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***Abstract*—Sustainable management of tropical forests has been identified as one of the main objectives for global conservation and management of carbon stocks. Toward this goal, managers need tools to determine whether current management practices are sustainable. Several international initiatives have been undertaken for the development of criteria and indicators to aid managers in moving toward sustainable practices. Despite these efforts, the question of how to apply and assess indicators remains to be answered from an operational, field-based perspective. Field surveys are expensive and time-consuming when management areas are large and in the face of logistical constraints. Thus, there is a need for an approach to prioritization. We sought to determine whether satellite imagery can be used, in conjunction with standard forest management data, to identify and rank priority areas for field surveys of bioindicators. The study area in Costa Rica, in forest areas managed by the Fundacion para el Desarrollo de la Cordillera Volcanica Central (FUNDECOR), was imaged by the Landsat-5 Thematic Mapper in 1986 and 2001. Through spatial statistical analysis applied to the wide dynamic range vegetation index, we were able to quantify and rank changes in canopy spatial structure. The resulting categories can be used by forest managers to identify which areas are in need of field surveys. More generally, we show how to generate a moving baseline for change analysis and evaluate for significant deviations in spatial structure.**

***Index Terms*—Field surveys, forest canopy heterogeneity, indicators, sustainable management, variography, wide dynamic range vegetation index (WDRVI).**

I. Introduction

Sustainable management of tropical forests has been identified as a key objective for global conservation, as they are among the largest and most endangered biomes [1]. Forests that are neither economically productive nor protected by conservation status are at risk of transformation into other land uses. Not all forest management practices are sustainable, but managers lack tools to gauge their sustainability.

Several initiatives have been undertaken to create sets of criteria and indicators (C&I processes) to be used as tools in the evaluation of the sustainability of specific operations within a given timeframe and with the ability to monitor sustainability trends [1]–[5]. These initiatives consider a wide variety of indicators that managers can assess in order to build an integrated view of the sustainability of their management practices. The majority of the indicators are based on scientific and theoretical approaches [1], [5].

In 1994, the Center for International Forestry Research (CIFOR) initiated one of the leading C&I processes. CIFOR brought together teams of experts on the ecological, economic and productive aspects that affect forest management sustainability, to design specific sets of C&I for each area, based on research, conceptual framework and field evaluations. The process resulted in a generic template that forest managers can use and adapt to the specific conditions of their operations [1], [5]. They stated that biodiversity maintenance is a surrogate of ecological sustainability; thus, many sustainability indicators seek to assess biodiversity levels within managed areas. However, the question of how to implement these indicators remains to be answered from an operational viewpoint, where logistical constraints become critical.

Tropical forests are not steady-state ecosystems; they exhibit a range of natural disturbance levels [4]. Their historical range of variability [6] embraces a dynamic of disturbances in addition to gap dynamics and creates a mosaic of habitats differing in microclimate, vegetation structure, and faunal composition. The distribution of these patches generates the specific vertical and horizontal heterogeneity of a forest. Management practices can change forest heterogeneity, depending on its harvest intensity (as measured by the number of trees or the basal area or the cubic meters of wood removed per hectare) [4], [6], [7]. Accordingly, CIFOR [1], established as one of its indicators *"The change in diversity of habitats as a result of human interventions are maintained within critical limits as defined by natural variation and/or regional conservation objectives."* Thus, a management scheme may be considered sustainable if it maintains the relative abundance and distribution of the successional stages that provide forests its diversity of habitats within the limits of natural variability. In contrast, forests exhibiting significant differences either in comparison with natural control areas or before and after harvesting (surveyed following a reasonable recovery period) would constitute *prima facie* evidence of unsustainable forest management.

Forest heterogeneity (diversity of habitats) and other indicators are usually surveyed in the field, which makes them very limited in extent and time-consuming [3], [5], [8]. Therefore, as

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the number of forests to be surveyed or the total area under management increases, the personnel and time required increases and comprehensive surveying becomes impractical.

On the other hand, for the same reasons, surveys generally only compare natural and managed areas directly—as a surrogate of before and after harvest—without considering the intrinsic dynamics of these natural forests [1], [3], [8]. Such an approach can confound natural variation with the effects of management practices [10]. Furthermore, the approach provides only a binary characterization of managed areas as similar or dissimilar to natural areas without addressing the magnitude of the dissimilarity or its statistical significance [10].

Forest spatial pattern may be detected and measured remotely by means of spaceborne sensors [11]–[13]. Remotely sensed data can be used to estimate biophysical parameters of vegetation cover through the use of vegetation indexes [14]–[16]. Given earth observation data spanning more than three decades and multiple sensors, there is the potential to characterize dynamic baselines in tropical forests that can embrace intrinsic processes of disturbance and regeneration in natural areas. Here, we have used a pair of Landsat-5 Thematic Mapper (TM) images to demonstrate how to characterize spatiotemporal variation in canopy structure and compare managed and natural areas.

II. Methods

A. Vegetation Indices

The analysis of forest canopy spatial patterns was made through the study of the spatial variability of a new vegetation index related to the normalized difference vegetation index (NDVI) [17]: specifically, the wide dynamic range vegetation index (WDRVI) [18], [19]. The NDVI has been commonly used to relate to biophysical characteristics of vegetation such as leaf area index (LAI), fractional vegetation cover, or aboveground biomass [18]–[20]. Yet, the NDVI begins to lose sensitivity when LAI is moderate (>2); thus, in high LAI environments—such as tropical forests—ecologically significant changes in canopy structure may not be detectable using NDVI [19], [20].

The WDRVI is a generalization of the NDVI proposed for use with denser vegetation [19], [20]

$$\mathrm{WDRVI} = \frac{(\alpha * \rho_{\mathrm{NIR}} - \rho_{\mathrm{RED}})}{(\alpha * \rho_{\mathrm{NIR}} + \rho_{\mathrm{RED}})} \quad (1)$$

where ρ_{NIR} is near-infrared reflectance (Band 4 of Landsat TM), ρ_{RED} is red reflectance (Band 3 of TM), and α is a weighting coefficient [18]. By down-weighting the contribution of the ρ_{NIR} with $0 < \alpha < 1$, the value of $\alpha * \rho_{\mathrm{NIR}}$ approaches ρ_{RED}, thereby improving the sensitivity of WDRVI to changes in vegetation biophysical parameters [19], [20]. Note that if $\alpha = 1$, then WDRVI = NDVI.

Following the approach in [19], we used the following to determine $\alpha = 0.3$ to be optimal with these data:

$$\alpha_{\mathrm{est}} = 2 * \frac{(\text{average } \rho_{\mathrm{RED}})}{(\text{maximum } \rho_{\mathrm{NIR}})}. \quad (2)$$

TABLE I
FIELD SURVEY PRIORITY LEVEL

Forest	Year of harvest	Area (ha)	Trees cut	Harvest intensity (trees/ha)	Priority level
1	1998	62	114	1.85	Low
2		22	100	4.55	Intermediate
3		118	231	1.96	Intermediate
4		40	73	1.83	Intermediate
5		65	88	1.35	Intermediate
6		45	85	1.89	Low
7		72	145	2.01	Low
8		357	1108	3.10	Intermediate
9	1999	14	41	2.93	Low
10		27	45	1.67	Low
11		50	96	1.92	High
12	2000	605	616	1.02	Low
13		58	62	1.07	Low
14		137	647	4.72	Intermediate
15		145	160	1.10	Intermediate

Based on WDRVI $\alpha = 0.3$ values spatial pattern change rates

B. Study Area

The study area is located in the canton of Sarapiqui, in the Atlantic slope of the Cordillera Volcanica Central in Costa Rica. Analysis focused on 15 forest management units (logged 1998–2000) and six nonlogged natural forest areas managed by the Fundacion para el Desarrollo de la Cordillera Volcanica Central (FUNDECOR).[1] Managed units were selectivelylogged at very low intensity (<5 trees/ha removed, minimum diameter at breast height is 60 cm; see Table I). Each management unit corresponds to a privately owned forest area that is subject to a management plan that is tuned to its specific conditions (e.g., topography, location, number of trees, species composition). The size of the forest management units ranged from 14–605 ha (Table I).

C. Data

Image data were two Landsat-5 TM scenes (WRS-2 Path 15, Row 53): one before logging from February 1986 and the other after logging from January 2001. Images were converted from digital numbers to reflectance following [21] and then coregistered. No atmospheric corrections were applied for several reasons: 1) elevations in the forest areas ranged from 100–1500 m above sea level; 2) no ground data were available; 3) we sought an approach that can be readily implemented by a forest manager's geospatial technician, and it requires more specialized knowledge that is likely available to do atmospheric correction well; and 4) our analysis relied on the relative differences between pixels within a single image date and then comparing these derived relationships through time; thus atmospheric correction is less of a concern [22], [23].

[1]FUNDECOR is a Costa Rican NGO that provides private landowners with forest management services under forest management certification standards established by the Forest Stewardship Council (FSC).

D. Canopy Spatial Patterns

We assessed canopy spatial patterns by fitting a spherical model to describe the semivariogram obtained for each forest management unit at each time point [24]–[29]. We used VARIOWIN 2.21 [30], [31] for the variography and model fitting. Estimates of the three parameters of a spherical model (sill, nugget variance, and range) served to summarize the spatial pattern observed among WDRVI values. Change in spatial pattern between 1986 and 2001 was inferred from change in model parameter estimates.

Range refers to the distance where the variance no longer exhibits spatial dependence. The sill corresponds to the portion of the total variation that exhibits spatial dependence and the nugget variance corresponds to local variability occurring at scales finer than the sampling interval. The possible sources of this finer scale variability include instrument error, sampling error, or the intrinsic heterogeneity of the measured phenomenon [24]–[29]. Beyond the range, the sum of the sill and the nugget variance constitute the total variation.

We sought significant differences in vectors that have both magnitude and orientation information. The orientation information is on a periodic scale (0° to 359°); thus, we need to use circular statistics to calculate correctly the means and variances [32] of the changes between natural and managed forests. Changes observed in natural forests served as a baseline against which to assess the significance of the changes observed in managed forests.

III. Results and Interpretation

Each forest exhibited change in spatial structure between acquisitions (Fig. 1). Natural forests exhibited, in general, a reduction in the sill/total variation ratio accompanied with an increase in the nugget variance. Ranges did not change substantially, except in one case [Fig. 1(a)]. Managed forests also exhibited a general pattern of reduction in the sill/total variation ratio. However, in this case, some forests presented an increase in the ratio accompanied by a decrease in the nugget variance. Changes in range were typically greater than the ones observed in natural forests, but the direction of the change was not uniform: some forests increased and others decreased [Fig. 1(b)]. Analysis of the mean change angle and magnitude between natural and managed forests revealed no significant differences between groups (Table II).

Even though management can increase forest heterogeneity [1], [3], [4], [7], [33]–[35], comparisons of canopy spatial patterns in terms of the mean change angle and magnitude in sill/total variation–range relation (Fig. 1 and Table II) did not show significant differences between natural and managed forests. This result was expected since the current management of these forests aims at sustainability through very low intensity logging, under FSC standards, that specifically tries to generate the least possible changes from natural dynamics [36].

However, comparison of group behaviors does not address specific changes within particular management units. To identify critical change thresholds for individual management units, it is important to consider that each forest has an intrinsic disturbance history as well as a disturbance context dictated by regional processes such as fragmentation and extreme meteorological events [5], [10], [35]. Ideally, each forest area would provide its own dynamic baseline from which to assess the impact of particular management practices [5], [36].

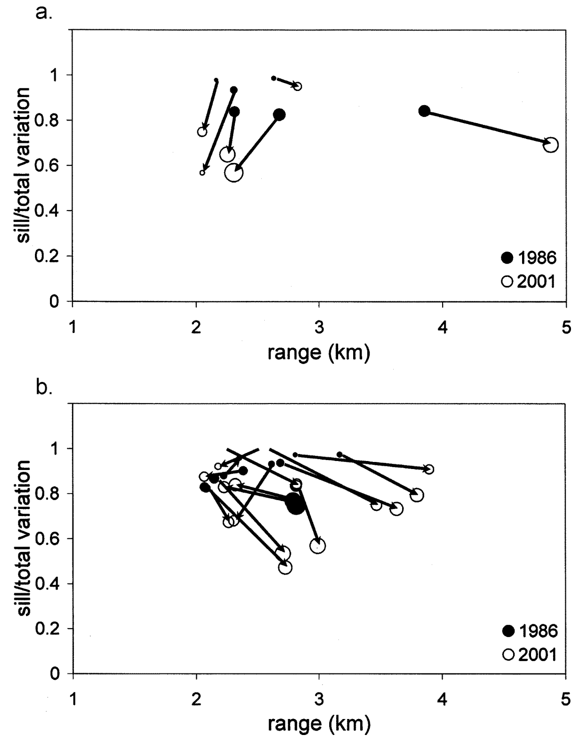

Fig 1. Changes in the relation sill/total variation. (a) Range observed in natural forests and (b) managed forests. WDRVI $\alpha = 0.3$ values between 1986 and 2001. Bubble size represents size of the nugget variance, which was sometimes equal to zero. Arrows connect the same forests between periods.

TABLE II
Differences in Change From 1986 to 2001 Between Natural and Managed Forests

Change dimension	Angle	Magnitude
Test	Watson U2 test	ANOVA (F-test)
P-value	0.50 > x > 0.20	0.40

Fig. 2 summarizes the changes in observed canopy spatial structure for forest management units on an individual basis. The elliptical areas represent the mean change in natural forests plus two and three standard deviations (SDs). The 95% confidence ellipse (the inner ring) bounds the observed natural range of variation. This threshold could enable managers to identify those managed forests that exhibit anomalous changes in spatial structure. Many, but not all, managed forests fall outside of this 2SD threshold. However, if we add another standard deviation to the threshold to account for the effects of recent harvest (within a decade), then only one managed forest falls outside the 3SD limit.

The location of managed areas with respect to each of the boundaries can be used as a mean of ranking forests for field surveys of sustainability bioindicators. For example, in the case of the solitary outlier beyond 3SD, managers might rank it as the highest priority for surveying, followed by the seven units with change rates between 2SD and 3SD, with the rest within the 2SD boundary ranking as lower priority (Table I).

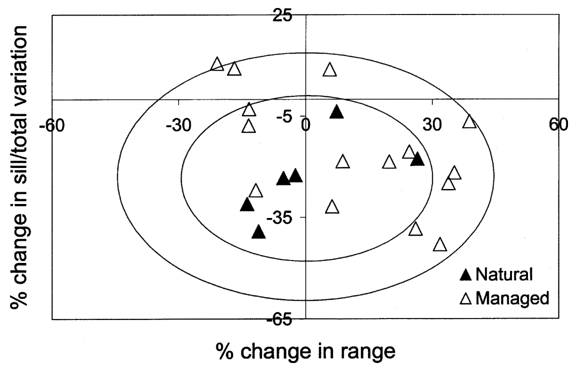

Fig. 2. Rates of change (percent) in spatial structure as observed in natural and managed forests between 1986 and 2001 using WDRVI with $\alpha = 0.3$. The elliptical boundaries show the average changes in natural forests plus two and three standard deviations. Location of a specific forest with respect to these thresholds enables an interpretation in terms of deviation from observed natural rates of change.

TABLE III
HARVEST INTENSITY AND MEAN ANGLE AND MAGNITUDE CHANGE RATES

Change dimension	Correlation P-value with harvest intensity (trees/ha)
Angle	0.57
Magnitude	0.76

It may be expected that observed changes in forest spatial structure and canopy heterogeneity would be directly related with harvest intensity. However, our results show no significant correlation between the mean change magnitudes or angles in managed forests and their harvest intensities (Table III). Further, we found no significant differences between priority rankings shown in Table I and harvest intensities (ANOVA p-value $= 0.375$). These findings reinforce the notion that change analysis in forests need to be conducted individually as management units. Every managed forest has a particular disturbance history and environmental context which leads to high variability within the group of managed forests. While this makes group generalizations difficult, managers do not operate on groups of forests, but rather specify treatments for individual units. This mismatch between the scientific urge to generalize and the managerial requirement to specify underlines the need for the kind of triage approach.

IV. CONCLUSION

We have presented an exploratory study of how dynamic baselines can be extracted from a pair of scenes. We have presented a first approach to using Landsat-scale imagery for prioritizing forests areas for field surveys of bioindicators. The next step requires field verification of the rankings. If bioindicators of ecological sustainability change similarly to canopy spatial patterns, then this approach could be extended from sustainable forest management to biodiversity conservation.

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