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Landscape pattern and spatial variability of leaf area index in Eastern Amazonia

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Abstract

Uncertainties about the implications of land-cover heterogeneity on the Amazonian carbon (C) and water cycles are, in part, related to the lack of information about spatial patterns of key variables that control these fluxes at the regional scale. Leaf area index (LAI) is one of these key variables, regulating a number of ecosystem processes (e.g. evaporation, transpiration and photosynthesis). In order to generate a sampling strategy for LAI across a section of Amazonia, we generated a landscape unit (LU) map for the Tapajós region, Eastern Amazonia, as a basis for stratification. We identified seven primary forest classes, stratified according to vegetation and/or terrain characteristics, and one secondary forest class, covering 80% of the region. Primary forest units were the most representative, covering 62% of the total area. The LAI measurements were carried out in 13 selected LUs. In each LU, we marked out three 50 m × 50 m plots giving a total number of 39 plots (9.75 ha). A pair of LAI-2000 plant canopy analysers was used to estimate LAI. We recorded a total of 25 LAI measurements within each plot. We used the field data to verify the statistical distribution of LAI samples, analyse the LAI variability within and among sites, and show the influence of sample size on LAI variation and precision. The LAI showed a high coefficient of variation at the plot level (0.25 ha), from 5.2% to 23%, but this was reduced at the landscape unit level (three co-located plots, 1.8–12%). The level of precision was <10% and 15% at the plot and landscape unit level, respectively. The LAI decreased from a dense lowland forest site (5.10) to a secondary forest (3.46) and to a pasture site (1.56). We found evidence for differences in the scale of spatial heterogeneity of closed canopy forest versus open canopy forest and palm forests. Landscape variables could, in part, explain differences in LAI among forest sites, and land use is an important modifier of LAI patterns. The stratified LAI sampling proposed in the present study could cope with three important aspects of C and water fluxes modelling: (1) optimise the information obtained from field measurements, which is an advance for models parameterisation, compared to the usual random sampling; (2) generate information for a subsequent scaling up of point field

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measurements to surfaces covering the whole region; and (3) build a useful basis for validation of estimations, based on remote sensing data, of LAI in the Tapajós region. The variability of LAI in the Tapajós region showed that this variable is a source of uncertainty for large-scale process modelling.

Keywords: GIS; Tapajós National Forest; LAI; Amazon forest; Land use; Remote sensing

1. Introduction

This study is a part of the efforts of LBA-Ecology, a Brazil-led international study, to understand the implications of forest heterogeneity and land use on the Amazonian carbon (C) and water cycles, which are important components of global biogeochemical cycling. The high C stocks, a total of 400 Pg C (IPCC, 2000), and the high forest productivity (Malhi et al., 1999) of the Amazon Basin suggest that the region has a significant role in the global carbon balance. However, the function of the Amazon as a biome is still unclear. Depending on the environmental conditions of specific sites, Amazon forest can act as a C sink (Malhi et al., 1998; Phillips et al., 1998) or a C source (Saleska et al., 2003). Nevertheless, spatially precise estimates of production and biomass are very rare due to the high heterogeneity of tropical ecosystems (Schimel et al., 2001). The goal of this study was to describe spatial patterns of a key variable that controls water–carbon fluxes at the regional scale in the Amazon ecosystem, the leaf area index (LAI). This information is crucial for characterizing changes caused by human intervention in forest ecosystems, as well as for allowing accurate large-scale estimations of forest dynamics (e.g. productivity). Land use planning in Amazonian region depends on the applicability of process-based models to quantify accurately the implications of land cover changes on the sustainability of forest systems.

Leaf area index (one side leaf area per unit ground area) is an important parameter that regulates a number of eco-physiological processes, such as evaporation, transpiration and photosynthesis (Cutini et al., 1998). The impact of changes in leaf area index on soil variables such as temperature and water content, which have indirect effects on production, has been also reported (Parton et al., 1996). LAI has been considered a key variable in scaling up forest productivity from leaf to canopy level in various stand- and regional-scale models (e.g. Running and Coughlan, 1988; Williams et al., 1996; Sellers et al., 1996). Incorporating the heterogeneity of variables like LAI across a range of scales, from stand to region, within predictive models, is vital. The lack of information about LAI values and their variability in the Amazon Basin currently restricts accurate estimations of forest production from process models. While extensive measurements and studies of LAI have been made for small-stature vegetation (agricultural crops and plantations), measurements and studies for natural ecosystems (forests and savannas) on global scale remain sparse (Shabanov et al., 2003). High biodiversity, and topographic and edaphic heterogeneity, as well as varied land use patterns, are the main factors that contribute to variability in LAI in Amazonian ecosystems. Human occupation in the Tapajós region has made inroads along the BR-163 route and other small roads. As in other Amazonian localities, this pattern of deforestation followed by fire and the establishment of subsistence cultures and pastures is strongly linked to the roads that cross Amazonian forest (Nepstad et al., 2001; Alves, 2002). Abandonment of unproductive areas after a few years of cultivation permits the reestablishment of forest. Deforestation and abandonment results in landscape fragmentation, with mosaics of secondary forests, pastures and cultivated areas inserted in a primary forest matrix. Quantifying and understanding how human intervention affects ecological variables (such as LAI) over landscapes are crucial to improving the accuracy of forest productivity estimations at the regional scale.

Franklin and Woodcock (1997) highlighted the importance of mapping vegetation patterns for understanding the responses and feedbacks of vegetation cover to global climatic changes. Their study emphasized the need to consider the landscape mosaic structure, where each area is grouped into distinct units in relation to a determined attribute. In this study, we adopt the 'landscape unit concept', reviewed by Zonneveld (1989), to generate homogeneous units based on available cartographic information, such as vegetation and topographic maps, to analyse landscape patterns and stratify, and thus simplify, LAI data collection in the field.

The landscape unit concept is based on the hypotheses that landscape heterogeneity results from the interaction of different types of vegetation, relief and land use. Thus, a combination of elevation, vegetation and land-use maps can be used as a basis for stratifying regions into homogeneous zones. We further hypothesise that leaf area index of each landscape unit is directly associated with the uniquely different combinations of landscape variables that define the unit, and that the variability of LAI, and consequently the precision of measurements, are dependent on the scale of observations.

The specific aims of this study were to: (1) generate a landscape unit map for the Tapajós region by the analysis and integration of vegetation and altimetry maps; (2) associate this map with a Thematic Mapper (TM)/Landsat scene, in order to identify disturbed areas, and in order to stratify leaf area index sampling in the field; (3) verify the LAI samples' frequency distribution; (4) analyse the LAI variability within and among the sites; and (5) evaluate the precision of the LAI measurements, and the sample size required for characterizing LAI variation at various scales with acceptable confidence limits.

2. Study area

The study was carried out at the Alto Tapajós region in Pará State. We selected a 13,164 km^2 area to the east of Tapajós River and south of Amazon River, lying between latitudes 2°24′2″S and 4°01′1″S and longitudes 55°30′2″W and 54°29′5″W. About a half of this area is occupied by the Tapajós National Forest (TNF).

According to Köeppen classification, the predominant climate is the AmW (Eidt, 1968). The annual precipitation average from 1968 to 1998 at the Santarém weather station was 2272 mm (ANEEL, 2000). The region has well-defined dry and wet seasons, with the preponderance of rain events concentrated between December and May (about 70% of the annual amount) (Espírito Santo, personal communication).

Soils in the region were classified mainly as dystrophic yellow latosol in two textural classes: clay and medium clay, according to the Brazilian system (RADAMBRASIL, 1976). Patches of red–yellow podisolic soils can also be observed in the north portion of the region, close to the Santarém city, in some parts along the right side of Tapajós River and in the southern section of TNF (PRIMAZ, 1998). A recent survey of soil textures found that soils dominated by clay or sand were found in close proximity in the northern TNF (Williams et al., 2002).

According to RADAMBRASIL (1976) physiognomic–ecological nomenclature, dense forest is the main vegetation type in the region with a high number of emergent tree species. Within this forest, there are patches of dense forest with uniform canopy, as well as open canopy forest without palms, characterized by presence of lianas. The canopy at Tapajós forest has a high biodiversity. Williams et al. (2002) surveyed 1380 stems across 13 studied sites (3.25 ha), identifying 505 distinct common names (species/genus) among them. The dominant canopy species in the region are the Castanheira (*Bertholletia excelsa*), Angelim (*Hymenolobium excelsum*, *Pithecelobium excelsum*, *Pithecelobium racemosum* and *Dinizia excelsa*), Tauari (*Couratari* spp.), Maçaranduba (*Manilkara huberi*), Jutaí açu (*Hymenaea courbaril*) and Pau d'arco (*Tabebuia* spp.) (Silva et al., 1985).

3. Materials and methods

3.1. Generation of landscape units

A vegetation thematic map (RADAMBRASIL, 1976) and two topographic maps (Diretoria de Serviço Geográfico, 1984) corresponding to the quadrants Santarém (SA-21-Z-B) and Aveiro (SA-21-Z-D) at 1:250,000 scale were digitised and processed in the SPRING 3.6 software (Câmara et al., 1996). The digital maps were georeferenced in the Universal Transverse Mercator (UTM) projection and in the South American Datum (SAD-69) and co-registered. Vegetation classes and topographic features, such as contours and drainage lines, and spot elevations, were extracted and stored in a vector format.

3.1.1. Vegetation

We quantified the number and the area of vegetation classes. For simplification, we used an aggregation routine based on the following criteria: (1) the six most representative classes of primary forest, which had areas >5% of the total, were maintained; (2) secondary vegetation types were grouped into two classes, with and without palms (Vss and Vsp); (3) all of pasture or agriculture classes (Ap) were grouped in one unique class; (4) dense forest with emergent trees classes (Dbe) that had an area <5% were aggregated in a Dbe plus others class (Dbe + Outras); and (5) all the other vegetation types were merged in a class called 'others' (Outras). For this aggregation and posterior integration, the vegetation map was converted from a vector to a raster format at 250 m × 250 m spatial resolution. The explanation of the abbreviations used to represent all the vegetation types considered in this study is provided in Table 1.

3.1.2. Topography

We built a digital terrain model for the study area using the digitalized terrain features. At first, a triangular irregular network (TIN) was produced using the drainage as brake lines. Afterward, we converted the TIN in a regular network with the same spatial resolution as the vegetation map. Finally, a raster altimetry thematic map was produced by slicing the region into six 50 m elevation intervals, varying between 0 and 300 m above the sea level.

Table 1
Description of the abbreviations used to represent the vegetation types considerate for this study in the Tapajós region

Abbreviation	Description
Asp	Open canopy sub-montana forest with palm
Dbe	Dense lowland forest with emergent trees
Dbu	Dense lowland forest with uniform canopy
Dse	Dense sub-montana forest with emergent trees
Abp	Open canopy lowland forest with palm
Asp	Open canopy sub-montana forest with palm
Abc	Open canopy lowland forest
Ap	Agriculture and pasture areas
Vsp	Secondary vegetation with palms
Vss	Secondary vegetation without palms
Outras	Other forests types

3.1.3. Landscape units

Boolean operations were used to integrate the vegetation and altimetry layers for the generation of a landscape units (LUs) map. Then, each vegetation class could be stratified in six distinct units according to altimetry characteristics. Similarly to the analysis of the vegetation map, we used a minimum area threshold analysis for reclassifying the landscape unit map. All the units containing primary forest, secondary forest, and pasture with a relative area lower than 2.5%, 3.0% and 10.0% of the total area, respectively, were considered unrepresentative and were excluded from the analysis. The excluded LUs accounted with 16.7% of the whole area.

3.2. Field survey

The fieldwork was undertaken in October 2002, during the dry season. To access the LUs, we used the BR-163 road. We used a TM/Landsat scene (path 227, row 62) (Fig. 1) over-layered by our LUs map to select the study sites. The satellite image interpretation permitted us to identify other units, including one characterized by fire occurrence, a forest dominated by the Babaçu palm (*Orbignya martiana*), and a open canopy forest at the southern of TNF, that were included in the sampling. We also surveyed a known selective logging site. In spite of having stratified the pasture areas into three units and the secondary vegetation in two units, we assumed for this study only one pasture and one secondary forest unit in the sampling design. We opted to group these units because we were mainly focussing on characterizing LAI patterns at primary forest sites that dominated the study region. We surveyed a total of 13 sites (from A1 to A13), including the two tower sites (km 83 and km 67) and the pasture site (km 117) of the Large-Scale Biosphere–Atmosphere Experiment in Amazônia (LBA) (Fig. 1).

Sites A1, A4, A5, A7, A8 and A10–A13 were located in nine primary forest areas, stratified according to vegetation and/or terrain characteristics, site A2 was situated in a selective logging area, that has been exploited since September 2001, while A6 was sited in a fire damage area, burned at least 4 years

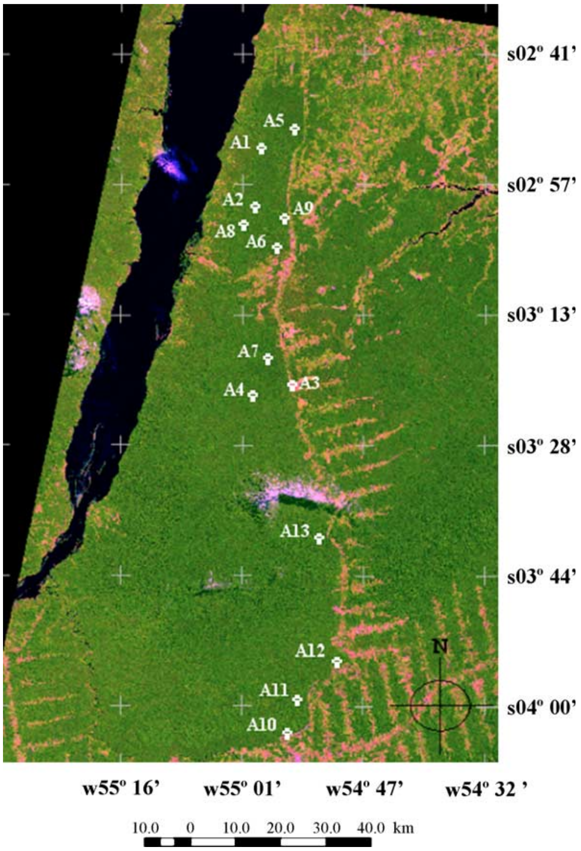

Fig. 1. The location of the 13 sites along the BR-163 Santarém-Cuiaba route (eastern Tapajós National Forest border) in Pará State, Brazil. Locations from A1 to A13 are marked on the Thematic Mapper/Landsat scene, path 227, row 62, 10″ dislocated south, from 2 August 1999, 30 m resolution. The image is composition of bands 5 (R), 4 (G) and 3 (B). The Tapajós River can be note in black along the western edge of the TNF. Differences in spectral and textural patterns permitted the separation of sites A5, A6 and A10 from the other primary forest sites.

ago. The primary forest sites A5 and A10 and the fire damage area A6 could be easily separated from the other sites due to particular spectral and textural characteristics in the Landsat image (Fig. 1). The pasture site (A3) was dominated by an incomplete *Brachiaria brizantha* canopy, with ~50 cm in height, in which the tussock structure of the grass was apparent. Within this area, it was possible note also the occurrence of shrubs and bare soil patches. The secondary forest corresponded to the A9 site and was an abandoned pasture area dating from the 1970s, according to local people, but the user practices after the abandonment are imprecisely known (Fig. 1).

3.3. Leaf area index sampling

A pair of LAI-2000 plant canopy analysers (PCA) (Li-Cor Inc., Lincoln, NE, USA) was used to estimate leaf area index. One sensor, set in the remote mode to monitor changes in sky conditions, was located in a clearing close to each site, and the other was deployed in the sampling plots. The two sensors were oriented in the same direction, pointed away from the sun. The measurements were done in the early morning or late afternoon to minimize the incidence of direct sun on the sensor. A 45° view cap was used in order to avoid the computation of points with a mixture of open and closed canopy, due to the presence of tree-fall gaps. Leaf area index values were calculated from the full five-sensor rings integration.

In each of the 13 selected units, we marked out 3 plots, each with a 0.25 ha area (50 m × 50 m) giving a total number of 39 plots (9.75 ha). Measurements within the plots were carried out in a regular grid with 10 m spatial resolution. We recorded a total of 25 LAI measurements in each plot. In addition to this sampling, we marked out in 3 (A4, A5 and A7) of the 13 sites, 2 extra plots (10 m × 250 m = 0.25 ha) that were used to investigate the effect of sample size (from 0.25 to 1.25 ha) in LAI variation. In each of the plots, we made 25 measurements spaced 10 m apart.

3.4. Statistical analysis

Shapiro–Wilk's *W*-test for normality was applied in order to verify the frequency distribution of the LAI samples in each one of the 39 plots. We used this test to confirm also the distribution of the 75 samples in each one of the 13 sites as well as the distribution of the whole LAI data ($N = 900$) in forest sites. The Shapiro–Wilk's *W*-test result for all LAI data, described in Section 4, justified the parametric statistics used to analyse LAI data in this study.

Coefficients of variation (standard deviation divided by the mean) were calculated in order to describe the intra- and inter-plot and inter-site variability. A linear regression analysis was carried out to assess the dependency of the coefficient of variation on the sampling size area in LAI samples collected at the sites A4, A5 and A7. We also calculated the level of precision (LOP), at 95% confidence limit, of these interactions.

In order to check the validity of our LAI sampling design at the sample, plot and unit levels, we investigated the relationship between sample size and precision of these measurements. The precision of an arithmetical mean of a sample is usually described by the confidence interval:

$$\left(\bar{x} - t_{n-1,\alpha}\frac{s}{\sqrt{n}}, \bar{x} + t_{n-1,\alpha}\frac{s}{\sqrt{n}}\right) \quad (1)$$

where $\bar{x}$ is the arithmetical mean, s the standard deviation of the sample, $t_{n-1,\alpha}$ the Student's t-value for $n-1$ degrees of freedom for $1-\alpha$ level of confidence, n the sample size (for this study, the total number of samples, number of samples per plot, and number of plots).

The half-width of this confidence interval, $d = t_{n-1,\alpha}s/\sqrt{n}$, gives an absolute measure of precision. The precision (r) is expressed as a percentage proportion of the arithmetical mean ($\bar{x}$):

$$r = t_{n-1,\alpha}\frac{s}{\bar{x}\sqrt{n}} \times 100\% \quad (2)$$

and gives a relative measure of precision. This measure is directly linked to the measured of relative variability that we are using here to evaluate LAI data, the coefficient of variation ($\mathrm{CV} = s/\bar{x}$). Assuming a 95% confidence level and exploiting the fact that $t_{n-1,\alpha=5\%} \approx 2$, the formula for relative precision can be rearranged, giving

$$n \approx \left(\frac{200\mathrm{CV}}{r}\right)^2 \quad (3)$$

as an approximate formula for the sample size required for a specified level r of relative precision. Note that low r percentage correspond to high levels of relative precision. The detailed derivation of the formula for estimating necessary sample sizes is given by Manly (1992) and Krebs (1999). Thus, using Eq. (3), we firstly calculated the CV for the 900 samples collected at forest sites and for the whole dataset ($N = 975$), which includes the pasture site, in order to assess the relationship between the sample size and the level of precision. Second, using the CV calculated for each one of the 39 plots, we estimated for each plot the required sample size at 5% and 10% level of precision. Third, given the number of measures in each plot ($N = 25$), we estimated the sampling precision for each plot. Fourth, using the CV estimated for each one of the 13 sites, we estimated the required number of plots to characterize each site at 5% and 10% level of precision. Finally, we assessed the level of precision of our sampling ($N = 3$) for each site. This estimation of the level of precision at 95% confidence limit was also applied to evaluate the samples used to test the effect of the sampled size area on the coefficient of variation for the sites A4, A5 and A7.

We also carried out a multiple comparison Tukey test to compare the mean LAI of all 75 samples for each site, among the 13 surveyed LUs. Afterwards, a more robust three-way nested design analysis of variance was used to test the effect of sites on LAI averages (Zar, 1984). For this test, we assumed each site as a fixed factor grouped in three-plot replicates (random factor), each one having 25 sub-samples.

4. Results

4.1. Map integration

4.1.1. Vegetation

The original vegetation map had a total of 34 classes of vegetation, one of city (AA) and one of water. After the analysis of the area results, we reduced the number of classes to 14, without affecting the most representative classes. The primary forest classes listed in Table 2 and the secondary forest (Vss + Ap + Db) were the most common in the region, representing 79.43% of the whole area (13,164.40 km^2). However, five secondary forest classes with an area <5% were merged into the Vss + Ap + Db class, increasing the relative area from 17.3% to 19.2% of the total area (Table 2). The reclassification process affected only about 20% of the total area. This analysis, therefore, permitted the generation of a visually similar and more simplified vegetation map (Fig. 2).

4.1.2. Terrain

Elevations ranged from 50 to 300 m, so the use of six altitudinal classes was reasonable. The 50–100 m class was the most common, covering 52%

Table 2
Result of vegetation classes' aggregation drawing attention to the classes name and description, the number of classes merged in each new class, the cover area (km^2) and the relative contribution (%) of each class for the total area (the "+" sign means the combination of two or three forest types[a] in the same area)

Class	Description	No. of grouped classes	Area (km^2)	Relative area (%)
Pecuaria e Pastagem_Ap	Agriculture and pasture	3	539.80	4.10
Vss	Secondary forest	6	2529.52	19.21
Vsp	Secondary forest	5	179.23	1.36
Dbe + Outras	Primary forest	3	812.00	6.17
Dbe	Primary forest	1	889.94	6.76
Dbe + Dbu	Primary forest	1	2028.42	15.41
Dbe + Dbu + Abc	Primary forest	1	2063.33	15.67
Dbe + Abp + Abc	Primary forest	1	1735.50	13.18
Dse + Asp	Primary forest	1	752.81	5.72
Dbe + Abc	Primary forest	1	708.98	5.39
Dse	Primary forest	1	317.42	2.41
Influencia Urbana_AA	Urban influence	1	46.96	0.36
Outras	Other forests	10	542.13	4.12
Agua	Water bodies	1	18.36	0.14
Total		36	13164.40	100

[a] Asp: open canopy sub-montana forest with palm; Dbe: dense lowland forest with emergent trees; Dbu: dense lowland forest with uniform canopy; Dse: dense sub-montana forest with emergent trees; Abp: open canopy lowland forest with palm; Asp: open canopy sub-montana forest with palm; Abc: open canopy lowland forest; Ap: agriculture and pasture areas; Vsp: secondary vegetation with palms; Vss: secondary vegetation without palms; Outras: other forests types.

(6834 km^2) of the total area. The classes of elevation 100–150 and 150–200 m contributed 22% (2840 km^2) and 24% (3214 km^2) to the total area, respectively. The other altimetry classes together covered a small portion (2.3%) in relation to the total. For example, the highest elevation (from 250 to 300 m), situated at the south portion of the study area, represented only 0.12% of the total area (Fig. 2).

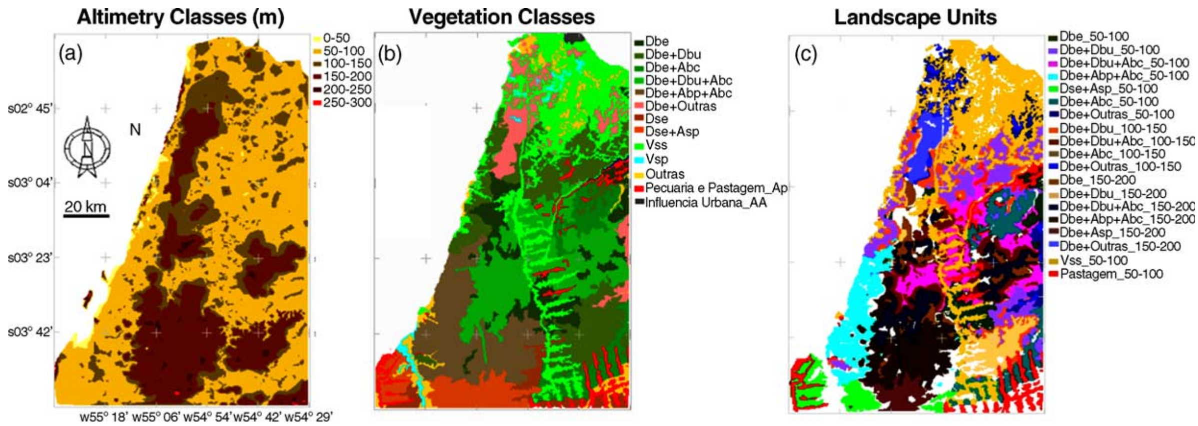

Fig. 2. Raster thematic maps used for the generation of landscape units (LUs) (250 m spatial resolution). (a) Altimetry thematic map, which was compiled after the slicing in six classes of the 250 m regular grid containing the terrain elevation information. (b) Vegetation thematic map, which was compiled after a reclassification process; note the 12 vegetation classes, including secondary forest, pasture sites and the urban area (Santarém city) in the north portion of the map. (c) Spatial distribution of the landscape units at Tapajós region generated after the Boolean integration of the vegetation and altimetry thematic maps. The white areas on the map correspond to areas without representative units. Definition of vegetation classes is showed in Table 1. Abbreviations used for the LU are composed by the vegetation associated to the altimetry classes' information.

4.1.3. Landscape units

Our integration resulted in 69 landscape units, which were reduced to 19 representative LU after the minimum area threshold analysis. The LUs containing primary forest (17 units) covered 62% of the total area studied, and corresponded to 89% of the total primary forest area (9232 km^2). The unit represented by secondary forest (Vss) covered 17% of the region and 86% of the secondary vegetation area (2588.94 km^2). With an area of 524.19 km^2 (3.95% of the total), the agriculture–pasture unit (Pastagem) incorporated 99% of whole pastures in the region (Fig. 2).

4.2. Leaf area index

4.2.1. Leaf area index frequency distribution

For 23 of the 39 surveyed plots, LAI distribution was significantly skewed ($P < 0.05$; $N = 25$) according to the Shapiro–Wilk's W-test for normality. Assuming the total number of samples per site ($N = 75$), only the pasture (A3) and primary forest (A13) had normal LAI distributions. However, the distribution of all forest samples ($N = 900$) was normal. This fact reinforces the idea that is necessary to obtain a large number of samples to characterize LAI and minimize bias in such a heterogeneous ecosystem as Amazonian forest. The normal distribution of the whole data justified our parametric three-way analysis of variance to compare sites.

4.2.2. Variability of LAI at the sample level

In forests, individual sample values of LAI varied from 2.18 (A8) to 8.18 (A1). For pasture (site A3), plot 9 contained both the lowest (0.15) and the highest (4.24) individual LAI samples measured. The high value was due to the occurrence of dense foliage shrubs in these unmanaged pastures, which are very frequent in the region.

The relationship between required sample size (RSS) and the level of precision at the sample level showed that, by decreasing the LOP, the RSS declines exponentially for forest sites analysed separately, for forest plus pasture sites and for pasture alone, but with a lower rate (Fig. 3).

Furthermore, the analysis showed that when forest and pasture samples are lumped together the RSS is increased, reflecting the high RSS obtained for the

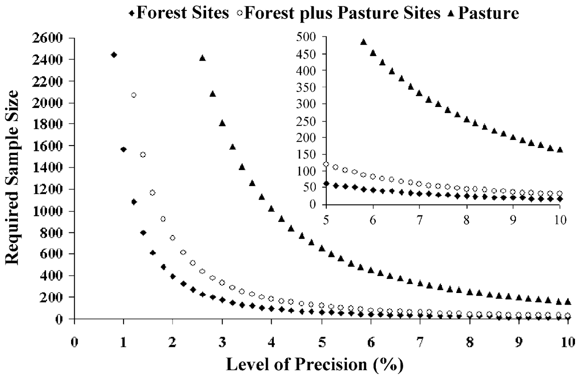

Fig. 3. Relationship between the level of precision (LOP) and the required sample size (RSS) given the coefficient of variation (CV) of LAI at the sample level. The pattern of forest sites samples alone ($N = 900$; CV = 20%) was compared to those of forest plus pastures samples together ($N = 975$; CV = 27%) and pasture alone ($N = 75$; CV = 64%). Inset: enlarged plot for a range of the LOP between 5% and 10%.

pasture site alone. At least 63 samples are required to characterize forest variability at a level of precision of ~5%; including pasture values in the analysis increases the RSS to 119. Pasture site account to a high variability at sample level and to reach <5% LOP, the required sample size is 653 samples. We obtained a level of precision of 1.32% for the sampling at forest sites ($N = 900$; CV = 20%) and 1.75% considering all the samples ($N = 975$; CV = 27%), while for pasture the LOP was 15% ($N = 75$; CV = 64%).

4.2.3. Variability of LAI at the plot level

At the plot level, the highest LAI was estimated for plot 3 (part of site A1), and lowest for plot 26 (part of site A9), in which the means (±standard deviation) were 5.85 ± 1.19 and 3.06 ± 0.31, respectively. These values represent the differences in the canopy structure between the primary forest (A1) and the secondary forest (A9). The coefficient of variation (CV) reached a maximum of 23% in plot 23 (site A8), which is located in a primary forest and had a mean LAI of 4.08, and the minimum of 5.21% in plot 36 (site A12).

Some plots in primary forest units, such as the numbers 23 (A8) and 3 (A1) (CV = 20.5%), had high CVs, mainly due to the occurrence of gaps caused by large tree falls. The three plots (7–9) located in the pasture unit had the lowest mean LAIs (1.59, 1.52 and

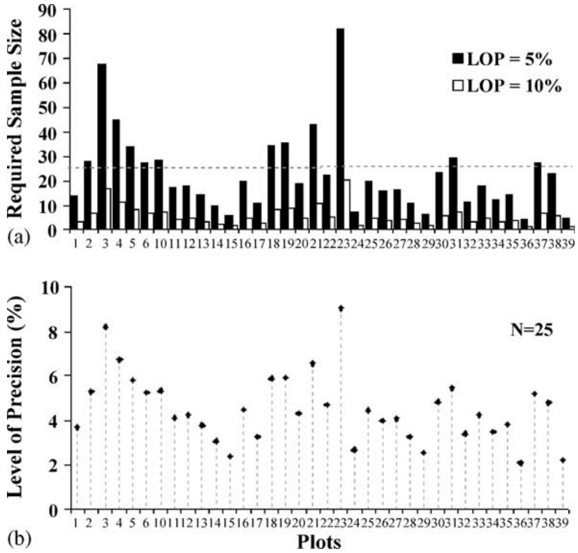

Fig. 4. Calculations for: (a) the required sample size (RSS) for a level of precision (LOP) of 5% and 10% using the coefficient of variation (CV) of LAI for each one of the 39 plots; (b) the LOP reached with the 25 samples used in the study to characterize each plot. The horizontal dashed line, in the plot (a), indicates the number of samples used in the study ($N = 25$).

1.57, respectively). These pasture plots had the highest CVs, varying from 61% (plot 7) to 69% (plot 9), due to the mixture of grasses, shrubs and bare ground in close proximity.

The RSS to explain the variation within each plot at <5% level of precision was satisfactory for the majority of the plots. We found 12 plots with a RSS higher than 25 samples at <5% LOP. However, the use of 25 measurements for each plot could characterize all the 39 plots at <10% LOP (Fig. 4a and b). The highest LOP (2%) was determined for plot 36 (A12) and the lowest (9%) for plot 23 (A8) (Fig. 4b). The plots located at the pasture site were not included in this analysis due to the very distinct pattern of variation (high CV), which made them consequently hard to compare with plots located at forest sites.

4.2.4. Using the plot level LAI measurements to represent the landscape units

4.2.4.1. LAI patterns among the sites. The highest mean LAI in primary forest areas was found in the A1 site (5.10 ± 0.66) and the lowest in the A12 site

Table 3
Association of the 13 sites with the landscape units[a] (LUs) and the mean leaf area index (LAI ± standard deviation) estimated for each of these

Site	Landscape unit	Leaf area index (LAI)
A1	Dbe + Outras_l50–200	$5.10 \pm 0.66^{***}$
A2	Selective logging	$4.63 \pm 0.12^{***}$
A3	Pasture	1.56 ± 0.04
A4	Dbe_l50–200	$4.84 \pm 0.32^{***}$
A5	Babaçu forest[(R)]	$4.38 \pm 0.08^{***}$
A6	Fire damage forest[(R)]	$3.87 \pm 0.10^{***}$
A7	Dbe + Dbu + Abc_150–200	$3.49 \pm 0.27^{***}$
A8	Dbe + Dbu_100–150	$4.17 \pm 0.32^{***}$
A9	Secondary forest	$3.46 \pm 0.42^{*}$
A10	Open canopy forest[(R)]	$3.73 \pm 0.19^{***}$
A11	Dse + Asp_50–100	$3.84 \pm 0.15^{***}$
A12	Dbe + Abc_50–100	$3.25 \pm 0.14^{***}$
A13	Dbe + Abp + Abc_l50–200	3.57 ± 0.43

The landscape units marked with "(R)" were identified by the differences in spectral and textural patterns during the TM/Landsat scene interpretation. The asterisks beside LAI values are the results of a Shapiro Wilk's *W*-test for deviations from the normality ($^{*}P < 0.05$; $^{***}P < 0.001$).

[a] Landscape units are defined by the association between vegetation and altimetry classes. Asp: open canopy sub-montana forest with palm; Dbe: dense lowland forest with emergent trees; Dbu: dense lowland forest with uniform canopy; Dse: dense sub-montana forest with emergent trees; Abp: open canopy lowland forest with palm; Asp: open canopy sub-montana forest with palm; Abe: open canopy lowland forest; Outras: other forests types.

(3.25 ± 0.14) (Table 3). This result demonstrates the contrast between the forest types in the northern portion of the Tapajós National Forest (tall, closed canopy) and those in the south, where the presence of a dense drainage network and accentuated terrain has led to a more open canopy close to the streams (Igarapés), which is in general shorter in height.

Selective logging practice in site (A2) did not indicate significant changes in LAI values (4.63 ± 0.12) when compared with the similar undisturbed forest type A1 (Table 3). The secondary forest (3.46 ± 0.42) and the burned forest (3.87 ± 0.10) sites had LAI values close to those found in open canopy primary forest A7 (3.49 ± 0.27), A10 (3.73 ± 0.19), A11 (3.84 ± 0.15), A12 (3.25 ± 0.14) and A13 (3.57 ± 0.43) sites, despite differences in the structure and species distribution (Espírito Santo, personal communication). The average LAI for the pasture was 1.56 ± 0.04 (Table 3).

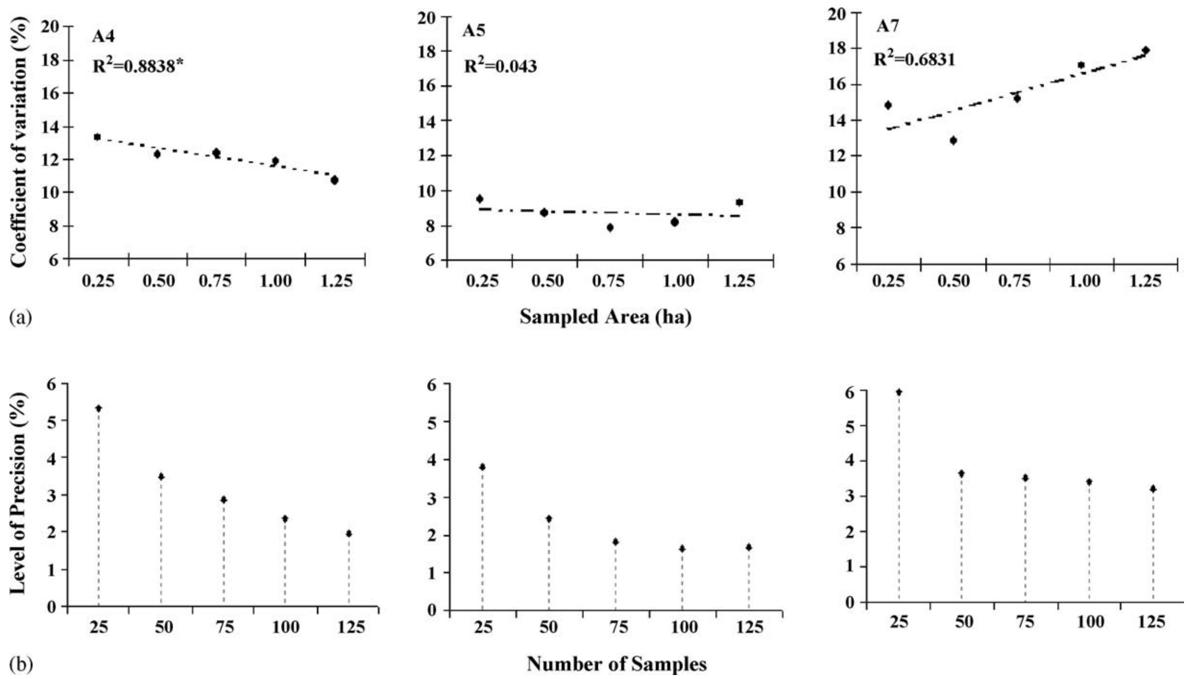

Fig. 5. (a) Linear regression between the coefficient of variation (CV) of the LAI for the sites A4, A5 and A7 and the size of the sampled area. Note the regression line (dashed) and the coefficients of determination, in which asterisk represent the significance at 95% confidence level ($^{*}P < 0.05$). (b) Relationship between the level of precision (LOP) of the mean LAI at sites A4, A5 and A7 and the number of samples, which is directly associated to the sampled area.

4.2.4.2. LAI variation. The use of the mean LAI from the three plots located in each one of the 13 sites investigated reduced the coefficient of variation (CV). The CV varied from 1.8% in the A5 (Babaçu palm forest) to 12.9% in A1 (primary forest). The pasture site showed a steep drop in CV when plots were aggregated. While the CV was 64% and 69% at the sample and plot level, respectively, after aggregating the three plots, the CV fell to 2.3%.

4.2.4.3. Size of sampled area. The linear regression analysis showed that only in site A4 did the CV depend on the sampling size ($P < 0.05$) (Fig. 5a). For this site, we observed a negative correlation, indicating that using a larger number of plots, and consequently increasing the surveyed area, reduced the CV. The A5 site did not show any linear behaviour (Fig. 5a). The A7 site, despite the absence of a significant correlation coefficient due to the low number of samples (five plots), showed a tendency for increasing CV with increasing sample size, indicating the higher heterogeneity of this site (Fig. 5a). However, all these three sites showed an increase in precision resulting from an increase of the number of samples (Fig. 5b).

The use of our three-plot design ensured that half of the sites (A2, A3, A5, A6, A11 and A12) had a level of precision (LOP) < 5%, and for 77% of sites LOP < 10% (Fig. 6a). For sites A1, A9 and A13, the RSS was 26, 24 and 23 plots, respectively (Fig. 6a), reflecting the high canopy heterogeneity. The LOP of LAI measurements for the 13 sites investigated varied from 2% (A5) to 15% (A1) (Fig. 6b).

4.2.4.4. Differences among sites. The mean LAI varied 23% (CV) among the 13 sites. The pasture site (A3) was significantly different from all the forest sites, for both Tukey and nested design tests ($P \leq 0.05$). The primary forest sites, A1, A4 and A5, as well as the selective logging forest (A2), had significantly distinct LAI patterns ($P \leq 0.05$), for both statistical tests, in relation to the primary forests in the south of the Tapajós National Forest (sites A10–A13), the secondary (A9) and the burned forest (A6) sites.

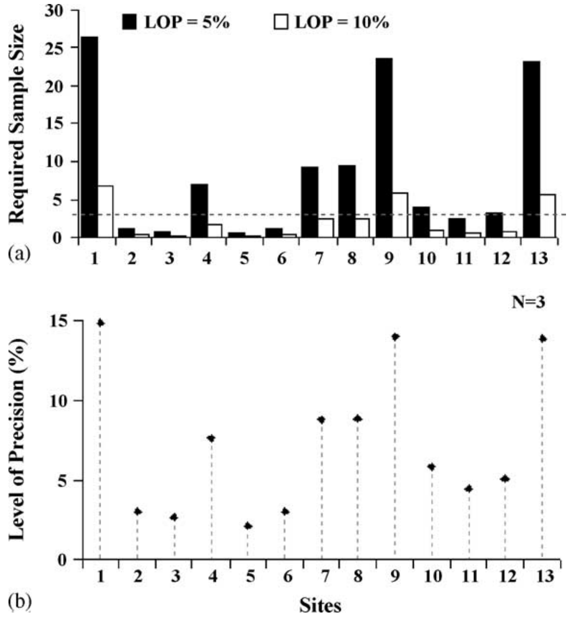

Fig. 6. Calculations for: (a) the required sample size (RSS) for a level of precision (LOP) of 5% and 10% using the coefficient of variation (CV) of LAI for each one of the 13 sites; (b) the LOP reached with the three plots used in the study to characterize each site. The horizontal dashed line, in the plot (a), indicates the number of plots used in the study ($N = 3$).

According to the nested analysis, the primary forest A8 was only significantly different ($P < 0.05$) from the A7 and the A12 sites, but the Tukey test results showed that A8 was statistically different ($P < 0.01$) from all the other forest types, except the A5, A6 and A11 sites.

Similar leaf area index was found among the primary forest A7 and the sites A10–A13 in the nested design analysis. But, in the Tukey test, the A7 site was significantly different from the A11 site ($P < 0.05$). All the latter five sites, in spite of having a different canopy structure compared to the secondary and the burned forest, had statistically similar LAI values using the nested design test. However, analysing Tukey statistics, the burned forest A6 had significant higher LAI values ($P < 0.01$) than the secondary forest A9, and was also significantly different from the A7 ($P < 0.01$) and the A12 ($P < 0.001$). Despite similarities appointed among A9 and A7 and A10–13 in the nested design test, Tukey analysis showed that A9 had significantly lower LAI values than A8 ($P < 0.001$) and A11 ($P < 0.01$).

Due to these differences in the results of the two statistical tests, we base our discussion and conclusion in the nested design ANOVA (Table 4), which is a more robust test than the Tukey for our factorial sample design.

5. Discussion

5.1. Spatial distribution and variability of LAI across the Tapajós region

The results indicated that LAI spatial distribution and variability, at different levels of observation, are directly associated with site-specific characteristics, as revealed by the LU stratification. The landscape

Table 4
Values of the probability (P) gave by the tree-way nested design analysis of variances for the comparison of all the pairs formed by the 13 plots

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13
A1		N.S.	0.001	N.S.	N.S.	0.05	0.05	N.S.	0.05	0.05	0.05	0.01	0.05
A2	N.S.		0.001	N.S.	0.05	0.01	0.01	N.S.	0.01	0.01	0.01	0.001	0.05
A3	0.001	0.001		0.001	0.001	0.001	0.001	0.001	0.01	0.001	0.001	0.001	0.01
A4	N.S.	N.S.	0.001		N.S.	0.01	0.01	N.S.	0.05	0.01	0.01	0.01	0.05
A5	N.S.	0.05	0.001	N.S.		0.01	0.01	N.S.	0.05	0.01	0.01	0.001	0.05
A6	0.05	0.01	0.001	0.01	0.01		N.S.	N.S.	N.S.	N.S.	N.S.	0.01	N.S.
A7	0.05	0.01	0.001	0.01	0.01	N.S.		0.05	N.S.	N.S.	N.S.	N.S.	N.S.
A8	N.S.	N.S.	0.001	N.S.	N.S	N.S.	0.05		N.S.	N.S.	N.S.	0.05	N.S.
A9	0.05	0.01	0.01	0.05	0.05	N.S.	N.S.	N.S.		N.S.	N.S.	N.S.	N.S.
A10	0.05	0.01	0.001	0.01	0.01	N.S.	N.S.	N.S.	N.S.		N.S.	0.05	N.S.
A11	0.05	0.01	0.001	0.01	0.01	N.S.	N.S.	N.S.	N.S.	N.S.		0.01	N.S.
A12	0.01	0.001	0.001	0.01	0.001	0.01	N.S.	0.05	N.S.	0.05	0.01		N.S.
A13	0.05	0.05	0.01	0.05	0.05	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	

No significant differences were reported by N.S.

variables, such as land cover, land use and terrain features, used for the stratification strategy in the Tapajós region, are likely to be a powerful tool for driving LAI field surveys in the Amazon Basin.

5.1.1. Variability within the LUs

Our data showed high intra- and inter-plot variability in the primary forest sites located in the plateau region in the northern portion of the study area. Sites with high variability were associated with two LUs: a mixture of 'dense lowland forest with emergents (Dbe) plus other at the 150–200 m elevation class' (A1) and 'Dbe plus dense lowland forest with uniform canopy (Dbu) at the 100–150 m elevation class' (A8).

For all the sites investigated, LAI variation was reduced after the aggregation of samples in plots. The most significant reduction from the intra- to the inter-plot coefficient of variation was observed in the pasture site, indicating that each 0.25 ha plot had a homogeneous contribution of the three components of pasture vegetation (bare soil, grass, and shrubs). An exception of this pattern was found for the secondary forest site (A9). This exception for secondary forest likely results from the combination of three main factors: (1) the previous land use pattern; (2) the recurrence of exploitation and fire, at different times and locations; and (3) the exposure to different levels of edge effect, grading from the border to the forest interior. Thus, the pasture site had a scale of LAI variation fine enough to be fully sampled within a plot, while secondary forest had a coarser scale of variation, only observed when plots were compared. LAI variability in each site was, in part, indicative of different ecological patterns among LUs.

5.1.2. Variability among the LUs

Analysing the differences among sites, we found two main patterns among undisturbed forests. Higher mean LAIs occurred for the dense forest sites situated on flat and stable terrain without streams, such as A1 and A4, and for forests sites with high density of palms, such as A5 and A8. Lower mean LAIs were found in forest sites (A7 and A10–A13) located in LUs that are associated with open canopy forest. These sites were mainly distributed along the scarped and more variable terrain with a dense drainage network in southern portion of Tapajós National Forest. These primary forest sites have an open canopy without contact among the top of the trees, comparable to disturbed forests (Veloso et al., 1991). Confirming this conclusion, the statistical analysis showed a similar mean LAI between the A7 and A10–A12 sites and the secondary and burned forest sites.

In relation to human modified sites, only pasture could be distinguished from all forest types, with a dramatic reduction in LAI value. The establishment of pastures in the region can lead to critical changes in ecological process dependent not only on LAI, but also on plant physiology, via changes from the C3 metabolism (forests) to the C4 (pastures). Secondary and burned forest had a similar LAI average, despite differences in forest structure. The change in natural landscape cover (i.e. primary forests) to burned or secondary forests has implications for forest structure. If we consider that these burned and secondary forest sites were located in a 'dense canopy' LU, and use a mean LAI value of 5.0 for the two dense forest sites sampled (A1 and A4), then, these land use changes lead to, at least, 20% reduction in the mean LAI of the primary forest in the same region. While fire and forest regeneration processes have had a significant impact on canopy structure, selective logging practices have not caused a significant shift in LAI. However, our measurements did not account for the impact of roads, skids and log decks in the selective logging site.

5.1.3. Precision of the sampling design

In the majority of the 0.25 ha plots, the use of 25 samples well described the within-plot LAI variation. The results showed two critical sites in terms of plot LAI variability, the primary forest plots 3 (A1) and 23 (A8), both located in the plateau region, that require 67 and 82 samples, respectively, to reach a LOP of 5%. An increase in sampling number within the 0.25 ha plot implies a reduction of the distance among samples, and this could lead to a high auto-correlation of the measurements, mostly because the overlap of the PCA sensor field of view in the top canopy. Thus, it would be better to increase plot size for sites with high heterogeneity. The intra-plot heterogeneity was, in part, related to the landscape unit pattern. Some sites, like A1, A7 and A8, had plots with LOP $> 5\%$ and required more than three plots to characterize the unit at this same LOP. Other sites, such as A2 and A6, also had some plots with LOP $> 5\%$, but at the unit level it was possible to reach a LOP $< 5\%$ using the three-plot design. A third situation was found at sites A9 and A13, which had a high precision at the plot level, but regarding the unit pattern at least seven plots are necessary to extract LAI information with a LOP better than 10%. We showed that for sites A1, A9 and A13 it is practically infeasible to assess LAI with high precision. The need for about 25 plots in each of these three sites to get 5% LOP in the sampling highlighted the difficulty in describing some landscape units at the field level. It also suggests that some LUs are not so homogeneous as expected, and the use of other landscape variables, such as soil physical and chemical properties, could assist in elucidating how LAI vary among the landscape units. The evaluation of how the coefficient of variation of LAI samples varied with the size of the sampled area showed different patterns for the three tested sites (A1, A4 and A7). This analysis reinforced that the spatial variability of LAI at the LU level is dependent on particular characteristics of each site. In this specific case, the behaviour of the CV with the increase of the sampled area represented the differences in the spatial heterogeneity of closed canopy forest (A4), open canopy forest (A7) and palm forests (A5).

With these analyses, we could quantify the confidence intervals for LAI sampling at sample, plot and unit levels. Therefore, it is clear, that more field measures with a stratified distribution should be carried out to minimize uncertainties in LAI values at the regional scale.

5.2. Comparison with other studies

As far we know, this was the first study in the Tapajós and other Amazon forest sites using sample stratification with plot replication to assess LAI values and explore LAI variability. Williams et al. (2002) surveyed in 1999 the LAI pattern in 3.25 ha of primary forest at Tapajós National Forest and found a similar range of individual values (from 2.19 to 8.89) to the range found in the present study (from 2.18 to 8.18). This same work showed a mean LAI varying from 5.2 to 7.0, although our study showed lower mean LAI varying from 3.14 ± 0.30 to 5.85 ± 1.19.

Williams et al. (2002) sampled three places located close to our A1, A4 and A10 sites. Close to the A1 and A4 sites, they found a mean LAI of 6 with a CV of 5% for the first and 10% for the latter. We found a mean LAI around 5 for these two sites, but the CV was 12% and 7% for the A1 and A4 sites, respectively. The difference may be related to inter-annual variability, perhaps caused by the La Niña episode in 1999 and the El Niño episode in 2002 (Batista et al., 1997; Araújo et al., 2002).

However, close to our A10 site, Williams et al. estimated a mean LAI of 6.48, 70% higher than the mean calculated in the present study. Probably the difference is related to the association of three main factors, the intra-site and inter-annual variability and the distinction of methodologies, where they used a transect approach. The factors that caused this discrepancy are not obvious, and need to be elucidated with further measurements and data analysis.

We calculated a mean LAI = 4.97 for the dense canopy forest sites (A1 and A4), 4.28 for the forest with high density of palms (A5 and A8), and 3.58 for open canopy forest sites (A7 and A10–A13). We compared our results with three sites located in different portions (Ji-Paraná, Paragominas and Manaus) of the Brazilian Amazon and also with sites in other forest biomes (Table 5).

The comparison among the biomes revealed that LAI values are independent of the biome type and do not have any relationship with climate patterns, based on the sampling geographical location (latitude or longitude). This data analysis reinforce the idea that the spatial distribution and variation of LAI is dependent on the site-specific landscape variables, such as land use and land cover, terrain features and soil patterns.

Law et al. (2002) found that the variation in LAI, across 21 different sites analysed, could be partially (39%) explained by the annual water balance (i.e. $\sum$(evapotranspiration − precipitation)), which is controlled, in part, by a combination of plant physiology and soil characteristics. However, the differences in LAI estimations inter and intra biomes can also be associated with differences in disturbance history, methodologies and sampling representation. Therefore, these data need to be carefully interpreted. As an example, Cutini et al. (1998) comparing LAI values from a direct (litter collection) and an indirect method (PCA LAI-2000), in a broad leaf deciduous temperate forest, showed that the exclusion of the external sensor ring (centred in a 68° angle) for LAI

Table 5
Comparison of LAI values measured in different tropical forest sites in the Amazon forest and in different forest biomes across the world

Site	Location	LAI	References
Tropical rain forests			
Tapajós National Forest, Pará State, Brazil	Dense canopy forests	4.97	This study
Tapajós National Forest, Pará State, Brazil	Forests with high density of palms	4.28	This study
Tapajós National Forest, Pará State, Brazil	Open canopy forests	3.58	This study
Jarú Reserve, Pará State, Brazil	10°55′S, 61°55′W	4.60	Wright et al. (1996)
Vitória Farm, Pará State, Brazil	10°45′S, 62°22′W	5.40	Nepstad et al. (1994), Jipp et al. (1998)
Ducke Reserve, Amazonia State, Brazil	2°57′S, 59°57′W	6.60	Roberts et al. (1993)
Evergreen coniferous forests			
Aberfeldy, Scotland	56°37′N, 3°48′W	8.00	Valentini et al. (2000)
Blodgett Forest, USA	38°54′N, 120°38′W	3.20	Law et al. (2001)
Deciduous broadleaf forests			
Gunnarsholt, Iceland	63°50′N, 20°13′W	1.40	Valentini et al. (2000)
Hesse, France	48°40′N, 7°5′E	6.00	Valentini et al. (2000)
Harvard Forest, USA	42°32′N, 72°11′W	5.50	Goulden et al. (1996)
Evergreen broadleaf forests			
Castelporziano, Italy	41°45′N, 12°22′W	3.50	Valentini et al. (2000)
Sky Oaks, USA	33°22′N, 116°37′W	3.00	Law et al. (2002)

computation, from LAI-2000, increase the agreement between LAI values estimated from the two methods. However, we do not have evidence about it for tropical forests, and this fact has yet to be investigated.

5.3. Implications for modelling regional carbon and water fluxes in the Amazon Basin

The necessity of accurate quantitative measurements of the spatial patterns of forest canopy processes and feedbacks, in relation to the global climatic changes, lead to the expansion of the development of models based on spatialised datasets and remote sensing information to estimate forest productivity at large scales (Running and Coughlan, 1988; Potter et al., 1993; Williams et al., 1997; Jiang et al., 1999). However, these models depend on the input of continuous surfaces of driver variables, such as LAI. The Earth Observation System (EOS) is, nowadays, the most effective means of collecting data and generating a range a quantitative biophysical variables surfaces in a regular basis (EOS Terrestrial Ecology products). These estimations are founded on models that use, as input data, the canopy spectral responses derived from the Moderate resolution image spectroradiometer (MODIS) (e.g. Myneni et al., 2002).

The stratified LAI sampling proposed in the present study could cope with three important aspects of C and water fluxes modelling. First, it was possible to optimise the information obtained from field measurements, representing not only different primary forest types, but also land use patterns across the region, which is an advance for the parameterisation of ecosystem models in the Amazon region. Second, this experimental design can smooth the progress of subsequent scaling up of point field measurements to surfaces covering the whole region, developing relationships between field LAI values and spectral information from satellite images (Turner et al., 1999; Tian et al., 2002; Cohen et al., 2003a, 2003b). Finally, these LAI data are, anchored in the two first aspects, a useful basis for validation of the EO estimations of LAI in the Tapajós region. Therefore, further exploration of the information exposed here permits, as proposed by Potter et al. (2001), the coupling and comparison of observational data, field measurements and ecosystem dynamics models.

A stratified random sampling procedure, with a global land cover map used as a basis for stratification has been proposed for the validation of EOS Terrestrial Ecology products (e.g. LAI and NPP) (Thomlinson et al., 1999). These authors stress also the necessity to subdivide the global cover classes in order to reduce the within-strata variation in LAI and NPP by mapping site factors, such as soils and slope position. These assumptions were considered in our LAI survey and showed that, in fact, the stratified design with three-plot replication in each LU sampled tends to reduce the LAI variability, being a positive methodological trait for regional studies. A random sampling probably will need a higher number of samples to describe the regional heterogeneity, requiring more time and resources.

It is important to highlight that even sites that did not show significant differences, mainly those with low mean LAI, should be considered individually for ecosystem modelling purposes. Williams et al. (1998) showed that C and water fluxes estimations have a high sensitivity to changes in LAI, particularly for LAI < 4. This concern has an important implication for the accuracy of the models results that do not consider the effects of land use (including pastures and secondary forests). As an example, Potter et al. (1998) applying the model NASA–CASA over Brazil at a spatial resolution of 8 km could not capture all these localized and transient effects of land use change. It means that models should be set to work in a spatial resolution at least finer than 1 km and accurate land-use maps based on satellite information should be considered in these modelling analyses.

6. Conclusions

This work has shown that the Tapajós region has a broad variety of vegetation types that become more complex assuming spatial geomorphologic and land use patterns as a modifier of vegetation typologies. The use and interpretation of a remotely sensed image was crucial for assessing the recent pattern in land cover and use, underlining fire damaged areas and unmapped vegetation types (e.g. Babaçu forest), thus increasing the sampling accuracy.

The complexity of the landscape in this region should be considered in bottom-up ecological surveys. The work also indicated the need for intensive fieldwork for a satisfactory characterization of the patterns of ecological variables, as well as the relevance of the improvement of top-down estimation of canopy biophysical and chemical characteristics using remote sensing technologies, due to the difficulty in accessing some sites.

The approach employed in generating the landscape units map was efficient in characterizing landscape heterogeneity, and the major advantages of the method were the preservation of the most representative features and the reduction of the number of sampling units. The employment of the LUs map was a key determinant in advancing the spatial LAI sampling coverage and can be applied to a broad range of scales and ecosystems.

The variability of LAI within each LU could be clearly associated with the landscape variables used in sampling stratification. Similarities in mean LAI values for some sites indicated that landscape variables do not completely explain the variability among the LUs, and other landscape variables, such as soil properties and/or terrain slope, should improve the stratification and, consequently, LAI characterization.

Leaf area index was very variable at 10 m spatial resolution (sample level). At 50 m spatial resolution, the variability decreased, but bias can be introduced into the mean LAI calculation because LAI samples were not, usually, normally distributed at this scale.

The methodological strategy was efficient for quantifying LAI and elucidating the confidence level of the measurements. We could describe 57% of the 23 LUs with at least 10% and 15% level of precision at plot and unit level, respectively.

The variability of LAI in the Tapajós region is evidence of the high ecological heterogeneity of the Amazon Basin. It reinforces the fact that this variable can be a source of uncertainty for the large-scale process-based modelling and must be treated carefully.

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