Monitoring forest degradation in tropical regions by remote sensing: some methodological issues

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ABSTRACT

Key issues related to the monitoring by remote sensing of open forest degradation in a tropical context are discussed. Degradation of forest-cover is often a complex process, with some degree of ecological reversibility and a strong interaction with climatic fluctuations. Only a representation of land cover as a continuous field of several biophysical variables can lead to an accurate detection of forest degradation. For this purpose, repetitive measurements of spectral, spatial and temporal indicators of the land surface have to be performed. Each set of indicators brings a specific type of information on the land cover. These indicators must therefore be combined to achieve a comprehensive description of the surface processes. The detection of inter-annual changes in landscape spatial structure is more likely to reveal long term and long lasting land-cover changes, while spectral indicators are more sensitive to fluctuations in primary productivity associated with climatic fluctuations. Different monitoring systems may be optimal for different ecosystems. A long time series of observations is always required. The monitoring of the spatio-temporal distribution of biomass burning may also give indications of open forest degradation.

Key words. Land-cover change, forest degradation, remote sensing, landscape, monitoring, tropical observations on the vegetation cover at a regional scale.

INTRODUCTION

Forest degradation is a process leading to a 'temporary or permanent deterioration in the density or structure of vegetation cover or its species composition' (Grainger, 1993, p. 46). It is a change in forest attributes that leads to a lower productive capacity. It is caused by an increase in disturbances. The time-scale of processes of forest degradation is in the order of a few years to a few decades.

Any in-depth understanding of the processes of forest degradation has to be based on an accurate monitoring of the degradation over large areas, for at least a few decades. When it has to be performed at a regional scale, this monitoring poses a number of methodological challenges. The objective of this paper is to discuss critical issues related to the monitoring of open forest degradation in a tropical context through a review of recent studies on this topic. The emphasis will be on remote sensing techniques as they allow researchers to obtain synoptic and repetitive observations on the vegetation cover at a regional scale.

The lack of quantitative, spatially-explicit and statistically representative data on land-cover change has left the door open to simplistic representations of forest-cover changes, for example, 'marching deserts' or disappearing tropical forests. Whilst it is possible to find local examples of such extreme changes, empirical studies in grassland, savannas or open forest ecosystems generally reveal the predominance of inter-annual climatic variability, ecosystem resilience and complex land-cover change trajectories over secular land cover conversions (Ringrose et al., 1990; Hellden, 1991; Tucker, Dregne & Newcomb, 1991; Prins & Kikula, 1996).

Previous studies generally distinguish between land-cover conversion, i.e. the complete replacement of one cover type by another, and land-cover modification, i.e. more subtle changes that affect the character of the land cover without changing its overall classification (Turner, Moss & Skole, 1993). Land-cover modifications are generally more prevalent than land-
cover conversions. In principle, the monitoring of land-cover conversions (e.g. agricultural expansion or deforestation) can be performed by a simple comparison of successive land cover maps, derived either by classification of remote sensing data or by field surveying. This change detection method is however limited by the classification accuracy of the land cover maps and, therefore, other change detection methods such as image differencing, change vector analysis, image regression or multi-temporal linear data transformation are also applied (Coppin & Bauer, 1996).

In any case, the comparison of land-cover classifications for different dates does not allow the detection of subtle changes within land-cover classes. Even if some of the attributes of one class have changed, the magnitude of these changes will not always be large enough to justify a shift from one land cover category to another, unless the vegetation classification identifies a very large number of narrowly defined categories. Therefore, monitoring forest degradation can only be achieved through repetitive measurements of biophysical attributes that characterize the land cover. These biophysical attributes must be surface characteristics that are measurable from space, such as vegetation cover, biomass, surface moisture or landscape heterogeneity. Variables such as vegetation community structure (e.g. tree:shrub:grass ratios), or species composition, cannot be observed reliably by remote sensing. In the following review, after a brief discussion of different representations of land cover, the main options for the measurement by remote sensing of indicators of the state of land-cover and its change are reviewed.

**DISCRETE VERSUS CONTINUOUS REPRESENTATION OF LAND COVER**

The land surface can be represented as a set of spatial units that are each associated with an attribute. These attributes are either a single land cover category (i.e. leading to a discrete representation of land cover) or a set of values for continuous biophysical variables (i.e. leading to a continuous representation of land cover) (DeFries et al., 1995). The correspondence between these two representations can be established through a table which associates to each land cover category the average range of values for the biophysical variables. An example of such a table, which is based on the IGBP-DIS global land cover map at 1 km

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>BARR</th>
<th>OPEN</th>
<th>GRAS</th>
<th>SAVA</th>
<th>CROP</th>
<th>WSAV</th>
<th>EVG</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z_w$ (m)</td>
<td>Roughness length for momentum</td>
<td>0.05</td>
<td>0.10</td>
<td>0.06</td>
<td>0.15</td>
<td>0.08</td>
<td>0.50</td>
<td>2.00</td>
</tr>
<tr>
<td>$d$ (m) Displacement height</td>
<td>/</td>
<td>0.70</td>
<td>0.70</td>
<td>0.35-7.00</td>
<td>0.70</td>
<td>0.35-7.00</td>
<td>14.00</td>
<td></td>
</tr>
<tr>
<td>LAI</td>
<td>Leaf Area Index</td>
<td>0.50</td>
<td>1.30</td>
<td>2.40</td>
<td>3.70</td>
<td>4.30</td>
<td>5.80</td>
<td>6.40</td>
</tr>
<tr>
<td>$p_r$ (%) Leaf reflectivity (in the visible)</td>
<td>0.00</td>
<td>0.01</td>
<td>0.10</td>
<td>0.11</td>
<td>0.10-0.11</td>
<td>0.11</td>
<td>0.10-0.11</td>
<td>0.10</td>
</tr>
<tr>
<td>$p_n$ (%) Leaf reflectivity (in the near infrared)</td>
<td>0.00</td>
<td>0.01</td>
<td>0.45</td>
<td>0.58</td>
<td>0.45-0.58</td>
<td>0.58</td>
<td>0.45-0.58</td>
<td>0.45</td>
</tr>
<tr>
<td>$\tau_v$ (%) Leaf transmissivity (in the visible)</td>
<td>0.00</td>
<td>0.01</td>
<td>0.05</td>
<td>0.07</td>
<td>0.05-0.07</td>
<td>0.07</td>
<td>0.05-0.07</td>
<td>0.05</td>
</tr>
<tr>
<td>$\tau_n$ (%) Leaf transmissivity (in the near infrared)</td>
<td>0.00</td>
<td>0.01</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>$g_v$</td>
<td>Green leaf fraction</td>
<td>/</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$r_s$</td>
<td>Minimum stomatal resistance</td>
<td>/</td>
<td>100</td>
<td>50</td>
<td>50-100</td>
<td>50</td>
<td>50-100</td>
<td>100</td>
</tr>
<tr>
<td>$\rho_{0.01}$ (s) Roof fraction upper 0.1 m soil</td>
<td>/</td>
<td>0.5</td>
<td>0.7</td>
<td>0.5-0.7</td>
<td>0.3</td>
<td>0.5-0.7</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>$t_v$</td>
<td>Internal plant resistance</td>
<td>/</td>
<td>$10^3$</td>
<td>$5.10^3$</td>
<td>$5.10^3-10^5$</td>
<td>$5.10^3$</td>
<td>$5.10^3-10^5$</td>
<td>$10^7$</td>
</tr>
<tr>
<td>$\pi$</td>
<td>Albedo</td>
<td>/</td>
<td>0.26-0.31</td>
<td>0.21</td>
<td>0.23</td>
<td>0.18</td>
<td>0.20</td>
<td>0.19</td>
</tr>
</tbody>
</table>

BARR, barren or sparsely vegetated (IGBP-DIS class 16); OPEN, open shrublands (IGBP-DIS class 7); GRAS, grasslands (IGBP-DIS class 10); SAVA, savannas (IGBP-DIS class 9); CROP, croplands/natural vegetation mosaic (IGBP-DIS class 14); WSAV, woody savannas (IGBP-DIS class 8); EVGR, evergreen broadleaf forest (IGBP-DIS class 2).

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Table 2. Discrete versus continuous representation of land cover and land-cover change.

<table>
<thead>
<tr>
<th>Land surface viewed as a continuum:</th>
<th>Land surface viewed as a discrete reality:</th>
</tr>
</thead>
<tbody>
<tr>
<td>*a set of biophysical attributes</td>
<td>= a land cover class</td>
</tr>
<tr>
<td>*their fine scale spatial variability</td>
<td></td>
</tr>
<tr>
<td>*their seasonal changes</td>
<td></td>
</tr>
<tr>
<td>*their large magnitude inter-annual dynamics</td>
<td>= a land-cover conversion</td>
</tr>
</tbody>
</table>

resolution, for the region of the African Sahel was produced by A. Sneessens, G. Schayes and E. F. Lambin (in prep.) (Table 1). The IGBP-DIS land cover map was derived through a classification of remote sensing data (Loveland & Belward, 1997). Each category corresponds to a dominant vegetation type or a mosaic of vegetation cover types. A study of the characteristics of each cover has allowed Sneessens, Schayes & Lambin (in prep.) to derive from literature and field observation data the range of values taken by each category for a number of biophysical variables that are discriminant between surface covers. Field campaigns such as HAPEX-Sahel in Niger (Prince et al., 1995) provide a strong empirical basis for relating land-cover categories to a distribution of attribute values.

The discrete representation of land cover has the advantages of concision and clarity, and represents a low data volume. It is, however, a highly abstract model of real landscapes. In the continuous representation of land cover, the biophysical variables vary continuously, not only in space but also in time, at the seasonal and inter-annual scales. By contrast, in the discrete representation of land cover, each spatial unit is represented by a single categorical value that is stable over a season (Table 2). Inter-annual changes in the values of the biophysical attributes of the surface are described as land-cover conversions only if the changes exceed the range of values that is characteristic of the land-cover category (i.e. if the magnitude of the change is such that the values of all biophysical attributes fall within the range of another land cover class during the entire seasonal cycle). A land-cover modification—which is not detectable with the discrete representation of land cover—implies that variations in the values of the biophysical attributes remain within the range of values that is characteristic of the land-cover category. Processes that lead to changes in the seasonal dynamics or in the fine scale spatial variability of biophysical attributes would also be described as land-cover modifications. Changes that would only affect the values of some of the biophysical attributes, for just part of the seasonal cycle would probably also enter in that category. In that case, there is, however, a fuzzy boundary between processes of land-cover modification and conversion.

This suggests that monitoring forest degradation by remote sensing requires the measurement of a set of indicators of the biophysical attributes of the surface, the seasonality of these attributes, and their fine-scale spatial pattern. These information requirements correspond to the three different major information sources that can be provided by remote sensing. As forest degradation usually occurs slowly through land-cover modifications (not conversions), improved understanding of this complex ecological process requires an integration of the spectral, spatial and temporal information domains of remotely sensed data.

SPECTRAL, SPATIAL AND TEMPORAL INFORMATION ON FOREST DEGRADATION

Spectral information

The estimation by remote sensing of biophysical attributes that are indicative of forest degradation has been conducted using either an empirical approach or a physically-based approach. In the empirical approach, many authors have characterized the surface using vegetation indices that are arithmetic combinations of spectral bands. Most of these indices are variants of the normalized difference vegetation index (NDVI), computed as the ratio between the difference and the sum of the radiances measured in the near infra-red and red parts of the electromagnetic spectrum. These variants display different levels of sensitivity to perturbing factors such as soil colour changes or atmospheric effects (Verstraete & Pinty, 1996).
Empirical studies and simulations with radiative transfer models support the interpretation of vegetation indices in terms of the fraction of photosynthetically active radiation absorbed by the vegetation canopy, canopy attributes (e.g. green biomass or green leaf area index), state of the vegetation (i.e. vegetation vigour or stress) and instantaneous rates associated with the activity of the vegetation (Myneni et al., 1995). Inter-annual variations in primary production in the Sahel have been monitored using annual integration of vegetation index data at a coarse spatial resolution (Holland, 1991; Tucker et al., 1991). Similar data have also been used to detect large-scale tropical deforestation (Tucker, Holben & Goff, 1984; Woodwell et al., 1987). The methods used in these studies are not necessarily suitable for the detection of changes associated with slow rates of land degradation due to spatial and temporal sampling issues. First, the level of spatial aggregation of the data used in these studies (i.e. 8 by 8 km in the case of pre-processed time series of Global Area Coverage data from the Advanced Very-High Resolution Radiometer on the NOAA series of orbiting platforms) is too coarse to allow for the detection of subtle changes in the density or structure of vegetation cover. Second, integrating vegetation index data on an annual basis hides variations in the phenological cycle of the vegetation cover. Third, the time consistency of the data over several years is not always ensured due to, in the case of AVHRR, a lack of on-board calibration of radiances, instrument change-over, and a drift in equator crossing-time of the satellite’s orbit over the years. Time series of high spatial resolution data can overcome several of these limitations.

Land surface temperature ($T_s$), derived from the thermal channels of satellite sensors, has also been used as a biophysical indicator of the surface in empirical studies. $T_s$ is related, through the surface energy balance equation, to surface moisture availability and evapotranspiration, as a function of latent heat flux (Carlson, Perry & Schmugge, 1990). For example, Franklin & Strahler (1988) applied a model inversion approach to generate regional estimates of tree size and density in West Africa, using Landsat TM data. They used the Li-Strahler canopy reflectance model (Li & Strahler, 1986). A woodland stand is modelled geometrically as a group of objects casting shadow on the background. The reflectance of a pixel is modelled as a linear combination of the signatures of the major scene components (i.e. illuminated tree crown, illuminated background, shadowed tree and shadowed background), weighted by their relative areas. Inversion results over a sample of observations were satisfactory for the estimation of tree density and cover but poor for tree size. The application of this type of approach for monitoring woodland degradation would probably require further developments for a more robust approach.
Spatial Information

A major attribute of a landscape is its spatial pattern. The concept of landscape spatial pattern covers, for example, the patch size distribution of residual forests, the location of agricultural plots in relation to natural vegetation, the shapes of fields and the number, types and configuration of landscape elements. Landscape spatial pattern is seldom static due both to natural changes in vegetation and to human intervention. The spatial dynamics of landscapes interact with ecological processes that have important spatial components (Turner, 1989), e.g. flows of energy, and matter between landscape elements, biological productivity of different components of the ecosystem, biodiversity, and the spread of disturbances.

Remote sensing offers the possibility to analyse changes in spatial structure at the scale of landscapes (e.g. Briggs & Nellis, 1991; Dunn et al., 1991; Turner & Gardner, 1991). Indicators of the degradation of the vegetation cover can be derived from such measures (Jupp, Walker & Pendridge, 1986; De Pietri, 1995). For example, Pickup & Foran (1987) developed a method to monitor arid landscapes used for pastoralism based on the spatial variability of the vegetation. The spatial autocorrelation function and mean-variance plots of a spectral indicator were found to be successful in discriminating between the cover responses typical of good and poor rainfall years. For drought conditions, the decrease in spatial autocorrelation with increasing spatial lag was rapid since the ground surface is bare and most of the vegetation signal comes from scattered areas of trees and shrubs. A low decay rate of the autocorrelation function indicated a greater spatial uniformity of the landscape, e.g. during wet periods, when more ground cover is present so reducing the contrast between the bare soil signal and that produced by trees and shrubs (Pickup & Foran, 1987).

Similar observations were made by Lambin (1996) over the seasonal and inter-annual cycle of three West African landscapes. Vogt (1992) also analysed the seasonal changes in spatial structure of a West African landscape, showing that there is a marked seasonal cycle in the spatial structure of a vegetation index (NDVI), surface temperature and albedo, and that zones of ecological transition have an identifiable seasonal dynamic in spatial structure. However, the monitoring of these spatial variability measures only provides for a qualitative description of the cover state.

Lambin & Strahler (1994) showed that the detection by remote sensing of land-cover change processes is improved when using both spectral (e.g. vegetation index and surface temperature) and spatial indicators of surface condition. Their study suggested that the detection of inter-annual changes in landscape spatial structure is more likely to reveal long term and long lasting land-cover changes while spectral indicators are more sensitive to fluctuations in primary productivity associated with the inter-annual variability in climatic conditions. The long term monitoring of landscape spatial pattern in addition to other biophysical variables can thus lead to the detection of a greater range of processes of landscape modification (Lambin & Strahler, 1994).

The spatial pattern of a changing landscape also contains some information on the processes of landcover change. Certain categories of changes in human land use tend to fragment the landscape (e.g. expansion of extensive agricultural exploitation, forest degradation driven by small-scale logging, overgrazing or desertification around deep wells). Other land use changes increase landscape homogeneity (e.g. large-scale intensive cultivation or ranching). Spatial processes of gap expansion in a forest cover have been modelled to predict the total gap area and gap size distribution (Kubo, Iwasa & Furumoto, 1996). One can hypothesize that landscapes with a very low or very high level of disturbance are characterized by a low spatial heterogeneity, while landscapes with a medium level of disturbance are very heterogeneous. This would lead to the relationship sketched in Fig. 1.

Recent remote sensing observations generally support this hypothesis, e.g. in a study of forest-cover disturbances in Papua New Guinea (Estreguil & Lambin, 1996) and another study of forest fragmentation in New England (Vogelmann, 1995). However, the validity of this model is likely to depend on the scale of analysis. It is only when the spatial scale of observation of the landscape pattern is slightly broader than the spatial scale of the impacts on landscape of a given disturbance that this inverted ‘U’ shape is likely to be observed.

Temporal Information

Land-cover changes take place at a variety of temporal scales, i.e. short events with detectable effects only for a few months, modifications in seasonal trajectories of ecosystem attributes, processes that affect the land cover through several seasonal cycles, and long-term, permanent changes. Open forest degradation may affect, and therefore be indicated by, the phenology of
the vegetation cover. The analysis of the temporal trajectories of vegetation indices based on high temporal frequency remote sensing data allows us to monitor vegetation phenology and biome seasonality (Justice et al., 1985).

Processes such as a shortening of the growing season, a dephasing of the phenology of different vegetation layers, or modifications of the cover due to disturbances such as fires, can only be detected if inter-annual changes in the seasonal trajectories of vegetation covers are analysed. For any landscape with a strong seasonal signal, the detection of inter-annual changes needs to take into account explicitly the fine-scale temporal variations. If data from only one or a few dates a year are used to measure inter-annual changes, the undersampling of the temporal series hinders the change detection accuracy and might lead to the detection of spurious changes (Lambin, 1996).

A quantitative evaluation of differences in seasonal development curves of remotely sensed data was applied for land-cover change analysis by Lambin & Ehrlich (1997). In this study, a measure of the deviation in seasonal trajectories was computed for 10 years of continental-scale remote sensing data. Subtle processes of land-cover change could be detected this way. Results suggested that land-cover changes in Africa mostly involve erratic variations in land-cover conditions due to droughts, temporary modifications in seasonality, shifts in the timing of rains and episodic events to which most ecosystems display a high resilience. In a study that opens a new line of research, Goward & Prince (1995) provided empirical data, measured by remote sensing, that indicate some persistence or lag between vegetation activity and climate dynamics. In some ecosystems, the response time of vegetation to short-term climatic fluctuations might provide useful information on the level of forest degradation. Actually, changes in species composition affect the resilience of a given vegetation cover as different communities of trees, shrubs and grasses are characterized by different phenological growth response rates.

In addition to the monitoring of remotely sensed indicators of forest degradation, one can integrate a monitoring of its proximate causes or of other surface processes closely associated with the state of the vegetation cover. The best example of such a process for tropical ecosystems is biomass burning. Recent research has improved the ability to monitor active fires and burnt areas by remote sensing (Justice et al., 1996; Eva & Lambin, 1998). On one hand, open forest degradation may result from repeated biomass burning or be caused by a change in the fire regime. On the other hand, ecosystem degradation is likely to lead to a modification of the seasonal distribution and spatial patterning of fires as the diffusion of fires through the landscape will be altered.

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Fig. 1. Sketch of the expected relationship between the level of landscape disturbance and the spatial heterogeneity of the landscape measured on spatial data at a spatial resolution of a few dozens of metres.
CONCLUSION

Some important lessons may be learnt from this review. (i) Degradation of forest-cover is often a complex process, with some degree of reversibility as the biological productivity of forests is partially controlled by climatic fluctuations. (ii) Only a representation of land cover as a continuous field of several biophysical variables can lead to an accurate detection of forest degradation. (iii) Repetitive measurements of spectral, spatial and temporal indicators of the land surface have to be performed. (iv) Each set of indicators brings a specific form of information on the land cover. These indicators must therefore be combined to achieve a comprehensive description of the surface processes. (v) A long time series of observations is required to be able to detect trends in forest degradation that depart in a significant way from short-term, climate-driven fluctuations in forest conditions. Finally, (vi) a monitoring system can combine indicators of the degradation itself, its proximate causes, and other surface processes linked with the vegetation cover.

One of the key implications of this review is the requirement for an integration of information from the spectral, spatial and temporal domains to monitor forest degradation. The main mechanisms for achieving this are: (i) construction of empirical indices, i.e. mathematical formulations combining metrics from different information sources; (ii) multi-criteria analyses of forest degradation, either using statistical classification methods or a set of knowledge rules; or (iii) development of invertible remote sensing models that represent key variables related to the level of degradation of forest covers. All three approaches need to be calibrated against a statistical sample of field observations of biophysical attributes that characterize forest conditions. As different monitoring systems may be optimal for different ecosystems, this calibration should probably be done at the level of ecosystems. We still need to accumulate case studies to identify which approach and which combination of information sources works best for different ecosystems.

REFERENCES


