulation of fragmentation categories (rows) with elephant abundance categories (columns) for 59 Asian elephant ranges (Fisher's exact test; $\chi^2 = 14.77$; d.f. = 2; $P = 0.001$). For explanation of fragmentation clusters, see Fig. 4.

	Abundance categories		
Fragmentation categories	<1000	≥1000	Total
Category A	2	4	6
Category B	12	4	16
Category C	35	2	37
Total	49	10	59

Projections of individual ranges onto principal components demonstrate gradients and reveal distinct elephant range groups (Fig. 4). Using K-means clustering on principal component scores, we separated ranges into three distinct clusters. Cluster A includes the large ranges within Asia's largest unfragmented wildlands. Cluster B is composed of ranges that are variable in size but have high human populations and are fragmented by dense transportation networks. The highly fragmented ranges of Southeast Asia and South Asia constitute cluster C.

Cross-tabulating population categories against fragmentation clusters revealed that clusters A and B had more ranges in population category 2 than expected by chance, while more ranges in cluster C were category 1. This indicates that, though not essential to elephant survival, large unfragmented wildlands are more likely to support large elephant populations.

Of ten ranges in population category 2, the first four are members of cluster A, and are characterized by large, unfragmented wildlands (Table 5). The next four belong to cluster B, and while these ranges have a large amount of wildland left (>3500 km^2), mean patch sizes are low (< 900 km^2). These ranges also have high scores on principal component 2, which represents a strong positive correlation with transportation network density and mean population density. The remaining two ranges fall into

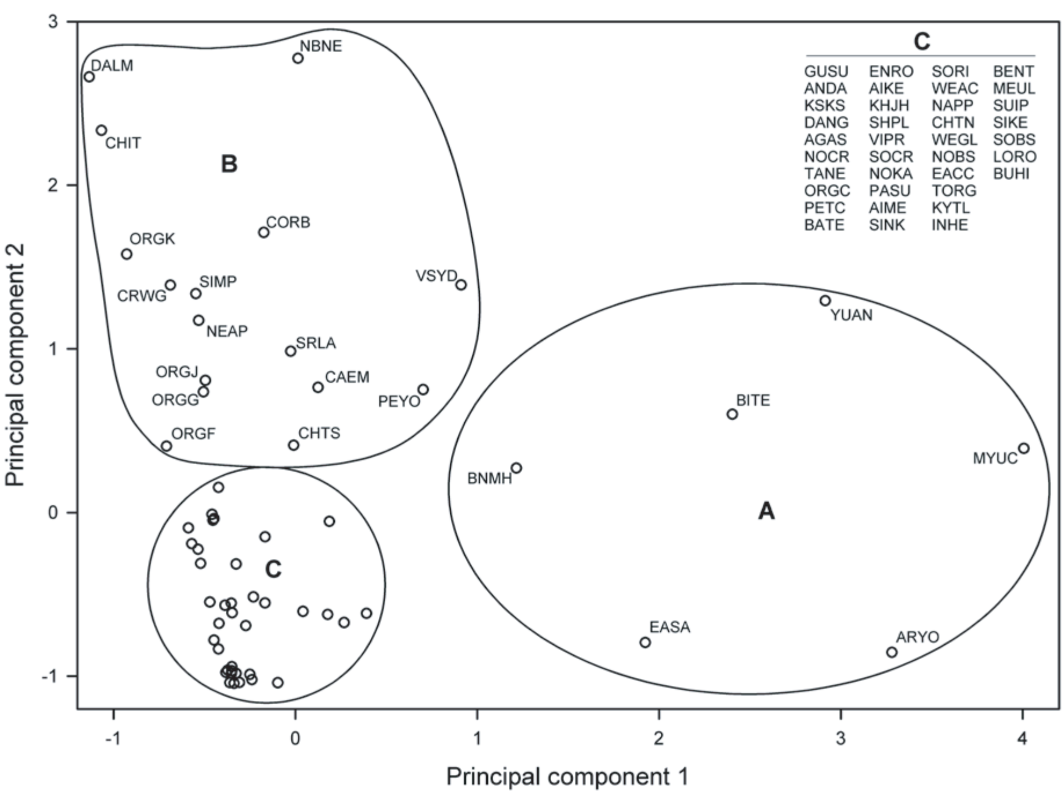

Fig. 4. Projections of 59 elephant ranges onto the first two principal components summarizing fragmentation, development and human populations. Clusters derived from K-means cluster analysis are indicted and represent distinct management categories. Cluster A represents large ranges with large unfragmented wildlands; cluster B includes ranges with dense transportation networks and high human population densities; cluster C is characterized by highly fragmented ranges with little road development and few people. Abbreviations for each range are given and can be compared to range information in Table 5.

Table 5. Wildland patch statistics, principal component scores, fragmentation clusters and population categories for 59 Asian elephant ranges

		Unfragmented wildland patches							
		Inside ranges		Intersecting ranges		Principal component scores			
Code	Elephant range	Number	Total area (km²)	Mean area (km²)	Largest patch area (km²)	Axis 1	Axis 2	Fragmentation cluster[a]	Population category[b]
ARYO	Arakan Yoma	2	39,332	19,666	218,965	3.281	–0.855	A	2
MYUC	Myitkyina/Upper Chindwin	10	98,375	9838	218,965	4.007	0.391	A	2
BITE	Bilauktaung/Tenasserim	13	62,339	4795	40,473	2.403	0.601	A	2
BNMH	Brahmaputra/Naga and Mishmi Hills	10	22,722	2272	218,965	1.215	0.271	A	2
EASA	Eastern Sabah	3	20,098	6699	498,575	1.925	–0.794	A	1
YUAN	Yunnan/Annamites	22	76,038	3456	146,449	2.915	1.294	A	1
NEAP	Nelliampathis-Anamalais/Periyar	5	3558	712	2148	–0.532	1.174	B	2
CAEM	Cardamon and Elephant Mountains	12	7527	627	2932	0.125	0.765	B	2
SRLA	Sri Lanka	12	4106	342	1180	–0.026	0.985	B	2
NBNE	Nagarhole/Bandipur-Nilgiris/Eastern Ghats/Nilambur-Attapadi	25	5860	234	1096	0.014	2.775	B	2
VSYD	Virachey/Snoul/Yok Do	26	22,205	854	11,337	0.911	1.391	B	1
PEYO	Pegu Yoma	12	9537	795	146,449	0.702	0.751	B	1
CHTS	Chittagong Hill Tracts South	4	1687	422	218,965	–0.010	0.411	B	1
ORGG	Orissa Group-g	5	1868	374	779	–0.506	0.737	B	1
CORB	Corbett	15	4481	299	2616	–0.174	1.711	B	1
SIMP	Simplipal	7	1599	228	1172	–0.548	1.337	B	1
ORGJ	Orissa Group-j	7	1544	221	351	–0.496	0.808	B	1
CRWG	Crestline of Western Ghats	6	1142	190	509	–0.688	1.390	B	1
DALM	Dalma	1	158	158	745	–1.134	2.662	B	1
ORGF	Orissa Group-f	1	141	141	222	–0.709	0.406	B	1
ORGK	Orissa Group-k	1	133	133	135	–0.928	1.578	B	1
CHIT	Chitwan	1	124	124	297	–1.066	2.335	B	1
KHJH	Khasi-Jaintia Hills	2	2050	1025	2300	–0.232	–0.516	C	2
CHTN	Chittagong Hill Tracts North	3	2820	940	218,965	0.267	–0.672	C	2
EAAC	Eastern Aceh	1	2656	2656	13,002	–0.097	–1.041	C	1
VIPR	Vientiane Province	5	9786	1957	138,035	0.391	–0.617	C	1
NAPP	Nam Phoun (Poui)	3	5355	1785	138,035	0.177	–0.623	C	1
WEGL	Western Gunung Leuser	1	1751	1751	13,002	–0.274	–0.691	C	1
PASU	Padang Sugihan	1	1493	1493	6953	–0.251	–0.989	C	1
AIME	Air Medak	1	1442	1442	12,811	–0.239	–1.022	C	1
KYTL	Khao Yai/Thap Lan	2	2572	1286	2666	–0.326	–0.315	C	1
PETC	Petchabun	4	4326	1082	2707	–0.167	–0.149	C	1
TANE	Taman Negara	10	9674	967	11,623	0.186	–0.054	C	1
LORO	Lower Rokkan	1	964	964	2469	–0.309	–1.039	C	1
BATE	Batang Tebo	1	908	908	33,050	–0.352	–0.554	C	1
SHPL	Shan Plateau	3	2693	898	146,449	0.042	–0.604	C	1
SIKE	Siak Kecil	1	685	685	13,110	–0.327	–0.983	C	1
INHE	Intan Hepta	1	667	667	7683	–0.350	–0.943	C	1
SOBS	South Barisan Selatan	1	648	648	3746	–0.352	–0.982	C	1
WEAC	Western Aceh	5	3214	643	11,658	–0.168	–0.553	C	1
KSKS	Khao Sok/Khlong Saeng	3	1321	440	2980	–0.455	–0.048	C	1
SOCR	South-central Riau	1	415	415	13,110	–0.421	–0.678	C	1
BUHI	Bukit Hitam	1	395	395	7829	–0.361	–1.040	C	1
SORI	Southern Riau	3	1122	374	8471	–0.348	–0.613	C	1
DANG	Dangrek	4	1386	347	2091	–0.423	0.154	C	1
BENT	Bentayan	1	331	331	12,811	–0.372	–0.963	C	1
TORG	Torgamba	1	329	329	4824	–0.521	–0.311	C	1
AIKE	Air Kepas	1	303	303	7683	–0.471	–0.547	C	1
NOKA	North Kanara	1	235	235	990	–0.448	–0.780	C	1
NOBS	North Barisan Selatan	1	212	212	7829	–0.424	–0.834	C	1
GUSU	Gunung Sumbing	3	632	211	33,050	–0.458	–0.011	C	1
MEUL	Mendahara Ulu	1	209	209	12,811	–0.382	–0.978	C	1
ANDA	Andaman	4	789	197	194	–0.448	–0.038	C	1
NOCR	North-central Riau	1	185	185	13,110	–0.536	–0.225	C	1
AGAS	Agasthyamalai	1	174	174	398	–0.571	–0.191	C	1
ORGC	Orissa Group-c	1	153	153	149	–0.589	–0.094	C	1
ENRO	Endau-Rompin	2	276	138	149	–0.387	–0.567	C	1
SUIP	Sungai Ipuh	1	135	135	33,050	–0.349	–0.967	C	1
SINK	Sinkinjang	1	115	115	33,050	–0.337	–1.044	C	1

[a]Clusters were created using K-means clustering on principal components scores (see Fig. 4).
[b]Population categories were assigned based on data in the literature: 1, <1000 elephants; 2, ≥1000 elephants.

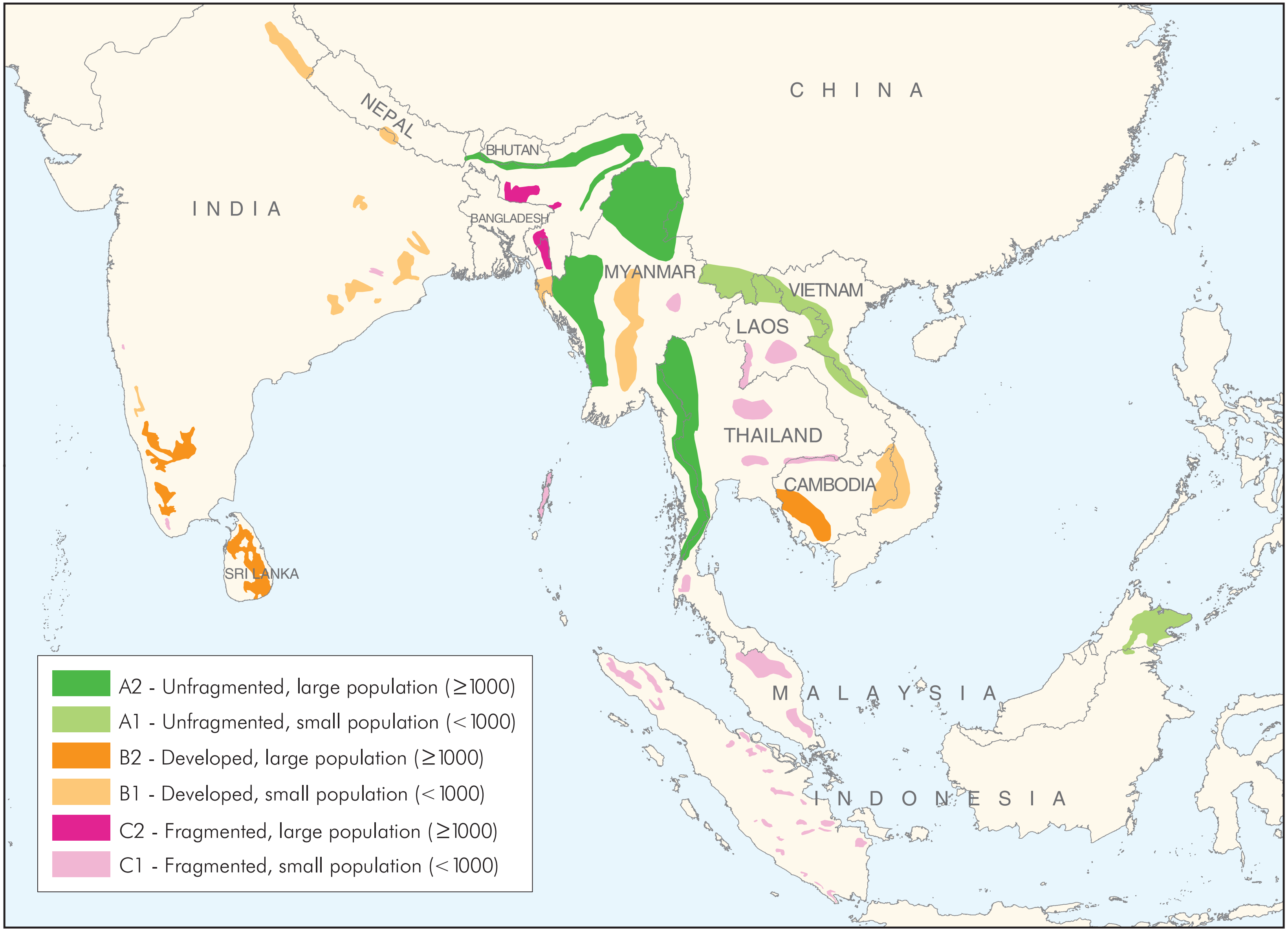

Fig. 5. Management categories for elephant ranges based on K-means clustering of principal components scores (capital letters) and population categories (numbers). Cluster A represents large ranges with large unfragmented wildlands; cluster B includes ranges with dense transportation networks and high human population densities; and cluster C is characterized by highly fragmented ranges with little road development and few people. Population category 1 indicates the range has an estimated elephant population below 1000 elephants; category 2 stands for ranges with estimated elephant populations above 1000.

cluster C and are more fragmented. However, all of the ranges in population category 2 have a total wildland area > 2000 km^2. This value may represent a threshold below which it is difficult to maintain large elephant populations in the long term. Only 23 of the 59 elephant ranges are above this threshold.

DISCUSSION

How much is remaining?

Our results indicate a dire situation for Asian elephants. We confirmed that only 51% of the geographic range consisted of unfragmented wildlands by the 1990s. Only 8% of the entire range was protected; little of that was unfragmented wildland. While 16% of the unfragmented wildland in the Asian elephant's range is protected according to IUCN, many protected areas may be paper parks, affording little protection for elephants (Kramer, van Schaik & Johnson, 1997).

Our assessment was based on data from the 1980s and 1990s. Since then the situation has become worse. Annual deforestation rates in Southeast Asia are increasing and are close to 1.9% as compared to global rates of 0.2–0.3% (Matthews, 2001). The disappearing forests may be prime elephant habitats. The resulting fragmentation may further threaten elephants by pushing them into shrinking habitat islands and increasing people–elephant conflicts (Sukumar, 1989; Desai, 1991; Johnsingh, 1993).

Most elephant ranges are very fragmented and contain little wildland area. These ranges may not sustain elephant populations over the long term unless range connectivity is improved. Sukumar (1989) estimated minimum viable area for long-term conservation of an elephant population (500 breeding individuals; 1:5 male to female sex ratio; 0.5 elephant/km^2) to be 4400 km^2. Only 14 of 59 ranges have wildland areas larger than this minimum (Table 5). In rainforest habitats, the minimum area increases to 13,000 km^2 because these habitats support fewer elephants (0.1 elephant/km^2). Most of the largest ranges are in rainforest, but only seven have a total wildland area ≥13,000 km^2.

Of ten ranges in population category 2, six have a wildland area ≥4400 km^2, and only four have a wildland area ≥13,000 km^2 (Table 5). The remaining four ranges in population category 2 have a wildland area ≥2000 km^2, which may sustain substantial elephant populations in the short term, if the habitat supports high elephant densities, as commonly found in savannas of India.

At the range level, three of six areas with the highest values for total wildland area and mean wildland patch area are inside Myanmar and its border regions. These include ARYO, MYUC, and BITE (Table 5). If the hill region separating MYUC and BNMH is permeable to elephants, the two ranges combined possibly embody Asia's single largest elephant range and largest remaining wildland.

The four ranges mentioned above are in population category 2, further signifying their potential for elephant conservation. Yet, no systematic surveys have verified the status of elephants in these areas and current information is based on outdated rough estimates (Myint Aung, 1997).

India, the country with the largest wild elephant population, also harbours three ranges in population category 2 (Table 5). BNMH has the most unfragmented wildland area, followed by the smaller but still sizeable NBNE and NEAP ranges. In cluster B, the latter two are among the ranges with large wildland areas, indicating that, despite high population and tranportation network densities, these ranges have retained fairly unfragmented areas. While Thailand has a large total area covered by wildlands, only BITE falls into cluster A and population category 2 (Table 5). All other elephant ranges in Thailand are in cluster C and are small and fragmented.

Fragmentation patterns and conservation implications

Fragmentation and development patterns differ widely across the Asian elephant's geographic range, reflecting economic, social and cultural differences among countries (Table 5; Fig. 5). The patterns also reflect differences in threats to elephant populations. Our ordination analysis identified distinct gradients in population density, transportation network development and fragmentation patterns, and delineated three major groups of ranges. Together with population size categories, fragmentation clusters can be used to stratify the Asian elephant range into conservation management zones with specific goals:

A 2 – Unfragmented ranges with large elephant populations: Cluster A ranges consist of large and unfragmented wildland tracts with virtually no roads and small human populations. Preliminary information from a deforestation study of Myanmar using Landsat imagery suggests that this is true for at least four cluster A ranges: ARYO, MYUC, BNMH and BITE (P. Leimgruber, unpubl. data). Large forest tracts connect the first three of these ranges, potentially facilitating migration and exchange of elephants between populations.

The A 2 category ranges have a high potential for long-term habitat conservation and maintenance of large wild populations. Highest priority should be given to fast-track establishment of protected areas. Targeted killing for ivory and medicinal products, perpetrated by organized poacher networks, may represent the greatest threat to A 2 elephant populations and must be effectively addressed. Because of the vastness of the area, its dense forests and pronounced topography, complete population surveys will be logistically difficult. In the short term, conservation success may be measured through systematic monitoring of relative densities and trends and through effective anti-poaching patrolling.

A 1 – Unfragmented ranges with small elephant populations: Reports on YUAN suggest that wildlands are severely degraded because rubber plantations have replaced forests. Elephant poaching is also a problem (Li Zhang, pers. comm.). We lack detailed information on EASA, but previous studies report that palm oil plantations break up the range (Andau, Dawson & Sale, 1997). Plantations are difficult to separate from closed-canopy forests in coarse-resolution satellite imagery and the wildland areas determined from our base map for EASA are probably overestimations. Elephant population in both ranges probably consists of a few, isolated groups.

The importance of A 1 ranges for elephant conservation is unclear. Fine-scale land-cover information providing greater detail about agroforestry crops, especially rubber and palm oil plantations, would be useful. Once more detailed maps become available, targeted population surveys need to be conducted to determine presence/absence of large elephant populations.

B 2 – Developed ranges with large elephant population: Cluster B characterizes well-developed ranges populated by people. Most B 2 ranges are found in South Asia, reflecting the differences in development and population density between South Asia and parts of Southeast Asia. While more fragmented than A ranges, some B 2 ranges have large wildlands remaining (Fig. 3).

The large number of Asian elephants surviving in South Asia's B 2 ranges attests that development and proximity to human populations are not always detrimental. However, many studies in South Asia have shown how further development negatively impacts these elephant populations (Sukumar & Gadgil, 1988; Sukumar, 1991; Williams *et al.*, 2001).

Conservation management should emphasize mitigation of people–elephant conflicts, wildlife law enforcement to prevent poaching, and continued population monitoring. The latter is logistically feasible because of the relative openness of the habitats in many of these ranges.

B 1 – Developed ranges with small elephant populations: All B 1 ranges appear to be located amidst dense human populations. Several of these populations are probably severely isolated, and conservation management needs to focus on increasing connectivity between populations for effective metapopulation management, development of strategies to reclaim elephant habitat and prevention of further habitat loss. For B 2 ranges, priorities should include mitigation of people–elephant conflicts, wildlife law enforcement and continued population monitoring.

C 2/C 1 – Fragmented ranges with large and small elephant populations: Cluster C contains a large number of small and fragmented elephant ranges, primarily in Southeast Asia. The C ranges are currently being degraded by logging, road construction and land conversion. In Indonesia and Malaysia, for example, ranges are threatened by expanding large-scale palm oil plantations (Santiapillai & Ramono, 1993; Andau *et al.*, 1997). Available habitat is being fragmented and converted. As elephant populations and habitats become more isolated and fragmented, risk of crop raiding and people–elephant conflicts increases.

Conservation efforts should focus on increasing the effectiveness of existing protected areas, identifying corridors for linking protected elephant ranges, and working with local and regional authorities to develop land-use planning which would allow for long-term conservation of wild elephants. Because elephant populations and habitats in clusters C 1 and 2 are subject to rapid changes, monitoring efforts should be concentrated in these categories.

Wildland fragmentation versus population size?

On first view, our study seems to reveal a striking dichotomy, with large unfragmented wildlands mostly in Southeast Asia but with almost half of the remaining elephant population surviving in developed and populated areas of South Asia. Closer inspection illustrates that all ranges with large elephant populations have wildlands of at least 2000 km^2; some of the South Asian ranges with very large elephant populations have no less than 4000 km^2.

Habitat loss, fragmentation and resulting increases in people–elephant conflicts are the leading causes for the Asian elephant's decline (Sukumar, 1989; Santiapillai & Ramono, 1993; Santiapillai, 1997; Williams *et al.*, 2001). Asian elephants require large areas, have a tremendous role in shaping the landscapes, and need a mixture of habitats to thrive (Sukumar, 1989; Santiapillai, 1997). Maintaining large unfragmented wildlands will be an essential tool in the long-term conservation of this landscape species. Our study identifies areas with the greatest potential for this type of conservation strategy.

Many of the important large ranges are not well studied and have received little attention from conservation practitioners. For example, published work on Asian elephant ecology and conservation has focused on a relatively few ranges in India, Sri Lanka, Malaysia and Indonesia (see citations in Olivier 1978*a*,*b*; Sukumar, 1989; Santiapillai & Jackson, 1990) but not on ranges in Myanmar, Northern Assam or Thailand. There is a stunning paucity of technical capacity and international conservation efforts in the largest remaining wildlands with potentially some of the largest remaining elephant populations. These wildlands have received little attention as a consequence of political instability, isolationist governments and lack of international donor interest.

Fragmentation has had an effect on elephants, but preserving wildlands is not a universal remedy to ensure elephant conservation. Asian elephants have lived in close proximity to people over centuries and appear to survive in populated and developed environments (Santiapillai, 1997). Many of India's elephants occur in highly fragmented habitats, in close proximity to sizeable human populations, and in areas with well-developed transportation networks. However, close proximity of people and elephants has its price. India and Sri Lanka suffer from the highest levels of people–elephant conflicts, often resulting in deaths among both species (Sukumar, 1989). Why and how substantial elephant populations can survive in fragmented and developed conditions has not been sufficiently addressed. Possible explanations are based on differences in:

Habitat quality: India and Sri Lanka's large elephant populations predominantly occur in savanna habitats.

Savannas provide ample access to grasses and important elephant food plants (Sukumar, 1989). Tropical rainforests have fewer food plants resulting in lower carrying capacities. To test this pattern further will require comparing behaviour, ecology and population densities between Asian 'savanna' and 'forest' elephants.

Conservation management: Improved management, legislation and wildlife law enforcement may explain high elephant densities in developed ranges. In India these conservation instruments are functioning better than in other parts of the range. Myanmar, for example, has an inadequate protected area system encompassing only 2.3–4.5% of the country (Rao, Rabinowitz & Saw Tun Khaing, 2002; Myint Aung, unpubl. data). Financial means to safeguard natural resources are lacking and most protected areas do not have sufficient physical infrastructure, personnel or technical capacity. Poaching appears to be common, and protected areas have been degraded by agricultural conversion. Live capture of elephants cannot be controlled because the current registration system for domestic elephants is outdated and ill- maintained (Shepherd, 2002).

CONCLUSIONS

Regional landscape analyses such as our study can provide new perspectives for future elephant monitoring and conservation. The demonstrated regional variation has its roots in the history of elephant management and conservation as well as in economic, social and cultural differences among range countries. Further research exploring some of these factors in depth is needed. Our analysis produced several important insights:

(1) Elephant population size and habitat fragmentation vary tremendously among regions.
(2) There are three distinct types of ranges that best summarize the regional variation.
(3) Large unfragmented areas and populations exist in Southeast Asia that have received little attention but will play a significant role in long-term elephant conservation.
(4) In South Asia large elephant populations do not always occur in large and unfragmented wildlands.
(5) Regional pattern demonstrate the need to adapt monitoring and management to regional conditions.
(6) We need comparative studies to understand better the differences between Asian savanna and forest elephants.
(7) Landscape level information on habitat conditions derived from satellite imagery will be useful to develop good monitoring and management strategies.

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Appendix 1. Data sources and mapping details

a. *Extracting potential wildlands.* The Global Land Cover Characterization (GLCC) was created from coarse-resolution Advanced Very High Resolution (AVHRR) satellite imagery acquired between April 1992 and March 1993, published in 1996 (http://edcdaac.usgs.gov/glcc/background.html; Loveland *et al.*, 2000). The GLCC data provide the most accurate regional land-cover data set currently available because of the extensive validation and accuracy assessments conducted on them (Husak, Hadley & McGwire, 1999; Loveland *et al.*, 1999; Scepan, 1999). More recent data sets are currently under development, but they do not provide the same validation. We conducted a coarse visual comparison of the available data sets with Landsat Enhanced Thematic Mapper (ETM+) for the region and found the GLCC to be the most accurate. The GLCC data set has been widely used for regional and global analyses (e.g., Sanderson *et al.*, 2002; UNFAO, 2001) and can be downloaded from the Internet.

b. *Removing areas with frequent fires.* Fires are often indicators of human activity, especially in moist tropical forests (Barber & Schweithelm, 2000; Cochrane, 2000; World Resources Institute, 2000). Tropical forests almost never ignite naturally but will burn when subjected to slash-and-burn agriculture. Areas cleared for timber or for plantation establishment also are often burned (Barber & Schweithelm, 2000). Even in fire-adapted dry forests, fire frequencies now are higher because of human agricultural activities. Elephants prefer successional habitats resulting from fires to unburnt habitats (Sukumar, 1989). However, early successional habitats resulting from fires and shifting cultivation, as well as crop areas and plantations, are unsuitable for long-term elephant conservation because of increased people–elephant conflicts and mortality risk in these areas (Santiapillai & Ramono, 1993; Williams *et al.*, 2001). Our procedure for removing fires from wildlands resulted in an area reduction of 105,401 km^2 (21%) from forest habitats, 9446 km^2 (20%) from shrubland/savanna habitats, and 1002 km^2 (8%) from grassland habitats.

c. *Removing areas accessible by transportation networks.* Wildlife studies have demonstrated the detrimental effect of roads on populations of wide-ranging mammals (Trombulak & Frissell, 2000). Current research on bushmeat extraction in Africa and its devastating effects on biodiversity (Wilkie *et al.*, 2000) indicates that roads provide hunters with access to remote and undeveloped areas, resulting in the depletion of wild animal populations. Sukumar (1989) cites a World Wildlife Fund report demonstrating how road construction led to significant habitat loss and reduction of an elephant herd in Sumatra.

d. *Minimum wildland area to support elephants.* A few studies have reported smaller home ranges (Douglas-Hamilton, 1972: 14–52 km^2, cited in Sukumar, 1989; Olivier, 1978*a*: 59 km^2), but these seem to have been explained by exceptional conditions, such as presence of movement barriers, water availability and abundance of secondary forest (Sukumar, 1989). Sukumar (1989) estimates the area required to maintain a minimum viable elephant population (500 breeding individuals) to be at least 4400 km^2, if one assumes population densities of 0.5 elephants/km^2.

e. *Wildland inside known elephant ranges.* Based on published elephant ranges (Sukumar, 1989; Santiapillai & Jackson, 1990), we further reduced our wildlands by excluding areas outside known elephant ranges or above 2500 m elevation.

f. *Wildland protection status inside elephant ranges.* We used a digital protected areas map (World Conservation Monitoring Centre, 1997) to assess how much of the remaining wildland inside the elephant ranges is protected under all IUCN categories for protected areas.

Appendix 2. Classification of land-cover categories from the International Geosphere-Biosphere Programme (IGBP) into potential wildland categories for our study. The land-cover categories were applied to the Global Land Cover Characterization data set.

IGBP Land cover	Potential wildland
Evergreen needleleaf forest	Forest
Evergreen broadleaf forest	Forest
Deciduous needleleaf forest	Forest
Deciduous broadleaf forest	Forest
Mixed forest	Forest
Closed shrublands	Shrubland/savanna
Open shrublands	Shrubland/savanna
Woody savannas	Shrubland/savanna
Savannas	Shrubland/savanna
Grasslands	Grassland
Permanent wetlands	Unsuitable
Croplands	Unsuitable
Urban and built up	Unsuitable
Cropland/natural vegetation mosaic	Grassland
Snow and ice	Unsuitable
Barren or sparsely vegetated	Unsuitable