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Applications of geographic information systems, remote-sensing, and a landscape ecology approach to biodiversity conservation in the Western Ghats

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The mountains along the west coast of peninsular India, the Western Ghats, constitute one of the unique biological regions of the world. Rapidly occurring land-cover and land-use change in the Western Ghats has serious implications for the biodiversity of the region. Both landscape changes as well as the distribution of biodiversity are phenomena with strong spatial correlates. Recent developments in remote-sensing technology and Geographic Information Systems (GIS) allow the use of a landscape ecology and spatial analysis approach to the problem of deforestation and biodiversity conservation in the Western Ghats. Applications of this approach include analyses of land-cover and land-use change; estimation of deforestation rates and rates of forest fragmentation; examination of the spatial correlates of forest loss and the socioeconomic drivers of land-use change; modelling of deforestation; analysis of the consequences of land-cover and land-use change in the form of climate change and change in distribution of biodiversity; biomass estimation; gap analysis of the effectiveness of the protected area network in conserving areas of importance for biodiversity conservation; and conservation planning. We present examples from our work in the Western Ghats, in general, and in the Agastyamalai region and Biligiri Rangan Hills, in particular, as well as that of other researchers in India on various aspects of applications of GIS, remote sensing, and a landscape ecology approach to biodiversity conservation.

THE mountains along the west coast of peninsular India, the Western Ghats, constitute one of the unique biological regions of the world. The Western Ghats extend from the southern tip of the peninsula (8°N) northwards about 1600 km to the mouth of the river Tapti (21°N). The mountains rise to average altitudes between 900 and 1500 m above sea level, intercepting monsoon winds from the south-west and creating a rain shadow in the region to their east. The varied climate and diverse topography create a wide array of habitats that support unique sets of plant and animal species. The level of endemism is high and the region is considered one of the world's biodiversity hot spots. Apart from biological diversity, the region boasts of high levels of cultural diversity as many indigenous people inhabit its forests.

The Western Ghats region, like other parts of the tropics, is undergoing rapid transformation. The deforestation rate is high and forests are being transformed into agriculture and monoculture plantations. Hydroelectric projects, mining, and extraction of forest products are also altering the landscape. The changes in land use and land cover have profound consequences for the biodiversity and economic well-being of the people. Although change in the Western Ghats is occurring at a rapid pace, the exact magnitude and patterns of change are not well understood. Moreover, drivers as well as consequences of change remain unexplored.

Recent developments in remote-sensing technology and Geographic Information Systems (GIS) allow us to use a landscape ecology and spatial analysis approach to address the problem of deforestation and biodiversity conservation in the Western Ghats. The landscape ecology approach departs from traditional approaches by focusing on the structure, function, and spatial patterns of landscape elements and on changes in the landscape mosaic through time. Furthermore, this approach has numerous applications to conservation planning because the total area, patchiness, and connectivity of ecosystems and habitats, and their representation in the protected area network are all important for biodiversity conservation. Moreover, the spatial data, when integrated with socioeconomic data, have the potential to reveal the complex role of social and economic factors underlying change.

GIS are computer-based systems that efficiently store, retrieve, manipulate, analyse, and display spatial data according to user specifications[1,2]. GIS is used as a decision support system involving integration of spatially referenced data in a problem-solving environment[3]. GIS is integrated with remote sensing systems in order to realize the full potential of both systems. Remote sensing systems collect vast amounts of biological and physical data on multiple dates, thus allowing both inventory and monitoring of the environment. Global Positioning Systems (GPS) aid in the collection of ground data for rectification and processing of remotely sensed imagery.

Detailed descriptions of the development and applications of remote sensing technology, particularly in India, can be found in the *Current Science* special issue on Remote Sensing for National Development (1991) and *Current Science* Special Section on IRS-1C (1996). Under the auspices of India's NNRMS (National Natural Resource Management System), satellite data has been used in agricultural crop acreage and yield estimation, drought warning and assessment, flood control and damage assessment, land-use and land-cover mapping for agro-climatic planning, wasteland, water resources, forest resources, and marine resources management, urban development, and mineral prospecting[4,5]. In their paper, Kasturirangan *et al.*[5] forecast applications to biodiversity conservation as one of the areas in which remote sensing will play an important role in the future.

Although this technology is readily available in India and India has been a leading developer in this technology, its use in landscape ecology and conservation of biodiversity has been very limited. Here, we demonstrate the use of these approaches in addressing problems related to the patterns, processes, and consequences of deforestation and land-use change. This is not an exhaustive summary of such applications but is based primarily on some examples of work done by our group in the Western Ghats, in general, and in the Agastyamalai region and Biligiri Rangan Hills, in particular, as well as that of other researchers in India. Applications related to patterns and processes of land-cover and land-use change include estimation of deforestation and fragmentation rates, spatial correlates of forest loss and socioeconomic drivers of land-use change, and modelling of deforestation. Applications related to the consequences of land-cover and land-use change include estimation of climate change, biomass change, and biodiversity distribution, as well as gap analysis and conservation planning. Finally, we explore future research needs and directions in this field.

Patterns of land-cover and land-use change and habitat fragmentation

It is well-known that extensive deforestation has taken place in the Western Ghats during the last 100 years. However, the pattern and magnitude of this change remain unknown. Spatial data from a variety of sources such as, topographic maps, thematic maps, aerial photographs, satellite imagery, and field studies, can be incorporated into a GIS to examine the spatial and temporal patterns of land-cover and land-use change as well as forest loss. Recent examples of studies quantifying land-cover and land-use changes in the tropics include those by Stone *et al.*[6] in Brazil, Brown *et al.*[7] in Malaysia, Liu *et al.*[8] in the Philippines, and Sader [9] in Guatemala as well as studies by FAO[10,11] for the entire tropics.

Besides quantifying forest loss, these datasets can also be used to quantify forest fragmentation which has serious consequences for biodiversity conservation. Increase in forest fragmentation gives rise to an edge effect with respect to microclimate changes, species invasion from surrounding vegetation, and the impact of surrounding anthropogenic activity[12] which can result in altered plant species composition within fragments. Furthermore, forest fragmentation affects the distribution of large animal species by reducing their core habitat. Tilman *et al.*[13] have demonstrated the negative effects of even a slight increase in habitat fragmentation. In their model, the more fragmented a habitat is, the greater is the number of extinctions caused by further habitat destruction. Habitat fragmentation accelerates extinction[14] due to factors such as demographic and environmental stochasticity, decrease in genetic heterozygosity, edge effects and human disturbance. Although several studies have examined the effects of fragmentation on biodiversity, only a few studies[15,16] have documented time series changes in numbers and size of fragments in the tropics.

Patch density, mean patch size, patch size standard deviation, and patch size coefficient of variation for forests and scrub can be compared between various time periods. Patch density and mean patch size serve as fragmentation indices for comparison between the two time periods. Patch size standard deviation measures absolute variation around the mean patch size. Patch size coefficient of variation measures variability as a percentage of the mean[17].

We examined deforestation rates in the Western Ghats between the early and latter parts of this century[18]. The study area comprised 19 districts covering a total geographical area of 81,870 km^2 within the states of Karnataka, Kerala, and Tamil Nadu. A land-cover map for the earlier time period was digitized from 1:253,440 scale Survey of India topographic maps based on surveys conducted from 1909 to 1928. Land cover and land use during the late 1980s/early 1990s were digitized from 1:250,000 scale Forest Survey of India forest vegetation maps produced from interpretation of 1987, 1989 and 1991 satellite imagery (Figure 1). Over a 70-year period (1920–1990), 40% of the original natural vegetation (forests and scrub) was lost or converted to one of the

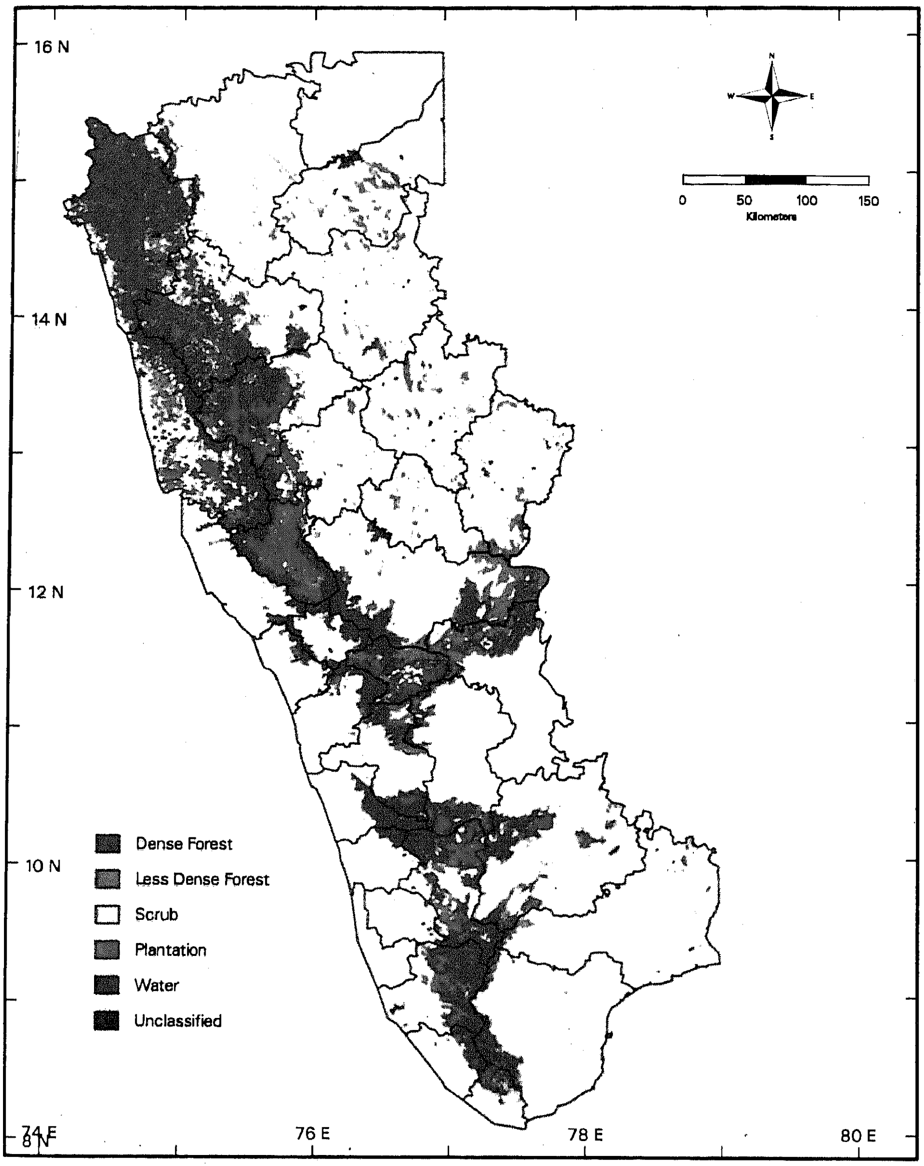

Figure 1. Land-cover and land-use patterns in the Western Ghats *circa* 1990.

following landuse types: open/cultivated lands, coffee plantations, tea plantations, and hydroelectric reservoirs. Open/cultivated lands accounted for 76% and coffee plantations for 16% of the conversion.

Deforestation has also resulted in extensive landscape fragmentation in the Western Ghats. The number of forest patches in the study area increased four-fold (from 179 to 769) with a simultaneous 83% reduction in average forest patch size[18]. The frequency distribution of perimeter/area (P/A) ratios of the forest patches in the two time periods (i.e. 1920 and 1990) is presented in Figure 2. Patches with smaller P/A ratios are less subjected to edge effects and are, in general, more suitable for biodiversity conservation. The graph demonstrates not only that the number of patches had greatly increased in the second time period, but also that most of the patches have higher P/A ratios than did the patches in the first time period.

Processes of land-cover and land-use change

Spatial correlates of change

Roads, reservoirs, and population centers can serve as indices of development and the correlation of forest loss with these indices can be determined with a GIS and spatial analysis approach. Buffer analysis (see ref. 8) is

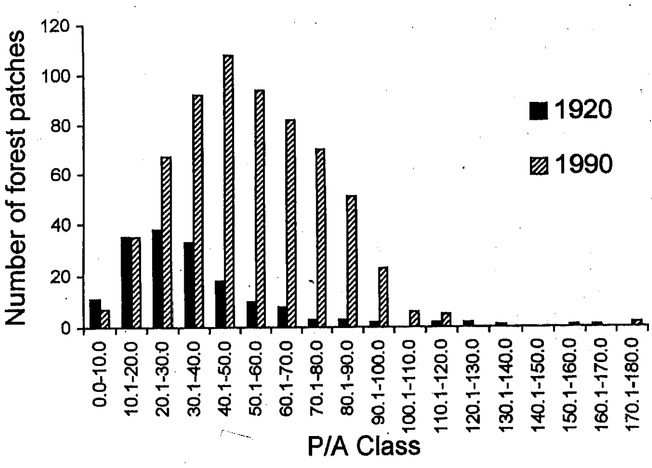

Figure 2. Frequency distribution of perimeter/area (P/A) ratios of forest fragments in the Western Ghats during two time periods.

one of the ways to examine the relationship of forest loss with the road network, reservoirs, and population centers. Buffer analysis involves the creation of buffer rings at equal (say 1 km) intervals around the road network or around population centers. Values for relative forest loss can be obtained as a per cent of the forest cover originally present in each buffer ring. A regression model can be run with relative forest loss in each buffer ring (%) as the dependent variable and distance of buffer rings from roads (km) as the independent variable to test the hypothesis that relative forest loss decreases as distance from indices of development increases.

In a study on spatial correlates of deforestation in the Western Ghats[18], we found that roads and population centers are significant factors affecting forest loss. Relative forest loss decreased as distance from roads and population centers increased. There was no clear relationship of relative forest loss with distance from reservoirs. However, when we did separate analyses on reservoirs within forests and those outside the forests of the Western Ghats, we found opposite results. For the reservoirs outside the Western Ghats, deforestation decreased as distance from the reservoirs increased. For reservoirs within the Western Ghats, there was an increase in deforestation as distance from reservoirs increased. The difference in the relationship of forest loss to reservoirs inside and outside the Western Ghats can be explained by the fact that reservoirs within the Western Ghats are established inside protected areas or, sometimes, protected areas are delineated around reservoirs after they are built. Encroachment and conversion of forests to plantation occur at lower rates within protected areas. Thus, reservoirs within the Western Ghats do not have the same relationship with forest loss as do reservoirs outside the Western Ghats.

Socioeconomic drivers of change

Spatial correlates of change indicate the proximate factors that influence land-use and land-cover change. Ultimate forces influencing land-use change are rooted in social and economic decisions concerning the use of land, but our understanding of social and economic factors leading to forest loss remains poor. Most analyses of social and economic factors underlying deforestation are based on cross-country analyses of correlations between a host of socioeconomic variables and deforestation rates (refs 19, 20 and references therein). Such analyses mask considerable variation within and among countries and only provide clues to the causal agents involved. Information about socioeconomic correlates and determinants of land use at the local level needs to be integrated with ecological data to fully understand the drivers of change. Such integration has not been often attempted, but GIS technologies make it possible to conveniently combine socioeconomic and spatial data, and we are in the process of examining social and economic dimensions of land-use changes in the Western Ghats.

Modelling deforestation

Spatially explicit and dynamic landscape modelling is increasingly being used to predict future deforestation based on past and current patterns and drivers of deforestation. For example, GEOMOD2 is a spatially explicit model which simulates future land-use change based on either a statistical analysis of how people have used land in the past or alternative hypotheses of how people will use land in the future[21]. The model contains algorithms of land-use change that follow the principles of adjacency (the tendency for people to develop land next to already developed land), geophysical desirability (selection of locations with the most favourable environmental factors), and regional heterogeneity (differences in land-use patterns in various districts, due to differences in demographic, economic, and political factors). The model uses maps of land-cover and land-use types along with a set of driver maps (elevation, aspect, slope, precipitation, soil, transportation network, rivers, biogeographic zone, and protected areas). GEOMOD2 is calibrated using the land use map from one point in time. The model is then run to the second point in time and the results are validated by comparing the simulated map with the actual land cover and land use of the second point in time. GEOMOD2 can then make a projection of future deforestation to highlight locations that are most susceptible to forest loss.

We used our GIS datasets on land-cover and land-use types in the Western Ghats in the 1920s and 1990s to carry out preliminary simulations of deforestation during

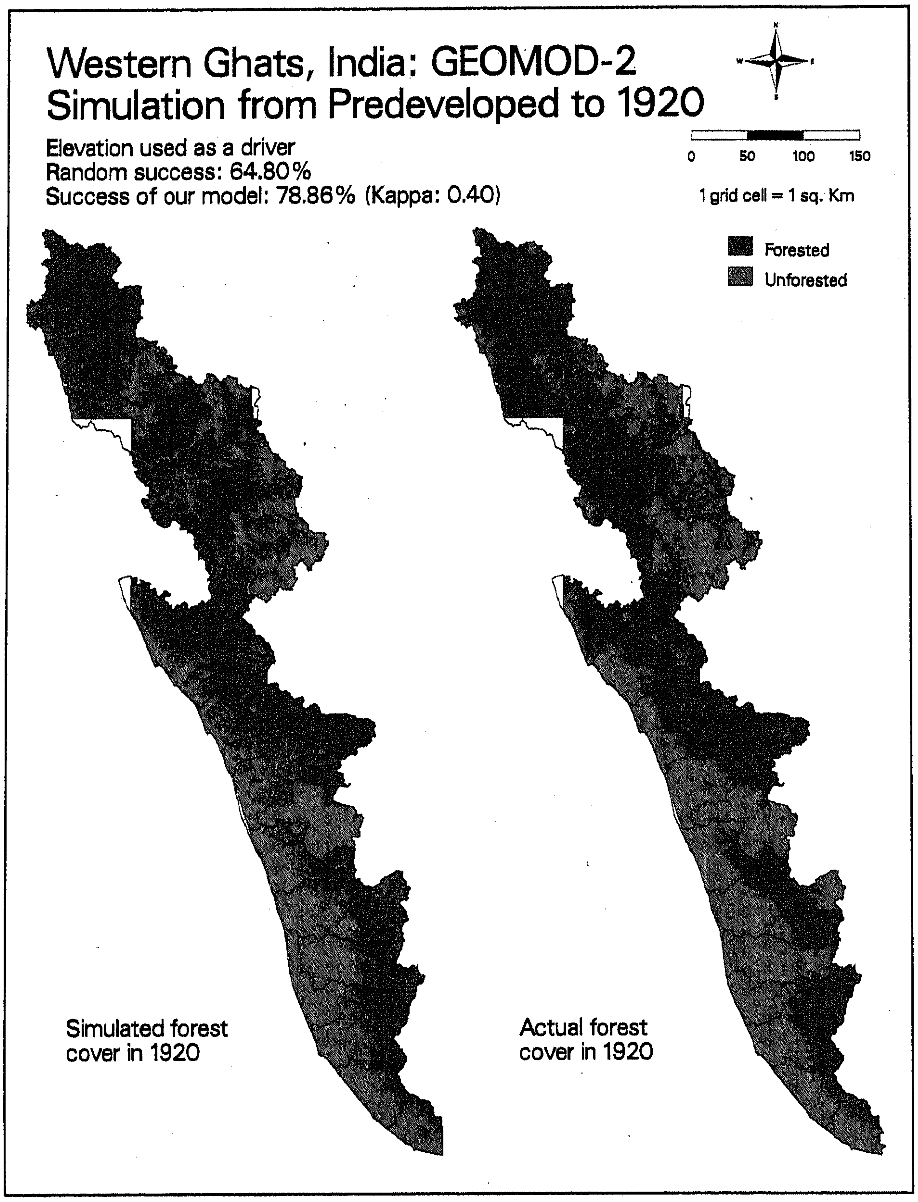

Figure 3 ***a*****.** Modelling deforestation in the Western Ghats. Predeveloped to 1920.

two time periods. The first simulation was from a 'predeveloped' state (during which the entire study area was assumed to be forested) to 1920 and the second simulation was from 1920 to 1990. For the preliminary simulation, we examined the role of elevation as a driver of land-use change. Elevation data was obtained from the USGS GTOPO30 1 km resolution DEM. We found that elevation was an important predictor of the location of deforestation during the first time period (Figure 3 *a*, kappa = 0.4) but was a less important predictor of the location of deforestation during the second time period (Figure 3 *b*, kappa = 0.2).

These preliminary results suggest that during the 'early' stages of deforestation, forests at lower elevations are much more likely to be converted to other land uses. However, after most of the land at lower elevations has become deforested, deforestation enters a 'secondary' phase during which elevation plays a less important role.

Consequences of land-cover and land-use change

Biomass estimation, climate change, and biome shifts

Land-use change also has important consequences for the emission and sequestration of greenhouse gases,

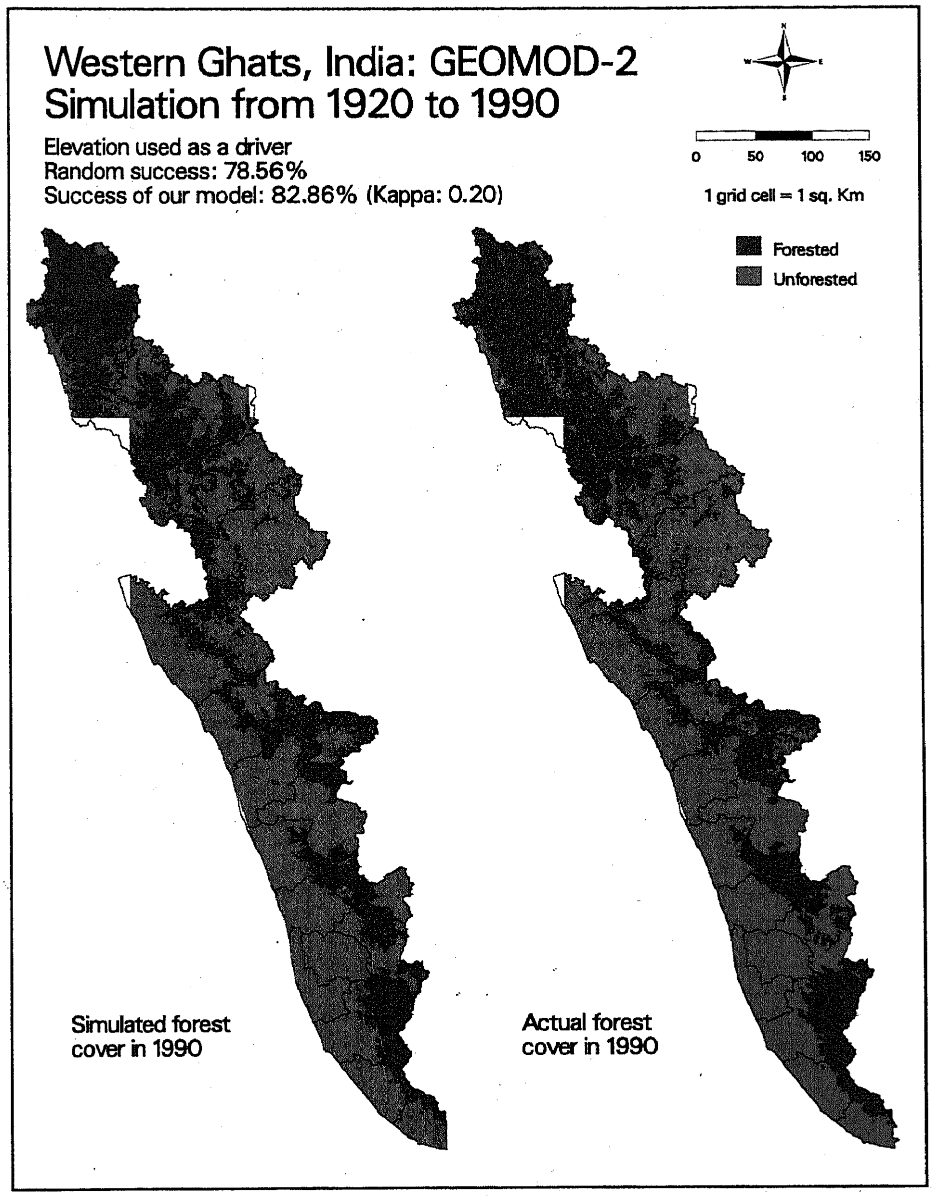

Figure 3 *b*. Modelling deforestation in the Western Ghats 1920 to 1990.

which in turn affect global climate change. Anticipated climate changes include rise in mean temperatures in the tropics[22] and intensification of the Indian summer monsoon[23]. Climatic changes, in turn, are expected to influence changes in the distribution of plant and animal species. For example, in the Western Ghats, montane evergreen forests can be expected to expand into grasslands, thus bringing about a shift in the grassland biomes and affecting the survival of animals such as the Nilgiri tahr, a mammal endemic to the montane grasslands of the Western Ghats[24].

There is, however, considerable uncertainty in the estimation of carbon fluxes due to tropical land-use change and, therefore, in projections of global climate change. Poor, unreliable or generalized data on biomass density of tropical forests is one of the main sources of this uncertainty[7,25,26]. Previous carbon exchange studies provided carbon release estimates based on countrywide estimates of deforestation provided by the FAO/UNEP. As pointed out by Hall *et al.*[21], these estimates of deforestation use highly aggregated data at the national level that do not accurately represent actual patterns of land-use and biomass change at the local/regional levels. Furthermore, although there can be no doubt that forest degradation plays a role in carbon loss, these estimates do not include biomass loss due to forest degradation. In

Figure 4. Vegetation index (NDVI) map of Biligiri Rangaswamy Temple Sanctuary.

reality, forest degradation may account for levels of atmospheric carbon dioxide above that expected as a consequence of deforestation alone[27].

A study by Iverson *et al.*[26] used GIS to spatially extrapolate local and subregional data on the effects of climate, topography, soil, population pressure, and land use to estimate biomass-density changes for continental South and Southeast Asia. Vegetation indices (VIs) derived from remotely sensed imagery have demonstrated usefulness as indicators of biomass and vegetative change[28,29]. These indices exploit the reflectance patterns of vegetation in the near-infrared and red wavelengths: vegetation is bright (demonstrates a high reflectance) in the near-infrared, but is much less bright (demonstrates much lower reflectance) in the red. In remotely sensed data, the slope of the line on the spectral signature varies according to vegetative factors such as leaf area index (LAI) and net primary productivity (NPP), and is the basis for nearly all vegetation indices[29]. Myneni *et al.*[30] used NDVI datasets derived from AVHRR imagery to demonstrate a global increase in the photosynthetic activity of terrestrial vegetation from 1981 to 1991. Their results suggest that increase in plant growth is associated with a lengthening of the active growing season and increased global warming.

We have investigated the usefulness of vegetation indices derived from Landsat Thematic Mapper (TM) imagery to assess the spatial patterns of biomass for a single time period in the Biligiri Rangan Hills, Karnataka, India (Figure 4). Preliminary results indicate that vegetation and structural patterns associated with varying levels of anthropogenic pressures, and thus varying levels of biomass, are distinguishable using this technique. Further work will use field data to associate biomass values with the floristic and structural types and will assess the manner in which the indices vary in response to local biomass change.

As is the case with biodiversity monitoring programs, although a number of studies have examined the effects of land-use change on the release of carbon to the atmosphere[27,31–33], only a few models have attempted to assess the spatial patterns of land-use change from a social, anthropological, or economic perspective[34] or an ecological perspective[35]. There is a need to replace our existing piecemeal and fragmented approach to the monitoring of the earth's life support systems by integrating land-use change, climate change, and biological and socioeconomic monitoring programs at the regional and global levels[36].

Conservation planning

Ultimately, the fate of biodiversity depends upon the existence and integrity of protected areas. Information about landscape changes can be integrated with data on

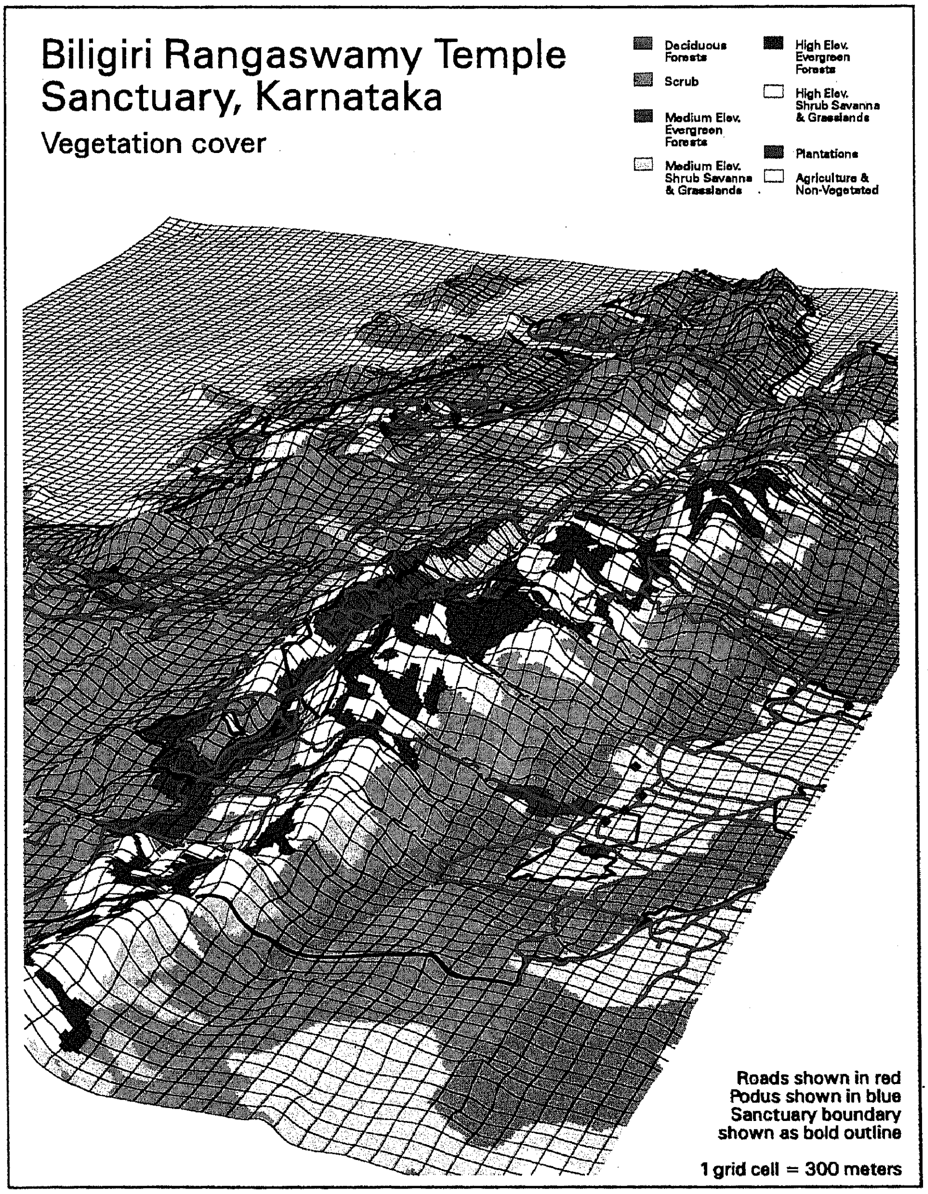

Figure 5. 3-D draping of vegetation types at Biligiri Rangaswamy Temple Sanctuary.

spatial distribution of biodiversity and protected areas in order to devise effective conservation planning strategies. Remotely sensed data along with digital elevation models (DEMs) and spatial terrain data such as slope and aspect can be combined with GIS layers of plant and animal species distribution to map hot spots of plant diversity, distributions of endangered species habitat, and the vulnerability of areas to change. For example, a study by Prasad *et al.*[37] used remotely sensed data and digital elevation and terrain data from the Mehao Wildlife Sanctuary in northeast India, to generate 3-D visualization of pheasant and takin habitats, hot spots of plant diversity, and areas vulnerable to human-induced changes. A 3-D draping of land-cover and land-use types over a digital elevation model of Biligiri Rangaswamy Temple Sanctuary is shown in Figure 5. The vegetation cover information is derived from vegetation maps produced by the French Institute, Pondicherry. Such a representation allows a visualization of the location of roads, settlements, and various vegetation types in relation to the terrain of the study area.

A landscape ecology approach also allows analysis of the degree of connectivity of habitat patches and examination of the land-use mosaic within which habitat patches are embedded. Landscapes, within which protected areas occur and seek to protect biodiversity, are dynamic matrices of habitat patches, interconnecting corridors, and a variety of agricultural and non-agricultural land uses. Daniels[38] has demonstrated an application of the principles of landscape ecology to the conservation of birds in the heterogenous and human-altered landscape matrix of the Western Ghats.

Gap analysis pools together spatial (and biological) data from various sources to provide a powerful tool for identifying gaps in conservation. Gap analysis uses GIS to superimpose layers of data on vegetation types, wildlife habitats, and protected areas[39]. Although a few studies in the neotropics have examined the representativeness of vegetation types within protected area networks[40], the approach has not been widely used for tropical regions. For example, in India, until fairly recently, not enough attention has been given to the 'conservation value' of an area during the establishment of protected areas. We conducted a study which focused on a set of protected areas in the Agastyamalai region of the Western Ghats, India[41]. The study area consisted of four Wildlife Sanctuaries (Kalakad–Mundanthurai, Neyyar, Peppara, and Shendurni) and six contiguous Reserve Forests (Kolathupuzha 1 and 2, Yerur, Pallod 1 and 2, and Kottur).

We examined forest loss and land-use changes in the study area between 2 time periods. Our results showed that deforestation rates were high in the study region. Between 1920 and 1960, 0.07% of the forest area was lost annually. Between 1960 and 1990, annual forest loss was 0.33% even though the entire study area had been under some form of protection during that period.

In order to perform a biodiversity gap analysis of the protected areas in the study site, we produced a detailed map of existing floristic types and used it to generate layers corresponding to floristic species richness, zones of floristic endemism, floristically unique areas, and habitat distribution of representative endemic faunal species. To generate the floristic species richness layer, each floristic type was assigned a value of the number of species for the type. Values related to floristic (tree) endemism were assigned according to the per cent of endemic species out of the total number of endemic tree species in the Western Ghats. Information for the layer on unique areas was based on field surveys and knowledge of the restricted distribution of different ecosystems and species. Uniqueness was determined at the ecosystem and floristic levels. Myristica swamps are unique areas at the ecosystem level and the *Hopea racophloea* and *Humboldtia decurrens* facies, the *Nageia wallichiana* facies, and the *Hopea utilis* facies are unique areas at the species level. We created the layer on representative endemic faunal habitats by assigning data values to each floristic type based on the number of endemic mammalian and bird species found in a particular type. We used only mammal and bird data because relevant details on the habitat preferences of other vertebrate classes such as reptiles and amphibians are not available in the literature. Detailed methodology related to the generation of these layers is provided in ref. 41.

We used two separate methods to derive data on conservation value. In the first method, we obtained a conservation value index for each protected area based on the geographical area covered by the highest class each of the 4 categories of floristic species richness, floristic endemism, unique areas, and endemic faunal habitats. In the second method, we produced a composite picture of conservation values in the form of a map (Figure 6) by combining the information in each of the layers (floristic species richness, zones of floristic endemism, floristically unique areas, and endemic faunal habitats). Finally, we combined the map of conservation values with a map of the protected area network in order to highlight areas of high conservation value that are excluded from adequate protection.

Based on the results from the first method, Shendurni Wildlife Sanctuary obtained the highest conservation value index (38.8%). This is because nearly 60% of Shendurni WLS is covered by wet evergreen forests with high levels of species richness and endemism (55% each) and most of the *Hopea racophloea* and *Humboldtia decurrens* facies are confined to this area. The conservation value index of Reserved Forests is 24.1% which is higher than that of other wildlife sanctuaries except Shendurni. The conservation value map obtained

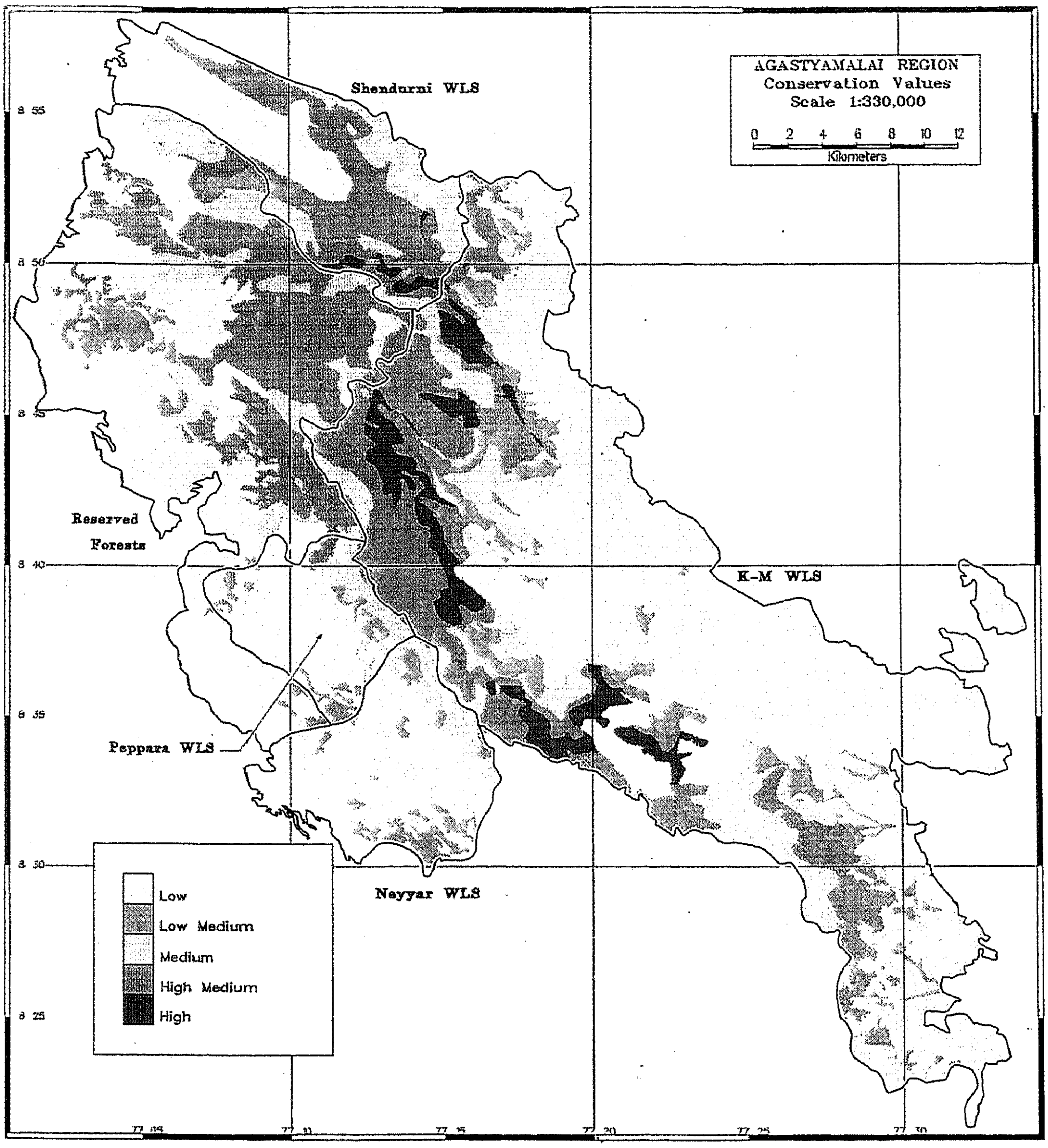

Figure 6. Map of conservation values in the Agastyamalai region of the Western Ghats.

from the second method also showed that Shendurni WLS contains a large area of high conservation value. The Reserved Forests have the next highest proportion of areas with high conservation values followed by Kalakad–Mundanthurai Wildlife Sanctuary. By contrast, both Neyyar Wildlife Sanctuary and Peppara Wildlife Sanctuary have less conservation value.

Thus, we found that several areas of high biodiversity value in Reserved Forests are excluded from the highest levels of protection. We consider this analysis to be a step toward developing a utilitarian conservation value index for assigning conservation and management priorities.

Concluding remarks

The last few years have witnessed an explosive growth in applications of geographical information system and remote sensing technologies and approaches to study changes in the landscape. We now have several tools available to rapidly assess changes in land use and land cover and the causes and consequences of such changes. A better understanding of the causes and a greater appreciation of the consequences can, in turn, allow us to develop appropriate mitigation strategies to either curtail deleterious changes or to counter their negative effects.

We cannot expect to effectively conserve biodiversity in the absence of precise information about how much, where and why forests are being lost. Analysis of remote sensing imagery together with adequate ground truthing provides an effective way of rapidly determining forest cover over relatively large areas. Time series analysis of such data allows more precise determination of changes in forest cover and gap analysis can assess the effectiveness of protected areas in conserving biodiversity. Spatial data on fragmentation and connectivity will allow us to develop more effective conservation plans.

Remotely sensed imagery can also be used to assess the health of forest ecosystems and the extent of forest degradation. We need to test the extent to which fuzzy classification models and vegetation indices (i.e. NDVI, PVI, etc.) may be used to estimate regeneration levels, biomass, and species composition at super- and sub-pixel levels. Relationships deduced from this analysis should be used to generate maps of regeneration, biomass, and species composition, and to investigate their relationship to anthropogenic pressures.

We also need to move forward with the integration of socioeconomic data and spatial data on land use change. Turner[42] points out that 'human sciences' have been relatively slow to explore the use of remote sensing and GIS technologies and advocates 'socializing the pixel', an approach which seeks to make remote sensing data (the pixel) directly relevant to socioeconomic issues (the human dimension) and to link them through GIS (the analytical tool). Such an approach would allow us to understand the dynamics of land-use change and would elucidate the ultimate causes of biodiversity loss.

For India, the wide disparity in reported deforestation rates, lack of information about the effect of land-use change on carbon emissions, a poor understanding of the causes of land-use change, and the exigency of protecting the country's remaining biota underscores the need for a more accurate assessment of the magnitude and patterns of land-use change. Government and non-government organizations in India are, of course, slowly beginning to capitalize on the opportunity offered by the high quality, high resolution imagery from Indian satellites (IRS-1A, IRS-1B, and IRS-1C). IRS 1-C's WiFs data has a 5-day repeat cycle which increases the probability of cloud-free data. This coupled with its low processing time requirement, will allow more frequent 'rapid change assessment'[43]. The LISS-III sensors with its 23.5 m spatial resolution will provide adequate detail for forest mapping at 1:25,000 scale[43]. The country certainly has the technology, human resources, and appropriate institutions to undertake a more thorough assessment and monitoring of its land-use changes; however, this tremendous potential needs to be rapidly transformed into concrete action to realize important goals in biodiversity conservation and sustainable use of our land resources.

1. Aronoff, S., *Geographic Information Systems: A Management Perspective*, WDL Publication, Ottawa, 1991.
2. Maguire, D. J., Goodchild, M. F. and Rhind, D. W., *Geographic Information Systems*, Longman Scientific and Technical, New York, 1991, vols 1 and 2.
3. Cowen, J. R., *Photogramm. Eng. Remote Sensing*, 1988, **54**, 1551–1555.
4. Rao, U. R., *Curr. Sci.*, 1991, **61**, 121–128.
5. Kasturirangan, K., Aravamudan, R., Deekshatulu, B. L., Joseph, G. and Chandrasekhar. M. G., *Curr. Sci.*, 1996, **70**, 495–500.
6. Stone, T. A., Brown, I. F. and Woodwell G. M., *For. Ecol. Management*, 1991, **38**, 291–304.
7. Brown, S. L., Iverson, L. R. and Lugo, A., *Effects of Land-use Change on Atmospheric CO_2 Concentrations: Southeast Asia as a Case Study* (ed. Dale, V. H.), Springer, New York, 1992, pp. 117–143.
8. Liu, D. S., Iverson, L. R. and Brown, S., *Forest Ecol. Management*, 1993, **57**, 1–16.
9. Sader, S. A., Sever, T., Smoot, J. C. and Richards, M., *Human Ecol.*, 1994, **22**, 317–331.
10. *Forest Resources Assessment 1990 – Tropical Countries*, 1993, FAO Forestry Paper 112. FAO, Rome.
11. *Forest Resources Assessment 1990 – Survey of Tropical Forest Cover and Study of Change Processes*, 1996, FAO Forestry Paper 130, FAO, Rome.
12. Saunders, D. A., Hobbs, R. J. and Margules, C. R., *Conserv. Biol.*, 1991, **50**, 99–135.
13. Tilman, D., May, R. M., Lehman, C. L. and Nowak, M. A., *Nature*, 1994, **371**, 65–66.
14. Burkey, T. V., *Conserv. Biol.*, 1995, **9**, 527–541.
15. Chatelaine, C., Gautier, L. and Spichiger. R., *Biodiversity and Conservation*, 1996, **5**, 37–53.
16. Sanchez-Azofeifa, A., Dissertation, University of New Hampshire, 1996.
17. McGarigal, K. and Marks, B., *FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure* (Version 2.0) Corvallis, 1994.
18. Menon, S. and Bawa, K. S., *Ecol. Appl.*, in review.
19. Bawa, K. S. and Dayanandan, S., *Nature*, 1997, **386**, 562–563.
20. Bawa, K. S. and Dayanandan, S., in *Tropical Forests: A Wider Perspective* (ed. Goldsmith, B.), Chapman and Hall, London, 1997 (in press).
21. Hall, C. A. S., Tian, H., Qui, Y., Pontius, G. and Cornell, J., *J. Biogeogr.*, 1995, **22**, 2547–2551.
22. *Climate Change: The IPCC 1990 and 1992 Assessments*, World Meteorological Organization and United Nations Environment Programme, 1992.
23. Hulme, M. and Viner, D., *Rep. Climat. Res. Unit*, University of East Anglia, 1995.
24. Sukumar, R., Suresh, H. S. and Ramesh, R., *J. Biogeogr.*, 1995, **22**, 533–536.
25. Hall, C. A. S. and Uhlig, J., *Can. J. For. Res.*,. 1991, **21**, 118–131.
26. Iverson, L. R., Brown, S., Prasad, A., Mitasova, H., Gillespie, A. J. R. and Lugo, A., *Effects of Land-use Change on Atmospheric CO_2 Concentrations: Southeast Asia as a Case Study* (ed. Dale, V. H.), Springer, New York, 1994.
27. Houghton, R. A., *Climate Change*, 1991, **19**, 99–118.
28. Baret, F. and Guyot, G., *Remote Sensing Environ.*, 1991, **35**, 161–173.
29. Huete, A. R., *Remote Sensing Environ.*, 1988, **25**, 295–309.

30. Myneni, R. B., Keeling, C. D., Tucker, C. J., Asrar, G. and Nemani, R. R., *Nature*, 1997, **386**, 698–702.
31. Woodwell, G. M., Hobbie, J. E., Houghton, R. A., Melillo, J. M., Moore, B., Peterson, B. J. and Shaver, G. R., *Science*, 1983, **222**, 1081–1086.
32. Houghton, R. A., Hobbie, J. E.,Melillo, J. M., Moore, B., Peterson, B. J., Shaver, G. R. and Woodwell, G. M., *Ecol. Monogr.*, 1983, **53**, 235–262.
33. Detwiler, R. P. and Hall, C. A. S., *Science*, 1988, **239**, 42–47.
34. Moran, E. F. (ed.), *The Ecosystems Approach in Anthropology: From Concept to Practice*, University of Michigan Press, Ann Arbor, 1990.
35. Leemans, R., *Systems Analysis of the Global Boreal Borest*, Cambridge University Press, New York, 1992.
36. Bawa, K. S. and Menon, S., *Trends Ecol. Evol.*, 1997, **12**, 42.
37. Prasad, S. N., Prabakaran, B. and Jeganathan, G., *Curr. Sci.*, 1996, **71**, 1001–1005.
38. Daniels, R. J. R., *Ibis*, 1996, **138**, 64–69.
39. Scott, J., Davis, F., Csuti, B., Noss, R., Butterfield, B., Groves, C., Anderson, H., Caicco, S., D'Erchia, F., Edwards, T., Ulliman, J. and Wright, R., *Wildl. Monogr.*, 1993, **123**, 1–41.
40. Fearnside, P. M. and Ferraz, J., *Conserv. Biol.*, 1995, **9**, 1134–1147.
41. Ramesh, B. R., Menon, S. and Bawa K. S., *Ambio*, 1991, in Press.
42. Turner, B. L., *LUCC Newsl.*, 1997, no. 1, 10–11.
43. Roy, P. S., Dutt, C. B. S., Jadhav, R. N., Ranganath, B. K., Murthy, M. S. R., Gharai, B., Udaya Lakshmi, V., Kandya, A. K. and Thakker, P. S., *Curr. Sci.*, 1996, **70**, 606–613.

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