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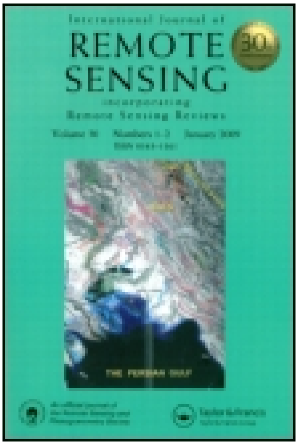

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Mesoscale changes in textural pattern of 'intact' Peruvian rainforests (1970s–1980s)

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Abstract. To assess changes in spatial heterogeneity of non-anthropogenically disturbed rainforests, we compared lacunarity of Landsat MSS imagery over the Peruvian lowlands from the 1970s and 1980s. The organizational patterns associated with lower NDVI values were found to be significantly more clumped during the 1970s whereas those associated with higher NDVI values became more clumped during the 1980s. These spatial dynamics suggest that these rainforests represent non-equilibrium systems at coarse hierarchical levels which are typically thought to be stable at decadal intervals.

1. Introduction

Forests, like many complex natural objects, possess scale-invariant, self-similar features and are geometrically described as fractals (Sugihara and May 1990, Lorimer *et al.* 1994). Landscape-level studies which examined two-dimensional spatial patterns of canopy gaps in tropical rainforests in Panama (Solé and Manrubia 1995) and spectral reflectance values of boreal forests in Russia (Vedyushkin 1994) found both systems resembled living fractals, which may self-organize into critical states. These fractal properties represent the aggregated or scaled-up product of physiologic (leaf-level) and associated demographic (population-level) processes. Presumably, changes in such spatial patterns reflect changes in functions and processes of the forested system (Li and Reynolds 1994).

Increases in tree mortality and recruitment (i.e., gap-phase dynamics) over a 30-year period across a number of allogenically undisturbed tropical rainforest sites (Phillips and Gentry 1994) illustrated that fine-grain spatial patterns of these systems are dynamic. While most rainforest research utilizing remote sensing has focused on classification (Singh 1987, Tuomisto *et al.* 1994, 1995) or broad-scale changes in landuse pattern, e.g., deforestation (Nelson *et al.* 1987, Skole and Tucker 1993), this study examined more subtle differences in remotely-sensed spatial patterns (i.e., canopy texture) exhibited across 'intact' rainforests.

2. Methods

To assess whether or not there have been corresponding landscape-level (i.e., $>10^3$ ha) changes in rainforest image texture which might be expected with plot-level (i.e., <1 ha) increases in canopy gaps, we obtained Landsat-MSS scene pairs from the 1970s and 1980s over the western Amazon basin (figure 1). We focused on heterogeneous lowland forests of Peru (Tuomisto *et al.* 1995) because of the availability of ground-data from the NASA Landsat Pathfinder Humid Tropical Forest

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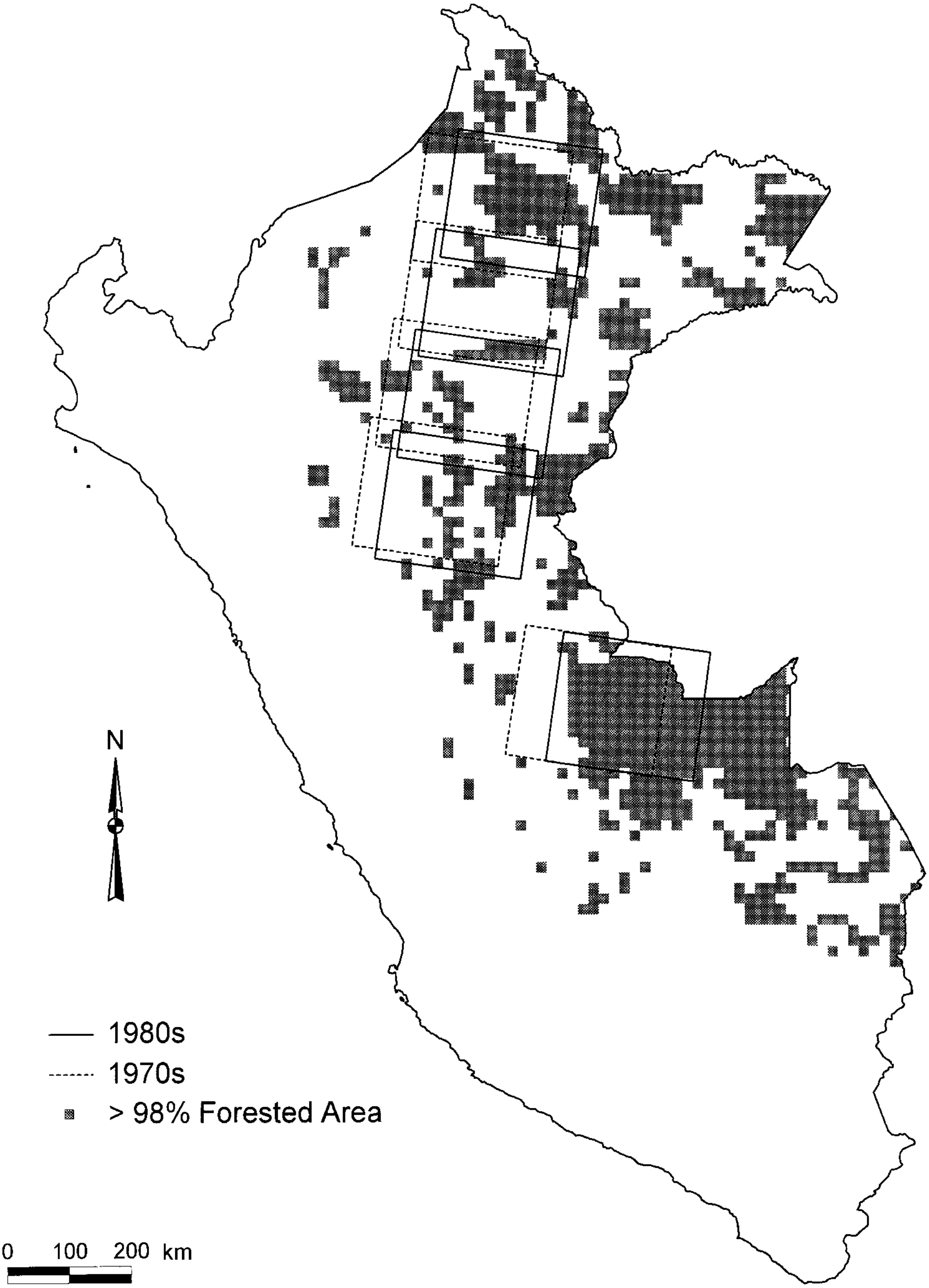

Figure 1. Map of Peru showing the intersection of bi-temporal Landsat MSS scenes and >98 per cent forest cover (Baker 1998) from which subsets were extracted.

Inventory Project (Chomentowski *et al.* 1994, Baker 1998) and the fact that neotropical forests (8 of 21 sites from Peru) were found to be more dynamic than paleotropical forests in field studies (Phillips and Gentry 1994). However, recent data (Phillips

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and Sheil 1997) reveal a decrease in differences between tropical forest turnover in Old and New World sites.

To minimize textural differences which may represent phenological changes, we selected five scene pairs (table 1) based on the proximity of their intra-annual dates (i.e., <3 months), per cent deforestation, per cent forest cover and low topographic relief. Because of the similarity in orbit geometry, scene acquisition times from different Landsat satellites were comparable which should reduce shadow effects. Radiance values from channels 2 (red) and 4 (near-infrared, NIR) were calculated from DN values using published post-calibration dynamic ranges for the different Landsat-MSS satellites (Markham and Barker 1987). These were converted to NDVI (i.e., $(\text{NIR} - \text{red})/(\text{NIR} + \text{red})$) values to emphasize vegetative (greenness) properties. This index has been used to characterize Amazonian rainforest phenology and has the added benefit of reducing variation caused from surface topography (Justice *et al.* 1985).

Each scene pair was co-registered based on readily locatable ground control points. However, since we were concerned with general spatial patterns, exact pixel to pixel agreement was not mandatory. To limit our study to forests undisturbed by clearcutting or extractive logging, we overlaid 16 km by 16 km grids of 1980s coverage data developed by the Pathfinder Project (Baker 1998) on the intersected region of the 1970s and 1980s scenes to locate areas designated as 0 per cent deforested with >98 per cent forest cover. Within these regions, 56 subsets comprised of 100 pixels by 100 pixels ($\approx 350\,000$ ha) were selected attempting to exclude areas with cloud cover, cloud shadows, and open water which could yield changes due to channel migration (Kalliola *et al.* 1992).

To measure textural properties, we utilized a gliding box lacunarity (Plotnick *et al.* 1993, 1996) routine in a manner similar to that used for radar imagery (Henebry and Kux 1995). Lacunarity is a measure of the 'gappiness' of a binary image and is related to the fractal properties of the image. It is estimated by the ratio of the variance of the number of occupied sites to the square of the mean number of occupied sites plus one within a window.

To compensate for striping (i.e., when one or more of the MSS detectors malfunction creating horizontal bands), quartiles based on NDVI values were calculated across rows and analyses were limited to one dimension. Pixel window sizes ranged

Table 1. Bi-temporal Landsat MSS scenes used in the analysis. The Landsat satellite which captured each image is designated by the number within parentheses.

Scene path and row	1970s acquisition date and time	1980s acquisition date and time	Number of 100 pixel by 100 pixel subsets
Path 5, Row 67	27 April 1976 14:13 hrs (2)	26 July 1986 14:20 hrs (5)	20
Path 7, Row 62	8 December 1973 14:37 hrs (1)	9 September 1985 14:37 hrs (5)	10
Path 7, Row 63	2 October 1972 14:40 hrs (1)	9 August 1986 14:30 hrs (5)	7
Path 7, Row 64	2 October 1972 14:40 hrs (1)	25 August 1986 14:30 hrs (5)	5
Path 7, Row 65	2 October 1972 14:40 hrs (1)	6 August 1985 14:39 hrs (5)	14

from 1 to 50 (i.e., ≈79 to 3950 m). This is feasible because striped data are valid in terms of their within-line contrast (Lillesand and Kiefer 1994). The first quartile (Q1) corresponds to the lowest (least green) values; the fourth quartile (Q4) corresponds to the highest (most green) values. By replacing the continuous NDVI values with quartiles, the influence of environmental variability associated with atmospheric conditions (e.g., haze) and incident solar radiation between scene pairs is reduced. To test for non-random behaviour of textural differences, we followed a Monte Carlo approach. For each subset, lacunarity differences between 100 paired 100 by 100 random quartile maps were calculated. The maxima and minima differences from these random maps were used to produce confidence envelopes ($P<0{\cdot}01$) across the window sizes.

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3. Results and discussion

NDVI values between the 1970s and 1980s were markedly different (figure 2) which could be attributed to a variety of biotic (e.g., canopy phenologic or successional) or abiotic (e.g., atmospheric or sensor calibration) issues. The overall mean NDVI quartile values from the 1970s were significantly ($P<0{\cdot}05$) higher than those from 1980s for the 56 subsets (based on a two-sample *t*-test). The variances in the NDVI values were significantly lower in the 1980s for all quartiles but Q4 (based on a two sample *F*-test). Moreover, 39 out of 56 of the within-row NDVI variances, averaged for each subset, in the 1980s were higher than those in the 1970s which indicates a general increase in heterogeneity in reflectivity values within 'intact' rainforests. Surprisingly, of the 17 subsets which had higher within row NDVI variance in the 1970s, 16 were from the Path 7, Row 63 and Path 7, Row 63 scenes. Because the NDVI values were divided into binary files based on quartiles, some exogenous differences, e.g., due to atmospheric or sensor variation, should not affect

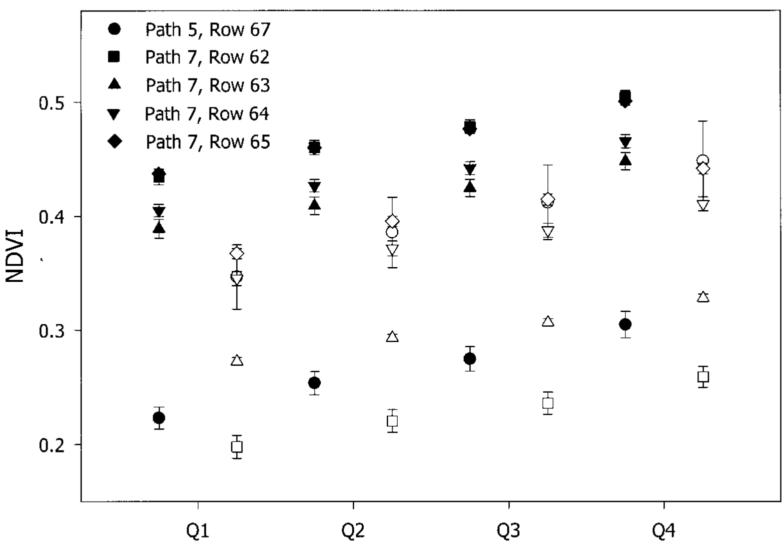

Figure 2. Average NDVI values divided into quartiles for corresponding subsets from the different scenes for the 1970s (black symbols) and 1980s (white symbols). The extensions above and below the quartile symbols represent ± standard error.

the textural analysis assuming effects were homogenous within a row and consistent among targets.

The average lacunarity patterns for the NDVI quartiles for the two time periods were fairly similar (figure 3). All images began with a lacunarity (window size = 1 MSS pixel) of 1·386 which was expected due to an equivalent number of occupied pixels, (i.e., 25) for each quartile. In both the 1970s and 1980s subsets, the lacunarity decay rate for Q2 and Q3 were closely aligned to a random pattern. The lacunarity for the Q1 and Q4 images decreased less rapidly signifying non-random clumping patterns for the lowest and highest NDVI values. Lacunarity for Q1 was slightly greater than Q4 in the 1970s; the opposite was true for the 1980s. When compared directly, the average lacunarity differences between the 1970s and 1980s subsets exhibited non-random patterns for all quartiles (figure 4). The lowest NDVI values (Q1) were more aggregated in the 1970s than in the 1980s. Higher NDVI values (Q2–Q4) were more aggregated in the 1980s than in the 1970s except for window

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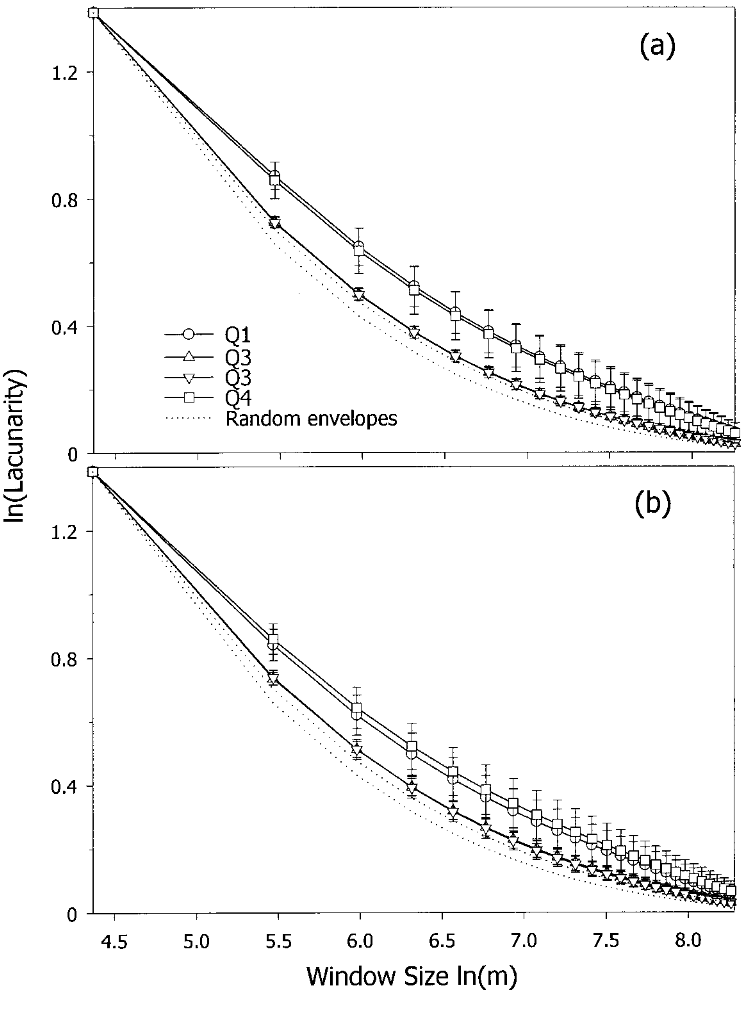

Figure 3. Average lacunarity for quartiles from (*a*) 1970s, and (*b*) 1980s. The extensions above and below the quartile symbols represent ± standard error.

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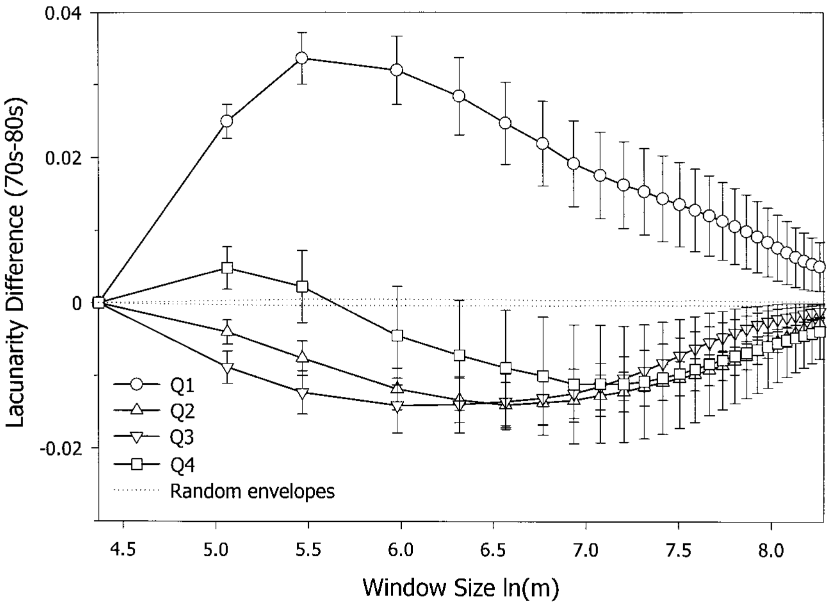

Figure 4. Average change in lacunarity for quartiles from 1970s to the 1980s. The extensions above and below the quartile symbols represent ± standard error.

sizes of two and three pixels for Q4. The maximal average difference in Q1 clumping corresponded to a window size of three MSS pixels (≈237 m). The maximal differences in Q2–Q4 clumping corresponded to window sizes between 5 and 13 pixels (≈395–1027 m). In general, these trends among quartiles were consistent when averaged on a scene by scene basis.

When viewed at coarser observational (landscape) scales, influences from relatively dynamic patch (gap) scale forest processes become negligible and the system is depicted as a steady-state mosaic (Smith and Urban 1988). Although single treefall gaps in a canopy should yield different reflection patterns than found in a continuous canopy, the spatial resolution of Landsat-MSS (≈79 m) is not the most appropriate for monitoring gap dynamics. Furthermore, it is unlikely that chance clustering of single treefalls would yield the coarser scales of pattern exhibited in these images. Differences in reflectance patterns could relate to changes in coarse-scale disturbance or mortality regimes caused by increases in multiple treefall gaps caused by windthrow, pathogen outbreak, drought or flood conditions, which could be manifest over a decade. Although the 1982–83 El Niño was reported to have a severe impact on neotropical rainforests, increased mortality during this time was not evident with the Phillips and Gentry (1994) turnover study (Condit 1997).

4. Conclusions

The explanation that the observed directional change in clumping of reflectance values is due to canopy gaps is speculative. Thus, further analysis of these systems which compares field data and finer grain data, e.g., Pathfinder TM (30 m) or synthetic aperture radar (SAR) imagery, is warranted to deconvolve the underlying causes of the observed textural dynamics. If these differences in spatial heterogeneity of NDVI values indicate a fundamental change in the landscape-scale organization or degradation (Phillips 1997) of these forests, rather than differences in Landsat sensors or atmospheric properties, other regions of tropical rainforest should be analysed for textural dynamics. Such broad-scale directional change in forest heterogeneity may have implications on biodiversity or global CO_2 cycling and carbon modeling as tropical rainforests may not function predictably as sources or sinks (Dixon *et al.* 1994).

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