Application of Geoinformatics for Landscape Assessment and Conserving Forest Biodiversity in Northeast India

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Abstract

Herein, we summarize our work,within forest ecosystems of Garo Hills in northeast India, on mapping vegetation and land cover conditions, delineating wildlife habitat corridors among protected areas, evaluating forest conservation values of influence zones bordering protected areas, analyzing dispersion patterns of native forests, and determining potential effects of shifting-cultivation agriculture and anthropogenic stressors on an umbrella species (Asian elephant) as an indicator of forest biodiversity. This work demonstrates our use of multiple geoinformatic methods to help advise on conservation of native forests, wildlife, and biodiversity at the landscape scale. We also suggest some recent advances in geoinformatic techniques and models that could be further applied to our study area and beyond.

Key words: Geoinformatics, Spatial Statistics, Forest Management, Biodiversity Conservation, Garo Hills, Meghalaya, Northeast India, Shifting Cultivation.

1. Introduction

Forest biodiversity -- the variety of life and its processes within forest ecosystems -- provides a wide array of goods and services including timber and non-timber forest resources, amenity values, genetic resources, and mitigation of adverse effects of climate change (Duffy, 2009). Spatially complex and compositionally heterogeneous forest ecosystems and landscapes offer diverse habitats for a variety of wildlife species (Hunter 1999). Here, we summarize and provide a new synthesis of our work on landscape-scale ecological assessments of tropical forests in Garo Hills, Meghalaya, Northeast India.We demonstrate our use of geoinformatics and spatial statistics in this region to evaluate natural and anthropogenic factors and to interpret ecological attributes for developing strategies to conserve biodiversity of native, tropical forests to help ensure sustainable use of their goods and services. We highlight our salient findings and discuss our methods, which entail use of remote sensing (RS) data and geographic information systems (GIS) for landscape assessments. We also explain our use of spatial statistics to index spatial patterns of forest vegetation and land cover, and our use of GIS to analyze zones of influence (ZIs) buffering existing protected areas (PAs). We also summarize how we have identified (1) potential additions to PAs (as with ZIs) to accommodate habitat requirements of wide-ranging wildlife requiring large areas of dense, undisturbed native forests, (2) connectivity corridors to link PAs for Asian elephants (*Elephas maximus*), tigers (*Panthera tigris*), and other species), and (3) potential new wildlife

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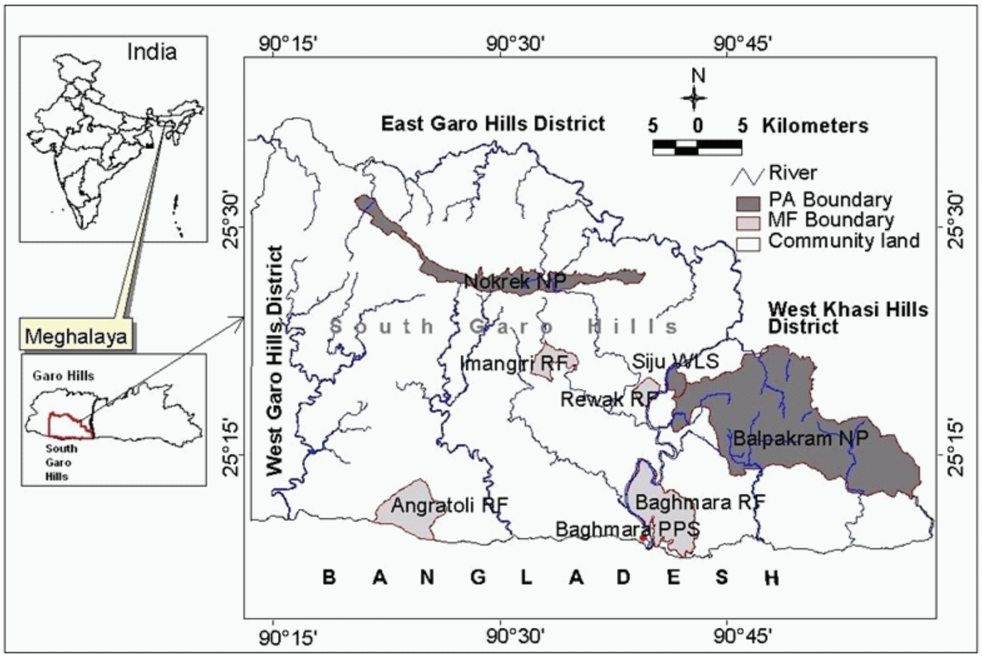

Figure 1. Location of Garo Hills, South Garo Hills, and protected areas, in western Meghalaya, northeast India.

sanctuaries to provide a diverse array of primary forests and seral stages.

2. Forests and Biodiversity in Garo Hills

The Garo Hills region consists of East, West, and South Garo Hills Districts, which collectively comprise 8167 km^2 of western Meghalaya in northeast India (Figure 1). Much of the community forest is heavily used for shifting (slash-and-burn) agriculture, locally called *jhum*, in which forest vegetation is cut and burned on site, the site is cultivated for food crops, and when final crop harvests are made the site becomes fallow and is allowed to return naturally to forest cover (Jha 1997).

Forest vegetation and land cover were inventoried using RS and mapped using GIS during 1996-2002 in a major project evaluating the region's biodiversity (Kumar *et al*. 2002). Results from that work suggested that the main forest types of Garo Hills are tropical moist evergreen forest (TMEF) and tropical semi-evergreen forest (TSEF); additionally, tropical moist deciduous forests (TMDF) are found mostly around habitations. Our field surveys from the prior study (Kumar *et al*. 2002, 2006) used systematic and opportunistic sampling from which we recorded >1,100 plant species including >400 tree species and many native animal species, and that tree species richness and diversity of the region are comparable to the world's most diverse tropical forests (Kumar *et al*. 2002, 2006).We also found that the region contains a wealth of regionally endemic plant and animal species, and that primary forests have greater tree species richness than do secondary forests or forest plantations of the region.

The southern portion of the Garo Hills region, including South Garo Hills District and adjoining Nokrek Ridge (Figure 1),encompasses 2459 km^2 and represents the very richest assemblage of forest biodiversity in western Meghalaya. This particular landscape is important for biodiversity conservation because it holds all PAs in Garo Hills, i.e., Balpakram National Park (BNP; 220 km^2), Nokrek National Park and Biosphere Reserve (NNPBR; 80 km^2), Siju Wildlife Sanctuary (SWS; 5.18 km^2) and Baghmara Pitcher Plant Sanctuary (BPPS; 27 ha). Also, the four reserved forests (RFs) in this area effectively serve as PAs due to the absence of human incursion and their being formally managed in protected status (Kumar et at. 2002). These RFs include Baghamara (BRF; 44.29 km^2), Rewak (RRF; 6.48 km^2), Emangiri (ERF; 8.29 km^2) and Angratoli (ARF; 30.11 km^2) Reserved Forests. The combination of PAs and RFs support a wide variety of native vegetation types and successional stages including primary forests and grasslands that collectively provide excellent habitats to many wildlife species (Kumar *et al*. 2006). These same wildlife species in the community forest matrix likely are quite vulnerable to habitat loss and increasing forest fragmentation due to high rates of jhum with truncated fallow periods (often < 5 years) that do not allow regeneration of older secondary forest with at least some mature forest conditions (Kumar *et al*. 2000), generally requiring at least 20-30 years (Kumar *et al*. 2006, 2008). This longer fallow period likely also provides more time for regeneration of soil productivity, although recent studies in Meghalaya by Saha and Khan (2011) suggest that jhum causes greater soil erosion than does permanent agriculture and livestock-based land-use.

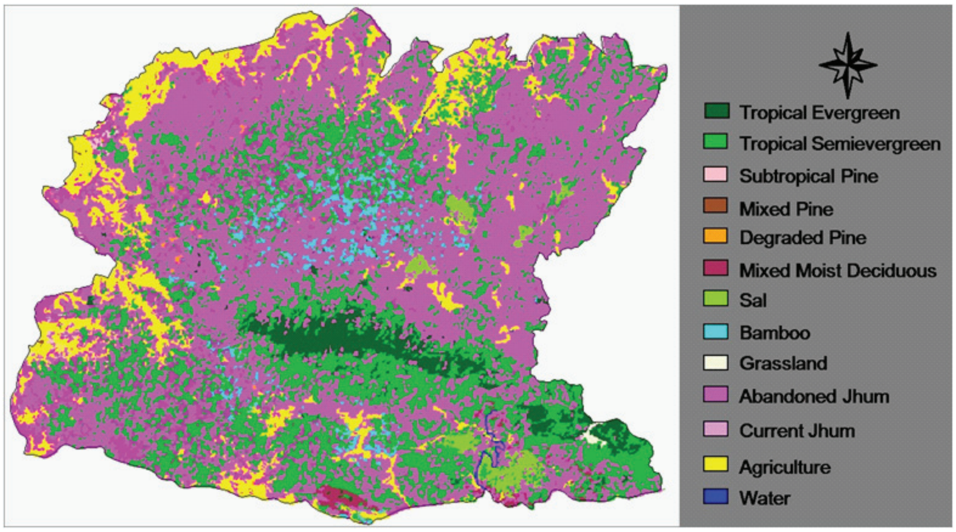

Figure 2. Land use land cover map of the entire Garo Hills of western Meghalaya, northeast India.

3. Land Use Land Cover and Vegetation as Wildlife Habitats

Remote sensing has long been identified as a technology immensely useful for creating wildlife habitat maps for extensive landscapes (e.g., Cowardin and Myers 1974; McDermid *et al*. 2009; Singh *et al*. 2010). We used remote sensing data to map land cover characteristics including forest vegetation at two spatial scales, i.e., for (1) the entire Garo Hills area (Figure 2; Talukdar, 2004) and (2) and South Garo Hills (Figure 3a; Kumar *et al*., 2008), with different methods appropriate to each scale. We used two scales, and two sources of RS data, because we wanted to analyze land use land cover and vegetation conditions as wildlife habitat in South Garo Hills at a finer spatial resolution and with greater ability to discern more specific vegetation types, than afforded by the previous mapping of the entire Garo Hills.

We mapped entire Garo hills at 1:250,000 using IRS 1D LISS III false color composite data for vegetation and broad land cover types (Figure 2). Subsequently, we mapped South Garo Hills from IRS ID LISS III data at 1:50,000 scale with field verification, to 9 categories: active jhum (0 to approximately 3 years old) and grassland, scrub and abandoned jhum (3-6 years old) on degraded sites, bamboo brakes and secondary forest (6-10 years old), TMDF, TSEF (approximately 15-30+ years old), TMEF, permanent agriculture, water bodies, and shadows (Table 1; also see Kumar *et al*. 2002). Classification error rates, based on field verification and represented by the kappa coefficient (a measure of classification accuracy), were 82% in Meghalaya as a whole including all of Garo Hills, and 80% in South Garo Hills.

The various vegetation and land cover categories mapped at both scales can be interpreted in terms of habitat conditions for a variety of wildlife species. We helped develop and apply matrices depicting such wildlife-habitat relationships for Garo Hills (Sajeev *et al*. 2002) by comparing information on habitats selected and used by wildlife species to the availability and dispersion of those habitats as denoted on our vegetation and land cover maps.

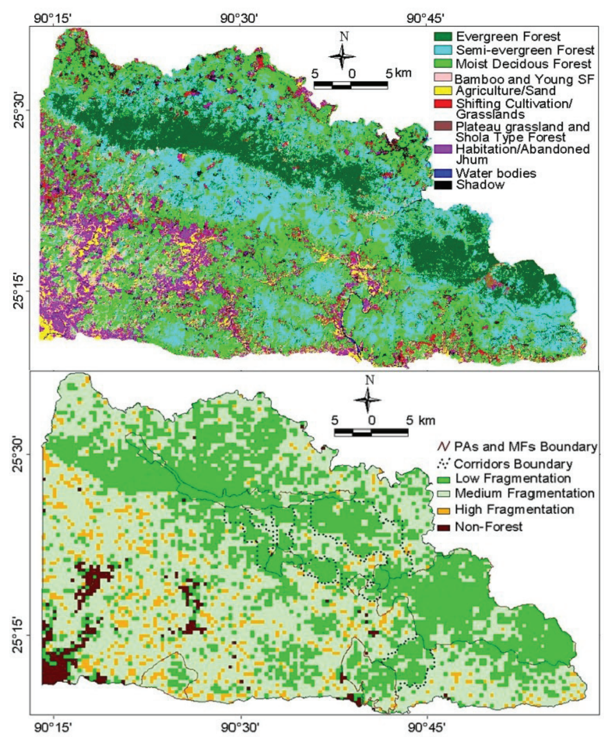

Figure 3. South Garo Hills (top) land use land cover map and (bottom) levels of forest fragmentation, and delineation of potential wildlife habitat corridors linking protected areas and reserved forests (Kumar *et al*. 2002).

Table 1. Forest cover and non-forest areas (km^2) within existing protected areas in South and All Garo Hills, Meghalaya, northeast India.

Existing Protected area	Tropical Moist Evergreen Forest	Tropical Semi-evergreen Forest	Tropical Moist Deciduous Forest	Non-forest area
Balpakram National Park	115	72	21	16
Nokrek National Park	26	14	4	4
Siju Wildlife Sanctuary		4	1	
Baghmara Reserved Forest		15	19	10
Angratoli Reserved Forest		10	13	7
Emangiri Reserved Forest		7	3	
Rewak Reserved Forest		2	2	1
All Garo Hills	353	624	703	778

4. Landscape Characterisation for Describing Wildlife Habitats

We computed the following landscape pattern variables with use of the Bio_CAP landscape analysis program (IIRS, 1999) and ArcInfo GIS (ESRI 1982-2008).

Topographic variables- We calculated an index of terrain complexity by using topographic data derived from a digital elevation model at a spatial resolution of 62.5 meters, procured from the Indian Institute of Remote Sensing, Dehra Dun (Figure 4a). Terrain complexity represents variance in terrain relief within a mask of specific dimension that is tiled across the landscape. High terrain complexity can be an important constraining factor for some terrestrial wildlife species traversing landscapes during dispersal or home range excursions (e.g., Carroll *et al*. 2010, Murphy *et al*. 2010); high terrain complexity can also signal native vegetation cover because of the difficulty of access by people for jhum cultivation. In calculating terrain complexity with GIS, we used a mask size of 500 m after testing mask sizes ranging 100-1000 m at 100-m intervals to determine the mask size that best captured the most terrain variability. We expressed the terrain complexity index as total area (km^2) in categories of low, medium, and high relief determined by applying Jenk's natural-breaks algorithm (Jenks 1967, Cromley 1996) to the frequency distribution of index values. We used terrain complexity values to indicate areas of intact and undisturbed forest.

Anthropogenic variables- Anthropogenic variables related to the presence and density of roads and village locations. Occurrence of roads and villages can have a detrimental effect on native wildlife by reducing habitat and allowing access for trapping and hunting. We represented roads by total length (km), road density (km/km^2), and total area in 5 road buffer classes demarcated at the specified distances of 200 m from centre of all main roads (Figure 4b). Other anthropogenic variables were total number of villages and density of villages (n/km^2). Of course, jhum itself also constitutes an anthropogenic activity, and that condition is included in the vegetation categories discussed above.

Forest vegetation and land cover variables.—We categorized and mapped forest, other vegetation and land cover variables from remote sensing data as of 2000. We calculated 5 indices to represent the spatial pattern and distribution of these vegetation categories of pertinence to wildlife, as follows.

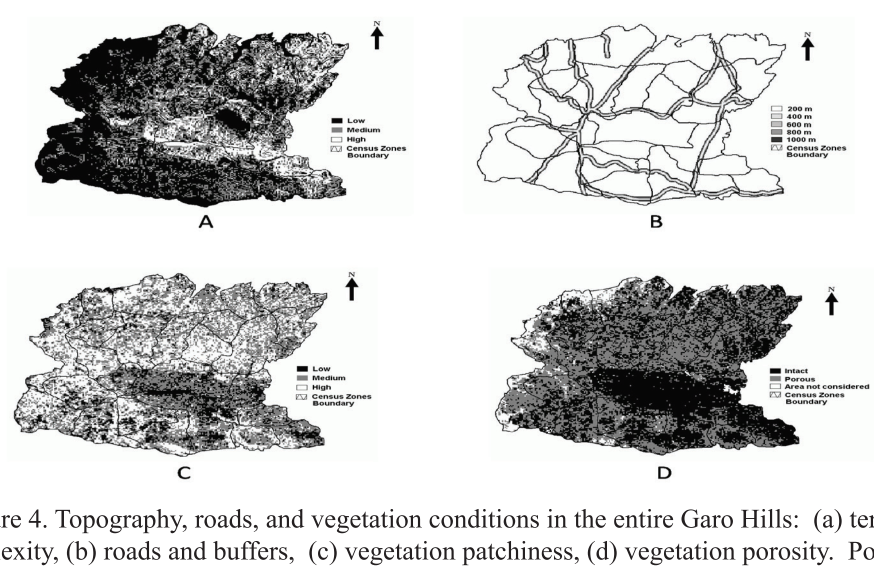

Figure 4. Topography, roads, and vegetation conditions in the entire Garo Hills: (a) terrain complexity, (b) roads and buffers, (c) vegetation patchiness, (d) vegetation porosity. Polygon outlines denote elephant census zones (Marak 1998; see Figure 5d).

Table 2. Calculations of forest vegetation and land cover variables.

Index name	Equation	Variable definitions	Reference
Patchiness index (P)	$P = \frac{\sum_{i=1}^{n} D_i}{N} \cdot 100$	N = number of boundaries between adjacent cells (pixels); and D_i = a dissimilarity value for the i^{th} boundary between adjacent cells, for all n cells	Romme (1982)
Porosity index (PO)	$PO = \sum_{i=1}^{n} c_{pi}$	Cp_i = the number of closed patches of the i^{th} cover class	Forman and Godron (1986)
Interspersion index (I)	$I = \frac{\sum_{i=1}^{n} SF_i}{N}$	SF_i is the shape factor $\sum_{i=1}^{n} \frac{Edge}{\sqrt{(Area_j \cdot \pi)}}$; Edge = the length of edge of the polygon, in both x and y direction; and Area = the area of the j^{th} polygon formed by groups in the i^{th} cover class	Lyon (1983)

The patchiness index (*P*) represents the relative size and isolation of vegetation cover patches (Table 2 and Figure 4c). We classified *P* values for each cell into low, medium, and high categories based on visually inspecting frequency histograms for natural breaks in values, and we summed the categories for total area and relative area. The porosity index (*PO*) represents the number of patches (GIS polygons) or density of patches within a particular vegetation type regardless of patch size (Table 2 and Figure 4d), and was calculated for the primary forest types of evergreen and semi-evergreen forest cover. We classified *PO* values, based on Jenk's natural breaks and verified using ground truth data, into three categories of intact, porous, and not considered (not applicable), and we summed values for total area and relative area. The interspersion index (*I*) is a count of dissimilar neighbors of a given cell (Table 2 and Figure 5a) and represents the intermixture of vegetation cover types across a landscape. *I* values were combined into low, medium, and high categories based on visual inspection of histograms of the frequency distributions, and summed for total area. The fragmentation index (Figure 5b) was calculated as the number of forest and non-forest type patches (polygons) per unit area. We used a roving window of 500 × 500 m on the vegetation map to derive the number of forest patches within the window. We defined forest as a combination of TMEF, TSEF, TMDF, sal and teak forests, bamboo brakes, and degraded forests; and non-forest as agriculture, current jhum, abandoned jhum, grassland and water. We normalized the fragmentation index values as the number of patches per window, in the range of 0 to 10, and

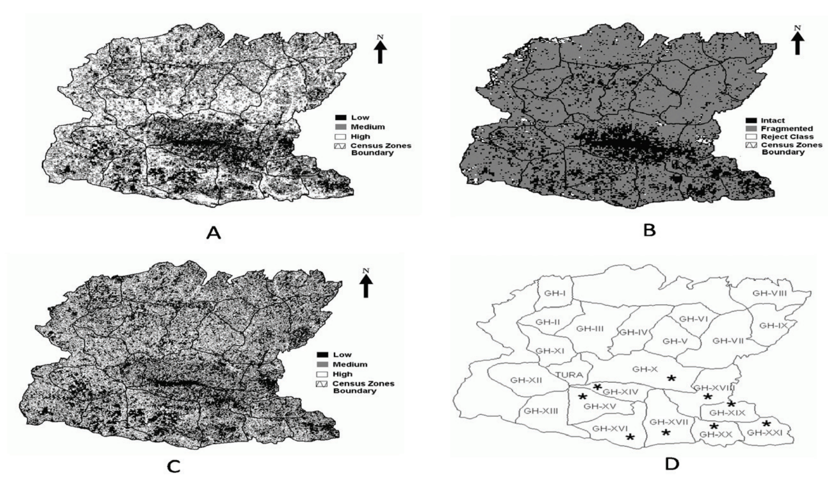

Figure 5. Vegetation conditions and elephant census zones in the entire Garo Hills: (a) vegetation interspersion, (b) forest fragmentation, (c) vegetation disturbance, (d) elephant census zone numbers (Marak 1998). South Garo Hills District included zones marked with an asterisk (*).

then lumped these 11 ranges into categories of low, medium, and high fragmentation based on visual inspection of the frequency histograms of index values. We devised the fragmentation map from the land use and land cover GIS theme of South Garo Hills using Bio_CAP (IIRS, 1999).

We computed the disturbance index (Figure 5c) from a linear combination of the above landscape indices using weighting factors for each index. The determination of weights was based on the degree of contrast of adjacent vegetation types (IIRS, 1999); weights ranged in value from 0 to 10 and were based on methods from Saaty (1997) as follows: forest adjacent to forest was given the highest weight; forest adjacent to non-forest was given the lowest weight; and intermediate weight values were set by expert judgment according to field observations and consultation with remote sensing specialists (Roy and Tomar, 2000; and IIRS, 2000). Disturbance index values were then combined into three categories of low, medium, and high based on visual inspection of natural breaks in the frequency histogram of values, and summed for total area and relative area.

5. Elephant Populations as Umbrella Species and Indicators of Biodiversity

Large, wide-ranging mammals, especially herbivores such as Asian elephant, can act as useful indicators of overall landscape biodiversity because they use large, often heterogeneous landscape areas to find resources (Sergio *et al*., 2006; Morellet *et al*. 2007). Elephants also provide vital ecological functions such as: creation and maintenance of forest paths and pools used in turn by many other species including ungulates; dispersal of fruits and seeds through dung deposition; alteration of vegetation composition and structure through browsing and trampling; and other functions (Butler, 1995; Fritz *et al*., 2002; Pringle 2008). Conserving elephants would also serve to conserve many other wildlife species; thus, elephants appropriately serve as an “umbrella species” (Fleishman *et al*., 2001).

Garo Hills support a dense population of Asian elephants. We used numbers of elephants as reported from direct counts made in delineated census zones during 1997-98 censuses (Marak, 1998) to calculate crude density as total number of elephants, of all reported sex and age classes, in each elephant census zone divided by total area of each elephant census zone (Table 3 and Figure 5d). We then computed the habitat variables (mentioned in the previous section) for each census zone, and developed multiple regression models to correlate them with elephant density in All Garo Hills (n = 21 elephant census zones) and in South Garo Hills including South Garo Hills district and adjoining Nokrek ridge in West Garo Hills (n = 9 elephant census zones). Results suggested that elephant density was greater in census zones with more

Table 3. Elephant crude density in Garo Hills based on 1997-98 census by Mark (1998).

Census zone #	Census zone name	Census zone area (km^2)	Number of Elephants	Elephant crude density (no/km^2)
GH-I	Dibru Hills - Chibinang	188.20	15	0.08
GH-II	Rongchugre - Ringre-Kalsingre	210.00	35	0.17
GH-III	Chasing - Dananggre - Manggakgre	441.50	46	0.10
GH-IV	Romgre - Rongsep - Marakgre	294.10	47	0.16
GH-V	Asil - Sokadam - Songsak	258.00	43	0.17
GH-VI	Dagal - Chimimit - Cheran	181.50	55	0.30
GH-VII	Dambu - Koknal - Baringgre	517.20	59	0.11
GH-VIII	Dhima - Kharkutta - Rajasimla - Ildek	299.00	37	0.12
GH-IX	Norangga - Gabilbila - Agrapathal	258.70	29	0.11
GH-X	Nokrek - Samanda - Rongrenggiri	574.80	65	0.11
GH-XI	Ranggira - Sadolpara - Sasatgre	238.60	26	0.11
GH-XII	Damalgre - Nengsangre - Rongmagre	332.40	34	0.10
GH-XIII	Kherapara - Medagre - Thalampara	341.20	74	0.22
GH-XIV	Dana Adugre - Nengsranggre - Rongmagre	168.00	61	0.36
GH-XV	Rongmagre - Dareng - Kakija - Warimagre	276.70	11	0.04
GH-XVI	Mibonpara - Ruga - Angratoli	333.40	10	0.03
GH-XVII	Rongdong - Tholegre - Rewak-jadigittim	364.60	78	0.21
GH-XVIII	Rekmangre - Emangre - Chengbagre	357.50	84	0.23
GH-XIX	Siju - Rongchu - Rongcheng - Balpakram	182.30	116	0.64
GH-XX	Baghmara - Halwa - Dambuk - Balpakram	193.40	156	0.81
GH-XXI	Mahadeo - Chimitap - Balpakram	214.30	216	1.01
GH-XXII	Banjengdoba - Rongsai	551.20	9	0.02
TURA	TURA	140.57	0	0.00

extensive and intact native forest with larger mean patch sizes, than in census zones with more fragmented native forest and greater extent of current and abandoned jhum and secondary forest conditions (Marcot *et al*., 2000 and 2001). Human alteration of native forests seems to have adversely influenced elephant density and, by dint of using elephants as umbrella species, overall native forest biodiversity, as corroborated by our forest vegetation and habitat assessments at multiple spatial scales ranging from field to landscape level (Kumar *et al*., 2002, 2006, 2008).

6. Protected Area Network Planning

PAs typically include national parks, sanctuaries and other areas designated independently to protect local resources of social and scientific value from anthropogenic disturbances. We expanded the PA concept to a landscape-scale approach of identifying a protected area network (PAN) in which the role of each PA is evaluated in spatial context of all others and the intervening matrix lands. A PAN approach goes beyond the focal PA approach by evaluating the needs and opportunities for linking individual PAs with habitat corridors (e.g., Rouget *et al*. 2006); complementing existing PAs to meet various broad-scale conservation objectives (e.g., redundancy, complementarity, and uniqueness of habitats and resources within PAs; e.g., Warman *et al*. 2004); determining boundary conditions around each PA including anthropogenic stressors such as jhum, roads and settlements (Kumar *et al*. 2010); and addressing human activities in the intervening matrix lands to help maintain selected habitat elements and conditions (Mathur and Sinha 2008).

All the PAs of Garo Hills are confined to South Garo Hills. These PAs, along with the adjoining RFs, support a wide variety of native vegetation types and many wildlife species (Kumar *et al*., 2006). However, several species, such as slow loris (*Nycticebus bengalensis*), hoolock gibbon (*Bunopithecus hoolock*), and Malayan giant squirrel (*Ratufa bicolor*), occur in smaller, weakly linked patches of native forest within the community forest matrix, and are thus vulnerable to increasing forest fragmentation from jhum and other development activities (Gupta 2005, Sawarkar 2005). Movement and intermixing of breeding individuals among such wildlife populations likely is necessary for long term survival of many species, including large mammals such as elephant, tiger, bear and others.

Table 4. Distribution of forest types within potential wildlife habitat corridors linking protected areas and reserved forests of South Garo Hills, Meghalaya, India.

Corridor	TMEF area (km^2)	TSEF area (km^2)	TMDF area (km^2)	Total area (km^2)
BNP/SWS-NNP	49	81	35	167
BNP-BRF	1	19	10	30
ERF-NNP	1	17	4	22
ERF-NNP	7	7	1	15
RRF-ERF	0	10	4	14
BNP/SWS-RRF	0	0	4	4
SWS-RRF	0	0	0	1
Total	58	136	58	253

ARF = Angratoli Reserved Forest, BRF = Baghmara Reserved Forest, ERF = Emangiri Reserved Forest, RRF = Rewak Reserved Forest, BNP/SWS = Balpakram National Park and Siju Wildlife Sanctuary: NNP = Nokrek National Park, TMEF= Tropical Moist Evergreen Forests, TSEF= Tropical Moist Evergreen Forests; and TMDF= Tropical Moist Deciduous Forests.

Therefore, as one component of a PAN strategy, we delineated potential wildlife habitat corridors (Figure 3b) using our map of vegetation and land cover fragmentation. We mapped 7 corridors among PAs and RFs based on existence of native forest cover and low levels of forest fragmentation (Kumar *et al*. 2010). The corridors collectively covered 274 km^2 (Table 4). Williams and Johnsingh (1996) had earlier identified three elephant habitat or elephant travel corridors in South Garo Hills based on a short-term field survey. Our analysis agreed with delineation of these three corridors, which we named Siju-Rewak, Balpakram-Baghmara and Emangiri-Nokrek and which covered 8 km^2, 31 km^2 and 48 km^2, respectively, and to which we added 4 more.

In addition to the 7 corridors, we also delineated zones of influence around PAs and RFs as a basis for other potential elements of the proposed PAN. In GIS, we created buffers of 2- and 5-km around each PA and RF. These 2 buffers divided community land into three zones of influence (ZIs), referred to as ZI1, ZI2 and ZI3, that represented the area within the 2-km buffers from PAs' boundaries; the area within the 5-km

Table 5. Land use and land cover in 3 zones of influence bordering protected areas and reserved forests of South Garo Hills, Meghalaya, India. The 3 zones are: ZI1 (2 km buffer), ZI2 (2-5 km buffer) and ZI3 (>5 km buffer).

Land use and land cover category	Area in ZI1 (km^2)	Area in ZI2 (km^2)	Area in ZI3 (km^2)
Tropical Moist Evergreen Forest	9	178	25
Tropical Semi-evergreen Forest	52	327	121
Tropical Moist Deciduous Forest	42	248	350
Habitation/Scrub/Abandoned *jhum* fields	5	37	186
Permanent Agriculture	4	21	68
Shifting Cultivation/ grasslands	9	66	91
Bamboo/Secondary Forests (6-10 years)	8	49	118
Water bodies	1	2	4

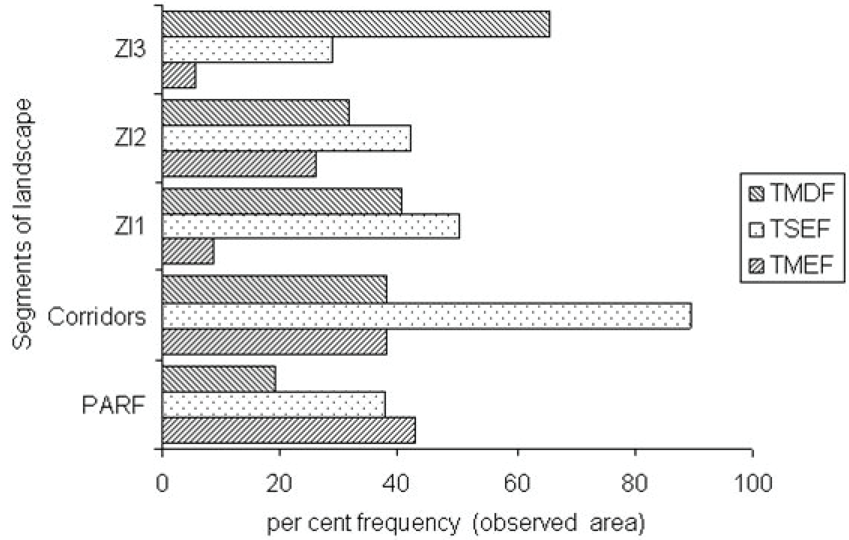

Figure 6. Proportion of 3 native forest types in protected areas and reserved forests (PARF), potential wildlife habitat corridors (see Figure 3, Table 4), and three zones of influence (ZI1, ZI2, ZI3; see Table 5), in South Garo Hills. TMEF= Tropical Evergreen Forest, TSEF= Tropical Semi-evergreen Forest, TMDF= Tropical Moist Deciduous Forest.

buffers (excluding the 2-km buffer area); and the area beyond the 5-km buffer within the Garo community land, respectively. ZI1 covered a total of 130 km^2 and contained more forest cover, i.e., TMEF, TSEF and TMDF combined (79% of the total ZI1 area) and less non-forest land use activities (21%) than found in the community forest matrix (ZI3), suggesting low anthropogenic pressures on old, intact native forests. Likewise, in ZI2 (area 928 km^2), the overall forest area (81%) was much greater than that of non-forest land use (19%). In contrast, ZI3 (area 963 km^2) contained a lower proportion of forest cover (52%), a higher proportion of non-forest land use (48%), and a substantially low proportion of TMEF (<3%) (Table 5).

Chi-square analysis revealed that relative proportions of three forest types differed significantly between PAs (inclusive of RFs), habitat corridors, and zones of influence (ZI1, ZI2 and ZI3) ($\chi^2 = 411.472$, df = 8, $p << 0.05$). All ZIs including ZI1, ZI2 and ZI3 are not independent of three forest types, i.e., overall forest cover ($\chi^2 = 180.260$, df = 4, $p << 0.001$) and forest cover varied significantly among ZIs with the highest proportion of area within ZI2 (Figure 6, Table 5). Relative proportions of land use activities, viz., habitation, permanent agriculture and *jhum*, differed significantly among the three ZIs ($\chi^2 = 28.920$, df = 4, $p < 0.001$) with the highest proportion in ZI3 (Figure 6 and Table 5) where habitation was the most prevalent activity followed by *jhum* and permanent agriculture. ZI1 and ZI2 supported a higher proportion of forest cover with almost negligible area under various land use activities and ZI3 had the least proportion of forest cover.

Thus, if the objective is to increase conservation of native forests in Garo Hills, then efforts in ZI3 could focus on restoration coupled with additional measures to protect larger forest tracts within the community land. In contrast, efforts in ZI2 may entail only protection measures, since most of the land within this zone sustained TMEF and TSEF tracts with a moderate proportion of TMDF and with low levels of anthropogenic land use activities. These findings also suggested that successful conservation of biodiversity within ZI2 (and the overall landscape as well) could be achieved by maintaining existing protection levels and encouraging the native community to avoid mass-scale clear felling and short-rotation jhum, coupled with community-scale participation in ensuring appropriate resource use.

7. Potential Geospatial Approaches and Implications for Biodiversity Conservation

The area of quantitative geographic analysis is advancing swiftly. Many new techniques in geoinformatics, such as advances in designs of wildlife linkages and ecological corridors (e.g., Kale *et al*. 2010, Roy *et al*. 2010), can be of use in Garo Hills and beyond (Table 6). One such technique is modeling optimal land allocations for protected area designation by use of such spatial tools as MARXAN (Ball and Possingham, 2000; Ball *et al*., 2009) and Zonation (Moilanen and Kujala, 2008; e.g., Carroll *et al*. 2010). These tools entail use of GIS to overlay existing land allocation boundaries to be retained, onto maps of biodiversity hotspots or distributions of species or habitats of conservation interest. Then, a "cost surface" is created that depicts social and economic factors, and an annealing or similar function is applied iteratively to determine best allocations, that is, the sufficient placement of PA boundaries to meet conservation

Table 6. Examples of potential geospatial modeling objectives, programs available on the Web, and potential use for wildlife and biodiversity conservation in Garo Hills, Meghalaya, northeast India. (See text for references and additional resources.)

Geospatial Objective	Examples of Programs and Web Sites	Potential Application in Garo Hills
Design of wildlife linkages and ecological corridors	CorridorDesign - http://www.corridordesign.org/ Circuitscape - http://www.circuitscape.org/Circuitscape/Welcome.html Connectivity Analysis Toolkit - http://www.klamathconservation.org/CAT/Help/index.htm	Validate and refine native forest corridors suggested in this paper. Identify new forest habitat linkages among known or suspected wildlife population centers, particularly for sedentary species occurring in disjunct habitat patches (e.g., slow loris, hoolock gibbon).
Delineation of potential reserves and protected areas	MARXAN - http://www.uq.edu.au/marxan/ Zonation - http://www.helsinki.fi/bioscience/consplan/software/Zonation/index.html	Evaluate efficacy of existing boundaries of protected areas for conserving native forest ecosystems. Identify changes in existing protected area boundaries, or potential new protected areas, to better meet conservation goals within specified cost constraints.
Species distribution modeling, niche modeling	Maxent - http://www.cs.princeton.edu/~schapire/maxent/ Biomapper - http://www2.unil.ch/biomapper/ Genetic Algorithm for Rule Set Production (GARP) - http://landshape.org/enm/garp-modelling-system-users-guide-and-technical-reference/	Develop maps of potential and likely habitat for key wildlife species. Identify possible new locations of species of conservation concern for inventory or surveys (e.g., hoolock gibbon, pigtail macaque, stumptail macaque, capped langur).
Species dispersal simulations	HexSim - http://hexsim.net/	Determine potential viability of wildlife populations (e.g,. elephant, tiger, bear) given their demographic and dispersal attributes and habitat dispersion patterns across the landscape. Identify locations where habitat corridors and linkages may help provide for population connections and viability.
Determine multispecies and biodiversity conditions at the landscape scale	RAMAS Multispecies Assessment - http://www.ramas.com/multispecies.htm Biodiversity Analysis Tool (BAT) - http://www.environment.gov.au/biodiversity/abif/bat/	Assess overall condition of the region for wildlife community and biodiversity conservation. Repeat assessments over time as a monitoring tool to detect trends.

objectives with minimal area given cost constraints (e.g., Christensen *et al*., 2009). Such approaches have been used to aid bird conservation in Chile (Meynard *et al*., 2009), to prioritize land acquisition for conservation in Florida, USA (Oetting *et al*., 2006), and many other uses.

Other related developments in geoinformatics pertain to modeling of most efficient habitat linkages across a landscape. These approaches include least-cost modeling (Watts and Handley 2010; Beier *et al*. 2009); use of graph theory (O'Brien *et al*., 2006), network theory (Schramski and Gattie, 2009), and circuit theory (McRae *et al*., 2008); and simulated annealing (McDonnell *et al*., 2002). Such approaches have been used to determine dispersal corridors of mountain lions (*Puma concolor*) in North America (LaRue and Nielsen, 2008), creation of nature reserves in China (Liu and Li, 2008), optimal dispersal corridors of rare plants in South Africa (Phillips *et al*., 2008), and other applications. Various approaches to designing wildlife linkages were reviewed by Beier *et al*. (2008).

The area of spatial statistics – the statistical analysis of landscapes, habitats, and species' spatial distributions -- is likewise advancing rapidly (Wagner and Fortin, 2005), such as used by Wimberly *et al*. (2009) to assess fire and fuel treatment approaches to forest management. Recent analysis and mapping tools in this arena include Maxent or maximum entropy analysis (Phillips and Dudik, 2008) and related information theoretic approaches (e.g., Horne *et al*., 2008; Gilioli *et al*., 2008).

A relatively new and exciting area of wildlife research is that of landscape genetics that combines landscape ecology and population genetics (Manel *et al*., 2003). It helps reveal unseen linkages, filters, and barriers of dispersal of organisms across landscapes with heterogeneous habitat and topographic conditions (Epps *et al*., 2007; Holderegger and Wagner, 2006). For example, landscape genetics have been applied to determine effects of reserve isolation on invertebrates in California USA (Vandergast *et al*., 2009).

The future of geoinformatics is bound to remain diverse, with many new techniques and modeling approaches being developed to help solve previously intractable problems of balancing nature conservation with social and economic objectives. For Garo Hills and beyond, such tools may prove to be invaluable for evaluating the efficacy of existing conservation allocations and suggesting changes to maintain and restore conservation values of wildlife habitats, species, and functions.

Acknowledgments

We thank V. B. Sawarkar, Ajai Saxena, P.K. Mathur, Atul K. Gupta, S.P. Singh, M.C. Porwal, Harnam Singh, Nupoor Prasad and Suddhasheel Ghosh for inputs in various activities of the project and follow up publications which this summary is based upon. We are grateful to S.B. Singh, T. T. C. Marak, A.K. Shrivastava, S. N. Sangma and James Pohsyngp from State Forest Department of Meghalaya for their generous support and help in extreme field conditions. We also thank Panna Lal for his fine help with GIS imagery. Funding and logistic support of US Forest Service (USA), Wildlife Institute of India, Dehradun, Indian Institute of Remote Sensing Dehradun and State Forest Department of Meghalaya are duly acknowledged. Mention of commercial products herein does not necessarily constitute endorsement.

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