BIOL. LETT. 2003, 40(2): 75–100
Available online at http://www.biollett.amu.edu.pl

REVIEW

Geoinformatics for biodiversity assessment

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(*Received on 14th July 2003; Accepted on 1st December 2003*)

Abstract: The relationship between natural and anthropogenic processes on biodiversity is complex. Thus, the holistic understanding of the complex mechanisms that control biodiversity, their spatial and temporal dynamics, requires synergetic adoption of measurement approaches, sampling designs, and technologies. In view of this, importance of satellite remote sensing, Global Positioning System (GPS), integrative tools, such as GIS, and information systems, is realized as a complimentary system to ground-based studies. Together, these technologies form the basis for geoinformatics. In the present paper, we make an attempt to bring out a general overview of regulators of biodiversity and potential use of geoinformatics in biodiversity assessment for the purpose of those professionals working in biodiversity who are not largely aware about fundamental and core issues of application of these technologies. We discuss the regulators of biodiversity on different spatial and temporal scales in terms of natural and anthropogenic impacts, and the effects, responses, and indicators in terms of structure and function. The paper explains the role of multisensor satellite data in understanding the spatial and temporal patterns of vegetation type and distribution as a precursor for biodiversity assessment. The potential use of GPS and GIS systems in integrating spatial and non-spatial data in evolving conservation plans and management strategies are also discussed. Additionally, we have brought out a future scenario in terms of requirements and adoption of these technologies.

Keywords: biodiversity, remote sensing, GPS, GIS, geospatial

INTRODUCTION

Biodiversity is the variety of living organisms considered at all levels of organization, from gene through species, to higher taxonomic levels, including the variety of habitats and ecosystems, as well as the processes occurring therein. Global Biodiversity Assessment (HEYWOOD 1995) estimates the total number of animal and plant species to be between 13 and 14 million. It further records that so far only 1.75 million species have been described and studied. UNEP-WCMC (2000) estimates around 270,000 species of vascular plants and 52,000 animals (Vertebrates).

Nearly 45% of the World's vascular plant species occur in closed tropical forests of the world (MYERS et al. 2000).

Vegetation in the Indian sub-continent is distributed mainly in four distinct geographical zones, viz. Himalayas, Vindhyans, Western and Eastern Ghats. India possesses a rich flora of flowering plants (17,000 species), with a high proportion of endemics (33.5%). Western Ghats of India alone supports 4,000 species of flowering plants, including 1,500 endemics (NAYAR 1989). It is regarded as one of the biodiversity 'hotspots' of the world (MYERS et al. 2000).

To a large extent, the world's biological diversity has co-evolved with human culture. People have eliminated competing or threatening species, domesticated plants and animals, cut forests, used fire to alter habitats, indiscriminately used pesticides and other chemicals, causing water, soil, and air pollution, applied destructive fishing practices, drained or flooded wetlands, converted wild habitats to agricultural and urban uses, and recently even significantly changed hydrological and geochemical cycles.

It is estimated that deforestation is occurring at a rate of 15–17 millions ha per year and 5 to 10 percent of tropical forest species may face extinction within the next 30 years largely due to human-induced land cover changes (WALTER et al. 1993). In an important study, a high correlation between threat rates and percentage of endemic species would seem attributable to the fact that a narrow geographic range makes species more vulnerable to extinction (MCKINNEY 1997, PURVIS et al. 2000).

In view of the above, several initiatives have been launched, at both global and national levels, for assessing, preserving and sustaining biodiversity. International effort includes the activity of the United Nations Environment Programme (UNEP); International Union of Biological Sciences (IUBS); United Nations Educational, Scientific and Cultural Organization (UNESCO); United Nations Conference on Environment and Development (UNCED); Global Biodiversity Strategy; Convention on International Trade in Endangered Species (CITES); World Conservation Monitoring Centre (WCMC); Global Change and Terrestrial Ecosystem (GCTE), etc. In India, also the Ministry of Environment and Forest (MoEnF); Governmental Department of Biotechnology and Department of Space; Wildlife Institute of India; Botanical Survey of India; French Institute of Pondicherry; as well as universities and non-governmental organizations are carrying out several programmes for assessment and conservation of biodiversity.

The investigations conducted have confirmed the importance of the contributions and interdisciplinary understanding in relation to taxonomy, physiology, reproductive biology, conservation biology, forest hydrology, soils, as well as socio-economic and climate change for holistic understanding of biodiversity patterns. Towards this, it is necessary that the professionals studying biodiversity require a synoptic view on the regulators of biodiversity and the tools through which the processes could be understood. In view of this, in this paper we made an attempt to bring out a general overview of regulators of biodiversity and potential use of geoinformatics in biodiversity assessment for those professionals who are not largely aware of fundamental and core issues of application of these technologies. We have focused on forest ecosystems and their transformations.

1. REGULATORS OF BIODIVERSITY

The relationship between natural and anthropogenic processes and biodiversity is complex. The organisation of biodiversity is a manifestation of the cyclic relationship between the kind and the magnitude of causes, impacts, responses and resulting ecological processes of the system (Fig. 1). In order to understand and quantify the interrelationship among these factors and to understand the biodiversity, it is necessary to reliably identify and quantify individually these parameters and their development.

1.1. Natural and anthropogenic factors

Spatial heterogeneity of the environment increases the number of different habitats, permitting a greater number of different resource use strategies, preventing competition equilibrium and exclusion. The scale of this environmental heterogeneity is different for different types of organisms. „As mowed lawn that is a homogeneous salad to a grazing sheep is a complex heterogeneous universe to a small, flightless insect" (HUSTON 1994). Mobility, the size of an organism, and its perceptive capabilities, are all-important when assessing the effect of habitat heterogeneity on an organism. For example, trees are sessile, so in the short-term their diversity is spatially stable. But the long-term generation of diversity depends on extinction and speciation.

If the environment is spatially very heterogeneous, extinction rates are low due to reduced competitive exclusion, and the range of habitats promotes speciation. This may potentially generate a high diversity in the environment. In addition, biodiversity in natural forests is also controlled by natural disturbance regimes. Changes in the disturbance regime (as intensity, frequency, or pattern) may consequently affect biodiversity. For example, the loss of large herbivores from coastal dune forests of South Africa due to hunting may have altered the gap phase dynamics (EVERARD et al. 1994). Logging can open up forests, so that they are more susceptible to wind throw, drought, etc. (FRANKLIN & FORMAN 1987).

Human interventions are complex in terms of large-scale conversion to other land uses and processes, which do not involve loss of forest but have a significant impact on biodiversity (Fig. 1). These processes include selective logging, removal of understorey trees for building material, grazing, trampling, burning, wildlife impact, collection of non-timber forest products (NTFP's: reproductive structures, like fruits, nuts, seeds, flowers, and non-reproductive structures, like bark, latex, branches for firewood, foliage), and of whole individuals (ornamentals, hunting, fishing), or associated infrastructure development. More than one type of intervention may occur at a given area and time, resulting in an integrated complex impact.

1.2. Effects, responses, and indicators

The natural and anthropogenic factors that regulate and maintain the biodiversity both individually and synergistically, can be characterized through the effects and response of the system. The effects and the responses both vary on spatial and temporal scales (Fig. 1). The details are as follows (STORK et al. 1997):

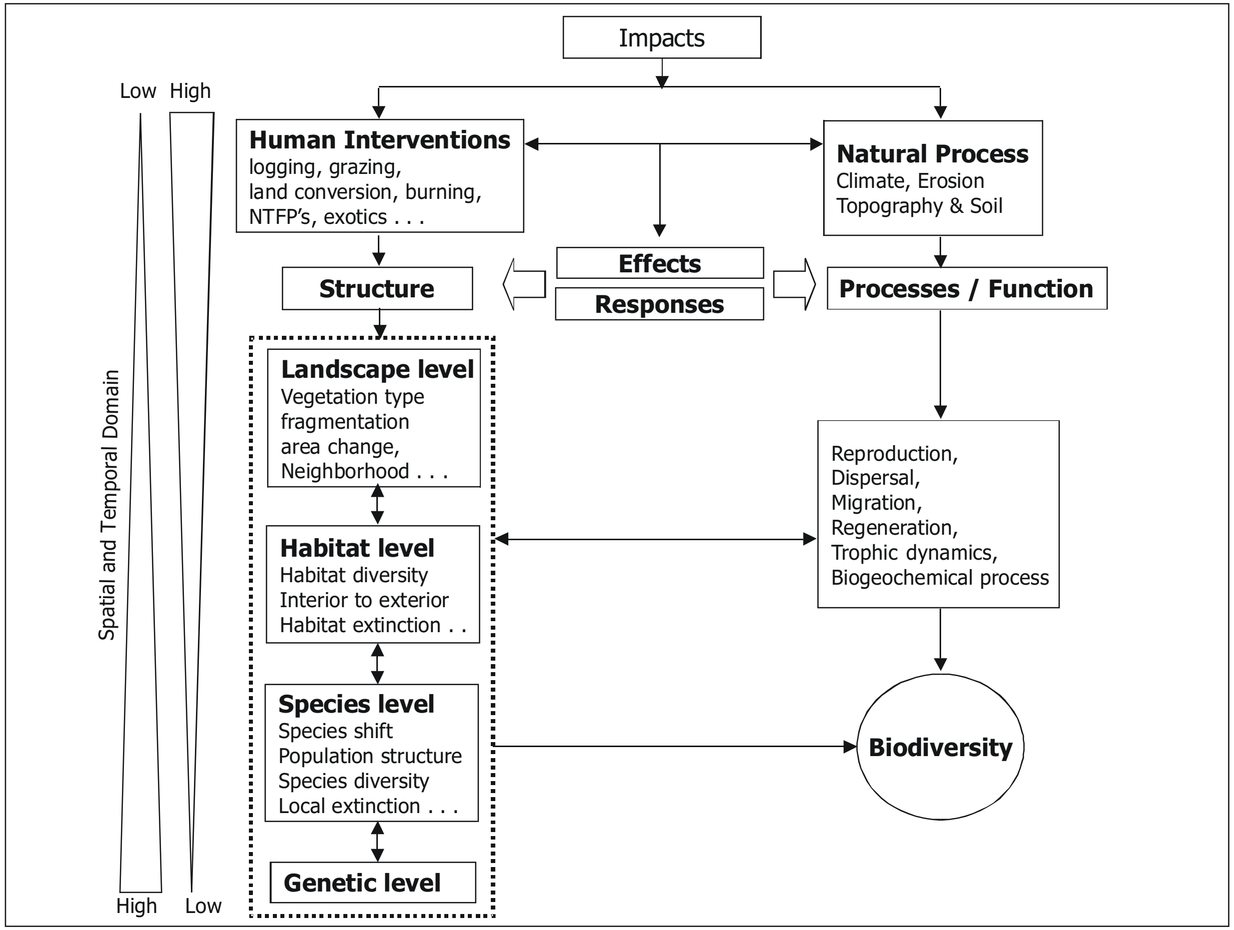

Fig. 1. Components of biodiversity assessment

1.2.1. Changes in area

The changes could be forests converted to non-forest, transformation of one forest type to another forest or to non-forest vegetation type.

1.2.2. Fragmentation and neighbourhood

When a forest becomes fragmented, there is a change in the spatial mosaic of the forest. For example, the number, size and/or shape of patches of a vegetation type may change. These changes may result in modifications in patch connectivity across the landscape. Patch edges can change both in their length and complexity. These spatial changes can affect the ability of an organism to move within a landscape, because for some organisms different vegetation types act as either barriers or corridors for movement and dispersal.

1.2.3. Habitat change

Changes in interior and core characteristics of a given habitat may lead to changes in community formation and species assemblages.

1.2.4. Loss of species

Some human interventions cause a direct loss of species. The loss of a species that acts as a mediator can cause the loss of certain other species (e.g., loss of obligate pollinators).

1.3. Processes

As shown in Fig. 1 and discussed above, mediators of human interventions (effects and responses) affect the processes that generate and maintain biodiversity. These processes are enumerated below.

1.3.1. Dispersal/migration

Human interventions may affect the capacity of the landscape to provide suitable sites for dispersal or migration. For example, in Neotropical forests the majority of tree species are dispersed by vertebrates, so hunting may affect the dispersal agent. Migration refers to the movement of organisms on which successful completion of the life cycle depends.

1.3.2. Reproduction

Impacts on the process of reproduction can have rapid, direct and dramatic consequences. In the case of species with short generation periods, non-overlapping generations or highly specific mutualisms, such as the *Ficus*-fig wasp interactions (JANZEN 1979), changes can be particularly devastating.

1.3.3. Regeneration/succession

An obvious, and highly publicized, consequence of logging is the reduction in area of mature, or old-growth forest, and replacement with forest dominated by pioneer or early successional species. However, other impacts are possible, such as the equally well-publicized change in successional dynamics of forests in the Yellowstone National Park (USA), due to fire suppression and control (SCHULLERY 1989).

1.3.4. Trophic dynamics

Trophic dynamics refer to the ways that species from different trophic levels interact. These include pollination, predation and herbivory. As each trophic level is dependent on other levels, impacts on trophic dynamics can be very serious.

1.3.5. Ecosystem processes

Ecosystem processes are the interactions of nutrients, water and energy that allow the growth and reproduction of species. These processes typically involve a complex mix of species, each influencing the processes in different ways, though not all species present in an ecosystem are essential for ecosystem functioning.

1.3.6. Local extinction

In some cases the dominant process determining change in species composition may be local extinction. For example, in a system characterized by small patches of a particular vegetation type, the loss of a patch and the ensuing local extinction of a species dependent on that vegetation type result in a more broad-scale extinction (LOMOLINO 1996).

2. TOOLS FOR BIODIVERSITY ASSESSMENT – GEOINFORMATICS

The holistic understanding of the complex mechanisms that control biodiversity, as well as their spatial and temporal dynamics, requires synergetic adoption of measurement approaches, sampling designs and technologies. It is very clear in the foregoing discussion on the regulators of biodiversity that the data requirements are both of spatial and non-spatial nature and also of various time scales. In view of this, the combination of satellite remote sensing, Global Positioning System (GPS), and integrative tools (such as GIS and information systems) is an important complimentary system to ground-based studies. Together these technologies form the basis for geoinformatics (Fig. 2). The various parameters required for biodiversity assessment and their amenability for measurements by different techniques is given in Table 1. The details on potentials of various technologies for biodiversity assessment are given below.

2.1. Remote sensing vs biodiversity

On global to local scales, the only feasible way to monitor the Earth's surface to prioritize and assess the success of conservation efforts is through remote sensing. Currently a suite of remote sensing satellites, having various resolutions, are available to generate spatial information on vegetation and land-cover from global to local level. The remote-sensing-based information on vegetation and land cover provides a potential spatial framework and works as one of the vital input layers for the following:

1. Vegetation, land cover losses and conversion
2. Stratification base for optimal ground sampling and assessment of diversity
3. Fragmentation and neighborhood analysis
4. Delineation of broader vegetation types and analysis of species assemblages along with ancillary data
5. Identification of gregarious and ecological important species

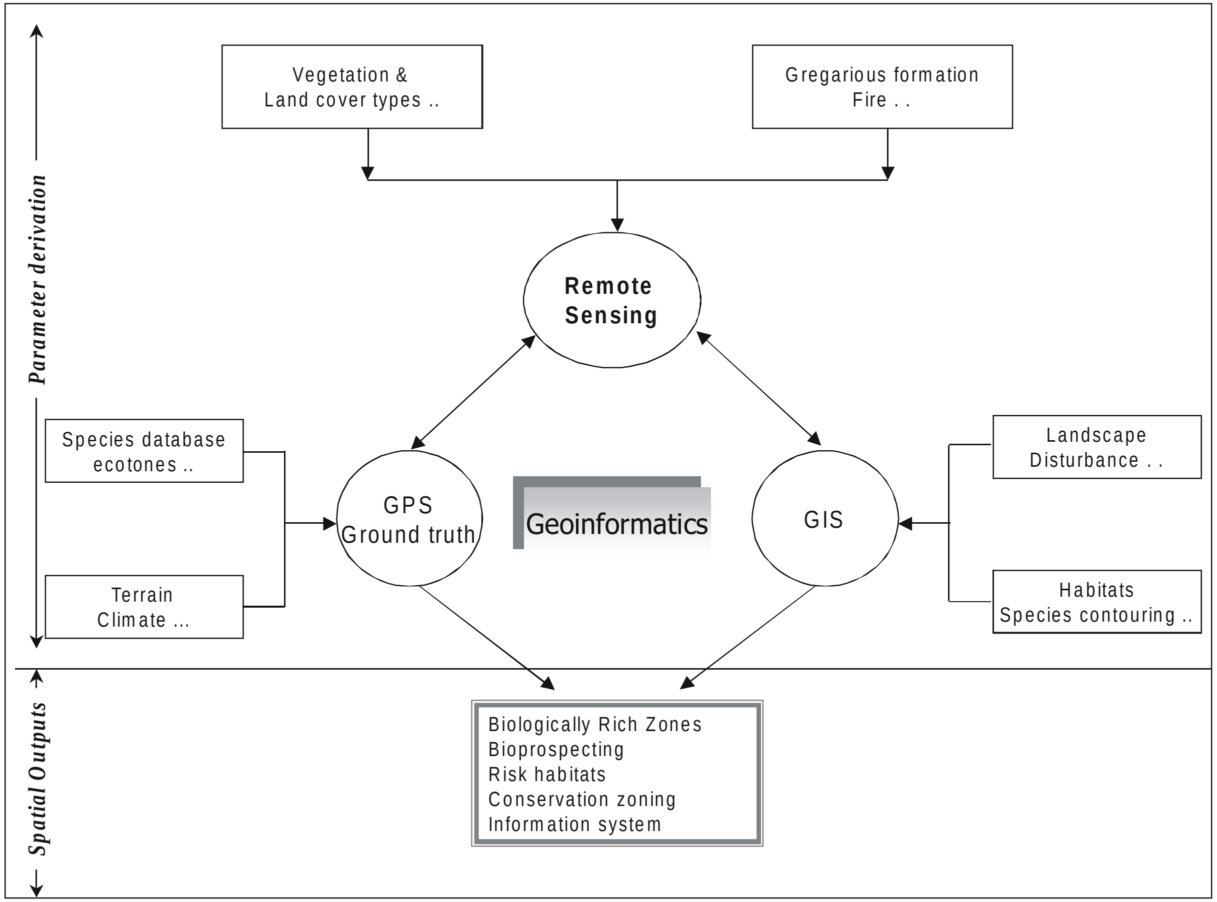

Fig. 2. Tools for biodiversity assessment – Geoinformatics

Table 1. Components of Biodiversity Assessment and measurement tools

No.	Parameters	Remote sensing	Ground Measurement / GPS	GIS Based (Derived / Integrated Spatial layer)
A	**Human interventions**	✓	✓	
1.	Logging	✓	✓	✓
2.	Grazing	✓	✓	✓
3.	Fire	✓	✓	✓
4.	NTFP resources extraction	✓	✓	✓
5.	Trampling	✓	✓	✓
6.	Plantation	✓	✓	✓
7.	Agriculture	✓	✓	✓
8.	Encoarchment / Clearances	✓	✓	✓
9.	Infrastructure	✓	✓	✓
B	**Natural Processes**	✓	✓	
10.	Climate	✓	✓	✓
11.	Erosion	✓	✓	✓
12.	Topography	✓	✓	✓
13.	Soil	✓	✓	✓
C	**Structure and Function**		✓	
14.	Vertical structure	✓	✓	✓
15.	Size class distribution		✓	
16.	Relative abundance		✓	
17.	Gap frequency	✓	✓	✓
18.	Canopy openness	✓	✓	✓
19.	Standing and fallen dead wood		✓	✓
20.	Trophic dynamics		✓	✓
21.	Other structural elements		✓	
D	**Landscape level**			
22.	Vegetation type and extent	✓		✓
23.	Landscape diversity	✓		✓
24.	Species diversity	✓	✓	✓
25.	Number of patches per unit area	✓		✓
26.	Neighbourhood	✓		✓
27.	Patch shape	✓		✓
28.	Core - edge ratio	✓		✓
E	**Habitat level**			
30.	Species assemblages / Communities	✓	✓	✓
31.	Species diversity	✓	✓	✓
32.	Interior to exterior habitat	✓	✓	✓
33.	Regeneration	✓	✓	✓
34.	Habitat extinction	✓	✓	✓
F	**Species level**			
35.	Reproduction		✓	
36.	Dispersal		✓	
37.	Regeneration		✓	
38.	Migration		✓	
39.	Local extinction		✓	

Presence of ticks in one or more columns indicate individual or synergestic approaches, respectively

Table 2. Satellite Remote Sensing Sensors and potential in biodiversity assessment

Scale	Data sources	Forest attributes	Spatial resolution	Temporal frequency	Mapping scale	Monitoring cost
Global	NOAA - AVHRR	Phenology types	180 - 1 Km^2	Daily	> 1:5000,000	Low
	MODIS	Forest / Non Forest				
	WIFS	Net Primary Productivity				
		Deforestation				
		Biomass burning				
Regional	IRS LISS	Forest / Habitat types	5 - 90 m	5 - 25 days	> 1:50,000	Low to high
		Secondary types				
	IRS PAN	Disturbance - logging / roads / fire / encoarchments				
		Plantations				
		Ecotones				
	Landsat	Wetlands				
	Spot	Gregarious formations				
	JERS - 1	Target species with gregarious distribution				
	ASTER					
Local	IKONOS	Target species	< 5 m	User defined	> 1: 10,000	High
	Aerial photography	Species assemblages / Communities				
	Aerial multispectral scanner	Regeneration				
	LIDAR	Forest distrubance				
	CASI	Agriculture				
		Logging / roads				
		Canopy gaps				
		Plantations				
		Harvest rates				
		Level of degradation				

6. Inputs for species habitat models
7. Spatial delineation of biologically rich zones
8. Developing conservation strategies

The potential of satellite data of different spatial and temporal resolutions in generating inputs for assessing the biodiversity are given in Table 2 and brief details are given below.

2.1.1. Coarse-resolution remote sensing

Over the past few years, global datasets from coarse spatial resolution sensors have become more and more readily available (e.g. TOWNSEND et al. 1994, ARINO & MELINOTTE 1995). Use of satellite image data for mapping and monitoring global land-cover, biomass burning, estimating geophysical and biophysical characteristics of terrain features, or monitoring continental-scale climate shift, is a primary input for biodiversity assessment. The rapid revisit time of AVHRR helps better understanding of land cover, burnt area, etc., at both global and regional levels (STONE et al. 1994, LOVELAND & BELWARD 1997, EVA & LAMBIN 1998). The global vegetation type maps, analyses of land-cover changes and burnt areas in conjunction with trends in human disturbance, are effectively used to generate coarse-scale biodiversity maps and identification of biodiversity hotspots. In addition, the Moderate Resolution Imaging Spectroradiometer (MODIS) is designed to provide consistent spatial and temporal comparisons of global vegetation conditions that can be used to monitor photosynthetic activity, which facilitate understanding the biodiversity function.

During broad-scale mapping of Western Ghats (1:1,000,000 scale), 205 patches belonging to 11 different landscape types consisting of topography, climate, population, agriculture and vegetation cover, were delineated using IRS 1B data (NAGENDRA & GADGIL 1998). In a detailed analysis in the tropical forests of the Western Ghats of India, NAGENDRA & GADGIL (1999) mapped a landscape into seven habitat types ranging from secondary evergreen forests to paddy fields, using supervised and unsupervised classification of IRS 1B LISS II satellite imagery. The nature and the extent of forest degradation and its causes have been intensely debated, using meso-scale analyses of forest condition in the region of Western Ghats (LELE et al. 1998).

2.1.2. High-resolution remote sensing

Rapid change in land-use in tropical areas and the need to map changes in land-use over large areas effectively, calls for application of high- or very-high-resolution satellite sensors. At the national or local level, IRS, Landsat or SPOT imagery can provide finer-scale information on forest type distribution and agricultural expansion. Radar systems, such as JERS and Radarsat, are not affected by clouds, and are useful for determining the extent of forest and non-forest landscapes where topographic relief is not substantial (<200m).

Vegetation type and land-cover mapping of the entire North-East India, Western Himalayas and Western Ghats of India, were mapped on a 1:250,000 scale by using IRS LISS data (IIRS 2002). Tropical evergreen forest along with other phenological types and major disturbed habitats (grassland, orchards, mangroves, *Myristica* swamps and *Ochlandra*) were mapped. The spatial data generated by remote sensing is useful in many ways in biodiversity monitoring and conservation efforts. Datasets from IRS 1C/1D LISS III have been used effectively in mapping the pure plant colonies of *Hippophae rhamnoides* in the Spiti region of India with prior knowledge of their occurrence and vegetation types of the area by using remote sensing (ROY et al. 2001). IRS 1C/1D LISS-III FCC has been used for stratification of *Ephedra gerardiana* in complex terrain conditions of Lahul and Spiti district (PORWAL et al. 2003).

In areas where vegetation structure varies greatly, structural rather than species differences may predominate in imagery. These methods may then prove less suitable for determining species composition and facilitate delineation of specific vegetation types and habitats. In 1995, WHITE et al. used Landsat TM imagery for an unsupervised classification of the forest of the Lassen Volcanic National Park. Genus-level mapping into *Pinus* and *Abies* forest classes was achieved with an accuracy of 63%. TREITZ et al. (1992) carried out a study in the Presqui'le Provincial Park, Canada. MEIS II data, with five bands of 3 nm, was related to species-based community classification. FRANKLIN (1994) carried out an analysis using satellite imagery to differentiate compositionally distinct vegetation communities. Landsat TM was used for estimation of species richness, indicating biodiversity hotspots in riparian and ecotonal areas (GOULD 2000).

Remote sensing based on habitats, in conjunction with information on species-habitat associations, can be generally used to derive information on the distribution of species, although a few exceptions may exist (e.g. TREITZ et al. 1992). The degree of correspondence between habitat and species distributions depends on the degree of habitat map generalization, and this should also be optimized to get maximum information on species diversity (STOMS 1992, COOPS & CATLING 1997). Habitat appears capable of providing information on the distribution of large numbers of species in a wide variety of areas. However, this is restricted to the spatial scale of tens of square kilometers. In smaller, local areas with limited species diversity, direct mapping can provide detailed information on the distribution of certain canopy tree species or associations.

2.1.3. Very-high-resolution remote sensing

Applications of very-high-resolution remote sensing techniques to the conservation of biodiversity, assessment of protected areas, and species protection, show that fine-grain remote sensing is underused in conservation of forest ecosystems. Very-high-resolution data (1-m panchromatic and 3-m multispectral), which are now available from the commercial IKONOS II satellite, may be useful for determining the actual activities on the ground that have led to forest clearing. Although such data can detect very small clearings, the scientific community as yet has very little experience with these data.

In addition, laser scanner data in combination with very-high-resolution satellite images, as e.g. IKONOS, Terra Aster platform, or aerial multispectral scanner data, can be applied to the assessment of heights of single trees, tree-wise timber volume calculations, and the detection of even single trees of other species, especially for forest inventory tasks. The synergy of these different data sources can guarantee foresters a high level of information extraction for these applications.

Mapping of diversity estimates is often accomplished by analyzing the variation in spectral signal, and correlating this variation with measures of landscape or taxonomic diversity (REY-BENAYAS & POPE 1995, JORGENSEN & NOHR 1996).

Mapping individual trees by using high-resolution data, poses problems not encountered when mapping associations or habitat patches. Pixels covering different component of a tree, such as bark and leaf, can be extremely variable in intensities. This makes the spectral signature of a tree species difficult to define. The factors like crown closure, crown geometry, stand density, topography, soil type, etc., regulate the reflectance properties of vegetated surfaces, so characterization of individual species, communities and vegetation types is a complex process.

However, few studies have reported on the use of hyperspectral image data for differentiation of several tropical species (FRANKLIN 1994, MARTIN et al. 1998) as well as discrimination of coniferous species (COCHRANE 2000, GONG et al. 2001). Researchers in the Yellowstone National Park used Landsat and a geographic information system (GIS) to categorize habitats a priori and then determined the relationship between remotely sensed habitat categories and species distribution patterns (DEBINSKI & HUMPHREY 1997, DEBINSKI et al. 1999, VAN HORSSEN et al. 1999).

2.1.4. Temporal monitoring

The amount of change that is occurring in tropical parts of the World has been of considerable interest in the past ten years. Remote sensing offers perhaps the only practical method of analyzing large areas over time. GREEN & SUSSMANN (1990) used a combination of aerial photography, forest maps, and satellite images to estimate deforestation rates in Madagascar from 1950 to 1985, spanning a total of 35 years. With the advent of availability of satellite remote-sensing data, several countries have recently launched temporal monitoring of forest cover, which facilitates analyzing biodiversity losses. However, these studies do not provide information on vegetation type transition and losses, which is primarily necessary for understanding shifts and losses in biodiversity. A few examples of the studies conducted in southern Western Ghats of India and Vindhyans of central and North-East India have provided details about vegetation type transitions. These transitions, when coupled with ground-based species databases, help in analyzing and quantifying biodiversity losses. Prediction of the spatial distribution and relative abundance of wildlife on the basis of multi-temporal satellite data and simulation models is also a recent development, COOPS & CATLING (2002) extensively reviewed such approaches.

2.2. Global Positioning System (GPS)

Ground-based measurements of various parameters are a vital input for effective biodiversity assessment. The parameters that need to be measured on the ground are given in Table 1. However, the translation of the ground-measured data into a spatial domain, or linking with any other spatial or non-spatial parameters to analyze the relationships and understand the trends, precise locations, and areas under consideration, are of primary importance. In this regard, Global Positioning Systems (GPS) provide powerful tools for acquiring accurate locations and areas. The relatively recent development of GPS and GIS technologies appear ideally suited to conservation effort because they empower ecologists to expeditiously acquire, store, analyze, and display spatial data on organisms and their environment (JOHNSTON 1998, WADSWORTH & TREWEEK 1999).

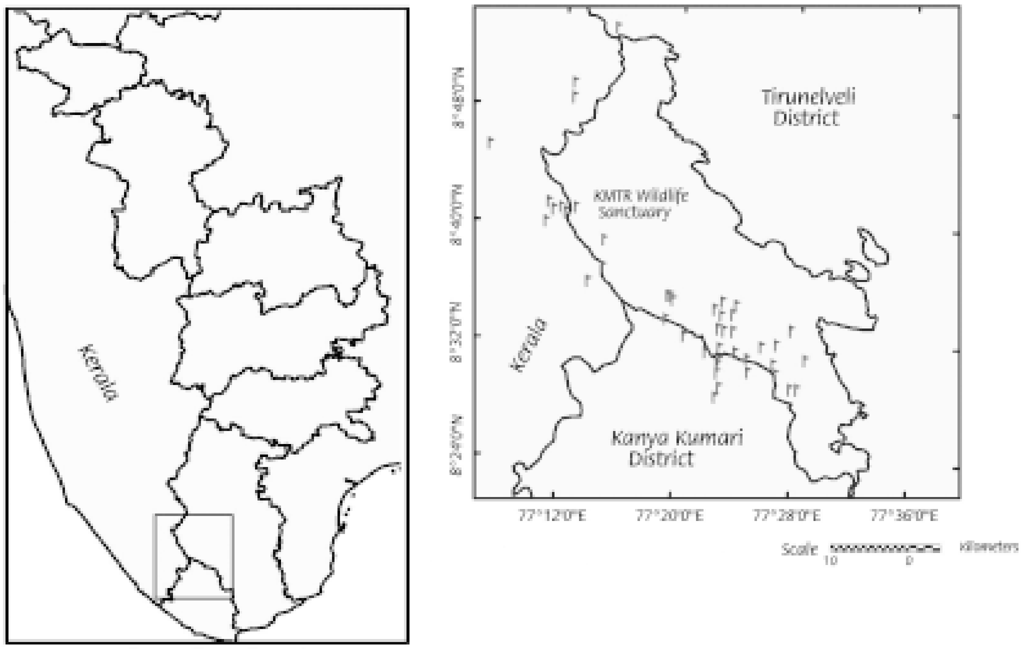

Fig. 3. Spatial distribution of *Aglaia elaeagnoidea* var. *bourdillonii* (Meliaceae) endemic to Western Ghats of Southern India: A. Western Ghats of Tamil Nadu; B. Precise location of the target species within the sanctuary

Currently available floras, which provide valuable information about the species distribution pattern, do not indicate specific locations. With the advent of availability of GPS, recent phytosociological surveys have provided enormous information on species distribution with specific locations. These include the endemic atlas of Western Ghats (RAMESH & PASCAL 1997), mapping of sandalwood (GANESHAIAH et al. 2000), and species databases of *Aglaia elaeagnoidea* (Juss.) Benth var. *bourdillonii* (Gamble) K.K.N. Nair (Meliaceae) with sample point locations (Fig. 3). Under the DBT-DOS project, studies conducted in North-East India and Western Himalayas, and Western Ghats of India (IIRS 2002), are noteworthy. These databases are helpful in further identifying species-specific habitats by showing the precise area under a given habitat.

Precise point-location data on microclimate, topography, and soil in association with species distribution helps in understanding the interrelationships and controls of biotic and abiotic factors on species distribution pattern. Such databases can be imported into biostatistical software packages, e.g. (Biopro, EstimatesS, SPSS, PCORD) to analyze species assemblage patterns. Studies conducted in the Tirunelveli hills of Western Ghats for identifying different community assemblages were based on statistical analysis of the point-location data on species and ancillary information (GIRIRAJ et al. 2003a, b). The application of integrated GPS/GIS technology to habitat utilization models is particularly powerful because it is capable of identifying the areas of threatened habitats that are most at risk of human encroachment. Thus both GPS and GIS are essential tools for monitoring. GPS-aided wildlife survey in terms of presence/absence data is useful in various studies to understand the habitat distribution patterns (TUTIN et al. 1991, LELE et al. 1998, GOLDSMITH 2000, KUSHWAHA et al. 2000).

The use of differential GPS surveys will help in estimating the accurate change in area and the kind of species alternation with pinpoint coordinates, demarcation of permanent plots, and patches for temporal monitoring. Recently studies were conducted in Vindhyan highlands (JHA et al. 2002), delineating disturbed and undisturbed patches by using GPS surveys for assessing temporal patterns of biodiversity. Global research efforts are taken up to develop databases on spatial patterns and dynamics of tropical forests in large permanent plots across tropical countries, where GPS surveys are effectively used in tree censuses and for collecting other associated information for long-term, large-scale ecological research in biodiversity (PELISSIER 1998, AYYAPPAN & PARTHASARATHY 1999, PLOTKIN et al. 2000, PELISSIER & GOREAUD 2001).

Within local environments under the same climatic conditions the development of spatial variation in habitat quality can be determined by the disturbance regime (such as fire, timber harvesting, or wind), the physical environments (such as soil texture, fertility, and nutrient status), and effects of biotic factors or neighbourhood (FRELICH & REICH 1999). In this regard, GPS is effectively used in precise location and mapping of fire-prone areas, logging, trampling, grazing, etc., which are in turn used to distinguish potential disturbance surfaces and relate with habitat structure and function.

2.3. Geographic Information Systems (GIS)

The integrated analysis of spatial data generated both from remote sensing and other sources, and also point information, becomes critical in order to generate information on several aspects of biodiversity. Landscape processes, habitat evaluation, characterization of disturbance regimes, analysis of forest structure and function in spatial domain, are the areas where GIS works as a powerful tool to undertake integrated analysis. The following sections give details on those fields of research where GIS plays an important role.

2.3.1. Landscape analysis

FORMAN & GODRON (1986) defined landscape as a “heterogeneous land area composed of a cluster of interacting ecosystems that is repeated in similar form throughout.” Landscapes are composed of a mosaic of patches. *Vegetation,* a dominant expression of the natural assemblage of various coexisting plant communities, plays a major role in characterizing a landscape with its biodiversity. Species diversity at any one point in a landscape is determined by multiple factors acting on multiple scales (TURNER 1989, WIENS 1989, TURNER & GARDNER 1991). On the landscape scale, the frequency and spatial distribution of critical habitats and resources deter-

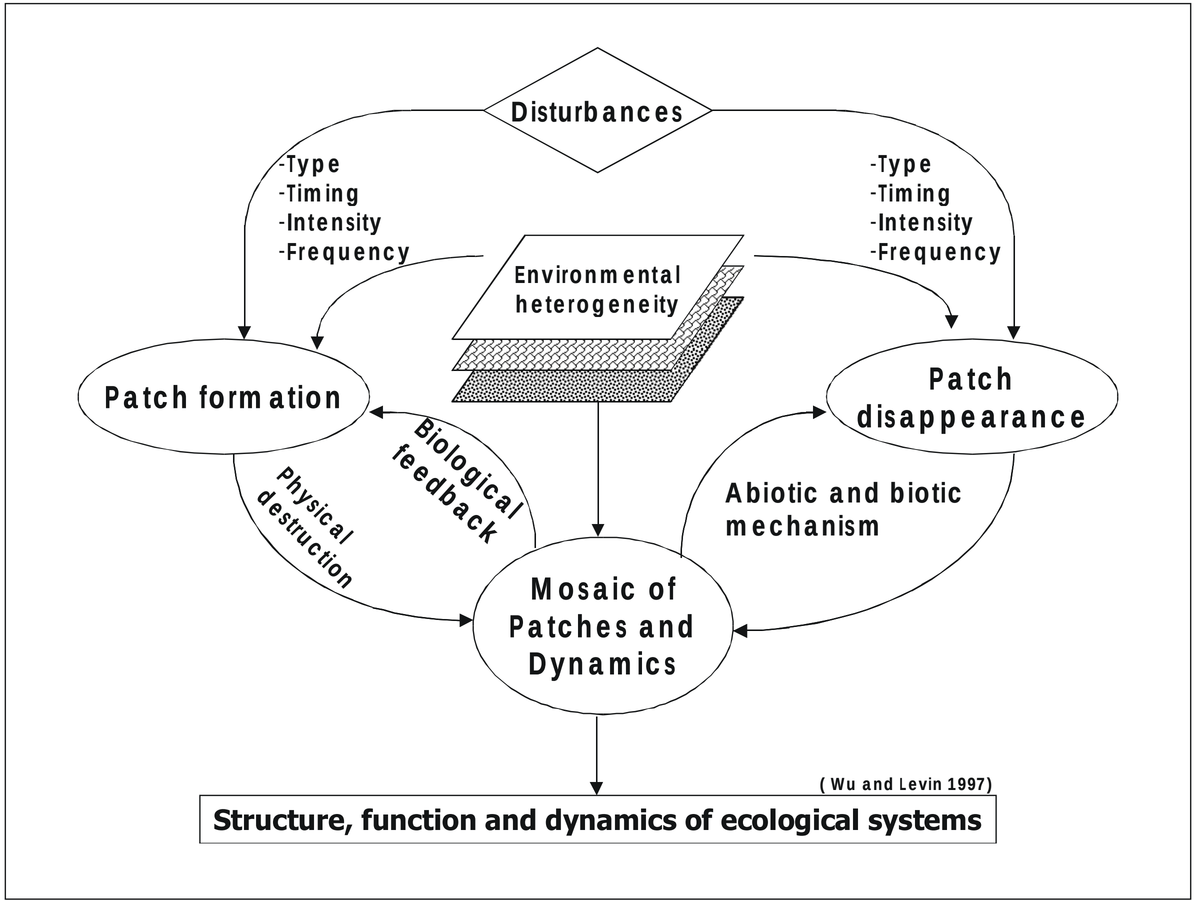

Fig. 4. Landscape Processes and Ecological System

mines species distribution patterns (SWINGLAND & GREENWOOD 1983, PEARSON 1993), while historical accidents, community interactions, and spatio-temporal variability further limit the distribution that is realized at any given time (WU & LEVIN 1997) (Fig. 4). On finer scales, populations may be separated in its patches of habitat within a landscape of less suitable habitat (e.g. ARNOLD & WEELDENBURG 1990, MERRIAM et al. 1991, OPDAM 1991). Plant species found in a resource patch can differ from species in other patches containing different levels of resources. Hence, patch characteristics and the pattern of patches within the landscape matrix influence the flows of species, and structure and composition within and between landscapes. Increasing heterogeneity usually reduces the number of larger patches, thus decreasing available habitat for interior species, which often need larger contiguous areas of relatively undisturbed habitat (DEBINSKI et al. 2001, PETERS & GOSLEE 2001). Several studies have linked measures of alpha and beta species diversity with landscape (patch) diversity.

Quantification of landscape heterogeneity is undertaken with the help of landscape metrics. Patch characterization is based on the analysis of various parameters, like *size, shape, fragmentation, porosity, patchiness, interspersion, juxtaposition.* The heterogeneous distribution of communities is conditioned by soil, climate, and human activities. Hence, patch characterization will provide insight into the spatial organization of communities. Various GIS-based software packages, like Fragstat, BIOCAP, and Patch Analyst, provide customized approaches to analysis of these parameters and to assessment of the impact on spatial biodiversity patterns.

In an important study of tropical deforestation in the Amazon rain forest, species in patches of various sizes have been compared to evaluate the importance of patch size for species number (LOVEJOY et al. 1984). Large patches have proved to be generally the richest in species, because small patches provide only edge conditions (LAVER & HAINES-YOUNG 1993). Moreover, in small fragmented patches population density is usually lower and the risk of extinction is increased (FARINA 1998). BROKAW & SCHEINER (1989) showed that differences in gap sizes lead to variations in species composition. WHITEMORE (1975), as cited by FORMAN & GODRON (1986), remarked that plant species composition and community structure varied according to the shape of open gaps in the Malaysian tropical rain forest. AMARNATH et al. (2003) used conjunctive analysis of patch characteristics and species distribution in identifying the areas of prioritization in terms of eco-restoration and conservation in wet evergreen forest of India.

Landscape connectivity is a measure of how spatially contiguous a landscape matrix is. Connectivity can exert strong influences on ecological processes, such as the movement and dispersal of organisms, the use of resources by animals, gene flow, and the spread of disturbance (PEARSON 1993). The importance of spatial heterogeneity to species diversity has been well documented, and is most closely related to beta species diversity (WHITTAKER 1960). The extension of these ideas to landscape diversity is more recent and several studies have linked measures of alpha and beta species diversity with landscape diversity (ROMME 1982, LAPIN & BARNES 1995). The diversity of trees and shrubs was found to be higher on plots with the greatest geomorphological heterogeneity increase, indicating an important connection between landscape diversity and species diversity (BURNETT et al. 1998, NICHOLS et al. 1998).

Changes in landscape diversity in time are related to fire frequency, and have been hypothesized to have important effects on species diversity as well as wildlife habitat (ROMME & KNIGHT 1982).

An extensive study was conducted in the Indian sub-continent, covering three major bioclimatic regions, viz. North-East India, Western Himalayas and Western Ghats, with the use of concepts of landscape analysis to identify biologically rich zones (IIRS 2002). Customized software, "Biocap", was developed, which facilitates analysis of landscape parameters, like porosity, fragmentation, juxtaposition, interspersion, and patchiness. These landscape parameters are in turn integrated to develop a spatial disturbance index map. The disturbance index map is integrated with ground-based parameters, like species richness, ecosystem uniqueness, terrain complexity, and biodiversity value, to identify biologically rich zones as shown in Fig. 5A.

2.3.2. Species composition and habitat analysis

Factors like crown closure, crown geometry, stand density, topography, and soil type, condition the reflectance properties of vegetated surfaces, so characterization of the individual species, communities and vegetation types by using satellite remote-sensing data is a complex process. In areas where vegetation structure varies greatly, structure rather than species differences may predominate in imagery. The remote-sensing data may then prove less suitable for determining species composition and delineation of specific vegetation types and habitats. Patterns of species distribution on the ground have been shown to be associated with the distribution of environmental variables, such as topography, rainfall, soil type, and disturbance. In such cases, a GIS model based on elevation, slope, aspect, and proximity to a water source, etc., in conjunction with ground-based species databases, and broad vegetation types derived from RS, will help in identifying the spatial pattern of the species assemblages and habitats.

FRANKLIN (1994) differentiated 28 compositionally distinct vegetation communities in the sub-alpine/alpine region of the Peter Lougheed Provincial Park, Canada, on the basis of a satellite-derived vegetation map and digital elevation model (DEM) in the GIS domain. WHITE et al. (1995), using Landsat TM data, elevation and soil data together in a GIS, distinguished *Pinus* and *Abies* forest classes. Researchers in the Yellowstone National Park used Landsat and a geographic information system (GIS) to categorize habitats a priori and then determined the relationship between remotely sensed habitat categories and species distribution patterns (DEBINSKI et al. 1999).

Altitude information is effectively used along with a remote-sensing-derived vegetation map to spatially delineate different species assemblages, which are largely controlled by altitude in Himalayan ecosystems (ROY et al. 2001, PORWAL et al. 2003). The tropical evergreen forests of Western Ghats, which are largely influenced by spatial and temporal patterns of monsoon rainfall, are further subdivided with the use of terrain, bioclimatic, and vegetation type maps (RAMESH et al. 1997). GIRIRAJ et al. (2003a, b) used multispectral remote-sensing data and elevation-slope complexes to delineate different species assemblages in evergreen forest of Tirunelveli hills of Western Ghats, Tamil Nadu (India). They also identified endemic habitat zones on the basis of the distribution pattern of endemic species in different vegetation-elevation-slope complexes (Fig. 5B).

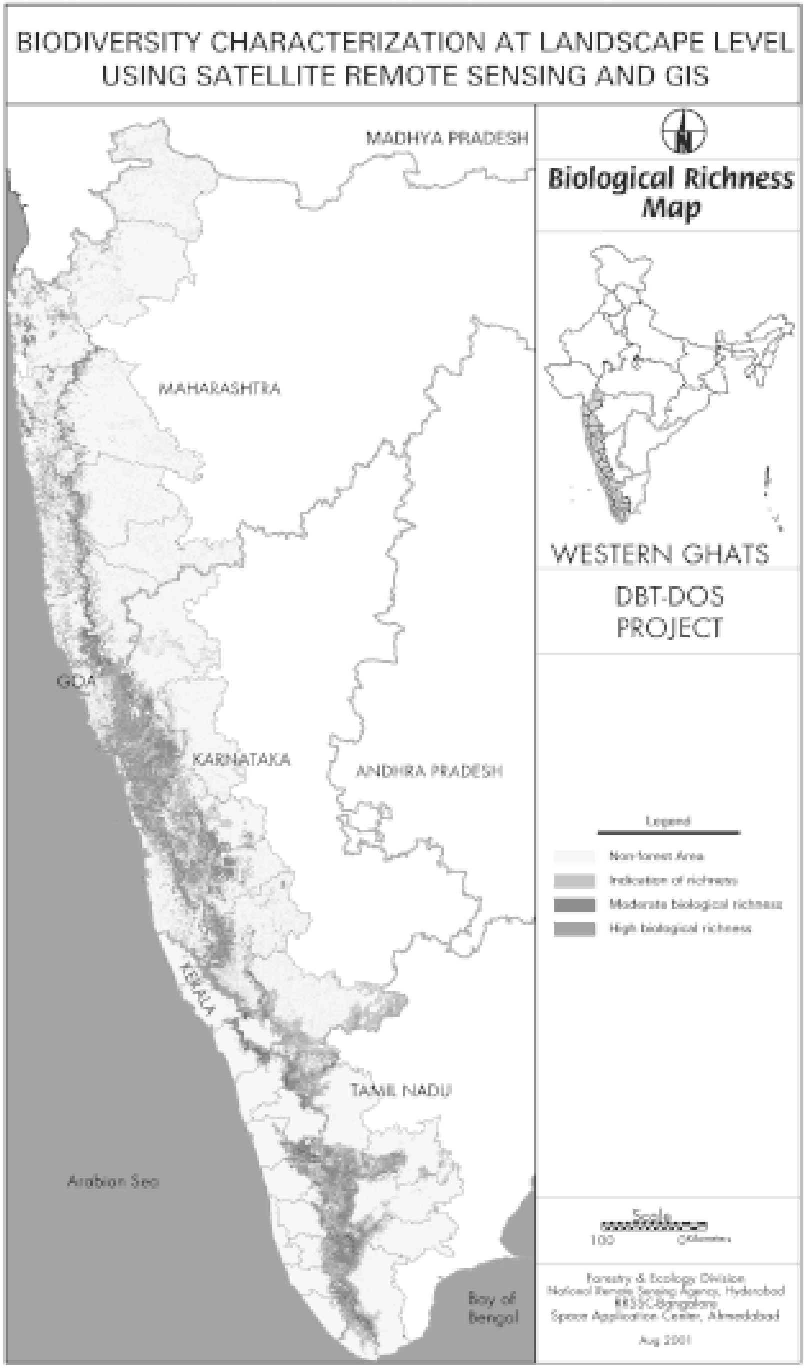

Fig. 5A. Biological richness map of Western Ghats (India)

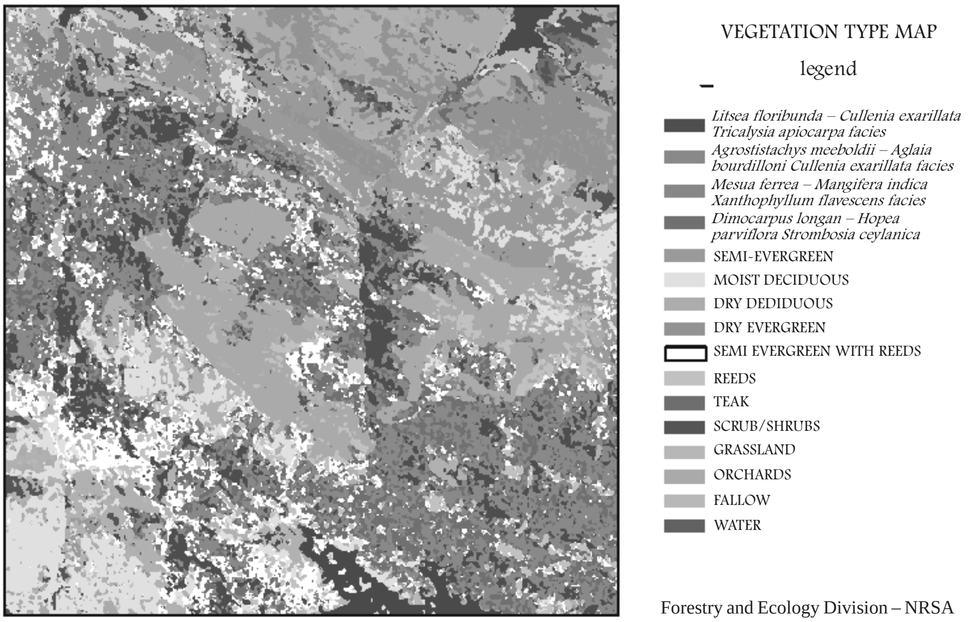

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Fig. 5B. Vegetation community and land cover classification Parts of Tirunelveli hills of Western Ghats, Tamil Nadu (India)

2.3.3. Geostastical analysis and spatial modeling

Geostatistical techniques are the modern tools to interpolate sample data to create a map of tree species distribution, estimate the possible occurrence, disturbance and effective prediction by spatial information on local variability. Currently the conservation of endemic, rare and endangered species is largely supported by point-level information in terms of species and their number. The effects of forest cut, forest fire, grazing, collection of non-timber forest products (NTFP), wildlife impact, encroachment, settlements, etc., are point-specific. In addition, climatic data, terrain, and soil information are also broadly available as point data.

The conversion of this kind of point-level database into a spatial domain helps in integrating with other vegetation type layers or species-level databases to understand the patterns of diversity and conservation zoning. However, such an effort requires an enormous amount of ground data, collected by using a well-designed sampling strategy, and interpolation using robust statistical approaches. In the absence of reliable quantitative databases, statistical approaches involving non-parametric models, such as multilogistic regression, probit regression, Bayesian conditional algorithms, are used to understand the relationship between species richness (or diversity) and environmental (or disturbance) variables. These statistical approaches can work on simple “presence or absence data” and also rank information. On the basis of such relationships, spatial layers can be generated in a GIS. In addition, geostatistical tools, like kriging are also used to generate spatial surfaces on species distribution pattern.

Ganeshaiah & Uma Shaanker (2003) generated contours of distribution patterns of *Eamboo, Ochlandra, Rattans*, medicinal plants and major NTFP products. Riemann Hershey (1996) used geostatisitical techniques, viz. kriging or sequential Gaussian conditional simulation to create an interpolated dataset – a "map" of individual species distribution (10 species in Pennsylvania) from known sample information. Giriraj et al. (2003a, b) developed potential disturbance surfaces based on presence-absence data collected on fire, logging, wildlife, grazing, and adjacency in Tirunelveli hills of Western Ghats to understand species distribution patterns in relation to disturbance.

2.4. Biodiversity Information System (BIS)

Organized databases and information on biodiversity in user-friendly format are necessary to help decision makers and researchers in developing strategic action plans for biodiversity conservation. The vast amount of available data needs to be collected and represented by Internet-based technology with advanced user-friendly decision tools, such as Spatial Decision Support Systems (SDSS), Knowledge-Based GIS (KBGIS), Object-Oriented GIS (OOGIS), customization GIS, Web GIS, 4D-GIS, etc. in order to facilitate future dissemination of the derived spatial and non-spatial information among the user community.

Datasets with spatial and non-spatial information on various spatial scales, such as bioclimatic maps, forest reserve boundaries, roads, railways, settlements, DEM, terrain complexity, or species-information database, can be integrated into a single system in a digital domain (Fig. 6). Such a system will enhance querying the spatial and non-spatial information, monitoring and assessment of biodiversity, identification of risk habitats, and developing suitable conservation strategies.

IIRS (2002), Sameer et al. (2003), and Pereira & Duckstein (1993) have developed a Biodiversity Information System (BIS) with the objective of collecting and organizing the available distributed spatial and non-spatial database into an interactive system, which is capable of presenting a user-friendly interface to its clients. It has been developed on the basis of an object-oriented design approach that proceeds from data collection and application process design, navigation and workflow design, to web page and web-flow design. The components of the BIS are Biospatial, Biospec, PhytoSIS, FRIS and BioCon. Individually all these components focus on separate but related issues of biodiversity and management of natural resources. All the components are scalable and upgradable. Development of such biodiversity information systems is of potential use and relevant especially in tropical environments, where the understanding of biodiversity and disturbance regimes is still limited.

3. FUTURE SCENARIO

In the coming decade, assessment of ecosystem vulnerability in relation to natural and anthropogenic factors, habitat prediction for rare, endangered and threatened (RET) species, extraction of resources, forest degradation versus biodiversity conservation, impacts of climate change, and biodiversity are a few critical areas of research in biodiversity studies. All the decision supports in these areas of working

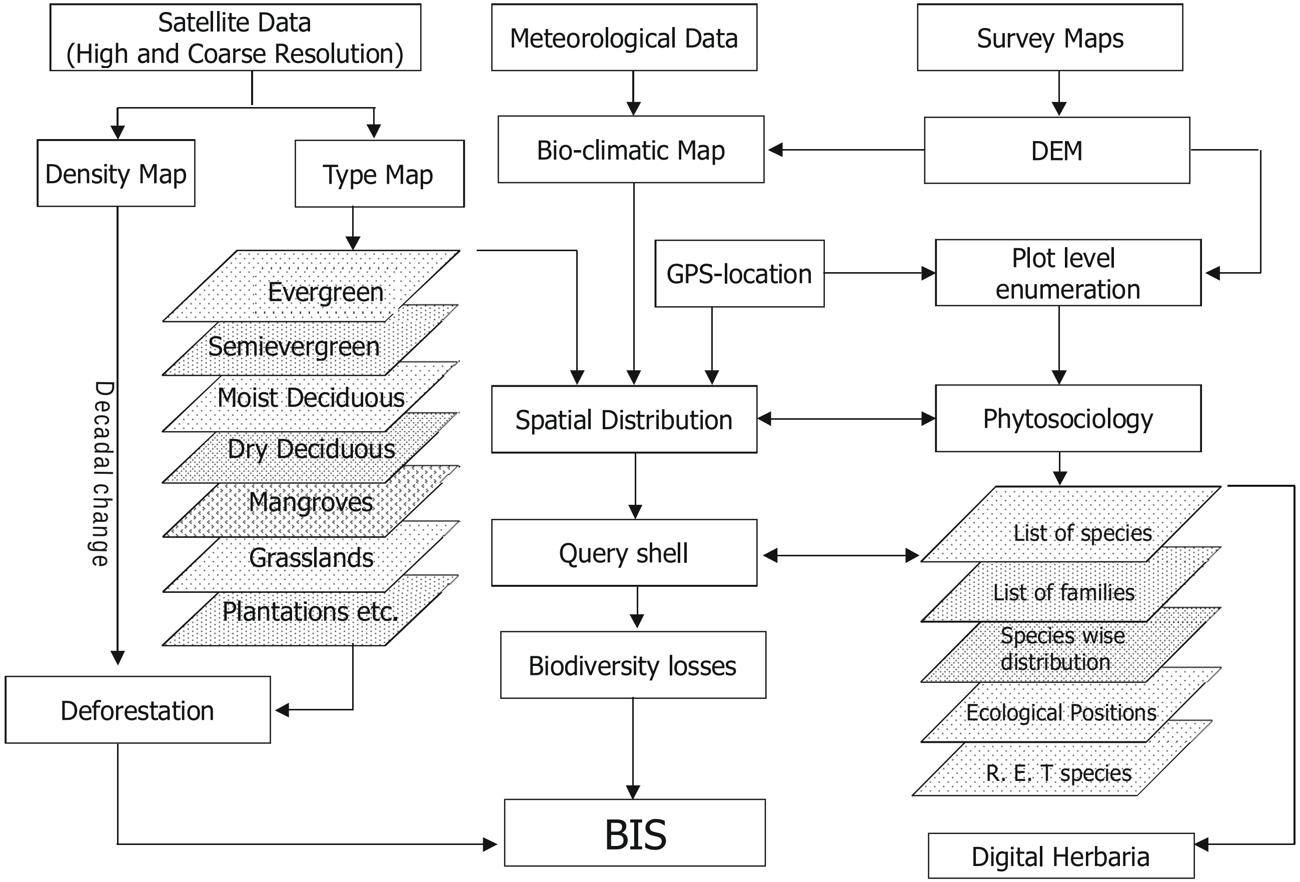

Fig. 6. Biodiversity Information System (BIS)

have to be data-driven and dependent on various resolutions and scales of spatial and temporal data, multithematic information, and terrain characteristics. The explicit organization of point-wise stand or species characteristics both in terms of growth and biophysical parameters, would drive the models for deriving meaningful outputs.

The question that always remains unanswered in the context of the burgeoning role of geoinformatics is the precision of information gathering and efficiency of information sharing. It is in this direction that future perspectives of geoinformatics are going to be a tightly integrated information system of remote sensing, GIS and GPS. In this regard, the synergy of satellite data from high spatial resolution, hyperspectral, and high temporal satellite sensors along with advanced differential GPS systems, and object-oriented GIS, plays a vital role. However, with regard to information dissemination, the strength of communications, especially the internet GIS (Web GIS) and the possible pervasive role of wireless GIS implemented through Internet and geo-stationary satellite communications through VSAT's (e.g. INSAT systems, etc.) may find a long way into the sustainable tropical forest management.

The development of the geo-informatics system for the entire tropical forests could be aimed through a consortium of all the tropical forest nations. The protocols on classification, coding, management, and sharing of information could follow. The connectivity within the tropical world could be done by using geo-stationary satellite communication networking through VSAT terminals among the nations and thereafter through web GIS, WAN and LAN, etc. Evolution of TROPNET (Tropical Forest Nations Networking) and TFNDI (Tropical Forest Nations Data Infrastructure) could be the bright prospects for geoinformatics in sustainable tropical forest management (DUTT 2001).

Acknowledgements: We thank Deputy Director and Director of National Remote-Sensing Agency for constant encouragement and support. We also thank colleagues of the Forestry and Ecology Division, Wildlife Wing, and Forest Department of Tamil Nadu for their support. We thank anonymous reviewers for providing many useful suggestions that have helped to improve the manuscript.

REFERENCES

AMARNATH G., MURTHY M. S. R., BRITTO S. J., RAJASHEKAR G., DUTT C. B. S. 2003. Diagnostic analysis of conservation zones using remote sensing and GIS techniques in wet evergreen forests of Western Ghats – An ecological hotspot, Tamil Nadu, India. Biodiv. Cons. 12: 2331–2359.

ARINO O., MELINOTTE J. M. 1995. Fire index atlas. Ear. Obs. Quart. 50: 10–15.

ARNOLD G. W., WEELDENBURG J. R. 1990. Factors determining the number and species of birds in road verges in the wheat belt of Western Australia. Biol. Cons. 53: 295–315.

AYYAPPAN N., PARTHASARATHY N. 1999. Biodiversity inventory of trees in a large-scale permanent plot of tropical evergreen forest at Varagalaiar, Anamalais, Western Ghats, India. Biod. Cons. 8: 1533–1554.

BROKAW N. V. L., SCHEINER S. M. 1989. Species composition in gaps and structure of a tropical forest. Ecology 70: 538–541.

BURNETT M. R., AUGUST P. V., BROWN J. H. JR., KILLINGBECK K. T. 1998. The influence of geomorphological heterogeneity on biodiversity. I. Patch-scale perspective. Cons. Biol. 12: 363–370.

COCHRANE M. A. 2000. Using vegetation reflectance variability for species level classification of hyperspectral data. Int. J. Rem. Sens. 10: 2075–2087.

COOPS N. C., CATLING P. C. 1997. Predicting the complexity of habitat in forests from airborne videography for wildlife management. Int. J. Rem. Sens. 18: 2677–2782.

COOPS N. C., CATLING P. C. 2002. Prediction of the spatial distribution and relative abundance of ground-dwelling mammals using remote sensing imagery and simulation models. Land. Ecol. 17: 173–188.

DEBINSKI D. M., HUMPHREY P. S. 1997. An integrated approach to biological diversity assessment. Nat. Areas J. 17: 355–365.

DEBINSKI D. M., JAKUBAUSKAS M. E., KINDSCHER K. 1999. A remote sensing and GIS-based model of habitats and biodiversity in the Greater Yellowstone Ecosystem. Int. J. Rem. Sens. 20: 3281–3292.

DEBINSKI D. M., RAY C., SAVERAID E. H. 2001. Species diversity and the scale of the landscape mosaic: do scales of movement and patch size affect diversity? Biol. Cons. 98: 179–190.

DUTT C. B. S. 2001. Proceedings of The International Conference on Forestry and Forest Products Research (CFFPR 2001) "Tropical forestry research in the new millennium: meeting demands and challenges", pp. 381-389, Kuala Lumpur, Malaysia.

EVA H., LAMBIN E. F. 1998. Remote sensing of biomass burning in tropical regions: sampling issues and multisensor approach. Rem. Sens. Env. 64: 292–315.

EVERARD D. A., VAN WYK G. F., MIGLEY J. J. 1994. Disturbance and diversity of forests in Natal, South Africa: lessons for their utilization. In: Botanical Diversity in Southern Africa: Strelitzia 1 (HUNTLEY B. J., Ed.), pp. 275-286, National Botanical Institute, Pretoria.

FARINA A. 1998. Principles and Methods in Landscape Ecology. Chapman and Hall, London.

FORMAN R. T. T., GODRON M. 1986. Landscape Ecology. John Wiley and Sons, New York.

FRANKLIN S. E. 1994. Discrimination of subapline forest species and canopy density sing digital CASI, SPOT PLA, and Landsat TM data. Phot. Eng. Rem. Sens. 60: 1223–1241.

FRANKLIN J. F., FORMAN R. T. T. 1987. Creating landscape patterns by forest cutting: ecological consequences and principles. Land. Ecol. 1: 5–18.

FRELICH L. E., REICH P. B. 1999. Neighborhood effects, disturbance severity, and community stability in forests. Ecosystem 2: 151–166.

GANESHAIAH K. N., MEERA C., RAO M. N., UMA SHAANKER R., SWAMINATH M. 2000. Conservation of sandal genetic resources in India: extraction patterns and threats to sandal resources in Karnataka. My For. 36: 125–132.

GANESHAIAH K. N., UMA SHAANKER R. 2003. A Decade of Diversity. 100 pp., ATREE and UAS, Bangalore.

GIRIRAJ A., MURTHY M. S. R., BRITTO S., DUTT C. B. S. 2003a. Phytodiversity in intact and fragmented evergreen habitats, Tamil Nadu, India - A conjunctive analysis using RS and ground data. Proceedings of the 30th International Symposium on Remote Sensing and Environment, 10–14th November 2003, Hawaii.

GIRIRAJ A., MURTHY M. S. R., DUTT C. B. S., RAMESH B. R. 2003b. Phytodiversity and endemic habitat analysis in wet evergreen forest of Tirunelveli hills (Tamil Nadu) using remote sensing and GIS. Nat. Rem. Sens. Agency Report, pp. 1–51.

GOLDSMITH M. L. 2000. Effects of ecotourism on the behavioral ecology of Bwindi gorillas, Uganda. Amer. J. Phys. Anthr. 30: 161.

GONG P., PU R., YU B. 2001. Conifer species recognition: effects of data transformation. Int. J. Rem. Sens. 17: 2471–2481.

GOULD W. 2000. Remote sensing of vegetation, plant species richness, and regional biodiversity hotspots. Ecol. Appl. 10: 186–187.

GREEN G. M., SUSSMANN R. W. 1990. Deforestation history of the Eastern rain forests of Madagascar from satellite images. Science 248: 212–215.

HEYWOOD V. H. (Ed.). 1995. Global Biodiversity Assessment. New York: Cambridge University Press.

HUSTON M. A. 1994. Biological Diversity: The Coexistence of Species on Changing Landscapes. Cambridge University Press, Cambridge.

IIRS 2002. Biodiversity Characterization at Landscape level in North East, Western Himalayas, Western Ghats using Satellite Remote Sensing and Geographic Information System, Indian Institute of Remote Sensing (IIRS-NRSA), Dehradun.

JANZEN D. H. 1979. How to be a fig. Ann. Rev. Ecol. Syst. 10: 13–51.

JHA C. S., SINGH J. S., RAGHUBANSHI A. S., DUTT C. B. S., GOPARAJU L., TRIPATHI A. 2000. Review of ISRO-GBP projects and the third workshop on scientific results from ISRO Geosphere Biosphere program. pp. 99–102.

JOHNSTON C. A. 1998. Geographic information systems in ecology. Blackwell Science, Oxford, UK.

JORGENSEN A. J., NOHR H. 1996. The use of satellite images for mapping of landscape and biological diversity in the Sahel. Int. J. Rem. Sens. 17: 91–109.

KUSHWAHA S. P. S., MUNKHTUYA S., ROY P. S. 2000. Geospatial modelling for Goral habitat evaluation. J. Ind. Soc. Rem. Sens. 28: 293–303.

LAPIN M., BARNES B. V. 1995. Using the landscape ecosystem approach to assess species and ecosystem diversity. Cons. Biol. 9: 1148–1158.

LAVER C.J., HAINES-YOUNG R. H. 1993. Equilibrium landscapes and their aftermath: Spatial heterogeneity and the role of the new technology. In: Landscape Ecology and Geographic Information Systems (HAINES-YOUNG R., GREEN D. R., COUSINS S., Eds). pp. 57–74, Taylor & Francis, London.

LELE S., RAJASHEKAR G., VENKATARAMANA R. H., PREVISH KUMAR G., SARVANAKUMAR P. 1998. Meso-scale analysis of forest condition and its determinants: A case study from the Western Ghats region, India. Curr. Sci. 75: 256–263.

LOMOLINO M. V. 1996. Investigating the cause of nestedness of insular communities: selective immigrations or extinctions? J. Biog. 23: 699–703.

LOVEJOY T. E., RANKIN J. M., BIERREGAARD R. O. JR., BROWN K. S. JR., EMMONS L. M., VAN DER VOORT M. E. 1984. Ecosystem decay of Amazon forest remnants. In: Extinctions (NITECKI M. H., Ed.), pp. 295-325, University of Chicago Press, Chicago.

LOVELAND T. R., BELWARD A. 1997. The IGBP-DIS global 1 km land cover dataset, DISCover first results. Int. J. Rem. Sens. 15: 3347–3364.

MARTIN M. E., NEWMAN S. D, ABER J. D., CONGALTON R. G. 1998. Determining forest species composition using high spectral resolution remote sensing data. Rem. Sens. Env. 65: 249–254.

MCKINNEY M. L. 1997. How do rare species avoid extinction? In: The Biology of Rarity (KUNIN W. E., GASTON K. J., Eds), pp. 110–129, Chapman & Hall, London.

MERRIAM G. K., HENEIN K., SMITH S. K. 1991. Landscape dynamics models. In: Quantitative Methods in Landscape Ecology (TURNER M. G., GARDNER R. H., Eds). pp. 399-416, Springer-Verlag, New York, NY, USA.

MYERS N., MITTERMEIER R. A., MITTERMEIER C. G., DA FONSECA G. A. B., KENT J. 2000. Biodiversity hotspots for conservation priorities. Nature 403: 853–858.

NAGENDRA H., GADGIL M. 1998. Linking regional and landscape scales for assessing biodiversity: a case study from Western Ghats. Curr. Sci. 75: 264–271.

NAGENDRA H., GADGIL M. 1999. Satellite imagery as a tool for monitoring species diversity: an assessment. J. Appl. Ecol. 36: 388–397.

NAYAR M. P. 1989. In situ conservation of wild flora resources. Bull. Bot. Surv. India 29: 319–333.

NICHOLS W. F., KILLINGBECK K. T., AUGUST P. V. 1998. The influence of geomorphological heterogeneity on biodiversity. II. A landscape perspective. Cons. Biol. 12: 371–379.

OPDAM P. 1991. Metapopulation theory and habitat fragmentation; a review of hoarctic breedings birds studies. Land. Ecol. 5: 93–106.

PEARSON J. E. 1993. Complex patterns in a simple system. Science 261: 189–192.

PELISSIER R. 1998. Tree spatial patterns in three contrasting plots of a southern Indian tropical moist evergreen forest. J. Trop. Ecol. 14: 1–16.

PELISSIER R., GOREAUD F. 2001. A practical approach to the study of spatial structure in simple cases of heterogeneous vegetation. J. Veg. Sci. 12: 99–108.

PEREIRA J. M. C, DUCKSTEIN L. 1993. A multiple criteria decision making approach to GIS based land suitability evaluation. Int. J. Geo. Info. Sci. 7: 407–424.

PETERS D. P. C., GOSLEE S. C. 2001. Landscape Diversity. In: Encyclopedia of Biodiversity (LEVIN S. A., Ed.), Vol 3: 645–658, Academic Press, New York

PLOTKIN J. B., POTTS M., YU D., BUNYAVEJCHEWIN S., CONDIT R., FOSTER R., HUBBELL S., LAFRANKIE J., MANOKARAN N., SENG L., SUKUMAR R., NOWAK M.A., ASHTON P. S. 2000. Predicting species diversity in tropical forests. Proc. Nat. Acad. Sci. 97: 10850–10854.

PORWAL M. C., SHARMA L., ROY P. S. 2003. Stratification and mapping of *Ephedra gerardiana* Wall. in Poh (Lahul and Spiti) using remote sensing and GIS. Curr. Sci. 84: 208–212.

PURVIS A., GITTLEMAN J. L., COWLISHAW G., MACE G. M. 2000. Predicting extinction risk in declining species. Proc. Royal Soc. London B 267: 1947–1952.

RAMESH B. R., PASCAL J. P. 1997. Atlas of Endemics of the Western Ghats (India), Institut Francias de Pondicherry.

RAMESH B. R., DE FRANCESCHI D., PASCAL J. P. 1997. Forest Map of South India, Thiruvanthapuram-Tirunelveli at 1:250,000 (Sheet 6). Institut Français, Pondichérry.

REY-BENAYAS J. M., POPE K. O. 1995. Landscape ecology and diversity patterns in the seasonal tropics from Landsat TM imagery. Ecol. Appl. 5: 386–394.

RIEMANN HERSHEY R. 1996. Understanding the spatial distribution of tree species in Pennsylvania. In: Spatial Accuracy Assessment in Natural Resources and Environmental Sciences (MOWRER H. T. et al., tech. coords). pp. 73–82. Second International Symposium. May 21–23. 1996. General Technical Report. RM-GTR-277. Fort Collins, CO. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station.

ROMME W. H. 1982. Fire and landscape diversity in subalpine forests of Yellowstone National Park. Ecol. Monogr. 52: 199–221.

ROMME W. H., KNIGHT D. H. 1982. Landscape diversity: The concept applied to Yellowstone Park. Bioscience 32: 664–670.

ROY P. S., PORWAL M. C., SHARMA L. 2001. Mapping of *Hippophae rhamnoides* Linn. in the adjoining areas of Kaza in Lahul and Spiti using remote sensing and GIS. Curr. Sci. 80: 1107–1111.

SAMEER S., GHOSH S., SHRIVASTAVA G., ROY P. S., GAUTAM T., NUPOOR P. 2003. Spatial decision support system for biodiversity conservation prioritization: A case study for web based approach. Asian J. Geoinform. 4: 21–30.

SCHULLERY P. 1989. The fires and the fire policy. BioScience 39: 686–694.

STOMS D. M. 1992. Effects of habitat map generalization in biodiversity assessment. Phot. Eng. Rem. Sens. 58: 1587–1591.

STONE T. A., SCHLESINGER P., HOUGHTON R. A., WOODWELL G. M. 1994. A map of the vegetation of South America based on satellite imagery. Phot. Eng. Rem. Sens. 60: 441–451.

STORK N. E., BOYLE T. J. B., DALE V., EELEY H., FINEGAN B., LAWES M., MANOKARAN N., PRABHU R., SOBERON J. 1997. Criteria and indicators for assessing the sustainability of forest management: conservation of biodiversity. CIFOR Working Paper No. 17: 1–29.

SWINGLAND I. R., GREENWOOD P. J. (Eds) 1983. The Ecology of Animal Movement. Claredon Press, Oxford.

TOWNSEND J. R. G., JUSTICE C. O., SKOLE D., MALINFREAU J. P., CIHLAR J., TEILLET P., SADOWSKI F., RUTTENBERG S. 1994. The 1 km resolution global data set: needs of the International Geosphere Biosphere Programme. Int. J. Rem. Sens. 15: 3417–3441.

TREITZ P. M., HOWARTH P. J., SHUFFLING R. C., SMITH P. 1992. Application of detailed ground information to vegetation mapping with high spatial resolution digital imagery. Rem. Sens. Env. 42: 65–82.

TURNER M. G. 1989. Landscape Ecology: the effect of pattern of process. Ann. Rev. Ecol. Syst. 20: 171–197.

TURNER M. G., GARDNER R. H. 1991. Quantitative Methods in Landscape Ecology, Springer-Verlag, New York, USA.

TUTIN C. E., WILLIAMSON E. A., ROGER M. E., FERNANDEZ M. 1991. A case of a plant-animal relationship: Cola lizae and lowland gorillas in the Lope Reserve, Gabon. J. Trop. Ecol. 7: 181–199.

UNEP-WCMC 2000. Global Biodiversity: Earth's living resources in the 21st century. Cambridge, World Conservation Press.

VAN HORSSEN P. W., SCHOOL P. P., BARENDREGT A. 1999. A GIS-based plant prediction model for wetland ecosystems. Land. Ecol. 14: 253–265.

WADSWORTH R., TREWEEK J. 1999. Geographic information systems for ecology: an introduction. Longman, Essex, UK.

WALTER V. R., SARAH A. L., CARRIE A. M., RODRIGO G., ANA S., DANIEL H. J., MICHAEL A. G., CALESTOUS J. 1993. Biodiversity Prospecting: Using Genetic Resources for Sustainable Development. World Resources Institute, Washington.

WHITE J. D., KROH G. C., PINDER J. E. III 1995. Forest mapping at Lassen Volcanic National Park, California, using Landsat TM data and Geographical Information System. Phot. Eng. Rem. Sens. 61: 299–305.

WHITEMORE T. C. 1975. Tropical rain forest of the Far East. 282 pp. Oxford University Press, Oxford.

WHITTAKER R. H. 1960. Vegetation of the Siskiyou Mountains, Oregon and California. Ecol. Monogr. 30: 279–338.

WIENS J. A. 1989. Spatial scaling in ecology. Func. Ecol. 3: 385–397.

WU J., LEVIN S. A. 1997. A patch-based spatial modeling approach: conceptual framework and simulation scheme. Ecol. Model. 101: 325–346.