# LANDSCAPE ECOLOGICAL PLANNING THROUGH A MULTI-SCALE CHARACTERIZATION OF PATTERN: STUDIES IN THE WESTERN GHATS, SOUTH INDIA

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**Abstract.** This article analyzes landscape pattern in the Western Ghats mountain ranges in south-western India at two scales, comparing small-scale, detailed studies of landscape pattern, with broader, regional-scale assessments of the Western Ghats. Due in large part to their inaccessibility, relatively little is known about the landscapes of this biodiverse region, which also supports some of the highest population densities in the world. A broad-scale NDVI-based IRS 1B satellite image classification is used to analyze north-south and east-west trends across the entire Western Ghats and western coast of India, an area over 170 000 km$^2$. Northern and eastern landscapes are more fragmented compared to the southern and western slopes. Western slopes also have greater landscape diversity with land cover types more interspersed compared to the eastern slopes. These differences can be related to north-south and east-west variations in rainfall and plant distribution. Data from thirteen landscapes 10–50 km$^2$ in area, are further utilized to analyze trends in landscape pattern, and describe the geographical distribution of major natural and managed ecotope types. At this scale, very high levels of intra-ecotope type variability in landscape pattern are encountered for all land cover types. Results at these two scales are integrated to suggest a hierarchical stratified approach for monitoring land cover and biodiversity in the region.

## 1. Introduction

Management of tropical mountain landscapes is an increasingly urgent imperative. The world over, these areas are facing increasing pressure for resources and undergoing change at ever-accelerating rates. Land use change due to human pressure has been identified as the major cause for biodiversity losses. Due in large part to their inaccessibility, relatively little is known about these regions (Southworth *et al.*, 2002; Rey-Benayas and Pope, 1995).

The hill chain of the Western Ghats of India is among the most diverse of tropical landscapes. This region forms one of the world's 25 biodiversity hot-spots: these are defined as areas with high levels of endemic species, which are currently under severe threat and therefore undergoing rapid change (Cincotta and

Engelman, 2000). Indeed, among the 20 described hotspots, this region supports the highest population densities. The range of environmental regimes across the Western Ghats, varying in topography, soil, rainfall and temperature, make for highly heterogeneous land cover. Over time, the extent and severity of human-affected landscape change has increased. As in several parts of the tropics, the Western Ghats region is now a heterogeneous, highly variegated mosaic of both natural and managed ecosystems, in need of informed strategies for conservation and management.

Little information is available on the Western Ghats landscapes (Daniels, 1994, 1996; Menon and Bawa, 1997). As in other parts of the mountain tropics (Rey-Benayas and Pope, 1995; Southworth *et al.*, 2002), high topographic variability and relative inaccessibility make this region difficult to map and study. Remote sensing provides an effective tool for landscape pattern analysis, though it is only in recent years that its potential for landscape analysis has begun to be fully utilized (Forman, 1995). Although remote sensing and GIS provide effective tools for this purpose, mapping land cover in these regions is extremely time, labor and resource intensive. Little is known about land cover composition and pattern in these complex landscapes (Menon and Bawa, 1997; Nagendra and Gadgil, 1999b). As in other parts of the world, the discussion has hitherto been dominated by analyses of percent forest cover per unit area (Riitters *et al.*, 2000). High topographic variability, dense cloud cover, relatively large numbers of land cover types and complex spatial patterns, contribute to the difficulty involved in mapping these mountainous areas (Nagendra, 1999b).

Drawing on remote-sensing derived maps (Nagendra and Gadgil, 1998, 1999a, b), this article characterizes the distribution of land cover and landscape pattern in the Western Ghats landscape at two scales. Figure 1 describes the objectives of this study. At a broad spatial scale, covering the entire western coast and Western Ghats ecoregion (over 170 000 km$^2$), we look for latitudinal and longitudinal variation in spatial pattern. At a more detailed landscape scale, using data from 13 landscapes (10–50 km$^2$ in area) we again look for north-south and east-west differences in landscape pattern, and synthesize data from this and other studies to summarize the distribution of ecotope types in the Western Ghats. The results increase our understanding of landscape pattern and distribution in the Western Ghats, and are used to develop a hierarchical stratified approach for monitoring changes in land cover and biodiversity in this complex dynamic mountain region.

## 2. Study Area

The Western Ghats of India run from the southern tip of peninsular India, 8°N, all the way up the western coast to the mouth of the river Tapti, 21°N and lie between 73°–77°E. This series of hill ranges runs north-south along the west coast for over 1600 km. Together with the bordering western coastal regions, it covers an area of
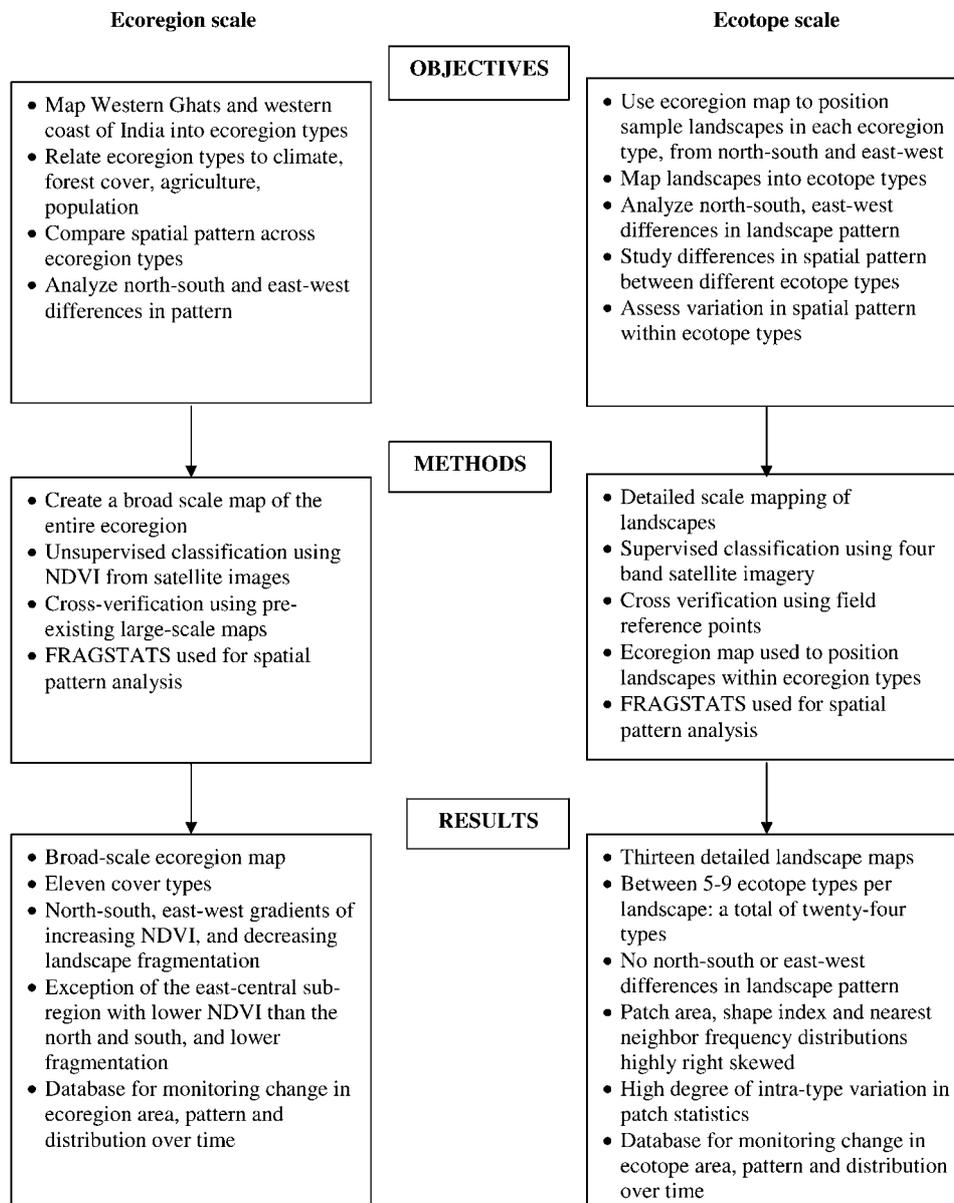
| Ecoregion scale | | Ecotope scale |
|---|---|---|
| | **OBJECTIVES** | |
| • Map Western Ghats and western coast of India into ecoregion types<br>• Relate ecoregion types to climate, forest cover, agriculture, population<br>• Compare spatial pattern across ecoregion types<br>• Analyze north-south and east-west differences in pattern | | • Use ecoregion map to position sample landscapes in each ecoregion type, from north-south and east-west<br>• Map landscapes into ecotope types<br>• Analyze north-south, east-west differences in landscape pattern<br>• Study differences in spatial pattern between different ecotope types<br>• Assess variation in spatial pattern within ecotope types |
| | **METHODS** | |
| • Create a broad scale map of the entire ecoregion<br>• Unsupervised classification using NDVI from satellite images<br>• Cross-verification using pre-existing large-scale maps<br>• FRAGSTATS used for spatial pattern analysis | | • Detailed scale mapping of landscapes<br>• Supervised classification using four band satellite imagery<br>• Cross verification using field reference points<br>• Ecoregion map used to position landscapes within ecoregion types<br>• FRAGSTATS used for spatial pattern analysis |
| | **RESULTS** | |
| • Broad-scale ecoregion map<br>• Eleven cover types<br>• North-south, east-west gradients of increasing NDVI, and decreasing landscape fragmentation<br>• Exception of the east-central sub-region with lower NDVI than the north and south, and lower fragmentation<br>• Database for monitoring change in ecoregion area, pattern and distribution over time | | • Thirteen detailed landscape maps<br>• Between 5-9 ecotope types per landscape: a total of twenty-four types<br>• No north-south or east-west differences in landscape pattern<br>• Patch area, shape index and nearest neighbor frequency distributions highly right skewed<br>• High degree of intra-type variation in patch statistics<br>• Database for monitoring change in ecotope area, pattern and distribution over time |

*Figure 1.* A comparison of objectives, methods and results at two spatial scales of analysis in the Western Ghats.

about 170 000 km$^2$. The chief soil types are red soils, laterites and black humid soils (Subramaniam and Nayar, 1974; Peterschmitt *et al.*, 1996).

Rainfall patterns vary across the Ghats. The westward side faces the south-western monsoon (June–August) winds and hence receives a very high amount of rainfall, while the eastern face falls within a rain-shadow area. There is also a large north-south variation in rainfall: the number of dry months in a year in the Western Ghats varies from eight months in the north, to two months in the south. Average temperatures range from 24 °C in the north to 20 °C in the south. There is frost, though no snow, in the higher reaches of the mountains.

This tremendous environmental variation in topography, soil type, rainfall, number of dry months per year and temperature makes for an extremely environmentally heterogeneous biogeographic area, with very high biodiversity (Gadgil, 1996). All or most of the original vegetation cover of this area has been influenced to varying extents by humankind over thousands of years (Chandran, 1997). Nevertheless, this tropical landscape contains many endemic species (Daniels, 1996). The first major gradient in the distribution of flowering plant species diversity is latitudinal: species diversity increases from north to south. This has been related to the southward increase in number of days of rainfall per year (Puri *et al.*, 1983). Species diversity also increases as one travels from the eastern face, in the rain shadow, to the western face that receives maximum rainfall (Gadgil, 1996).

Although originally covered by tropical wet evergreen, moist deciduous and dry deciduous forests, the Western Ghats have been extensively modified by human activities (Pascal, 1988). As with several parts of the tropics, this region is undergoing extensive changes in land cover. In recent years, the introduction of plantation crops, the extension of high profit tree and timber plantations, and the submergence of large stretches of land while constructing hydro-electric plants, have resulted in rapid transformation. As a result, the landscape is now a heterogeneous and highly variegated mosaic of both natural and managed ecosystems (Daniels *et al.*, 1995; Pramod *et al.*, 1997).

Given the rapid pace of human landscape modification, the monitoring of changes in land cover, land use and biodiversity has become a major focus of the global change research agenda over the next decade (NRC, 1999; Lambin *et al.*, 2001). The Global Biodiversity Assessment (Heywood, 1995) recommends the use of remote sensing for country studies at multiple spatial scales, to identify components necessary for biodiversity conservation and maintenance: including of landscape structure and composition. Little information of this kind exists, particularly in parts of the tropics where accessibility limits mapping (Rey-Benayas and Pope, 1995; Nagendra and Gadgil, 1999b). This research illustrates the potential of such an approach for assisting in the development of spatially focused, informed strategies for monitoring land cover change.

## 3. Methods

Our analysis is at two spatial scales. The first scale covers the ecoregion of the Western Ghats and western coast of India, and extends over 170 000 km$^2$. At the second scale we analyze ecotope distribution using thirteen detailed land cover maps of landscapes between 10–50 km$^2$. For the purpose of this study, given its reliance on remote sensing derived maps, ecotopes are defined as the smallest mappable, homogeneous units of land cover in the landscape (after Forman and Godron, 1987; and Forman, 1995). Figure 1 summarizes the methods used at these two separate scales of analysis, which are discussed in further detail below.

### 3.1. ECOREGION SCALE

Fifty scenes from the Indian Remote Sensing satellite IRS 1B LISS 2 sensors, covering the Western Ghats and western coast of India, were used to create an ecoregion scale map. The satellite data consisted of intensities at four wavelengths: 450 to 520 nm, 520 to 600 nm, 630 to 690 nm, and 730 to 900 nm, with a pixel size of 36.25 by 36.25 m (Kasturirangan *et al.*, 1991). All images were from the pre-monsoon season, which ranges from mid-February to mid-June as the rain-bearing monsoon winds move northwards up the coastline. During this season, deciduous trees are leafless, enhancing the chances of discriminating deciduous forests from evergreen. As in large parts of southeast Asia, the chances of acquiring cloud-free images in this region are greatly reduced due to persistent cloud cover (Achad and Estreguil, 1995; Nagendra and Gadgil, 1998). Our scene dates range from 1992 to 1994 depending on availability of cloud free data in the pre-monsoon season: however, a majority of scenes are from 1993. Manual co-registration of images was carried out to remove overlap areas, and the scenes pasted together to create a composite image of the total study area.

In order to facilitate scene comparison, the Normalized Difference Vegetation Index (NDVI) (Jensen, 2000) was utilized. This index is correlated with vegetation biomass and photosynthetic vigor, and reduces problems of inter-scene variability (Jensen, 2000). For each pixel in the composite image, the NDVI was computed. The resultant composite image contained in the order of 10$^6$ pixels, from fifty scenes. Pixel-based classification at this scale would create far too many small patches, and result in a map which we could not compare with other, less detailed (1:1 000 000) maps of topography, climate, population and agriculture that are published for this region. A pixel-reduction technique was thus employed, with non-overlapping sets of fifty by fifty pixels, covering 1.8 by 1.8 km, used to create a 'super-pixel'. Each super-pixel was characterized by the distribution parameters (mean, standard deviation, skew and kurtosis) of the set of NDVI values of the 2500 constituent pixels, after ensuring that NDVI distributions of constituent pixels were unimodal. Super-pixel units of 1.8 by 1.8 km were input into an unsupervised maximum likelihood classification of the study area, using the i.cluster algorithm of

the Grass 4.1 image processing software (United States Army Corps of Engineers, 1994): this algorithm takes into account the fact that the distribution parameters used as input into the classification are not independent quantities.

This classification delineated 12164 patches belonging to fourteen NDVI cover types (Nagendra and Gadgil, 1998). Several of these patches were only a few square kilometers in extent and very small relative to the size of the total study area of 170 000 km$^2$. We wished to compare this map to other maps of topography, rainfall, temperature, forest cover and agricultural land use of the Western Ghats, which are printed at much less detailed scales of 1:1 000 000. In order to facilitate comparison with these maps, we eliminated all patches smaller than 100 km$^2$ (a relatively arbitrary cut-off point, but one we thought appropriate considering the scale of the entire ecoregion: 170 000 km$^2$) by merging them with the type most predominant in the vicinity. The resultant map had a total of 205 patches belonging to eleven cover types. The distribution of these types was interpreted with reference to maps of topography, rainfall, temperature, forest cover and agricultural land use of the Western Ghats (Nagendra and Gadgil, 1998). It must be noted here that as mapping at this scale is based on the NDVI, tree plantations would be considered as forest cover.

As noted previously, north-south and east-west gradients are identified as having a major effect on plant species diversity. An analysis was carried out to explore north-south and east-west variation in landscape pattern. The ecoregion map of the Western Ghats was partitioned into six sub-regions (Figure 2). Sub-regions 1 and 2 run from 15 to 21°N, and are separated from sub-regions 3 and 4 at the region corresponding to the gap created by the Kali Nadi, a river drainage created due to uplifting and faulting (Radhakrishna, 1991). Sub-regions 3 and 4 (10°30′ to 15°N) are separate from sub-regions 5 and 6 (8 to 15°N) at the Palghat gap. This natural break in the hill ranges, described in Section 2.1., is known to partition the hill ranges into regions that differ widely in the species they harbor (Subramanyam and Nayar, 1974).

While exact boundaries of these sub-regions are arbitrary, in general, these divisions of the Western Ghats conform to gradients and barriers known to influence patterns of species diversity (Subramaniam and Nayar, 1974). Rainfall, temperature and topography act differently upon each of these sub-regions to produce differing vegetation complexes. This exercise assesses whether these sub-regions of the Western Ghats, varying in species diversity, topography, climate and vegetation, differ in landscape composition and configuration.

For each sub-region, the program Fragstats 2.0 was used to derive parameters of landscape pattern (McGarigal and Marks, 1994). Several of these metrics are wholly or partially redundant, as they emphasize similar or identical aspects of pattern. Four metrics of landscape structure: patch area, patch shape, the Shannon index of landscape diversity, and the interspersion-juxtaposition index of patch interspersion: were identified as providing important information (Riitters *et al.*, 1995; Haines-Young and Chopping, 1996). The patch area index is self explanat-
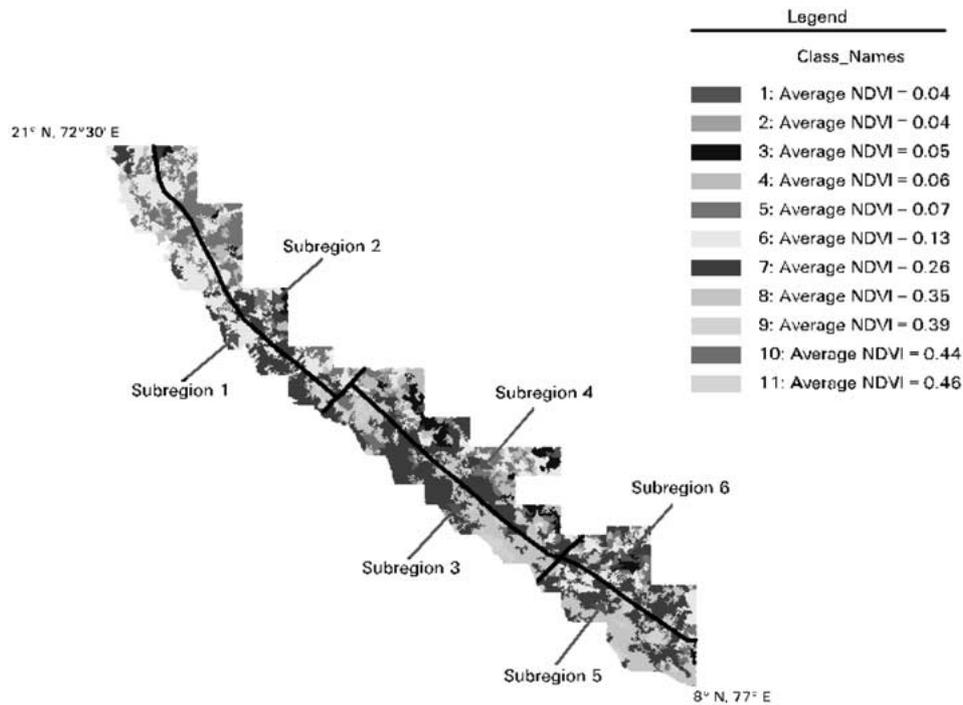
*Figure 2.* The ecoregion scale map of the Western Ghats, depicting eleven cover types mapped based on four distribution parameters of the NDVI: average, standard deviation, skew and kurtosis. Boundaries of the six sub-regions are delineated on the map. Color figure available for viewing at http://www.cipec.org/publications/nagendra_utkarsh2002.html

ory, and increases as patch size increases. The patch shape index is 1.0 for most compact patches, and increases without limit as patch shapes become increasingly elongated and irregular. Each subregion is composed of a number of patches, and the area and shape indices were computed for all these patches, and the median values of patch area and shape were then calculated for the subregion. The Shannon's index of landscape diversity ranges from 1.0 to infinity, increasing as the number of land cover types increase and/or as the proportional area distribution of these types becomes more equal. The interspersion-juxtaposition index ranges from 0 to infinity, increasing as patches belonging to different land cover types become increasingly interspersed. These four indices are frequently utilized in analysis of landscape pattern (Forman, 1995). Further details are provided in McGarigal and Marks (1994).

## 3.2. ECOTOPE SCALE

Several schemes have been proposed for classification of the Western Ghats landscape. We use a scheme of classification that largely conforms to the UNESCO

(1973) classification of vegetation. For all major ecotope types found in the Western Ghats (forests and their stages of degradation, tree plantations, agricultural crops and fresh water habitats), their occurrence is described in terms of latitude, altitude, aspect and slope. This description is based on existing literature, large-scale vegetation maps (Pascal, 1982, 1986, 1988; Nair and Daniel, 1986; SOI, 1988; NATMO, 1989) and our personal experience through over ten years of extensive field visits in this ecoregion.

A set of thirteen landscapes belonging to five of the eleven NDVI cover types described at the ecoregion scale were taken up for more detailed investigations, as part of a related study for multi-scale species diversity assessment (Nagendra and Gadgil, 1999b). These areas belong to cover types 5, 7, 8, 9 and 10, which cover 66% of the Western Ghats at the ecoregion scale (Nagendra and Gadgil, 1998). Essentially, during selection of these landscapes, the degraded, low biomass areas, and the high biomass, shola-grassland composite landscapes have been left out. These areas range from 9–54 km$^2$ in area: further descriptions are provided in Nagendra and Gadgil (1999b).

Imagery from the Indian Remote Sensing satellite IRS 1B LISS 2 sensors (Kasturirangan *et al.*, 1996) were geo-corrected with reference to 1:50 000 scale Survey of India topographic sheets, with the assistance of WIPS-32 systems from the Regional Remote Sensing Service Centre, Bangalore. Field visits provided data to create a pixel-level supervised classification for the major ecotope types (cover types at this scale) within these landscapes. The GRASS 4.1 image processing software (United States Army Corps of Engineers, 1994) was utilized for this purpose.

For each landscape, the software FRAGSTATS 2.0 was used to derive indices of pattern at the landscape level: median patch size, median patch shape, median nearest neighbor distance, Shannon's landscape diversity, and interspersion-juxtaposition: and at the patch level: patch area, patch shape index, and nearest neighbor distance. Nearest neighbor distance is the distance between a patch and the nearest neighboring patch of the same ecotope type, in meters. Other indices have been described in the previous, Ecoregion section.

For the twenty-four ecotope types situated within the 13 mapped landscapes, median values of patch area, patch shape and nearest neighbor distance were computed, and the variation in distribution of these variables analyzed by computing the range between the first and third quartiles. A nonparametric rank correlation analysis (Sokal and Rohlf, 1981) was performed between latitude and longitude, and indices of patch pattern, to look for north-south and east-west trends in pattern at the landscape scale. The non-parametric Mann-Whitney U test (Sokal and Rohlf, 1981) was conducted to test whether pairs of ecotope types differed significantly in patch area, shape and nearest neighbor distance.

TABLE I

The six sub-ecoregions delimited within the Western Ghats, in terms of their geographic location (latitude and aspect), and landscape pattern (median patch area, median patch shape, Shannon's landscape diversity and interspersion-juxtaposition). Detailed description of these metrics is provided in the Methods Section

|  | Latitude | Aspect | Median patch area (km$^2$) | Median patch shape | Shannon diversity | Interspersion-juxtaposition |
|---|---|---|---|---|---|---|
| Sub-region 1 | 15–21°N | Eastern | 14 947 | 2.12 | 1.42 | 55.11 |
| Sub-region 2 | 15–21°N | Western | 11 170 | 1.90 | 1.30 | 47.32 |
| Sub-region 3 | 10°30′–15°N | Eastern | 15 769 | 2.12 | 1.87 | 65.61 |
| Sub-region 4 | 15–21°N | Western | 16 097 | 2.40 | 1.23 | 50.56 |
| Sub-region 5 | 8°–10°30′N | Eastern | 15 440 | 2.48 | 1.59 | 56.31 |
| Sub-region 6 | 15–21°N | Western | 18 890 | 2.57 | 1.37 | 51.15 |

## 4. Results and Discussion

### 4.1. ECOREGION SCALE

Figure 2 depicts the ecoregion scale map of the Western Ghats, with the six sub-regions delineated. Cover types 1 and 2 have identical average NDVIs of 0.04, but differ in NDVI standard deviation, skew and kurtosis. Definite north-south trends in vegetation index are apparent from Figure 2 as well as from Table I, which describes landscape pattern in each of the six sub-regions. On the western slopes, the northern end of the Ghats is dominated by relatively low NDVI cover types 5 and 6, with an increase in NDVI while traveling further southwards, giving way to cover type 7 and further on, to cover type 8. On the eastern slopes, a similar trend is noted, with increasing NDVI from north to south: barring the east-central hills with low-NDVI cover types 3 and 4. Differences between the eastern and western slopes are also pronounced, with the western slopes dominated by cover types with higher vegetation index (Figure 2, Table I).

This can be related with known causal climatic differences (Subramanyam and Nayar, 1974). As the south-western winds are the major source of monsoon rain, the northern and western slopes receive far less rainfall compared to the southern and western regions. As a result, these landscapes are dominated by dry deciduous forest, leaf-off in our image dates and hence with lower NDVI, while the natural vegetation in the high-rainfall belts is predominantly moist evergreen, with high NDVI (Pascal, 1998).

Table I reports the summary statistics of median patch area, median patch shape, Shannon's index of diversity and the interspersion-juxtaposition index, for the six

sub-regions of the Western Ghats. North-south differences in landscape pattern are observed. Median patch area increases from north to south, with the exception of a further increase in patch area in the east-central region (Table I, sub-region 3). The median patch shape index also shows an increasing north-south trend, although the indices of Shannon diversity and interspersion-juxtaposition do not however demonstrate consistent north-south differences.

Clear differences between eastern and western flanks are apparent. Median patch area is greater in the west (Figure 2 and Table I, sub-regions 2, 4 and 6) as compared to the east (sub-regions 1, 3 and 5), as are indices of median patch shape, landscape diversity and interspersion-juxtaposition. Landscape fragment-ation on the eastern slopes is therefore much greater compared to the western slopes. These differences can be correlated with the climatic and topographic dif-ferences known to exist between the western and eastern flanks (Subramanyam and Nayar, 1974; Pascal, 1988), as well as the NDVI gradients observed. The western slopes are steeper, with primary forest vegetation being moist evergreen with high NDVI levels. The eastern face merges more gradually with the peninsula, and water availability is limited, with lower NDVI levels. It is relatively easier to deforest the dry deciduous forest areas as compared to the evergreen regions which are dominated by thick dense forest: this can explain why the low rainfall northern and eastern slopes that are dominated by dry deciduous forest appear more fragmented compared to the high rainfall dense evergreen forests of the southern and western slopes.

## 4.2. ECOTOPE SCALE

Table II describes the distribution of major ecotope types found in the Western Ghats, in terms of latitude, altitude and slope. Major forest types (montane, ever-green, semi-evergreen, moist deciduous and dry deciduous), and their associated stages of degradation are described, along with major tree plantations, agricultural crops and aquatic ecotopes. Cardamom, coffee and pepper are excluded: these are typically forest undergrowth crops, difficult to distinguish from their associ-ated forest. Only two major agricultural crops, paddy and sugarcane, have been described. These are irrigated crops, and grown in permanently irrigated zones (ICAR, 1962). In partially irrigated or non-irrigated areas, rice may be grown dur-ing the rains. The rest of the year, however, sees a succession of millets, pulses and/or groundnut planted. These and other rotating, transient crops are also ex-cluded from description.

Field verification in the thirteen landscapes mapped at a detailed scale, in early 1995, and fall 1997, found the mean accuracy of supervised classification to be 84% with a range from 70 to 92%, as shown in Table III. This table also describes the geographic location, altitude range, rainfall, ecoregion type, and number of ecotope types for these landscapes, as well as statistics of landscape pattern: me-dian patch size, median patch shape index, median nearest neighbor distance, the

TABLE II

For major ecotope types found in the Western Ghats, distribution in terms of geographic location, altitude, aspect and slope is described

| Ecotope | Latitude (∘N) | Altitude (>msl) | Eastern aspect | Western aspect | Valley | Slope | Ridge |
|---|---|---|---|---|---|---|---|
| **Primary ecotopes** | | | | | | | |
| Shola forest | 8–11 | 1500–2300 | + | + | # | + | + |
| Evergreen forest | 8–19 | 100–1500 | + | + | + | # | + |
| Semi-evergreen forest | 8–20 | 50–1500 | + | + | + | + | + |
| Moist deciduous forest | 8–21 | 500–900 | + | + | + | + | + |
| Dry deciduous forest | 8–21 | 300–900 | + | – | + | + | + |
| Bamboo brake | 8–21 | 0–1000 | + | + | + | + | – |
| Montane grassland | 8–11 | 1500–2500 | + | + | + | + | # |
| **Secondary ecotopes** | | | | | | | |
| Sec. evergreen forest | 8–19 | 0–1500 | + | + | + | + | + |
| Sec. semi-evergreen forest | 8–20 | 0–1500 | + | + | + | + | + |
| Sec. moist deciduous forest | 8–21 | 0–1500 | + | + | + | + | + |
| Sec. dry deciduous forest | 8–21 | 0–1500 | + | – | + | + | + |
| Woodland/open forest | 8–21 | 0–1000 | + | + | + | + | + |
| Scrub | 8–21 | 0–2500 | + | + | + | + | + |
| Thicket | 8–21 | 0–2500 | + | + | + | + | + |
| Savanna | 8–21 | 0–2500 | + | + | – | + | + |
| Degraded grassland | 8–21 | 0–1000 | + | + | + | + | + |
| Bare rock/open soil | 8–21 | 0–2500 | + | + | – | # | # |
| **Created ecotopes** | | | | | | | |
| *Acacia* plantation | 8–21 | 0–1000 | + | + | + | + | + |
| *Areca* plantation | 8–18 | 0–1000 | + | + | + | + | + |
| Cashew plantation | 8–19 | 0–200 | + | + | – | + | + |
| *Casuarina* plantation | 8–21 | 0–200 | + | + | + | + | + |
| Clove plantation | 8–10 | 0–400 | + | + | + | + | + |
| Coconut plantation | 8–18 | 0–400 | + | + | – | + | – |
| *Eucalyptus* plantation | 8–18 | 0–2100 | + | + | + | + | + |
| Pine plantation | 10–11 | 1500–2300 | + | + | + | + | + |
| Rubber plantation | 8–12 | 50–600 | + | – | + | + | + |
| Tea plantation | 8–11 | 400–2100 | + | + | + | + | + |
| Paddy field | 8–21 | 0–1000 | + | + | + | – | – |
| Sugarcane field | 8–21 | 0–1000 | + | + | + | – | – |
| **Aquatic ecotopes** | | | | | | | |
| Streams/Rivers | 8–21 | 0–2500 | + | + | + | + | – |
| Waterfalls | 8–21 | 0–2500 | + | + | + | + | – |
| Natural pools/ponds | 8–21 | 0–2500 | + | + | – | + | – |
| Manmade tanks/reservoirs | 8–21 | 0–2500 | + | + | – | – | + |

+: Present; –: absent; #: most common location.

Shannon index of diversity, and the interspersion-juxtaposition index. Although the average values of patch area, shape and nearest neighbor distance vary appreciablg between landscapes, and the standard deviation of these variables within a landscape is high, the median patch area, patch shape index and median nearest neighbor distance do not vary across landscapes (Table IV). Therefore, although there is a high degree of variation in statistics of patch spatial pattern within a landscape, most of this variation can be ascribed to a few patches at the extreme tail end, and median values of distribution remain fairly invariant at this scale. A nonparametric rank correlation analysis found no significant correlation between latitude or longitude, and median patch area, median patch shape index, median nearest neighbor distance, Shannon's diversity or interspersion-juxtaposition ($p = 0.05$): i.e. no significant north-south or east-west gradients in landscape pattern could be discerned at this scale.

The thirteen landscapes mapped contained between five and nine ecotope types each, and a total of twenty-four ecotope types were encountered within these landscapes (Nagendra and Gadgil, 1999b). These were evergreen forests, degraded evergreen forests, semi-evergreen forests, degraded semi-evergreen forests, moist deciduous forests, degraded moist deciduous forests, woodlands, scrub, bamboo brakes, thickets, savanna, grasslands, rocky areas, *Acacia auriculiformis* plantations, *Areca catechu* plantations, Areca-coconut mixed plantations, *Casuarina equisetifolia* plantations, coconut plantations, *Eucalyptus* plantations, paddy fields, rubber plantations, tea plantations, teak plantations and water.

All patch level frequency distributions were strongly right skewed, and standard transformations including log-transforms did not succeed in converting these into normal distributions. Table IV summarizes statistics of patch spatial pattern for the 24 ecotope types mapped. Median values of patch area, patch shape and nearest neighbor distance were reported, and the variation described by the range between first and third quartiles of distribution. Median values do not differ much between ecotope types, although variation in patch area is very high, with the range between the first and third quartiles often equal to or greater in magnitude than the median value (Table IV). Variation in patch shape statistics is somewhat less, and the difference in magnitude between the first and third quartiles of distribution ranged between one-third to two-third of the median value, while the variation in nearest neighbor distance values was again high, and often equal to or greater in magnitude than the median value (Table IV).

A Mann-Whitney U test (Sokal and Rohlf, 1981) was carried out to test whether ecotope types from within a given landscape differed significantly in patch characteristics. No consistent distinctions in ecotope types could be made based on patch area, patch shape index or nearest neighbor distance: differences observed varied from landscape to landscape, and even within a landscape, based on which statistic of patch pattern was used. When data for all ecotope patches of a given type was pooled across landscapes for analysis, no consistent and significant ranking or differences were found between ecotope types based on patch area, patch shape and

TABLE III

For thirteen landscapes, the ecoregion type, latitude, longitude, altitude and average annual rainfall: as well as the area, number of ecotope types, accuracy of supervised classification, and landscape statistics of median patch size (MPS), median patch shape (MSI), median nearest neighbor distance (MNN), Shannon's diversity index (SHDI), and the interspersion-juxtaposition index (IJI), are reported

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ecoregion type | 5 | 10 | 7 | 8 | 7 | 9 | 7 | 7 | 7 | 7 | 7 | 8 | 9 |
| Latitude (°N) | 18° 20'–23' | 14° 32'–34' | 14° 25'–27' | 14° 16'–19' | 13° 39'–41' | 13° 28'–30' | 12° 58'–13°01' | 12° 39'–42' | 11° 27'–29' | 10° 54'–56' | 10° 52'–54' | 10° 07'–09' | 8° 39'–41' |
| Longitude (°E) | 72° 53'–55' | 74° 48'–50' | 74° 33'–35' | 74° 52'–54' | 75° 27'–29' | 74° 59'–75°01' | 75° 28'–31' | 75° 36'–38' | 75° 27'–29' | 76° 34'–36' | 76° 36'–38' | 76° 41'–43' | 77° 08'–10' |
| Altitude (meters above sea level) | 280 – 320 | 160 – 597 | 20 – 299 | 400 – 600 | 620 – 1049 | 60 – 126 | 1212 – 1456 | 123 – 369 | 400 – 882 | 300 – 1100 | 200 – 1099 | 100 – 488 | 300 – 1091 |
| Avg. annual rainfall (mm) | 4000 | 2500 | 3500 | 3000 | 3000 | 4000 | 3000 | 4000 | 4000 | 4000 | 2000 | 3000 | 2500 |
| Area (km²) | 12 | 54 | 31 | 28 | 9 | 29 | 39 | 30 | 17 | 20 | 14 | 32 | 14 |
| Number of ecotope types | 8 | 8 | 7 | 7 | 7 | 5 | 9 | 8 | 7 | 7 | 9 | 8 | 8 |
| % accuracy supervised | 91.7 | 91.5 | 86.5 | 89 | 88.5 | 70.3 | 88.8 | 85.5 | 82.1 | 83.3 | 84.6 | 70.8 | 80.7 |
| MPS (ha) | 2628 | 2628 | 2628 | 2628 | 2628 | 2628 | 2628 | 2628 | 2628 | 2628 | 2628 | 2628 | 2628 |
| MSI | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 |
| MNN (m) | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 |
| SHDI | 1.90 | 1.85 | 1.61 | 1.62 | 1.77 | 1.52 | 1.83 | 1.95 | 1.63 | 1.73 | 1.85 | 1.96 | 1.90 |
| IJI | 83.6 | 78.8 | 71.0 | 78.8 | 81.4 | 81.3 | 80.4 | 76.5 | 76.6 | 79.2 | 79.4 | 84.5 | 83.0 |

TABLE IV

For 24 ecotope types in 13 mapped landscapes, the median patch area, patch shape and nearest neighbor distance, and the variation or difference between the first and third quartiles is reported. Frequency of occurrence describes the number of landscapes in which an ecotope was encountered. Landscape metrics are described in the Methods Section

| Ecotope | Patch area in ha | Patch shape index | Nearest neighbor distance | Frequency occurrence |
|---|---|---|---|---|
| | | (median and quartile range) | | (in 13 landscapes) |
| Evergreen | 2628 | 1.06 | 36 | 7 |
| forest | 1314–5256 | 1.00–1.41 | 36–72 | |
| Sec. evergreen | 2628 | 1.06 | 36 | 6 |
| forest | 1314–2628 | 1.00–1.06 | 36–36 | |
| Semi-evergreen | 2628 | 1.06 | 36 | 9 |
| forest | 1314–6570 | 1.00–1.44 | 36–72 | |
| Sec. Semi- | 2628 | 1.06 | 36 | 2 |
| evergreen forest | 1314–5256 | 1.00–1.43 | 36–72 | |
| Moist deciduous | 2628 | 1.06 | 36 | 6 |
| forest | 1314–5256 | 1.00–1.41 | 36–72 | |
| Sec. moist | 2628 | 1.06 | 36 | 3 |
| deciduous forest | 1314–5256 | 1.00–1.41 | 36–72 | |
| Woodland | 2628 | 1.06 | 36 | 5 |
| | 1314–5256 | 1.00–1.44 | 36–51 | |
| Savanna | 2628 | 1.06 | 36 | 6 |
| | 1314–5256 | 1.00–1.41 | 36–72 | |
| Thicket | 2628 | 1.06 | 51 | 1 |
| | 1314–5256 | 1.00–1.41 | 36–108 | |
| Scrub | 2628 | 1.06 | 36 | 2 |
| | 1314–5256 | 1.00–1.41 | 36–51 | |
| Grassland | 2628 | 1.06 | 36 | 10 |
| | 1314–5256 | 1.00–1.41 | 36–81 | |
| Acacia plantation | 1314 | 1.00 | 81 | 2 |
| | 1314–3942 | 1.00–1.34 | 51–149 | |
| Areca plantation | 2628 | 1.00 | 36 | 5 |
| | 1314–6570 | 1.00–1.41 | 36–72 | |
| Areca/Coconut | 1314 | 1.00 | 36 | 1 |
| mixed plantation | 1314-2628 | 1.00–1.41 | 36–72 | |
| Banana plantation | 2628 | 1.06 | 36 | 1 |
| | 1314–7884 | 1.00–1.44 | 36–72 | |
| Casuarina | 2628 | 1.15 | 36 | 2 |
| plantation | 1314–7884 | 1.00–1.57 | 36–81 | |

TABLE IV
*(continued)*

| Ecotope | Patch area type in ha (mean ± s.d.) | Patch shape index (mean ± s.d.) | Nearest neighbor distance (mean ± s.d) | Frequency occurrence (in 13 landscapes) |
|---|---|---|---|---|
| Coconut plantation | 2628 | 1.00 | 36 | 4 |
| | 1314–5256 | 1.00–1.20 | 36–72 | |
| Eucalyptus plantation | 1314 | 1.00 | 36 | 2 |
| | 1314–3942 | 1.00–1.25 | 36–51 | |
| Rubber plantation | 2628 | 1.06 | 36 | 4 |
| | 1314–3942 | 1.00–1.15 | 36–81 | |
| Tea plantation | 1314 | 1.00 | 36 | 1 |
| | 1314–6570 | 1.00–1.34 | 36–51 | |
| Teak plantation | 2628 | 1.06 | 36 | 4 |
| | 1314–5256 | 1.00–1.41 | 36–72 | |
| Paddy field | 2628 | 1.06 | 36 | 8 |
| | 1314–6570 | 1.00–1.44 | 36–72 | |
| Rocky outcrops | 2628 | 1.06 | 51 | 3 |
| | 1314–6570 | 1.00–1.41 | 36–109 | |
| Water | 2628 | 1.06 | 51 | 4 |
| | 1314–5256 | 1.00–1.41 | 36–81 | |

inter patch distance ($p = 0.05$). The extensive within-ecotope type variation in patch statistics that exists from landscape to landscape thus obscures any between-type differences that might exist across different landscapes.

## 5. Conclusions

This article analyzes the distribution in landscape composition and spatial pattern at two spatial scales within the Western Ghats, to help devise a strategy for monitoring changes in land cover and biodiversity within the region. We observe landscapes to be more fragmented in the relatively dry north, known to have lower plant biodiversity, and less fragmented with larger patch sizes in the moist south, known to have great plant biodiversity (Subramanyam and Nayar, 1974). We also find differences in NDVI and landscape pattern between eastern and western flanks, with the moister western slopes that are known to have higher levels of plant biodiversity (Nair and Daniel, 1986) being less fragmented than the eastern slopes. At the eco-region scale, therefore, we find a relationship between climatic gradients in rainfall, previously known to modulate gradients in plant diversity, and landscape fragment-

ation. High rainfall appears to be correlated with increased plant diversity, greater NDVI and lower levels of landscape fragmentation, with the converse holding true.

Preliminary statistical explorations using a Monte Carlo simulation, suggested that the landscapes belonging to the same ecoregion cover type have greater similarity in landscape pattern when compared to landscapes belonging to different types (Nagendra and Gadgil, 1999b). While thirteen landscapes is not a large enough sample size for rigorous statistical tests, this is a strong indicator of a hierarchical linkage between the ecoregion and the landscape level of investigation. At the detailed, landscape scale, we find no significant north-south or east-west trends in landscape pattern, high levels of within ecotope type variation in patch statistics, and no consistent between ecotope type differences in patch statistics. This high local variability in ecotope pattern can be ascribed to the predominant effect of local-scale, historical and human-influenced drivers of landscape change, which can create highly local variations in landscape pattern and may obscure large-scale gradients in patch pattern at this scale.

Several studies of landscape structure have paid especial emphasis to enumerating pattern at the patch level. Although it is widely recognized that commonly computed statistics of patch pattern such as area and shape tend to be skewed and deviate significantly from normal distributions (Forman, 1995; McGarigal and Marks, 1994), commonly used software including GRASS r.le, FRAGSTATS and ArcInfo Patch Analyst still summarize and report average measures of patch structure at the landscape level, which indeed continue to be widely reported (see for example Tang and Gustafson, 1997; Hietala-Koivu, 1999; Peralta and Mather, 2000; Ochoa-Gaona and Gonzalez-Espinosa, 2000; Zomer and Ustin, 2000). Our results demonstrate the need for caution in interpreting averages of patch statistics for highly skewed, non-standard distributions such as we observed. If, as in our landscapes, the variation is of the same order of magnitude as the mean or even larger, then parametric patch statistics such as mean and standard deviation may only be of limited use in demonstrating differences between landscapes, and it is advisable to utilize nonparametric measures.

We use the information obtained at our two spatial scales of analysis, to develop a hierarchical stratified approach for monitoring land cover change in the Western Ghats (Figure 1). Previous studies have demonstrated that landscapes belonging to different ecoregion types differ significantly in spatial pattern (Nagendra and Gadgil, 1999b). The ecoregion scale map can therefore be used as a basis for designing a program of field sampling. Study landscapes of 10–100 km$^2$ can be located within different ecoregion types, so as to cover the range of variability in ecoregion types from north to south, and east to west. These landscapes can then be mapped at a further detailed scale into ecotope types. This process of hierarchical sampling of landscapes within ecoregions, and quadrats within ecotopes, combined with a repeated mapping of these sample landscapes over time, will allow a systematic assessment of spatial patterns of land cover across the Western Ghats. If linked with accounts of species distributions within ecotope types (such as Bhatta, 1997;

Pramod *et al.*, 1997), this approach can provide valuable inputs for biodiversity assessment and monitoring (Nagendra and Gadgil, 1999a; Nagendra, 2001).

The driest regions fall in the north-eastern zones of the Western Ghats, and our analysis shows these areas to be the most fragmented. They therefore need to be given high priority, with detailed field studies conducted in the region to determine the effect of this high level of landscape fragmentation and decreased landscape diversity on biodiversity distribution (Nagendra and Gadgil, 1999b). Another anomalous region in need of attention is the east-central sub-region (sub-region 4) which has the least landscape fragmentation, with larger and more complex patches, compared to both northern and southern ends, and clearly deserves further attention.

The information gained, on spatial location, association and fragmentation of landscape spatial pattern, can be used to derive greater insight into patterns of land cover and land use in the region, guide focused strategies of land cover change monitoring, and assist in the formulation of informed land management strategies (Verburg and Chen, 2000; Southworth *et al.*, 2002). Our results provide us with identification of location and distribution, as well as spatial information that can be used as more complex inputs into environmental sampling and monitoring of land cover change: a focus of major concern for global change research (NRC, 1999; Lambin *et al.*, 2001).

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