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Relationships between forest structure and vegetation indices in Atlantic Rainforest

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Abstract

The alliance between remote sensing techniques and biophysical indicators can be valuable to studies on diagnosis and monitoring, especially in threatened habitats, such as the Atlantic Rainforest. This approach may improve monitoring through diagnosing forest fragments instead of quantifying only forest area reduction. This paper aims to evaluate relationships between forest structure and vegetation indices in Atlantic Rainforest fragments, in southeastern Brazil. Two Landsat 7 ETM+ images acquired in humid and dry seasons were used, and measurements of forest structure in nine forest fragments and in a continuous forest area in the Guapiaçú River Basin, in Rio de Janeiro State were taken. Three vegetation indices (normalized difference vegetation index (NDVI), moisture vegetation index using Landsat's band 5 (MVI5) and moisture vegetation index using Landsat's band 7 (MVI7)) were correlated with measurements of forest structure (frequency of multiple-stemmed trees, density of trees, mean and range of tree diameter, mean and range of tree height and average of basal area). Models describing the relationships between forest structure and vegetation indices using linear regression analysis were also developed. MVI5 and MVI7 showed the best performances in dense humid forests, whereas NDVI seems to be a good indicator of green biomass in deciduous and dry forests. Moreover, the saturation matter in vegetation indices and the transferability of relationships between biophysical characteristics and vegetation indices to other sites and times were discussed.

Keywords: Remote sensing; NDVI; MVI; Tropical forest; Forest fragmentation; Conservation

1. Introduction

Habitat fragmentation is defined as the changes in habitat configuration that result from its breaking apart (Fahrig, 2003). Effects of habitat fragmentation have been assessed through measurements of biophysical characteristics in forest fragments using a continuous forest or large fragments (>1000 ha) as contrast (Soulé, 1986; Laurance and Bierregaard, 1997; Fahrig, 2003). Measuring forest biophysical characteristics aims at documenting forest integrity in many aspects, such as structural, functional and species diversity (Gascon et al., 2001). However, these measurements

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often depend on extensive and expensive fieldwork, encompassing a restricted study area. Remote sensing enables monitoring studies in a wide area at constant time periods (Wilkie and Finn, 1996). The alliance between remote sensing techniques and biophysical indicators could be valuable to studies on diagnosis and monitoring, especially in threatened habitats, such as the Atlantic Forest. Corlett (1995) suggests the use of remote sensing as a tool to fill the gap between local/intensive and global/wide studies, providing useful information for decision makers (Kangas et al., 2000).

Vegetation indices obtained from remote sensing may be used as a biophysical indicator (Gamon et al., 1995). Vegetation indices are formed from combinations of several spectral values that are mathematically recombined in such a way as to yield a single value indicating the amount or vigor of vegetation within a pixel (Campbell, 1996). In tropical forests, vegetation indices were associated with tree species diversity and forest biomass (Amaral et al., 1997; Sousa and Ponzoni, 1998; Boyd et al., 1999; Foody et al., 2001, 2003). In Brazil, most studies have been done in the Amazonian Forest, which is more similar in physiognomic characteristics than floristic aspects to the Atlantic Forest (Oliveira-Filho and Fontes, 2000). Therefore, the relationships found between vegetation indices and forest structure may be different in the Atlantic Rainforest.

There are many vegetation indices, but the most popular is the normalized difference vegetation index (NDVI) that uses a ratio between red and near-infrared bands (Rouse et al., 1974). However, Huete et al. (1997) showed that the structure of the NDVI equation, a non-linear transformation of the simple ratio (near-infrared/red), is the major cause for non-linearity and saturation in high biomass situations. Thus, NDVI may be a bad indicator of biophysical characteristics in dense tropical forests. An option is to use a vegetation index based on mid-infrared bands, such as moisture vegetation index (MVI) (Sousa and Ponzoni, 1998). Sousa and Ponzoni (1998) showed that timber volume changes could be detected by reflectance values at middle infrared wavelengths (Landsat TM bands 5 and 7), and thus proposed the moisture vegetation index. Comparing NDVI and MVI, Freitas and Cruz (2003) observed a weaker saturation effect and a higher sensitivity to MVI over dense canopies in the Atlantic Rainforest.

The use of vegetation indices as an indicator of forest structure may be a valuable tool for landscape planning, and for decisions on conservation and restoration strategies. In the Atlantic Rainforest, this analysis improves monitoring through diagnosing forest fragments instead of quantifying only forest area reduction (Rede de Ongs da Mata Atlântica et al., 2001). This paper presents an evaluation of the relationships between forest structure and vegetation indices in Atlantic Rainforest fragments, in south-eastern Brazil.

2. Methods

2.1. Study site

The Guapiaçú River Basin is located in the Municipalities of Guapimirim and Cachoeiras de Macacu (22°39′36″S, 43°01′02″W and 22°21′13″S, 42°39′46″W), in Rio de Janeiro State, southeastern Brazil (Fig. 1). The basin has 573.54 km^2 and its main land-cover type is dense evergreen rainforest (Rizzini, 1979). It is situated in the Atlantic slope of Serra do Mar, encompassing hills and lowlands towards the Guanabara Bay. Most forest fragments occur on hilltops from 100 to 200 m above sea level, and are surrounded by pasture and crop land. These forest fragments are usually found inside small farms (family agriculture, settlement areas or country houses) and sometimes within large farms (cattle raising) (Cabral and Fiszon, 2004). The forest is dense and evergreen, highly diverse, 45 m or taller, with three layers of trees, emergent trees, over a main canopy from 5 to 10 m, with smaller, shade-dwelling trees below (Mello et al., 2003). Common tree species belong to the following families: Myrtaceae, Sapotaceae, Palmae, Rutaceae, Meliaceae, Rubiaceae, Euphorbiaceae, Leguminosae, Melastomataceae and Araliaceae (Kurtz and Araújo, 2000).

Nine forest fragments and continuous forest areas nearby were studied (Fig. 1). The forest fragments are small (less than 100 ha) and surrounded by pasture and crop lands. The continuous forest area is situated at the base of the mountain of Serra dos Órgãos, inside a park called Estação Ecológica do Paraíso, which is mainly covered by dense humid evergreen forest.

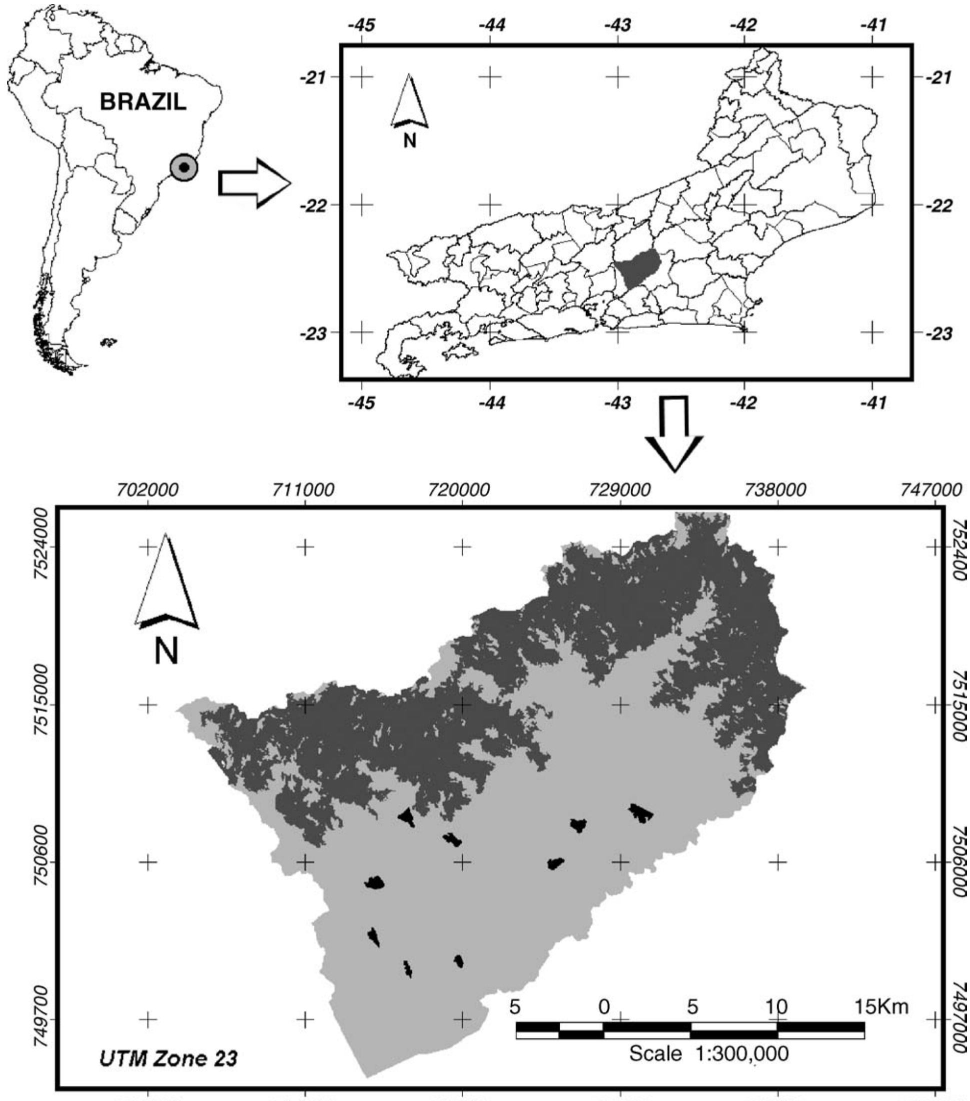

Fig. 1. Location of nine forest fragments (black) and continuous forest (dark gray) studied in the Guapiaçú River Basin, in Rio de Janeiro State, southeastern Brazil. In the upper-right inset, the Guapiaçú River Basin is shown in Rio de Janeiro State, using lat/long unit.

2.2. Image preprocessing

Two Landsat 7 ETM+ images acquired in humid (February 28, 2000) and dry (August 9, 2001) seasons (path 217/row 76) were used. The use of images from different seasons was due to the fact that vegetation indices change because of seasonal variations in vegetation vigor (Campbell, 1996; Poveda and Salazar, 2004). The six spectral bands of ETM+ sensor with 30 m spatial resolution (bands 1, 2, 3, 4, 5 and 7) were registered through planimetrically corrected maps, obtaining a 0.70 pixel precision RMSE of registration model. The Universal Transverse Mercator (UTM) projection with longitude origin at 45°00′00″W and datum SAD69 were used. All image preprocessing was done in SPRING, a GIS and remote sensing image processing system with an object-oriented data model that provides the integration of raster and vector data representations in a single environment. The software was developed by the Brazilian National Institute for Space Research (INPE) and available on the web free of charge (http://www.dpi.inpe.br/spring/index.html).

Ratio values and vegetation indices may be sensitive to atmospheric degradation (Campbell, 1996). To correct atmospheric degradation, the Improved Chavez Method, which showed good results, was used (Pax-Lenney et al., 2001). Chavez (1996) proposed an atmospheric correction method based on image data, without the need of meteorological measurements at the time of image acquisition. This method acts on atmospheric scattering (additive scattering and multiplicative transmittance effects) using a dark object or feature in the scene, which has near zero reflectance, to calculate the value contributed by atmospheric scattering for each band (Campbell, 1996; Chavez, 1996). To compare values of vegetation indices over time, digital values were reduced to radiances before calculating ratios, to account for differences in calibration of sensor (Campbell, 1996). A LEGAL routine in SPRING, called reflete_float.alg, was used to transform digital values to radiances (Luiz et al., 2003).

Three vegetation indices: normalized difference vegetation index, moisture vegetation index using Landsat's band 5 (MVI5) and moisture vegetation index using Landsat's band 7 (MVI7) were used. NDVI is formed by combinations between the red band and near-infrared band, whereas MVI5 and MVI7 use a similar equation substituting the red band with the mid-infrared band (Table 1). In NDVI, the ratio between red and near-infrared bands is used to emphasize the spectral differences between these bands, showing vegetation conditions (Rouse et al., 1974). Nevertheless, visible bands suffer more atmospheric scattering than infrared bands (Campbell, 1996). Using mid-infrared bands instead of red band, which suffer less atmospheric scattering, may produce higher correlations to vegetation targets on land surface (Sousa and Ponzoni, 1998). Another constraint of visible and near-infrared bands usage is the asymptotic behavior of reflectance when a biophysical parameter of vegetation increases continuously. This constraint, called saturation, is often found in tropical forests (Huete et al., 1997). Using mid-infrared bands, we expect to reduce the saturation effect and increase sensitivity over dense canopies as showed by Freitas and Cruz (2003).

Table 2
Variables representing vegetation indices for each study site

Variables	Description
NDVIm00	Mean of NDVI in humid season
NDVIr00	Range of NDVI in humid season
MVI5m00	Mean of MVI5 in humid season
MVI5r00	Range of MVI5 in humid season
MVI7m00	Mean of MVI7 in humid season
MVI7r00	Range of MVI7 in humid season
NDVIm01	Mean of NDVI in dry season
NDVIr01	Range of NDVI in dry season
MVI5m01	Mean of MVI5 in dry season
MVI5r01	Range of MVI5 in dry season
MVI7m01	Mean of MVI7 in dry season
MVI7r01	Range of MVI7 in dry season

The vegetation index values were extracted from each polygon representing the forest fragment and the continuous forest studied in the field, through the Idrisi 32 software (Clark Labs, Clark University). The variables used to represent vegetation indices of each study site were mean and range of each vegetation index, for each season (Table 2). All variables were transformed into logarithms to satisfy the test assumptions of normality as well as to examine correlation (Gamon et al., 1995; Legendre and Legendre, 1998).

2.3. Measurements of forest structure

Measurements of forest structure were taken in dry season (from June to August 2001) to coincide with the dry season image. Two transects were established crossing each forest fragment in north–south and east–west directions. In the continuous forest area, four transects were set 300 m away from the forest edge.

Table 1
Equations of vegetation indices used in this study

Vegetation indices	Equation
Normalized difference vegetation index	NDVI = (NIR − RED)/(NIR + RED)
Moisture vegetation index using Landsat's band 5	MVI5 = (NIR − MIR5)/(NIR + MIR5)
Moisture vegetation index using Landsat's band 7	MVI7 = (NIR − MIR7)/(NIR + MIR7)

Table 3
Size and sample size of forest fragments

Fragments	Size (ha)	Number of rectangular plots	Sample size (m^2)
Frag4	30.33	31	1550
Frag5	19.62	32	1600
Frag6	26.73	35	1750
Frag9	41.13	37	1850
Frag13	61.38	33	1650
Frag16	84.33	30	1500
Frag17	37.35	37	1850
Frag18	24.39	30	1500
Frag19	20.88	24	1200
Continuous forest	20429.00	45	2250

Along each transect, 5 m × 10 m rectangular plots were set 30 m apart (Table 3). The following measurements were taken in each rectangular plot: tree diameter at breast height ($H = 1.30$ m), tree and trunk heights. Tree height was measured from ground level to tree top, while trunk height was measured from ground level to crown base. The threshold used in selecting trees for measurement was a diameter at breast height larger than 1.59 cm. The variables of forest structure were: multiple-stemmed trees, density of trees, mean and range of tree diameter, mean and range of tree height and average of basal area (Table 4). All forest measurements were transformed into only one value per variable representing each one of the nine forest fragments and the continuous forest studied, similarly to vegetation indices, allowing a forest fragment level of analysis. All variables were transformed into logarithms to satisfy the test assumptions of normality (Legendre and Legendre, 1998).

Basal area is the cross-sectional area of the trees from a forest block (Whitmore, 1990). This tree measurement shows strong correlations with tree crown cover and can be used as an indicator of forest biomass (Cain and Castro, 1959; Brunig, 1983). The measurements chosen aimed to represent the structural maturity of forest, including biomass. By studying tropical forest at different successional stages, Oliveira (2002) found a positive correlation between forest age and mean tree diameter, mean canopy height and basal area and a negative correlation between forest age and multiple-stemmed trees. Thus, a mature tropical forest should have more big trees and fewer multiple-stemmed trees than those found in a young forest. Multiple-stemmed trees may be caused by human activity or natural causes (Dunphy et al., 2000; Oliveira, 2002). An example of human activity causing a higher number of multiple-stemmed trees is subsistence agriculture, where people slash and burn trees, but usually keep trunks on the ground, allowing stem re-growth after land is abandoned to fallow (Oliveira, 2002). On the other hand, some natural treefall gaps and hydric or saline stresses may cause higher frequencies of multiple-stemmed trees (Dunphy et al., 2000). However, in the forest fragments studied here, multiple-stemmed trees seem to be related to human activity because evidence of forest exploitation was observed (Freitas, 2004).

2.4. Analysis

Data analysis was done in two parts: (1) using combined forest fragments and continuous forest sample data and (2) using only forest fragments sample data. Pearson correlation was used to associate values of vegetation indices and forest measurements of nine fragments and continuous forest area. Linear regression analysis was done to describe the relationships between forest structure and vegetation indices. Forest measurements were used as the dependent

Table 4
Equations of variables of forest structure

Forest variables	Equation
Multiple-stemmed trees (%)	Number of trees with trunk height lower than the breast height (1.30 m)/total of trees measured in the fragment
Density of trees (trees/m^2)	Total of trees measured in the fragment/sample size
Tree diameter (DBH) (cm)	$DBH = PBH/\pi$
Basal area of tree (BA_t) (m^2)	$BA_t = ((DBH^2 \times \pi)/4)/10{,}000$
Average of basal area (BA) (ha/m^2)	$BA = (\text{sum of } BA_t \times 10{,}000)/\text{sample size}$

Where PBH, tree perimeter at breast height (1.30 m).

Table 5
Pearson correlation between variables of forest structure and vegetation indices, using combined forest fragments and continuous forest sample data, showing correlation coefficients (R) and significance test (p)

	NDVI m00	NDVI r00	MVI5 m00	MVI5 r00	MVI7 m00	MVI7 r00	NDVI m01	NDVI r01	MVI5 m01	MVI5 r01	MVI7 m01	MVI7 r01
Multiple-stemmed trees	−0.485	−0.073	−0.699*	−0.602	−0.657*	−0.038	−0.513	−0.394	−0.703*	−0.251	−0.671*	−0.391
Density of trees	0.613	0.045	0.808**	0.471	0.816**	0.113	0.508	0.201	0.591	0.215	0.564	0.434
Mean of tree diameter	−0.290	0.444	−0.246	0.048	−0.327	0.208	−0.217	0.322	−0.007	0.179	−0.050	0.155
Mean of tree height	0.094	0.347	0.424	0.313	0.247	0.377	0.152	0.390	0.748*	−0.177	0.717*	0.073
Range of tree diameter	0.360	0.171	0.312	0.796**	0.399	0.173	0.585	0.270	0.427	0.409	0.482	0.140
Range of tree height	0.532	0.169	0.785**	0.405	0.680*	0.305	0.346	0.406	0.850**	−0.045	0.816**	0.414
Average of basal area	0.514	0.249	0.646*	0.714*	0.650*	0.216	0.513	0.445	0.628*	0.406	0.609	0.512

Vegetation indices abbreviations: m, mean; r, range; 00, humid season; 01, dry season.
* $p \leq 0.05$.
** $p \leq 0.01$.

variables and vegetation indices were the independent variables in the regression models. The intention is to generate models that could explain field-measured characteristics of forest structure through remote sensing based indices. In linear regression analysis, stepwise procedure was used to select significant variables for model. Pearson correlation and linear regression analysis were done in the STATISTICA computer package (StatSoft Inc.).

3. Results and discussion

On the analysis using combined forest fragments and continuous forest sample data, strong correlations between the vegetation indices MVI5 or MVI7, and forest structure were observed (Table 5). MVI5 and MVI7 means in humid season were positively correlated with tree density, canopy height range, average of basal area and negatively with multiple-stemmed trees (Table 5). MVI5 range in humid season was positively correlated with tree diameter and average of basal area (Table 5). MVI5 and MVI7 means in dry season were positively correlated with mean and range of canopy height, and negatively with multiple-stemmed trees (Table 5). Moreover, MVI5 mean in dry season was positively correlated with average of basal area (Table 5). No NDVI variable was significantly correlated with forest structure measurements (Table 5). Most of MVI5 and MVI7 variables showed similar correlations except for MVI7 ranges in the humid season.

Linear regression using stepwise procedure showed MVI5 in both seasons and MVI7 mean in humid season as the best fitted models (Table 6). Forest measurements associated to stratification, mean and range of tree height, density of trees, range of tree diameter and basal area, showed a positive slope of linear regression line, whereas that associated to forest degradation, multiple-stemmed trees, showed a

Table 6
Linear regression models using forest structure as the dependent variables and vegetation indices as the independent variables, using combined forest fragments and continuous forest sample data

Model	R^2	F	p
HEIGHTr = 3.714 + 0.850 × MVI5m01	0.723	20.91	<0.002*
DENS = −0.148 + 0.816 × MVI7m00	0.666	15.92	<0.004*
DBHr = 2.769 + 0.796 × MVI5r00	0.634	13.84	<0.006*
HEIGHTm = 1.726 + 0.748 × MVI5m01	0.559	10.15	<0.013*
BA = 2.349 + 0.714 × MVI5r00	0.509	8.303	<0.021*
MULTSTEM = −8.280 − 0.703 × MVI5m01	0.494	7.801	<0.024*

Where HEIGHTr, range of tree height; BA, average of basal area; DENS, density of trees; DBHr, range of tree diameter; HEIGHTm, mean of tree height; MULTSTEM, multiple-stemmed trees. Vegetation indices abbreviations: m, mean; r, range; 00, humid season; 01, dry season.
* $p \leq 0.05$.

Table 7
Correlation between variables of forest structure and vegetation indices, using only forest fragments sample data, showing correlation coefficients (R) and significance test (p)

	NDVI m00	NDVI r00	MVI5 m00	MVI5 r00	MVI7 m00	MVI7 r00	NDVI m01	NDVI r01	MVI5 m01	MVI5 r01	MVI7 m01	MVI7 r01
Multiple-stemmed trees	−0.377	0.131	−0.625	−0.352	−0.538	0.184	−0.444	−0.237	−0.701*	−0.014	−0.662*	−0.064
Density of trees	0.550	−0.254	0.797**	−0.063	0.762*	−0.168	0.444	−0.091	0.598	−0.128	0.560	−0.004
Mean of tree diameter	−0.357	0.431	−0.325	−0.063	−0.443	0.178	−0.265	0.300	−0.039	0.140	−0.083	0.100
Mean of tree height	0.119	0.385	0.486	0.520	0.309	0.419	0.174	0.445	0.785*	−0.173	0.753*	0.137
Range of tree diameter	0.210	−0.022	0.106	0.670*	0.171	−0.029	0.536	0.062	0.361	0.211	0.430	−0.369
Range of tree height	0.449	0.025	0.739*	0.115	0.592	0.181	0.252	0.280	0.856**	−0.307	0.816**	0.179
Average of basal area	0.4415	−0.045	0.619	0.259	0.521	−0.128	0.521	0.242	0.801**	0.076	0.765*	−0.058

Vegetation indices abbreviations: m, mean; r, range; 00, humid season; 01, dry season.
* $p \leq 0.05$.
** $p \leq 0.01$.

negative slope. This pattern suggests that MVI5 and MVI7 should explain the structural maturity of forest. MVI5 and MVI7 better performance in comparison to NDVI could be explained by the saturation effect, reducing the sensitivity over dense canopies to NDVI (Huete et al., 1997). Gamon et al. (1995) showed a non-linear relationship between NDVI and vegetation measurements (leaf area index, green biomass and chlorofila) in temperate forest. However, they pointed out the restrictions of using NDVI as an indicator of canopy structure and chemical contents for well-developed canopies. They considered that beyond a certain canopy density, the addition of more canopy layers make little difference in the relative reflectance of red and near-infrared radiation, and thus little difference in NDVI. This constraint caused by saturation was also noted by Shimabukuro et al. (1998) in Amazonian regenerating forests, and by Bawa et al. (2002) in Indian evergreen forests. In the Guapiaçú River Basin, a stronger saturation in NDVI, followed by MVI7 and MVI5 was observed (Freitas and Cruz, 2003). However, NDVI showed good results in a study on vegetation at early successional stages in Amazonian Forest, establishing relationships to basal area and leaf area index (Amaral et al., 1997). Similarly, studies in drier forests did not find constraints due to saturation in NDVI, such as deciduous tropical forest in India (Bawa et al., 2002), and dry tropical forest in Costa Rica (Arroyo-Mora et al., 2003). It seems that MVI5 and MVI7 show best performances in dense humid forests, whereas NDVI is a good indicator of green biomass in deciduous and dry forests.

On the analysis using only forest fragments sample data, most of the high correlations were maintained but a stronger correlation between mean of MVI5 and MVI7 in dry season to average of basal area was noticed (Table 7). This shows that these variables are sensitive to small differences in structural maturity of forests, because by excluding the continuous forest area, the extreme point of analysis (with the highest value of average of basal area, 62.3 m^2/ha) was lost. It is important to notice that NDVI produced weak correlations with forest measurements, whereas MVI5 and MVI7 in dry season produced higher correlations than those in wet season. As discussed before, this stronger correlation between forest measurements and MVI5 and MVI7 in dry season may be related to the similar time period of forest measurements and image acquisition or to a stronger saturation effect observed in NDVI.

Linear regression models using only forest fragments sample data had mean and range of MVI5 in both seasons and range of MVI7 in wet season in the best fitted models (Table 8). Using only fragments, the higher R^2 found were those using MVI5 from dry season image, except for MVI7, maybe due to edge effect. Forest fragments could be more sensitive to climate variations than a continuous forest because of edge effect (Laurance and Bierregaard, 1997). Thus, on the analysis using only forest fragments sample data, vegetation indices from dry season, which is the same season and year of field data, were included in the best-fitted models. As found in the linear regression including continuous forest, basal area, mean and range of tree height, density of trees and

Table 8
Linear regression models using forest structure as the dependent variables and vegetation indices as the independent variables, using only forest fragments sample data

Model	R^2	F	p
BA = 3.641 + 1.067 × MVI5m01 + 0.572 × MVI5r01	0.898	26.28	<0.001*
HEIGHTm = 2.047 + 0.519 × MVI7r00 + 0.847 × MVI5m01	0.882	22.47	<0.002*
HEIGHTr = 3.529 + 0.856 × MVI5m01	0.733	19.23	<0.003*
DENS = 1.668 + 0.797 × MVI5m00	0.635	12.16	<0.010*
MULTSTEM = −7.346 − 0.701 × MVI5m01	0.491	6.751	<0.036*
DBHr = 2.785 + 0.670 × MVI5r00	0.448	5.688	<0.049*

Where HEIGHTr, range of tree height; BA, average of basal area; DENS, density of trees; HEIGHTm, mean of tree height; MULTSTEM, multiple-stemmed trees; DBHr, range of tree diameter. Vegetation indices abbreviations: m, mean; r, range; 00, humid season; 01, dry season.
* $p \leq 0.05$.

range of tree diameter showed a positive slope of linear regression line, whereas multiple-stemmed trees showed a negative slope. This confirms the pattern indicating that MVI5 and MVI7 could explain stratification and structural maturity of forest. Notice that MVI5 is more frequent than MVI7 in all regression models. So, as observed by Freitas and Cruz (2003), a lower saturation of MVI5 seems to improve the relationship between forest measurements and this vegetation index. These results indicate that MVI5 could be a powerful tool to estimate structural forest maturity in tropics.

The relationships between forest structure measurements and vegetation indices found here must be tested in other tropical rainforest sites, before they are widely used to estimate forest structure from space. This tool may be useful to evaluate tropical forest types instead of only mapping them. It does not substitute fieldwork, but a first assessment in a large area would be interesting to select field study sites. A few studies have found correlations between vegetation indices based on infrared bands and structure vegetation in tropics. Boyd et al. (1999) showed a better performance in vegetation indices based on mid-infrared than in NDVI, when they were correlated to total biomass of Cameroonian tropical forests. Sousa and Ponzoni (1998) found higher correlations between timber volume and MVI5 in comparison to NDVI, in a tropical pine plantation. Foody et al. (2001) observed a higher sensitivity of Landsat's band 5, followed by bands 2 and 4, and a lower sensitivity of Landsat's band 3 to estimate biomass of Bornean tropical rain forests. It is important to notice that MVI5 uses Landsat's bands 5 and 4, the more sensitive bands to estimate biomass, as remarked by Foody et al. (2001). Relating many vegetation indices and forest stand parameters in the Amazon basin, Lu et al. (2004) found a stronger correlation between these parameters and vegetation indices using Landsat's band 5 than those using bands 3 and 4. Despite its high popularity, NDVI seems to provide good estimates in deciduous and dry forests, whereas MVI5 is a better indicator of structural forest maturity in tropics.

Regarding the transferability of relationships between biophysical characteristics and vegetation indices to other sites and times, Foody et al. (2003) pointed out some constraints, such as differences in image processing techniques used, biomass estimate depending on specific allometric equations, dbh threshold used in selecting trees for measurement and differences between season and year of field work and image. When there is no general allometric equations available and no floristics studies were done, the use of basal area instead of biomass is proposed here, because basal area does not depend on specific allometric equations (Araújo et al., 1999). Moreover, image acquisition time must be in the same season and year of field data. Following this advice and using similar image processing techniques, we expect to increase the transferability of relationships between forest structure measurements and vegetation indices found here for other tropical rainforest sites.

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