

The progress on remote sensing technology in identifying tropical forest degradation: a synthesis of the present knowledge and future perspectives

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Abstract Since the launch of the first satellite in 1972, ecologists have been equipped with new tools to address the degradation of tropical forests, previously limited by field-based methods. This article is a review of the state of remote sensing technology in characterizing the degradation of tropical forest. The factors responsible for the structural and functional degradation of the tropical forest and its likely impacts are described in view of generating remote sensing based inputs. In order to assess the degradation and utility of geo-informatics tools, 32 parameters are identified. The research developments at different levels of information extraction from the historic to recent periods are elaborated, and future challenges are predicted. The article concludes that an additional momentum of research is required to answer many unresolved questions of tropical forest degradation.

Keywords Remote sensing · Tropical forest · Degradation · Scale · Multispectral · Hyperspectral

Introduction

Tropical forest ecosystems are highly complex systems that play a significant role in regularizing and stabilizing the climate, biogeochemical cycles, and biological diversity. They contain ~25% of the carbon in the terrestrial biosphere (Bonan 2008), account for ~33% of terrestrial net primary production (NPP) (Sabine et al. 2004) and can sequester large amounts of carbon annually (approximately 400 g C/m²/year) (Luyssaert et al. 2007). Tropical forests also act as reservoirs of biodiversity, contain more than half of all plant and animal species, even though their area is only 7% of the total land mass (Groombridge 2000). As a result, 18 of the world's 25 biodiversity hotspots owe their status to tropical forests (Myers et al. 2000).

The stability of forest systems which has evolved in geologic time scale is being seriously threatened today (Chapin et al. 2000). The physical, chemical and biological environments of tropical trees have been altered considerably over the recent decades (Lewis et al. 2004). There are several reports that current degradation may be irreversible in tropical forests (Brook et al. 2003; Lamb et al. 2005; Diaz et al. 2006; Miles et al. 2006 and Anitha et al. 2009). Food and Agricultural Organization (2002) defines this degradation as 'changes within the vegetation which negatively affect the structure or function of the stand and site, and thereby lower the capacity to supply products and/or services'. Such a tropical forest may have lost its structure, species composition or productivity normally associated with the natural forest type expected at that site (Convention on Biological Diversity 2002). International Tropical

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Timber Organization (2002) estimated that 500 million hectares of primary and secondary tropical forests have been degraded, and 350 million hectares have been deforested.

The loss of tropical forests is partially due to a lack of knowledge on their structure and function. Demographic, economic, technological, cultural, political and institutional factors also contribute to tropical forest degradation in a significant manner (Geist and Lambin 2002 and Lambin et al. 2003). In addition to these, globalization in combination with national debt in developing countries of tropical region is a major factor driving deforestation (Bawa and Dayanandan 1997 and Rudel 2006). The major forces driving tropical forest degradation can be broadly categorized into two groups, viz., proximate and underlying causes. Proximate causes refer to activities that directly result in a transformation of land use/cover, while underlying causes indicate the driving forces that give rise to the proximate actions affecting landscape change. A centroid model which relates proximate and underlying causes to vegetation degradation is depicted in Fig. 1. In this model, underlying causes exert pressure on the proximate causes to drive forest degradation. The proximate causes could be infrastructural development, livelihood dependence, agricultural expansion and extraction of timber and non-timber forest products, and the underlying causes could be demographic, economic and policy factors.

The adverse impacts of degradation vary depending on the intensity, magnitude and severity of the degradation. It includes the changes in functional attributes (impairment of

primary productivity, reduced light and water use efficiencies) and structural attributes (prevalence of self- or wind-pollinated species in the community, increases in non-native species or exotics, altered community dominance favouring ‘r’-selected species, and increased instability in component populations) (Wardle et al. 2004; Biesmeijer et al. 2006; Diaz et al. 2006; Anitha et al. 2007 and 2010; Bonan 2008). On a landscape scale, the impacts can be seen as vegetation cover loss, density changes and vegetation-type transitions (Lambin 1999; Chambers et al. 2007 and Joseph 2008).

Geoinformatics: state-of-the-art technology

Technological innovations in recent times have given a new dimension for understanding the ecological problems of the earth. A system of geospatial technologies has been developed, which is the combination of remote sensing, geographical information systems (GIS), global positioning systems (GPS) and spatial modelling which are found to be effective tools in offering solutions to many problems related to forest degradation. The improvements accomplished in spatial, spectral, temporal and radiometric resolutions of remote sensing data over the past few decades have kept pace with the information needs for the management of forests. The GIS software packages have also been developed rapidly to accommodate large data files and, therefore, larger data on geographical areas, multiple spatial and non-spatial data integration and analysis, and the incorporation of complex geo-statistical tools. With all these developments, the role geoinformatics in assessing and monitoring the landscape turn out to be more effective, scientific, realistic and economical than conventional tools. Also, it has opened up new ways of analysing and monitoring biodiversity at various gradients and in studying the ecological niches of species and population for developing strategies for conservation (Murthy et al. 2003, 2006; Varghese and Murthy 2006).

The conventional image-centred approach (analysing the image based on colour, texture, tone and shape) is slowly being transitioned to a data-centred approach (direct measurement of properties of objects based on its reflectance in the EMR spectrum). The spectral response or some kind of derivative like a vegetation index derived in the first approach and its empirical correlation with field observations is highly affected by the sensor characteristics (spectral bands used for the observation, spatial resolution of the sensor etc.) and by multiple boundary conditions such as time of day and year, actual state variables of the ecosystem components and the atmosphere (Darvishzadeh et al. 2008). The second and to some extent more physical approach involves the application of (inverse) radiative

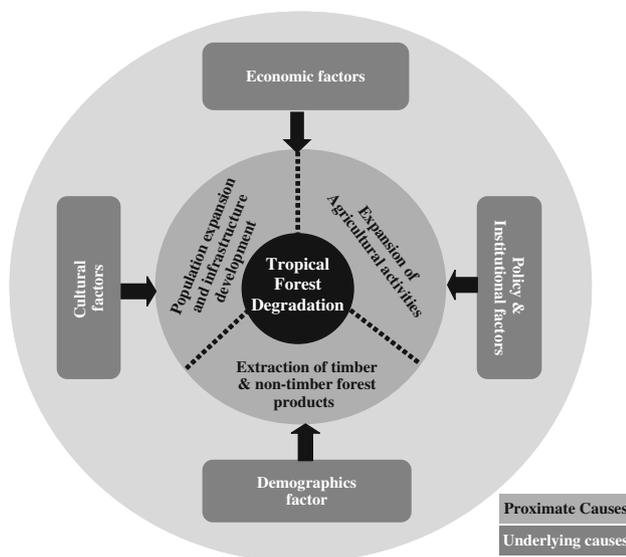


Fig. 1 Centroid model depicting the causes and driving forces of forest degradation. In the model, driving forces such as demographic, cultural, economical and policy factors exert pressure on proximate causes to drive the degradation

transfer models. These models accurately describe the spectral characteristics of the canopy though there are many potential error sources which could be partially attributed to the recent origin of the modelling concepts (Baret et al. 2007; Jacquemoud et al. 2009). Neglecting atmospheric influences, the sensor signal can be modelled as a function of the sensor characteristics and sampling conditions, the physical canopy properties (e.g. leaf density and crown dimensions), the biochemical plant properties (e.g. photosynthetic physiology) and the properties of the local, regional and global scales.

The present day applications of remote sensing data vary from biome level classification to molecular assessment of individual species. A conceptual diagram depicting the application of multispectral to ultraspectral data sets in vegetation assessment with respect to their technical complexity of processing is given in Fig. 2. At present, the maximum resolution which could be achieved in practical terms is given in Table 1 with suitable examples of sensors and applications.

These developments have considerably increased the ability of ecologists to address tropical forest degradation more efficiently. Table 2 details 32 parameters in the forest degradation assessment and the role of geoinformatics tools in addressing these components. Based on the scale of application, the parameters are divided into two, viz., as coarse- and medium-scale assessments, and as fine-scale assessment. Each category is further subdivided into two: change in structural and functional properties, and causes of changes. While most of the parameters could be assessed using remote sensing sensors, some of them need GPS-based ground survey.

One of the most widely used applications of remote sensing sensors may be the deforestation assessment and monitoring. The other major applications include fragmentation analysis, neighbourhood and functional impairment assessments (for example, change in primary

productivity). A suite of remote sensing platforms having various resolutions are available to generate spatial information on such parameters (Table 3). New sensors and satellites are expanding the scope of such observations. Though remote sensing-based assessment has increased dramatically in recent years, it has limited application in the assessment of certain parameters such as species richness, diversity and density.

Coarse resolution remote sensing instruments and their applications

Coarse scale satellite images have been widely used for mapping and monitoring global land cover change (Gutman and Ignatov 1995, Friedl et al. 2002; Hansen et al. 2008), estimating geophysical and biophysical characteristics (Huete et al. 2002, Fensholt et al. 2003, Drolet et al. 2005, Anaya et al. 2009) and monitoring continental-scale climate shift (White et al. 2000, Nemani et al. 2003, Turner et al. 2005, Miles et al. 2006). The most widely used sensors are AVHRR (Advances Very High Resolution Radiometer), MODIS (Moderate Resolution Imaging Spectroradiometer) and SPOT VEGETATION. These sensors provide consistent spatial and temporal comparisons of vegetation conditions at both the global and regional levels. A range of operational monitoring programs have been implemented to understand tropical deforestation and assess its drivers based on these sensors. Notable programs include NASA’s Landsat Pathfinder Project on Deforestation in the Humid Tropics (Townshend et al. 1995; Kalluri et al. 2001) and the TREES (Tropical Ecosystem Environment Observations by Satellite) project (Stibig and Achard 2003). Most recent program of this series is launched by Brazil’s National Institute for Space Research (INPE), named ‘DETER: Real-time Deforestation Monitoring’ which provides 15-day alerts on newly deforested large areas in Amazonia (Gilberto Camara, *Personal communication*). These programs demonstrated that satellite remote sensing can provide satisfactory results for forest cover mapping and for obtaining rough but up-to-date estimates of the forest cover change within a region. NASA’s MODIS team have developed a series of land products including calibrated surface reflectance, land surface temperature, thermal anomalies, albedo, vegetation indices, leaf area index, carbon sequestration, and land cover type and changes (Justice et al. 2002), all of which are potentially useful to researchers interested in mapping and monitoring tropical deforestation. (all the Algorithm Theoretical Basis Documents (ATBD’s) are available at http://modis.gsfc.nasa.gov/data/atbd/land_atbd.php).

One of the most widely used applications of these high temporal resolution data is the detection of forest fire and

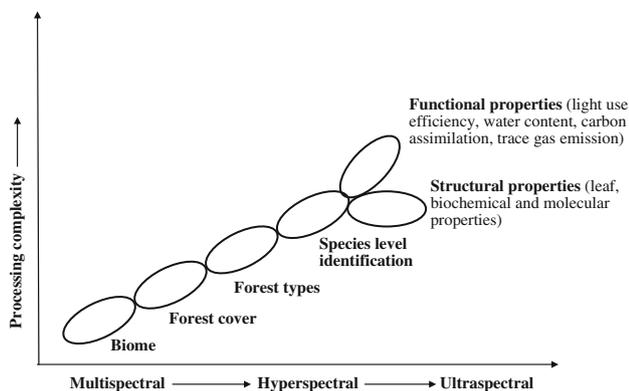


Fig. 2 A conceptual diagram showing the application of multispectral to ultraspectral remote sensing technique for vegetation assessment

Table 1 The maximum possible resolution which can be achieved by different types of sensors at present

Sensor type	Max. spatial resolution	Max. spectral resolution	No. of bands	Example of sensor
Panchromatic	0.65 m	~ 300 nm	1	Quickbird
Multispectral	2.4 m	~ 100 nm	4	Quickbird
Space borne hyperspectral	30 m	2–5 nm	220	Hyperion
Airborne hyperspectral	1.2 m	2–4 nm	288	CASI
Ultraspectral	30 km	0.2–0.3 nm	8000	SCIAMACHY

fire scars (Crutzen and Andreae 1990; Penner et al. 1992; Cochrane 2003, Kiran Chand et al. 2006; Schmerbeck and Seeland 2007). Earth-observing satellite sensors have been used since the 1970s to detect forest fire, quantify the burnt areas and to determine the composition and distribution of by-products after the fire (see the reviews by Robinson (1991), Fuller (2000) and Joseph et al. (2009a)). Now, operational fire monitoring using remote sensing data has become a standard activity of many governments and international agencies. MODIS Rapid Response System Global Fire Maps, GLOBSCAR, European Forest Fire Information System, WEB FIRE MAPPER, GOF/GOLD Fire Monitoring and Mapping Implementation Team, Canadian Wildland Fire Information System and Indian Forest Fire Response and Assessment System (INFFRAS) are some examples.

The use of coarse scale remote sensing sensors in assessing the other structural and functional changes of tropical forest might not have picked up largely in comparison with temperate forest; and the few efforts that was made in the tropics were mostly concentrated on the Neotropics with very little in the Old world tropics. Using AVHRR NDVI data, Vina and Henebry (2005) quantified the impacts of El Nino/Southern Oscillation (ENSO) events on phenological cycles of tropical vegetation in South America. Ewers and Laurence (2006) used fractal dimension as a landscape index to examine the area—perimeter ratio of deforested areas in the Amazon rainforest. Secondary forests have been identified by using time series of SPOT-4 VEGETATION (Carreiras et al. 2006) and MODIS (Braswell et al. 2003). Ensuing habitat loss and degradation impair ecosystem function (Defries 1999) and reduce the value of ecosystem services for humans (Daily 1997). A combination of AVHRR, Landsat TM and radar data was used to detect the impact of deforestation on the burn likelihood of forests in East Kalimantan, Indonesia (Siegert and Boehm 2001).

Recently, scientific community understands the importance of frequent repeat measurements using coarse resolution data much more than before in context of global change research, albeit of its limited capacity in characterizing the site-specific attributes (Goetz et al. 2009). For example, previous studies that link Above Ground Biomass

(AGB) measurements from the field to satellite observations, based on sensitivity of the optical reflectance to variations in canopy structure, have not proven to be consistent over large areas because surface conditions may change more rapidly than the repeat time of the cloud-free satellite observations, producing artefacts in the derived maps. This drawback has been overcome using frequent repeat measurements from sensors such as the MODIS onboard the AQUA and TERRA satellites across all of Africa (Williams et al. 2007; Baccini et al. 2008) and Amazon basin (Saatchi et al. 2007).

Medium resolution remote sensing instruments and their applications

A major limitation of coarse scale outputs is that each pixel is generally labelled as single cover class, whereas high-resolution observations suggest that such pixels are likely to contain complex mixtures of different cover types. In a classical example, Jin and Sader (2005) illustrated that deforested areas were not detected in the MODIS and VEGETATION data for patches of less than 20-ha size. Another study found that changes due to fire could be accurately detected but only when burned areas were at least 10 km² (Fraser et al. 2003). Medium resolution imagery offer satisfactory solutions to overcome such problems. At the national and regional levels, Landsat, IRS (Indian Remote Sensing) and SPOT-HRVIR can provide better information on forest cover loss, forest type transitions, stand density changes and their causes of change (see the case studies by Ingram et al. 2005; Peres et al. 2006; Joseph 2008, 2009b). Recent research has demonstrated relationships between deforestation and fragmentation rates due to human activities (Trigg et al. 2006). The encroachment and shifting cultivation have been monitored successfully worldwide. Landsat TM and ETM+ data have been used for detection and mapping of logging roads and burn scars, which serve as indicators of forest exploitation in the near future or recent past (Dennis and Colfer 2006).

In one of the more recent reviews in landscape ecology, Newton et al. (2009) pointed out that the Landsat satellite sensor images (i.e. MSS, TM, ETM+ etc.) contribute 42%

Table 2 Different parameters in forest degradation assessment and the role of geoinformatics tools in assessing those parameters

No	Degradation assessment parameters	Remote sensing	Ground measurement using GPS	GIS/geostatistics (integration of field data with spatial data)
A. Coarse and medium scale assessment				
<i>i. Structural and functional change</i>				
1	Deforestation (Vegetation Cover Conversion)	✓		✓
2	Phenological change	✓		✓
3	Crown Density Change	✓		✓
4	Fragmentation	✓		✓
5	Gap Area and Frequency	✓		✓
6	Patch Size and Shape	✓		✓
7	Neighbourhood	✓		✓
8	Core–edge ratio	✓		✓
9	Secondary Formations	✓		✓
10	Greenness Change	✓		✓
11	Net Photosynthesis and Primary Productivity	✓		✓
12	Evapotranspiration	✓		✓
<i>ii. Causes of changes</i>				
13	Encroachment/Clearances	✓	✓	✓
14	Shifting cultivation	✓	✓	✓
15	Forest Fire	✓		✓
B. Fine Scale Assessment				
<i>i. Structural and functional change</i>				
16	Vertical Structure	✓	✓	✓
17	Community/Assemblages	✓	✓	✓
18	Species Richness		✓	✓
19	Density		✓	✓
20	Diversity		✓	✓
21	Dominance		✓	✓
22	Age structure		✓	✓
23	Leaf and Molecular Properties	✓		✓
24	Health of the Forest (Diseases and nutrient deficiency)	✓		✓
25	Canopy water content	✓		✓
26	Canopy light use efficiency	✓		✓
<i>ii. Causes of change</i>				
27	Logging/Selective Felling	✓	✓	✓
28	Infrastructure development	✓	✓	✓
29	Grazing		✓	✓
30	NTFP resources extraction		✓	✓
31	Dispersal failure		✓	✓
32	Absence of Pollinators		✓	✓

For further details, please refer Asner and Martin (2009); Asner and Vitousek (2005) Chambers et al. (2007); Ghiyamat and Shafri (2010); Joseph et al. (2009a); Murthy et al. (2003, 2006); Peres et al. (2006); Townsend et al. (2008); Varghese and Murthy (2006)

of the studies on spatial patterns and its relationships to ecological processes. Imagery acquired by sensors on board other satellite series were employed by a small minority of studies, namely SPOT (e.g. HRV, RG) (3%), NOAA (AVHRR) (4%), IRS (LISS) (1%), Ikonos (1%) and QuickBird (0.5%). 2% of studies employed multiple

sources of remote sensing data (i.e. more than two). The study pointed out that remote sensing-based mapping of landscape pattern or spatial structure are essential to understand the landscape dynamics and prioritize conservation actions. Using Landsat ETM+ data, Broadbent et al. (2008) calculate that 53% of the 1.1 million km² Brazilian

Table 3 Potential remote sensing sensors for the assessment of forest degradation at different levels

Level/scale	Sensors	Spatial resolution (m)	Spectral resolution	Temporal frequency
Coarse scale assessment	MODIS	250–1000 m	36 bands	1–2 days
	NOAA-AVHRR	1000 m	6 bands	1–2 days
	IRS WiFS	188 m	2 bands	5 days
	ERS	15–1000 m	1 band (C)	35 days
	ENVISAT	30–1200 m	1 band (C)	35 days
Medium scale assessment	LANDSAT TM/ETM+	30 m	7 bands	16 days
	LANDSAT MSS	75 m	4 bands	14 days
	IRS AWiFS	56 m	4 bands	5 days
	IRS LISS-III	23.5 m	4 bands	5 days
	SPOT MSS	20 m	4 bands	26 days
	ASTER	15–90 m	14 bands	4–16 days
	HYPERION	30 m	220 bands	16 days
	CASI	4–20 m	288 bands	User defined
	AVIRIS	20 m	220 bands	User defined
	ERS	15–1000 m	1 band (C)	35 days
	JERS	18 m	1 band (L)	44 days
	ENVISAT	30–1200 m	1 band (C)	35 days
	RADARSAT	8–100	1 band (C)	24 days
	ALOS	10–100 m	1 band (L)	46 days
Fine scale assessment	IKONOS PAN	1 m	1 band	3–5 days
	IKONOS MS	4 m	4 bands	3–5 days
	Quickbird PAN	60 cm	1 band	1–4 days
	Quickbird MS	2.4–2.8 m	3 bands	1–4 days
	ASTER	15–90 m	14 bands	4–16 days
	CASI	4–20 m	288 bands	User defined
	HyMap	2–10 m	128 bands	User defined
	AVIRIS	20 m	220 bands	User defined
	Cartosat PAN	1.0–2.5 m	1 band	5 days
	IRS LISS-IV	5.8 m	3 bands	5 days
	DLR-ESAR	4 m	4 bands	User defined

forests are within 2 km, and ~37% are within 1 km of a forest edge. Moreover, 6.4% of all the remaining forests are within 100 m of a forest edge, a distance to undergo extensive edge impacts.

A usual criticism about the application of optical imaging data is that it cannot penetrate clouds, which persist over many parts of the tropics during the wet season and, indeed, throughout the year in many tropical upland and montane environments (Trigg et al. 2006). Researchers have therefore turned increasingly to cloud-penetrating radar imagery provided by such satellite platforms as the Japanese Earth Resources Satellite (JERS-1) and the European Remote Sensing Satellite (ERS) as alternatives to study tropical forest cover. Sgrenzaroli et al. (2002) and Podest and Saatchi (2002) reported acceptable forest classification accuracies and thus recommend synthetic aperture radar (SAR) imagery for upscaling deforestation estimates to the continental scale due to its all-weather

capability. The potential of microwave energy to penetrate through smoke and clouds have been utilized for mapping fire, fire scars and tree damage (French et al. 1999; Couturier et al. 2001; Cochrane 2003). Research and theoretical modelling have shown that the C-band data from SAR satellite sensors with steep incidence angles have the potential to be used in conjunction with TM data for high-accuracy mapping and fire scar monitoring (Bourgeau-Chavez et al. 2002).

Fine resolution remote sensing instruments and their applications

The advent of very-high-resolution multispectral as well as panchromatic imagery appears particularly promising as a source of information for assessing the various aspects of forest degradation. The revolution began with the launch of

IKONOS with 1-m resolution in panchromatic and 4 m in multispectral in 1999. Since then, a number of agencies have launched their own sensors, notably Quickbird, WorldView and Cartosat, and now they have become commercially available for the users. A number of studies have proven that high-resolution satellite imagery is effective in measuring tree crown sizes, detecting tree mortality, delineating invasive species, estimating the effects of selective logging and distinguishing secondary forests from old growth (Asner et al. 2002; Read et al. 2003; Clark et al. 2004, 2005; Ouma et al. 2008). These data sets have also been shown to be correlated with key forest structural parameters such as plot biomass, basal area and total gap area (Malhi and Román-Cuesta 2008). These studies using GIS platforms have yielded valuable insights into the assessment of the rate of succession, drivers of land cover change, dynamism at ecotones, invasion of weeds and the effects of ownership on land cover change. However, a word of caution is that there are practical difficulties to classify these very-high-resolution images on a pixel-by-pixel basis due to the high level of information captured by these images (Puissant et al. 2005; Yu et al. 2006; Ouma et al. 2008).

The advance in solid-state technology and the division of multispectral to hyperspectral is a promising step forward in analysing vegetation degradation. Acquired in narrow bands, as many as 200 or more, hyperspectral imageries are able to provide even the molecular properties of an object. Also, this hyperspectral data are excellent in identifying the different groups and can detect very subtle changes of an object over time. Given sufficient spatial resolution and sensor performance, hyperspectral data have shown a much higher accuracy than multispectral datasets (van Wagtenonk et al. 2004). Thenkabail et al. (2004) evaluated four sensors—Hyperion, IKONOS, ALI (Advanced Land Imager) and ETM+ for classifying complex moist forest vegetation and found that the performance of Hyperion was the best. Although the first airborne hyperspectral sensor (AVIRIS) was invented in 1989, research did not gain momentum until the launch of the space-borne Hyperion sensor in 2001. Thereafter, a number of studies using different sensors such as CASI, Hymap and modified version of AVIRIS have been conducted to identify tropical tree species, mapping of invasive species and assessing the changes in forest conditions (Clark et al. 2005; Jia et al. 2006; Kokaly et al. 2007).

Asner and Vitousek (2005) combined AVIRIS measures and photon transport modeling to map non-native tree *Myrica faya* and Himalayan understory herb *Hedychium gardnerianum* across a Hawaiian montane rain forest landscape. Asner et al. (2008) further studied the uniqueness of hyperspectral signatures of 43 Hawaiian native and invasive trees and concluded that it is possible to utilize the full AVIRIS spectrum to differentiate Hawaiian tree

groups, which they exercised in a subsequent operational mapping study (Asner et al. 2008). Clark et al. (2005) used high spectral and spatial resolution imagery acquired over tropical rain forest canopy of La Selva biological station for automated discrimination of individual tree species. In addition to these, most of the other studies were based on the spectra of leaves or branches alone (Ghiyammat and Shafri 2010). For example, Cochrane (2000) demonstrated the potential for separation of different tropical species based on the foliage reflectance (450–950 nm) of 11 species in southern Pará, Brazil.

The assessment of nutrient deficiency and the health status of forests may be one of the well-established uses of hyperspectral imaging (Goetz and Prince 1996, Asner 1998, Curran 2001, Sims and Gamon 2002; Ustin et al. 2004; Asner and Martin 2008, 2009). Reduced photosynthetic activity due to environmental stress can be detected using narrow band hyperspectral instruments (Moya et al. 2004, Grace et al. 2007). Several leaf-level spectral reflectance studies have demonstrated that hyperspectral bands can be useful for the detection of foliar characteristics such as chlorophyll, nitrogen, phosphorous, carotenoids and water content (Chambers et al. 2007; Townsend et al. 2008; Asner and Martin 2008). Asner (1998) have shown through end member and modelling methods that it is possible to map forest regrowth, new logging, primary forest, and underlying surface litter and slash in the Amazon forests. They concluded that by combining canopy reflectance models and hyperspectral data, hyperspectral remote sensing also helps to retrieve forest canopy parameters, including canopy closure, leaf area index (LAI), or stand density. However, it is important to recognize that a large of amount research is still required to incorporate these data sets into an operational monitoring system.

Future directions

In order to study vegetation degradation and to answer questions about the relationships between the pattern and processes of vegetation degradation, we need to be able to detect pattern reliably and to quantify its characteristics as an input to process models. The complexity of ecological systems is beyond our capacity to comprehend and ability for the technological tools can assess. At the same time, the present day problems are four-dimensional (x, y, z, t) in nature. Quantitative description of three-dimensional patterns of vegetation and its changes in response to time is therefore an important component in assessing vegetation degradation. Even without complete knowledge about technological specifications, we can speculate about new methods that could be developed to deal with the four-dimensional analysis of vegetation.

Fractal geometry is an attractive approach (Dale 1999). The utilization of microwave data in deriving the fractal geometry of vegetation structure would be a topic of interest in the future. The use of LIDAR in vertical analysis of vegetation and its integration with optical fine spatial resolution data could also produce comparable fractal geometry. Once we are able to develop fractal geometry of vegetation based on remote sensing data of different time series, it would be possible to compare it by importing wavelet technique-based analysis. The advantage of the wavelet approach is that different wavelet templates (the sequence of waves with regard to frequency and position) can examine the data for different shapes of spatial pattern, thus providing a fuller evaluation of its characteristics in different time periods.

The implementation of hyperspectral data in operational monitoring of forest conditions may be another approach. As the uncertainties in data analysis and knowledge extraction associated with hyperspectral data are still a challenging task to the scientific community, there are number of factors needed to be overcome to implement this in practical sense. The process of development of new classification algorithms, radiative transfer models, canopy reflectance models and data mining techniques is still being improved. The interface between spectroscopy and hyperspectral remote sensing may get more attention in the near future. The integration of spectroscopy methods into these techniques needs further investigation. Coupling of Infrared spectroscopy and NMR (nuclear magnetic resonance) could be useful for explaining the molecular properties and reflectance of leaves. For example, red edge shift could be correlated with chemical shift.

Fusion of hyperspectral data with other remote sensing data sets like microwave, thermal and LIDAR is another developing field. The efforts to fuse high-resolution images with LIDAR systems by Zaremba and Gougeon (2006) and Mutlu et al. (2008) are welcome initiatives in this regard. This may lead to solving several unresolved questions in the structural and functional assessment of forest ecosystems like structural degradation, alien species invasion, regeneration dynamics, species and habitat diversity and the overall ecological functioning of landscapes.

High-definition technical tools are required for the partitioning and modelling of linkages between ecological elements. In order to analyse and disseminate the resultant high volume of information, the user interface needs to be a sophisticated one. The incorporation of statistical and mathematical models to GIS is limited, primarily because of their computational requirements (Guisan and Zimmermann 2000). Therefore, it can be stated that the future of system analysis depends upon the development of information technology. Advanced computer design, user-friendly software, high disk capacity as well as internet-based

information dissemination are some of the prerequisites in the in-depth analysis of ecological systems.

The whole picture of tropical forest degradation assessment so far indicates that we are not yet at the point where a final conclusion can be drawn; however, the field of vegetation degradation analysis in ecology is progressing. Unlike other land degradation, biodiversity and floristic inventorying using satellite remote sensing have practical limitations in tropical forests (Nagendra and Rocchini 2008; Nagendra et al. 2010) which have been known for their astonishing diversity of life forms and species that have been shaped by natural selection and biotic and abiotic factors associated with a wide variety of different habitats. This is particularly evident in tropical countries such as Brazil, which is estimated to have more than 11,000 tree species that reach diameters of up to 10 cm, and more than 3,000 species amongst which there are more than a million individuals (Hubbell et al. 2008). Further research is still necessary as there are countless problems to be solved, techniques to be developed and questions to be answered.

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