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IKONOS imagery for the Large Scale Biosphere–Atmosphere Experiment in Amazonia (LBA)

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Abstract

The LBA-ECO program is one of several international research components under the Brazilian-led Large Scale Biosphere–Atmosphere Experiment in Amazonia (LBA). The field-oriented research activities of this study are organized along transects and include a set of primary field sites, where the major objective is to study land-use change and ecosystem dynamics, and a smaller set of 15 operational eddy flux tower sites, where the major objective is to quantify net exchange of CO_2 with the atmosphere. To supplement these studies and help to address issues of fine-scale spatial heterogeneity and scaling, high-resolution satellite imagery (IKONOS, 1–4 m) have been acquired over some of these study sites. This paper begins with a description of the acquisition strategy and IKONOS holdings for LBA. This section is followed with a review of some of the most promising new applications of these data in LBA.

Keywords: IKONOS; Remote sensing; Spatial heterogeneity; Land use; Land cover; LBA

1. Introduction

Tropical deforestation in Amazonia has been a growing ecological and climatological concern for several years (Fearnside, 1990; Nepstad et al., 1999; Skole & Tucker, 1993). In 1997, the Large Scale Biosphere–Atmosphere Experiment in Amazonia (LBA) was initiated as an international research initiative led by Brazil with strong United States and European Union participation. LBA is designed to understand the climatological, ecological, biogeochemical, and hydrological functioning of Amazonia, the impact of land-use change on these functions, and the interactions between Amazonia and the earth system. The scientific questions of LBA are: (1) How does Amazonia currently function as a regional entity? (2) How will change in land use and climate affect the biological, chemical and physical functions of Amazonia, including the sustainability of

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Table 1
Summary statistics on IKONOS holdings for LBA

	~ Area (km^2)	*N*
Total Final	5268	71
Total Beta	1540	19
Total Complete	6808	90
Total Final Unique	3761	46
Total Beta Unique	1491	18
Total Unique	5252	64

Beta and Final are the two data versions. Beta is a preliminary data product.

development in the region and the influence of Amazonia on global climate (The LBA Science Planning Group, 1996)?

In order to address these and related scientific questions, multidisciplinary investigations at a variety of spatial and temporal scales are underway. Knowledge of phenomena such as organic-matter decomposition, photosynthesis, plant-community succession, and large-scale patterns of fire, land use, and land abandonment must be understood and integrated. To this end, data are being collected across a range of scales, from short-term leaf-level measurements, to forest-stand statistics, to remote sensing over the entire region. New models are also being developed to integrate observations and concepts across biological, temporal, and spatial scales. In addition, new remote sensing instruments including MODIS, MISR, and EO-1 Hyperion are being brought to bear on the research topics of the LBA program. One new instrument being employed in LBA is the IKONOS satellite.

Launched from Vandenberg Air Force Base in September 1999, the IKONOS satellite is the world's first commercial instrument to collect imagery at 1-m resolution. IKONOS is polar orbiting, sun-synchronous, and has a 98.1° orbital inclination relative to the earth. Images have one panchromatic band at 1-m resolution and four spectral bands (blue, green, red, near-infrared, similar to Landsat TM spectral bands 1–4) at 4-m resolution. With the support of the NASA Terrestrial Ecology and NASA Scientific Data Purchase (SDP) programs, an ongoing effort to obtain an IKONOS database of Amazonia has become an important part of LBA. This paper begins with a description of the acquisition strategy and IKONOS holdings for LBA. This discussion is followed with a summary of some of the most promising new applications of these data in LBA. High-resolution remote sensing data such as from IKONOS are powerful tools for helping to meet LBA objectives and should be included in future project planning.

2. Initial acquisition strategy and database

The initial strategy for acquiring IKONOS data for the LBA project has focused on obtaining imagery at key LBA study sites. For the purposes of this study, sites can be categorized into two groups: eddy-flux tower sites and field-study sites. Eddy-flux tower sites are foci for local estimates of CO_2 flux between the atmosphere and land surface and other important ecophysiological measurements. In addition, they are typically the focus of many supporting

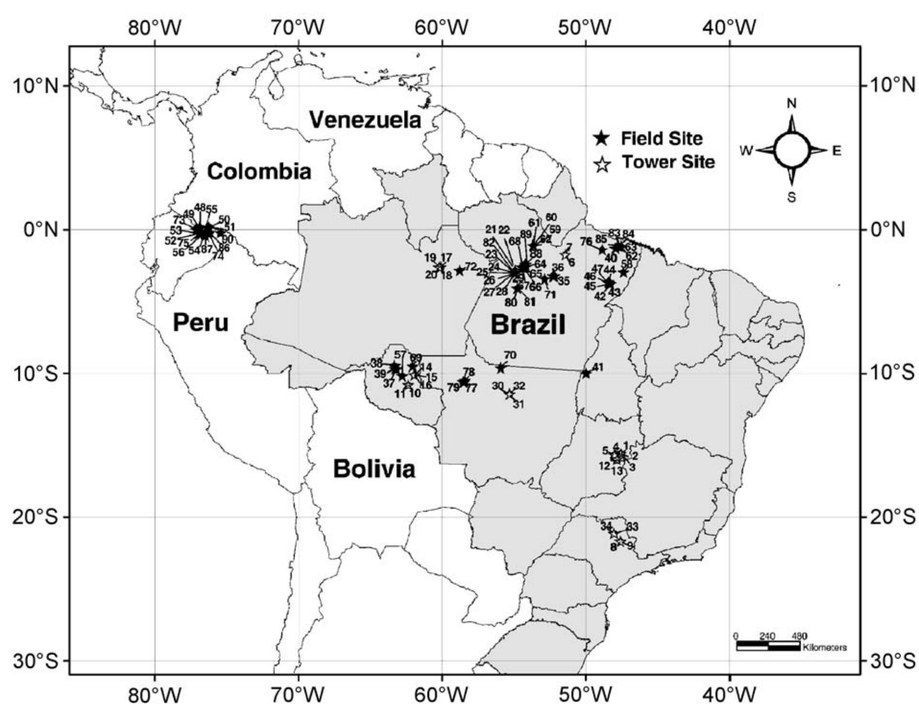


Fig. 1. Locations of IKONOS images for LBA-Ecology study sites acquired. Open stars represent locations of eddy-flux tower sites, and solid stars represent field study sites. Map-ID labels for each star are used to cross reference site names listed in Appendices A and B.

ground-based studies. Field-study sites are mainly used for ground-based studies of ecosystem structure and dynamics, land-use change, and recovery following disturbance. Fine-scale disturbances such as selective logging are also studied at some of these sites.

Input from the LBA research community was solicited and used to obtain specific coordinates for sites suitable for IKONOS tasking. To date, imagery requested by 19 different investigation teams has been tasked and acquired. In some cases, repeat images of the same location have been obtained for studies of land-cover change. In all, 90 images covering over 6808 km^2 have been acquired, consisting of approximately 5268 km^2 at the final product level (Table 1, Fig. 1, Appendices A and B). Fig. 2 provides examples of IKONOS imagery collected for two key study regions outside the cities of Manaus and Santarém.

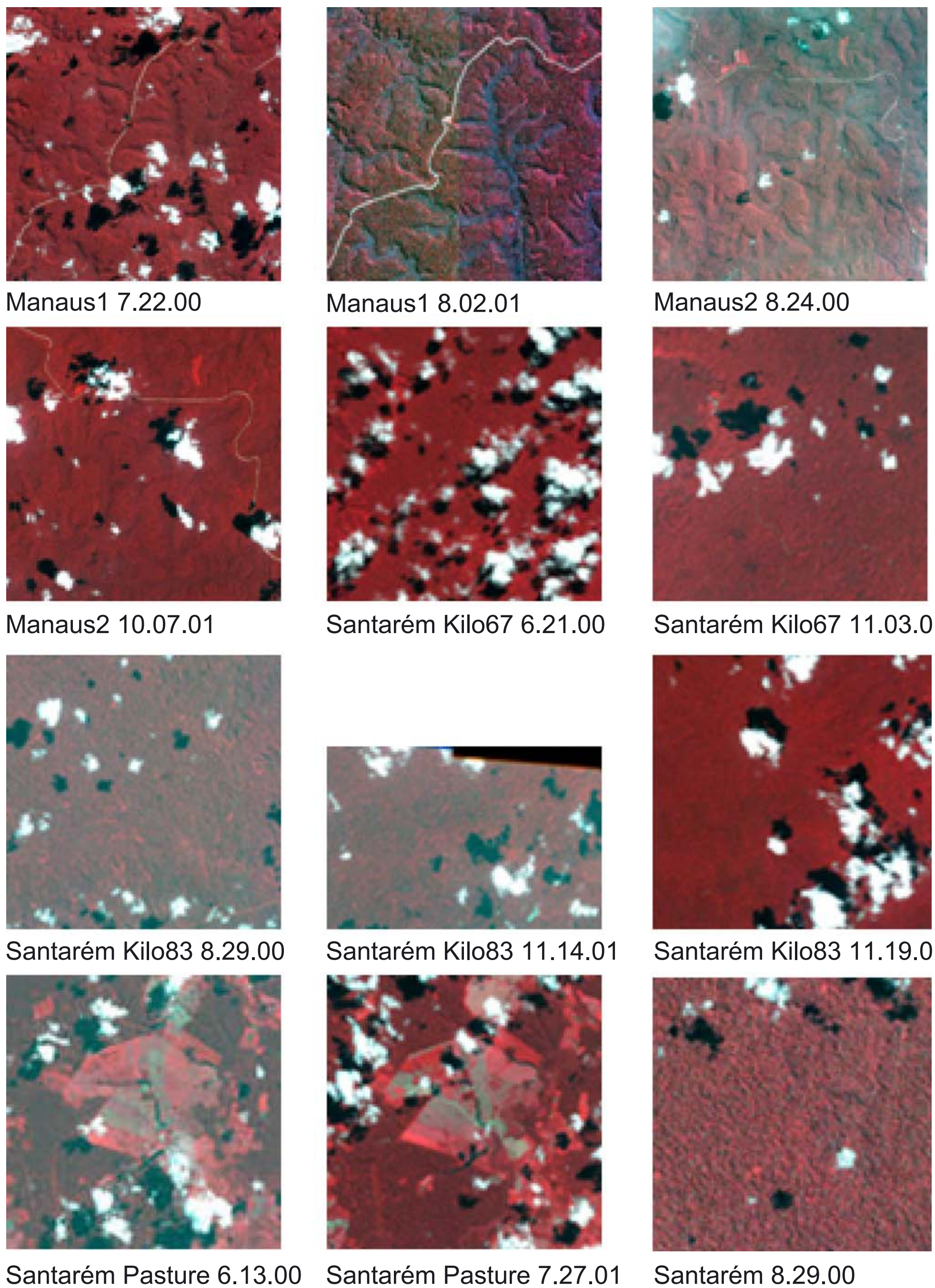


Fig. 2. Examples of IKONOS imagery for two important LBA study regions near the cities of Manaus and Santarém. The images displayed are false color representations of multispectral (4 m) imagery and, with the exception of Santarém Kilo83 11.14.01, cover a domain size of 7 × 7 km. Greater detail is available in larger-scale (i.e. smaller domain) subsets of these images. White patches, which are clouds, can be seen in several images along with cloud shadows. Standard tasking criteria require images to have less than 10% cloud coverage. This figure "includes material© Space Imaging L.P."

Table 2
Cumulative statistics from EOS-WEBSTER (http://www.eos-webster.sr.unh.edu) pertaining to IKONOS holdings for LBA

Number of investigators/team requests	19
Number of registered IKONOS users	47
Number of visitors to IKONOS subsystem	1248
Number of IKONOS products ordered	671
IKONOS data available to users (GB)	16.6
IKONOS data distributed (GB)	87.6

Data first became available on EOS-WEBSTER in 2001.

All IKONOS holdings collected for LBA are available to LBA researchers following data-sharing guidelines established between NASA and Space Imaging (Thorton, CO, USA). The data are listed in the LBA Data Information System Beija-Flor and are featured holdings at the NASA Earth Science Information Partner EOS-WEBSTER (http://www.eos-webster.sr.unh.edu). To date, EOS-WEBSTER has nearly 50 registered IKONOS users and has had more than 1200 visitors to the IKONOS data collection during the past year (Table 2).

3. Promising applications of IKONOS imagery in LBA

The primary motivation for incorporating IKONOS imagery in the LBA Experiment is for enhancing studies of fine-scale heterogeneity in vegetation, land use, and land-use change. Multispectral imagery with a resolution of 4 m and panchromatic with a resolution of 1 m can potentially provide valuable information on the composition of vegetation and specific details of land-use changes. In LBA, these data are being used to address a variety of different research topics including:

- Improvement of land-cover remote sensing;
- Estimates of forest crown diameter, basal area, and biomass;
- Detection and quantification of selective logging;
- Effects of fine-scale heterogeneity in vegetation on carbon balance;
- Detection of biochemical and biophysical changes on small land holdings;
- Mapping agroforestry systems and small-scale agriculture.

This paper reviews some of the most promising new research in LBA using IKONOS data on these topics. This research is at an early stage of development, as IKONOS has been introduced only recently to LBA. The review is intended to summarize and synthesize ongoing research at the early stage of development when feedback and sharing of ideas can be most valuable.

3.1. Improvement of land-cover remote sensing

Having precise estimates of the area coverage of different land cover types is important to carbon cycle and land surface studies. Medium- to coarse-resolution optical sensors (e.g., AVHRR, Terra-1 MODIS, SPOT-4 VEGETATION) provide daily observations of land cover for the globe. However, the land surface in the Amazon is often a mixture of land-cover types at the spatial resolution of these sensors (0.5–1 km). Quantifying the fractional coverage of broad land-cover types within large pixels by extrapolating knowledge that is obtainable by visual or automated interpretation of IKONOS is a remote sensing problem of current interest to LBA research. All of the approaches discussed below rely on the development of scaling relationships between the spectral information in regional-scale data and the spatial information in high resolution data (IKONOS in this case), a process known as "spectral unmixing".

A number of spectral unmixing approaches have been developed to estimate subgrid-scale land cover fractions. In general, the methods are either based either on linear mixture modeling (Boardman, 1989; Cross, Settle, Drake, & Paivinen, 1991; Smith, 1990), or on nonlinear regression using artificial neural networks (e.g. Foody, Lucas, Curran, & Honzak, 1997). In traditional spectral mixture modeling, the surface reflectance at each pixel of the image is assumed to be a linear combination of the reflectance of each end-member present within the pixel. For an image pixel that has M spectral bands and N end-members, the spectral linear unmixing model is described in the following equation:

$$R_i = \sum_{k=1}^{N} r_{ki} f_k + \varepsilon_i \tag{1}$$

where R_i is the reflectance of spectral band i in a multi-spectral image ($i = 1, 2, \ldots, M$), f_k is the fractional cover of end-member k ($k = 1, 2, \ldots, N$) within a pixel, r_{ki} is the reflectance of end-member k at spectral band i, and ε_i is the residual term. Nonlinear regression takes the converse approach, directly modeling the fractions as a function of reflectance $f_k = G_k(R)$, where G is normally defined by a simple back-propagation neural network (Foody et al., 1997). To avoid overfitting, a Bayesian modification can be made to these algorithms (Bishop, 1995; Braswell et al., 2000) so that all the available high-resolution data can be used in training the model.

Some studies have explored the use of linear spectral unmixing of AVHRR data for sub-pixel characterization of cropland (Quarmby, Townshend, Settle, & White, 1992) and tropical forests (Cross et al., 1991). These studies have had some success, but have been limited by sensor resolution and the lack of relevant spectral bands in AVHRR data (only red and near infrared bands for vegetation). The MODIS sensor has higher resolution and more spectral bands related to land cover and vegetation (2 bands at 250 m resolution plus 5 bands at 500 m resolution). Because of the increased resolution and added bands, research using MODIS data has the potential to provide improved estimates of land cover and land-cover changes.

Recently, Xiao et al. have begun using IKONOS images to improve the spectral definition of end-members (Fig. 3). In an exploratory study, a 7 × 7 km IKONOS image acquired on April 6, 2000 covering the Jaru eddy-flux Tower in Rôndonia was used to select end-members of six land cover types (primary forest, secondary forest, crop, pasture, river, soil) through visual interpretation and delineation of region of interest (ROI) for each land cover type. The resulting end-members of individual land cover types were co-registered and reconciled with an MODIS image (standard 8-day composite product of surface reflectance at 500 m spatial resolution, July 20–26, 2000). Spectral unmixing analysis of the MODIS image was then conducted, using a spectral linear unmixing algorithm implemented in the commercial software (ENVI version 3.2), which is based on earlier works of Boardman (1989, 1992). The resulting MODIS-based fractional coverage maps of land-cover types compared favorably to Landsat 7 ETM+ data acquired on August 6, 1999. By using IKONOS data at select sites to improve region-wide land cover algorithms that rely on MODIS data, this research may lead to improved land-cover mapping across the entire Amazon basin benefiting both carbon cycle science and land surface studies. Additional advances may come from greater use of non-linear or Bayseian statistical methods.

A second application addresses the issue of shadows in remotely sensed images. The biological and structural complexity of tropical forests and savannas results in marked spatial variation in shadows inherent to remotely sensed measurements. While the biophysical and observational factors driving variations in apparent shadow are known, little quantitative information exists on the magnitude and variability of shadow in remotely sensed data acquired over tropical regions. Even less is known about shadow effects on multispectral observations from satellite instruments often employed in tropical studies (e.g., Landsat). The IKONOS satellite, with 1 m panchromatic and 4 m multispectral capabilities, provides an opportunity to observe tropical canopies and their shadows at spatial scales approaching the size of individual crowns and vegetation clusters.

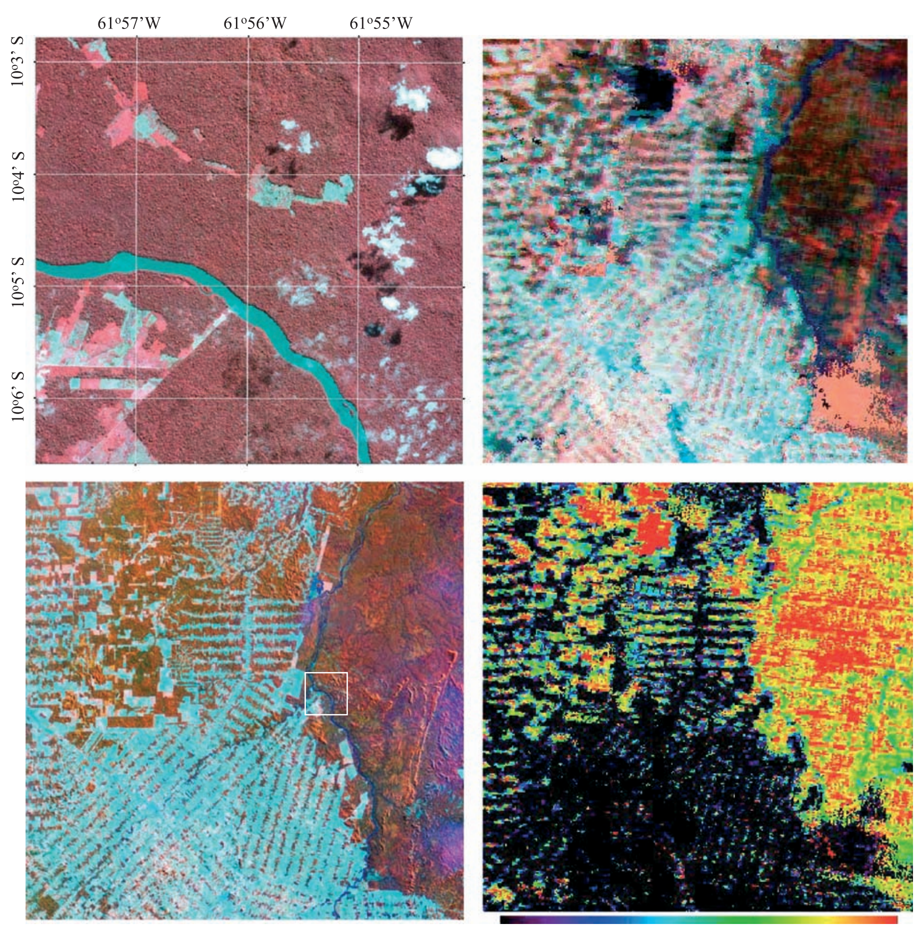


Fig. 3. A comparison of IKONOS, Landsat 7 ETM+ and MODIS images. Upper left panel-IKONOS image acquired on April 6, 2000, false color composite (band 4-3-2). Lower left panel-Landsat 7 ETM+ image acquired on September 6, 1999, false color composite (band 4-5-3). The white box illustrates the domain of the IKONOS image in the upper left. Upper right panel—MODIS image (8-day composite of surface reflectance, July 20–26, 2000), false color composite (band 2-6-1). Lower right panel—Fractional cover of forest within 500 m pixels, derived from spectral mixture analysis of MODIS data. This figure "includes material© Space Imaging L.P."

Asner and Warner (in review) used 44 IKONOS images from the LBA data archive to quantify the spatial variation of canopy shadow fraction across a broad range of forests in the Amazon and savannas in the Cerrado. Forests had substantial apparent shadow fractions as viewed from the satellite vantage point. The global mean ($\pm$ S.D.) shadow fraction was 0.25 ± 0.12, and within-scene (e.g., forest stand) variability was similar to inter-scene (e.g., regional) variation. The distribution of shadow fractions for forest stands was skewed, with 30% of pixels having fractional shadow values above 0.30 (Fig. 4). Shadow fractions in savannas increased from 0.0 ± 0.01 to 0.12 ± 0.04 to 0.16 ± 0.05 for areas with woody vegetation at low (< 25% cover), medium (25–75%) and high (>75%) density, respectively. Landsat-like observations using both red (0.63–0.70 μm) and NIR (0.76–0.85 μm) wavelength regions were highly sensitive to sub-pixel shadow fractions in tropical forests, accounting for ~ 30–50% of the variance in red and NIR responses. Asner and Warner also found that a 10% increase in shadow fraction resulted in a 3% and 10% decrease in red and NIR channel response, respectively. However, the NDVI of the Amazon forests was weakly sensitive to changes in shadow fraction. For low-, medium- and high-density savannas, a 10% increase in shadow fraction resulted in a 5–7% decrease in red-channel response. Shadows accounted for ~ 15–50% of the overall variance in red-wavelength responses in the savanna image archive. Weak or no relationships occurred between shadow fraction and either NIR reflectance or the NDVI of Brazilian savannas. Quantitative information on shadowing is needed to validate or constrain radiative transfer, spectral mixture and land-surface models of the Amazonian biosphere and atmosphere.

3.2. Estimates of forest crown diameter, basal area, and biomass

In forests, allometric relationships exist between different measurements of tree size such as tree diameter at breast height (DBH), tree height, crown diameter, and tree biomass. Foresters and ecologists often use these relationships as a basis for estimating important quantities such as biomass or carbon stock from relatively simple ground-based measurements of DBH and/or height (Araujo, Higuchi, & Carvalho, 1999; Brown, 1997; Keller, Palace, & Hurtt, 2001). Remotely sensed estimates of vegetation height using lidar have been used to estimate important fine scale characteristics of vegetation including vegetation biomass (Drake, Dubayah, Clark, Knox, & Blair, 2002; Drake, Dubayah, Clark, Knox, Blair, Hofton et al., 2002; Harding, Lefsky, Parker, & Blair, 2001; Lefsky, Harding, Cohen, Parker, & Shugart, 1999; Means et al., 1999). In addition, high-resolution imagery based on aerial photographs and videography, declassified historical reconnaissance imagery, and other satellite sensors have been used in analyses to estimate attributes of forests including properties of gaps, stand age, height, and biomass (e.g. Bradshaw & Spies, 1992; Cohen & Spies, 1992; Cohen, Spies, & Bradshaw, 1990; Shugart, Bourgeau-Chavez, & Kasischke, 2000). The IKONOS satellite adds a new resource

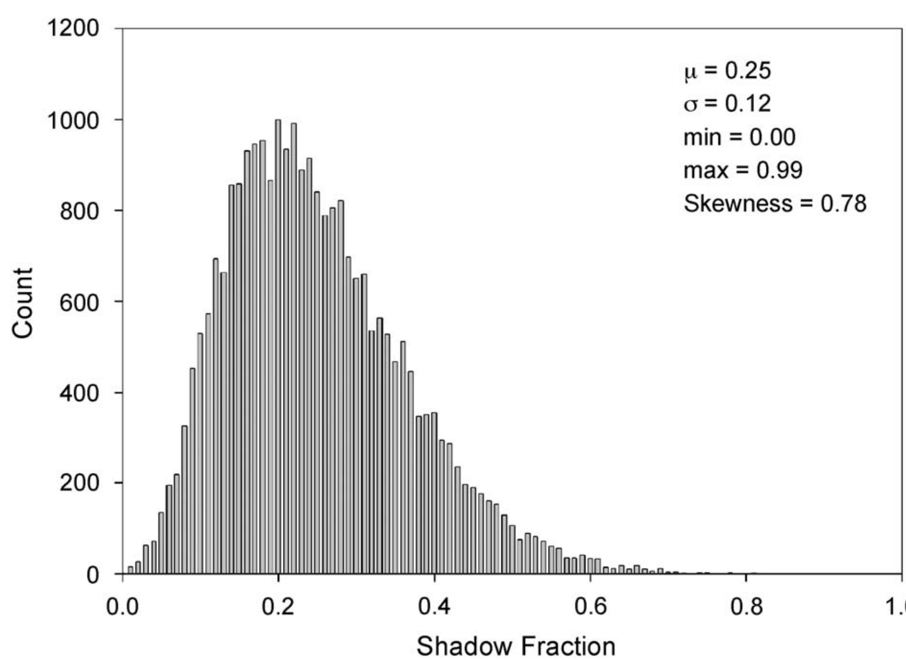


Fig. 4. Histogram of shadow fractions from 29 IKONOS pan-chromatic images of Amazon tropical forests. Descriptive statistics are provided in upper right. From Asner and Warner (submitted for publication).

with which to advance these studies using contemporary high-resolution imagery.

Read, Clark, Venticinque, and Moreira (submitted for publication) conducted a pilot study at a reduced-impact logging operation in tropical moist forest near Manaus, Brazil to assess the potential application of IKONOS satellite data to research and management of tropical forests. As part of this study the authors assessed the feasibility of using pan-sharpened IKONOS data for estimating forest crown diameter. The pan-sharpening transformation exploits the spatial resolution of the 1-m panchromatic data and the spectral resolution of the four 4-m multispectral data by merging the two to create a 1-m multispectral dataset. Crown areas for nine clearly distinguishable trees were derived by manually digitizing tree crowns from the pan-sharpened IKONOS image. Measured trunk diameters and an index of crown area calculated from ground-based measurements for the same nine trees were correlated with the digitized crown area measurements. Trunk diameter was found to be significantly correlated with digitized crown area, suggesting that estimates of trunk diameter, and thus biomass, may be possible with IKONOS data. The ground-based index of crown area although correlated yielded a weaker relationship. In a similar study of tropical wet forest in Costa Rica, Clark et al. (submitted for publication) found highly significant correlations between crown area digitized from IKONOS data and the same ground-based index of crown area. In both studies, the trees studied were selected for having clearly defined crowns on the IKONOS image, and these correlations are likely to weaken for trees with less defined crown edges or partially obscured crown sections, or where shadows from neighboring trees obscure sections of the crown. These observations highlight the importance of further research on shadow effects and crown edge detection methods.

In another set of studies, Asner et al. (submitted for publication) have made ground-based measurements of important tree parameters and compared these to IKONOS-based estimates with the goal of advancing and applying this technology in LBA. In order to develop a calibration data set, ground-based measurements of tree height, crown diameter and crown depth in a lowland tropical forest in the eastern Amazon, Brazil were first obtained using a handheld laser rangefinder. The sample included 300 trees stratified by diameter at breast height (DBH). Significant relationships between DBH and both tree height and crown diameter were then derived from the ground-based measurements. Ground-based measurements of crown diameter and area were then compared to estimates derived manually from the 1 m panchromatic IKONOS satellite imagery. The statistical distribution of crown diameters from IKONOS was biased toward larger trees, probably due to merging of smaller tree crowns, underestimation of understory trees, and over-estimation of individual crown dimensions in the manual estimates (Fig. 5a).

Building on this work, the team is developing new automated techniques to identify properties of trees from IKONOS imagery to replace the manual interpretations (Fig. 5b–e). The approach scans through an image's digital numbers and uses a derivative calculation to test for the edge of a crown in multiple directions from a seeded point. The threshold, number of directions scanned, and method for estimating crown shape are tunable in the program. The method allows for gaps to be present in the analysis, and for crowns to overlap, both of which are typically not done in manual interpretation methods. Current work using the program has proven promising in analyses of tropical forests in the Cauaxi and Tapajós regions and will be expanded in future work.

3.3. Detection and quantification of selective logging

The Amazonian tropical moist forest is experiencing intensive logging in many regions (INPE, 2000). As roads are built through the forest, large areas of previously unlogged forest become attractive to the timber industry. While causing less damage to the ecosystem than clear-cutting, selective logging significantly changes the rain-forest by creating canopy gaps, disturbing understory vegetation, and altering the litter layer on the forest floor. Reduced impact logging is practiced in some areas, but the relative damage caused by both types of logging has only begun to be documented (Asner, Keller, Pereira, & Zweede, 2002; Pereira, Zweede, Asner, & Keller, 2002). In general, maps of logging areas are only preliminary (Nepstad et al., 1999). Read (in press) visually compared 15-m pan-sharpened Landsat Enhanced Thematic Mapper (ETM+) and 1-m pan-sharpened IKONOS images of selectively logged areas in a reduced-impact logging operation near Manaus, Brazil. The coarser resolution ETM+ data were capable of discriminating major logging roads and logging decks (cleared areas in the forest for temporary storage of logs) but the finer spatial resolution of the IKONOS data was necessary for distinguishing smaller logging features, including some minor logging roads and treefall gaps.

Methods that analyze the spatial patterns of surface features in remotely sensed data have been found to be useful for characterizing a variety of landscape features, and there is potential with such methods for detecting fine-scale differences in forest canopy structure using the new higher-resolution satellite data. Read (in press) compared performances of selected spatial methods using 15-m panchromatic and 30-m multispectral Landsat-ETM+ data, and 1-m panchromatic and 4-m multispectral IKONOS data, for distinguishing differing degrees of canopy disturbances resulting from reduced-impact logging at the site near Manaus. The study reports the calculated fractal dimension, spatial auto-correlation and texture measures using visible, near-infrared and NDVI data for each dataset at two plot sizes (10 and 335 ha) over a gradient of canopy disturbance. The distur-

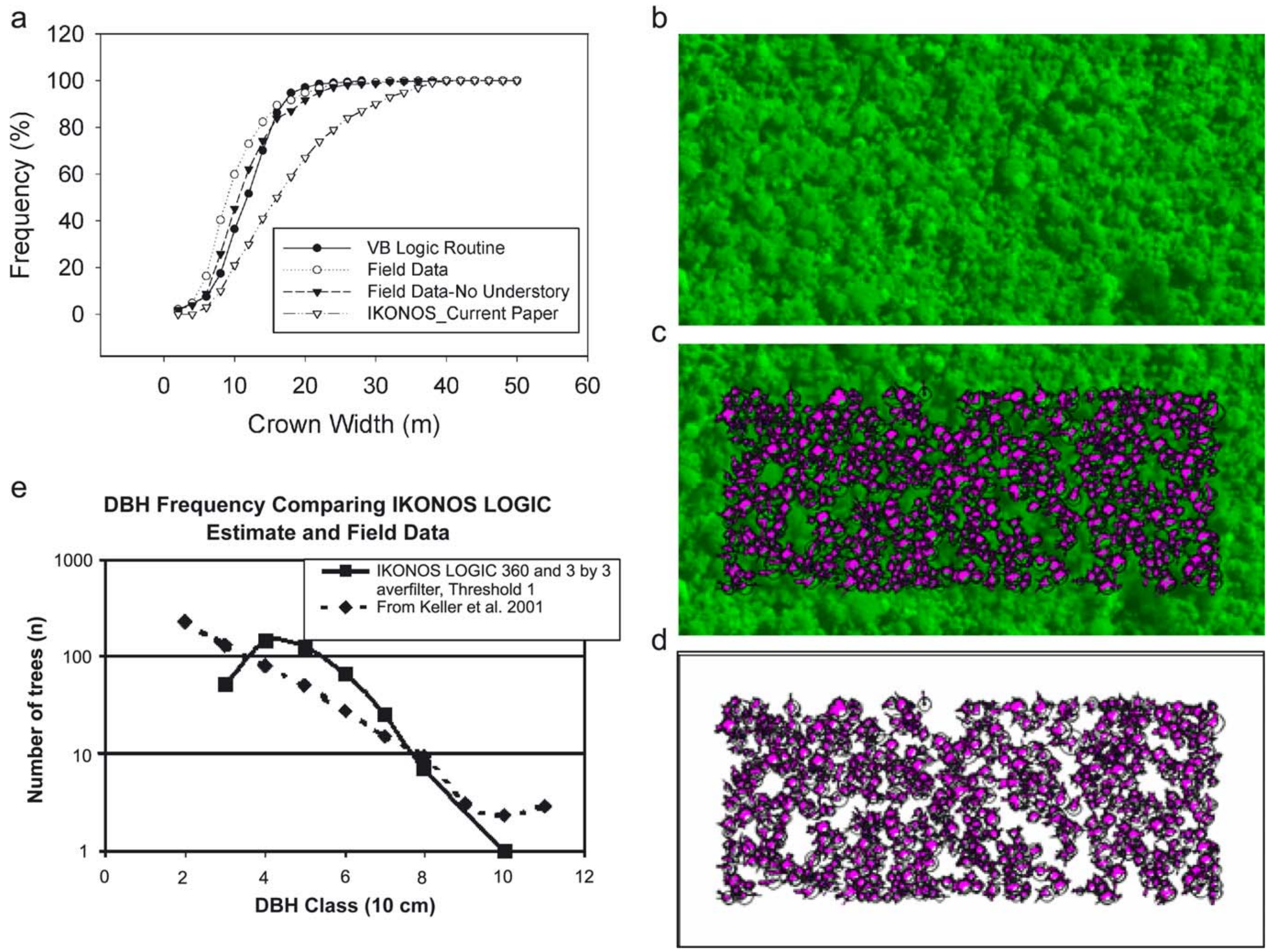


Fig. 5. (a) Cumulative frequency distributions of crown area detected by various methods. "IKONOS_current_paper" refers to manual interpretation. "VB Logic Routine" refers to automated method. (b–d) Automated crown detection algorithm of an IKONOS image. (e) Number of trees vs. DBH class. Analyses of Tapajós km 83 Tower area. This figure "includes material© Space Imaging L.P."

bance gradient comprised three treatments: areas of old-growth (undisturbed) forest, logged forest excluding major roads and logging decks, and logged forest including major roads and decks. In all cases the spatial methods were successful at discriminating between the three treatments. These results indicate that it may be possible to combine spatial analyses of higher-resolution datasets over small areas with coarser resolution datasets over large areas, for assessing basin-wide fine-scale canopy disturbances such as those resulting from selective logging.

Using 4 m multispectral IKONOS data, Hagen et al. have been examining a section of the Tapajós National Forest, south of Santarém, a Brazilian city in central Amazonia. This field research area has been separated into 1 km plots, some of which were selectively logged at various times in the last ~5 years. A spatial analysis of IKONOS data was conducted in an attempt to automate the discrimination of logged and intact forests. As an alternative to analyzing the raw IKONOS panchromatic brightness data, spectral bands were combined to calculate the normalized vegetation index (NDVI). This vegetation index is related to the fraction of absorbed photosynthetically active radiation and the leaf area index of the forest (Myneni, Hall, Sellers, & Marshak, 1995). Logged areas can have reduced NDVI levels due to an increase in shadow fraction and reduction in the amount of green vegetation relative to soil and non-photosynthetic vegetation. Several test areas were analyzed in an attempt to quantify differences in harvested and unlogged areas. Each area chosen was 50 × 50 pixels (200 × 200 m). Nine areas were selected with no logging history and ten areas were selected that have been logged.

The analysis involves two separate metrics. First, semi-variograms were created for each block. The variogram captures the spatial variation and length scales of the vegetation in the block. A curve was then fit to the empirical variogram and the parameters of this fitted function were examined. As expected, the variogram parameters for the two types of forest are similar, probably because the basic spatial structure in the two forests is essentially the same. Canopy diameters will dominate the length scales identifiable in the variograms because most trees in a block remain intact even after logging. However, slightly higher sill (value of semivariance as distance reaches its asymptotic value; Cressie, 1991) and longer range (distance beyond which observations are least correlated; Cressie, 1991) for the logged areas were detectable. The higher sill is a direct result of the higher variance in the block (low NDVI areas of shadow and soil signal, mixed with the high NDVI of remaining canopies). The longer range is likely due to disturbances in the regular pattern of canopies. An irregular pattern reaches an asymptote (sill) at a longer range.

To create the second metric, binary images were created for each block by setting an NDVI threshold, above which pixels are assigned a value of one and below which pixels are assigned a value of zero. The numbers of pixel clusters, consisting of three or more pixels with values of zero, were tallied. By setting an NDVI threshold and creating a binary image for each block, relatively clear separation between logged and unlogged plots is identifiable (Table 3). Using these two metrics in a combined decision algorithm, suggests that recently logged forests can be separated from non-logged forests imaged with IKONOS, and that further investigation might also provide insight into reduced impact effects versus traditional logging practices.

3.4. *Effects of fine-scale heterogeneity in vegetation on carbon balance*

Fine-scale heterogeneity in land cover, such as is introduced by fine-scale disturbance and selective logging, is hypothesized to be important to the carbon balance of ecosystems (Moorcroft, Hurtt, & Pacala, 2001; Nepstad et al., 1999). Work by Vourlitis and Priante-Filho is expanding measurements of the net CO_2 exchange, evapotranspiration, and energy balance of intact tropical transitional forest to include selectively logged systems and cattle pasture. These land forms are readily visible from multi-temporal, high resolution IKONOS imagery, making this imagery useful for locating potential study sites and quantifying annual variations in forest re-growth and/or land-cover change (Fig. 6). The group has already used IKONOS data for estimating the spatial and temporal spread of selective logging over the last 2 years because the development of logging roads is readily visible in the high-resolution imagery (Fig. 6). They are currently trying to calibrate IKONOS and other imagery (i.e., AVHRR) to ground-based measurements of the fraction of photosynthetically active radiation (f_{PAR}) absorbed by the intact and selectively logged forest canopies to provide a way to link the canopy physiological measurements obtained from eddy covariance towers (net CO_2 exchange and evapotranspiration) to satellite data. Data collected indicate that net CO_2 exchange and evapotranspiration are closely linked to seasonal variations in leaf area index (LAI), and thus, f_{PAR} (Vourlitis et al., 2002, in press). Because satellite reflectance data appear to be sensitive to spatial and/or temporal variations of surface biophysical features such as f_{PAR} and LAI (Sellers et al., 1997), the multi-temporal nature and high spatial resolution make IKONOS a potentially powerful tool for estimating the effects of land cover change on net CO_2 exchange and evapotranspiration of tropical transitional regions.

Table 3
The number of clusters identified in each of the 19 plots (9 logged and 10 not logged) using the Threshold-Binary Analysis with an optimal threshold value (T) of 0.41 and group size (GS) of three pixels

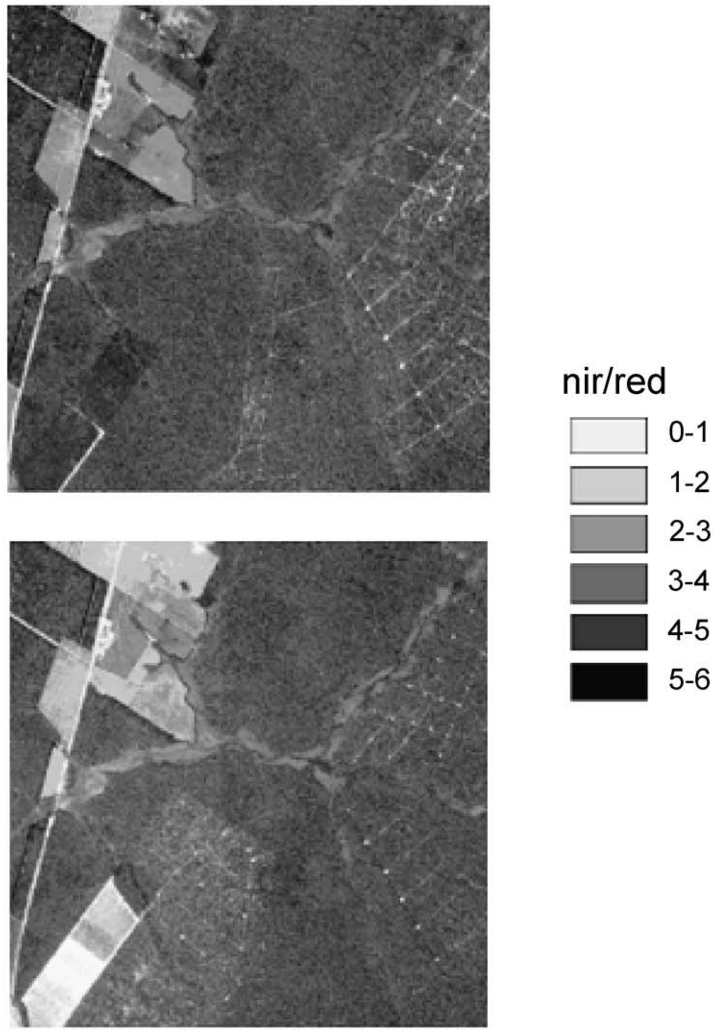
	Threshold-binary analysis (T = 0.41, GS> = 3)	
	Logged	Not logged
	4	0
	5	0
	7	0
	3	1
	0	0
	6	0
	4	0
	1	0
	7	0
		1
Mean	4.11	0.20
S.D.	2.47	0.42

The logged plots have more clusters than the not logged plots.

3.5. *Detection of biochemical and biophysical changes on small land holdings*

Secondary forests in Amazonia serve as a potentially important carbon sink offsetting some of the carbon released to the atmosphere from land-use conversion of primary forest, and slash and burn agriculture. As the area affected by land uses grows, the area and importance of secondary forests is likely to grow. The functioning of secondary forests, however, may be limited due to intensified land use, shortened fallow periods, and increased vulnerability to climate fluctuations (de Sá, de Oliveira et al., 1998; de Sá, de Oliveira, de Araújo, & Brienza Júnior, 1997). Guild, Sá and others are studying the influence of seasonal and interannual climate fluctuations on secondary forest dynamics and agricultural water, nutrient and productivity status under contrasting land-use/conversion practices. The goal of the research is to determine the extent to which secondary forests and agricultural systems are differentially susceptible to extreme climate events (e.g. droughts) under contrasting land-use/clearing practices. A secondary goal is to determine the extent to which remote sensing can quantify productivity, nutrient, and water relations in these secondary forests and agricultural fields.

Alternative land-use/clearing practices (mulching and fallow vegetation improvement) may make secondary forests and agriculture more resilient to the effects of agricultural pressures and drought through (1) increased biomass, soil organic matter and associated increase in soil water



Land cover	NIR/Red	Year 2000	Year 2001
Recently cleared	0-2	0.02	0.07
Cleared	2-3	0.14	0.18
Intact	>3	0.84	0.75

Fig. 6. The ratio between NIR/red for April 2000 (top panel) and May 2001 (bottom panel) for the transitional forest site near Sinop, Mato Grosso. The lighter surfaces (NIR/red = 0–1) show the recently cleared areas while darker areas (NIR/red > 3) show forest. This figure "includes material© Space Imaging L.P."

storage, and nutrient retention and (2) greater rooting depth of trees planted for fallow improvement. New alternatives to burning (mulching and fallow vegetation improvement) are under study by the Brazilian agricultural research agency (EMBRAPA) in eastern Amazonia. These practices include cutting, chopping, and mulching secondary vegetation, and fallow improvement by planting with fast-growing legumes. This experimental practice (chop-and-mulch with enrichment) has resulted in increased soil moisture during the cropping phase, reduced loss of nutrients and organic matter, and higher rates of secondary forest biomass accumulation (Brienza Júnior, 1999; de Sá & Alegre, 2001; de Sá, de Oliveira et al., 1998; de Sá et al., 1997; de Sá, Vielhauer, Denich, Kanashiro, & Vlek, 1998; Sommer, 2000; Vielhauer et al., 2001). All of these practices improve the sustainability of the land-use regime.

Due to the large area involved, operational monitoring in Amazonia generally requires the use of Landsat, MODIS, ASTER, AVHRR or other regional monitoring system. However, the spatial resolution of these systems (30–1000 m) is insufficient to resolve several of the study plots associated with small land holdings. Therefore high spatial resolution satellite imagery from the IKONOS system is a superior surrogate to address biochemical and biophysical effects introduced by these small land-holding practices. Radiometrically calibrated data from the IKONOS system offers spatial resolution with spectral bands approximating those of Landsat Thematic Mapper bands 1–4. In the

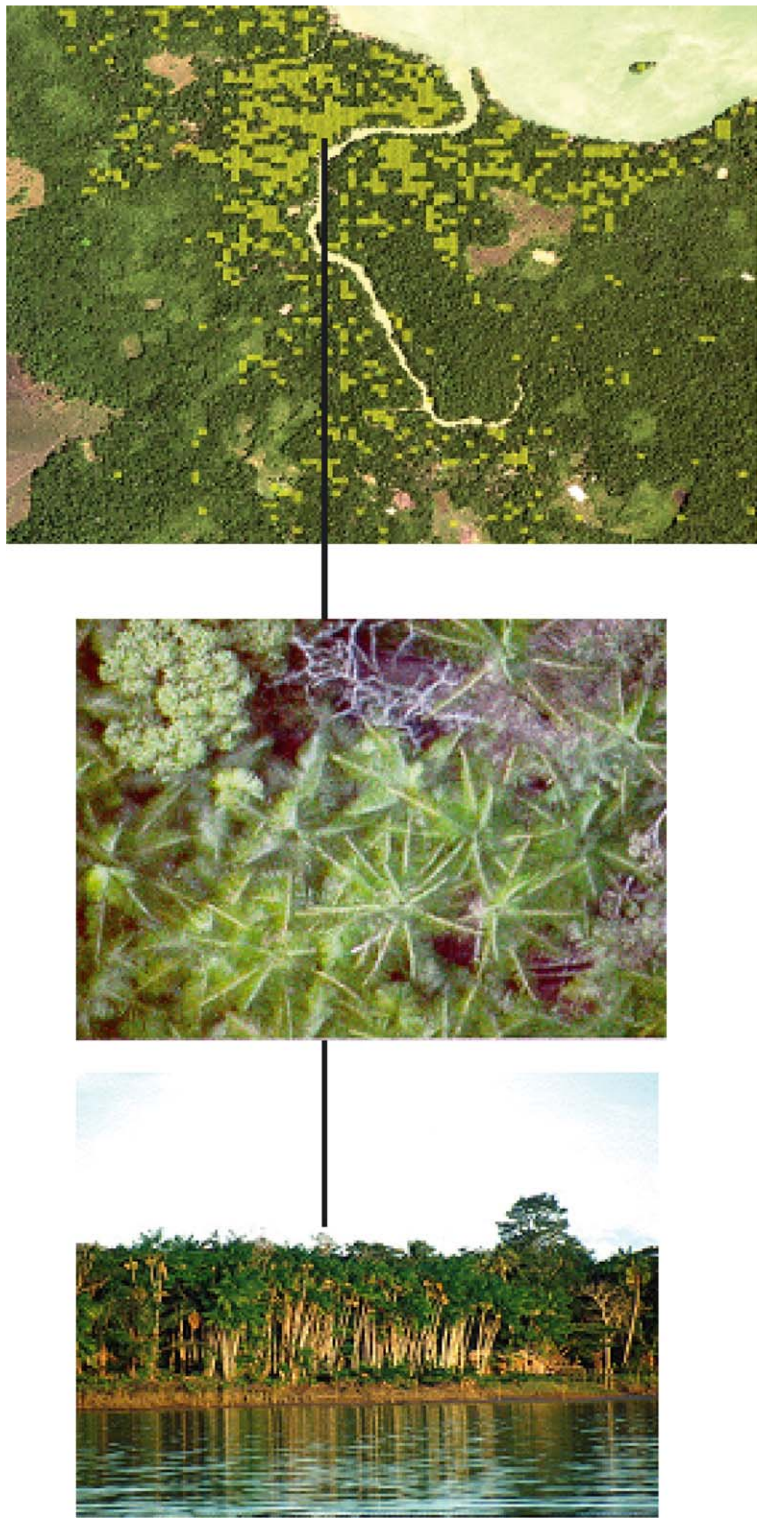


Fig. 7. Multi-scale analysis of Açaí palm agroforestry system and floodplain forests in the Amazon estuary. Classified Landsat TM over IKONOS multi-spectral image (top), aerial view of agroforestry canopy (middle), ground view of intensively managed agroforestry (bottom). This figure "includes material© Space Imaging L.P."

vicinity of Igarapé-Açu, Pará, Guild and Sá are converting IKONOS imagery to NDVI or similar vegetation indices, and comparing them to ground measurements of leaf area index (LAI) and f_{PAR}, which is expected to be influenced by plot treatment effects. Ground measurements for this study focus on the key factors of leaves and canopies of secondary forest and crops that can indicate canopy condition for remote detection of changes in biomass and drought effects. These measurements include leaf water potential, stomatal conductance, LAI, and leaf and canopy radiative properties. Additional data includes vapor pressure deficit, soil moisture, temperature, and precipitation as these measurements indicate the status of the mechanisms influencing drought stress. Mechanisms by which alternative practices of chop/mulch decrease vulnerability to drought include increased soil organic matter, increased soil water holding capacity during the cropping phase and increased rooting depth to exploit soil water at depth during the fallow phase. It is expected that these differences will be manifested through LAI, canopy architecture, canopy water relations, and canopy biochemistry.

3.6. Mapping agroforestry systems and small-scale agriculture

Mapping and characterizing Amazonian agriculture and land-use systems are among the most challenging tasks required to fulfill the mission of the LBA program. These tasks relate to questions of fundamental importance and provide research opportunities for scientists studying biogeochemical cycles and the human aspect of the program. Low data availability (e.g., cloud cover during the production season), the spatial and temporal scales of production systems vis-à-vis the resolution of remotely sensed data, similarities among land cover classes (e.g., agroforestry systems and secondary succession) have limited our understanding of the regional agriculture systems and land-use cycles. This limitation has been particularly pervasive for studies of managed agroforestry systems where changes in vegetation structure are usually subtle, such as changes in species composition and canopy architecture. This is the case of the açaí palm fruit production (*Euterpe oleracea* Mart.), arguably the economically most important land-use system of the Amazon estuary. In most studies, this type of agroforestry system was not distinguished from surrounding floodplain forests. Managed açaí palm forest cover between 10,000 and 20,000 km^2 in the Amazon estuary. This is probably the most significant Amazonian land-use system maintaining forests of high economic output without deforestation and displacement of local communities.

Previous work integrating Landsat TM, field inventories, and land-use interviews has allowed discrimination between unmanaged floodplain forests and intensively managed açaí palm agroforestry to a level of 81% accuracy (Brondízio, Moran, Mausel, & Wu, 1994, 1996). Estimates of management intensity based on açaí palm's importance value (a ranking index based on density, frequency, dominance) have been successfully correlated to Landsat TM's NIR, MIR, and red bands. IKONOS offers new opportunities to the understanding of this type of land-use system as well as associated small-scale upland agricultural systems. IKONOS images help to reveal the level of management intensity across agroforestry areas, thus, providing means to estimate production and economic return of agroforestry stands. In addition, IKONOS images may help to refine the accuracy of Landsat-based agroforestry mapping, particularly by contributing to the delineation between areas under different management intensities as well as to quantify changes in the structure of forest canopies. Another important application of IKONOS in this area refers to the analysis of swidden agricultural systems (shifting cultivation) and associated stages of secondary vegetation regrowth. IKONOS images can also be used in the delineation of riverine house-gardens important to the understanding of resource management strategies in the Amazon estuary. These are key features for the analysis of land-use intensification and settlement patterns in the region.

Building upon previous research, data from IKONOS images are being used to correlate to field inventories of floodplain agroforestry areas managed under different intensities, as well as secondary succession in different stages of regrowth. Measures of vegetation structure and species composition are compared to textural and spectral indices in IKONOS and ETM+ data re-sampled at different spatial resolution. Also, IKONOS data are being applied to the definition of shifting cultivation cycles and to improve the delineation of small-scale agriculture not visible in Landsat TM and ETM+ data. Preliminary results using IKONOS images in multiscale analyses (Fig. 7) indicate improvements in the definition of intensive and intermediary managed agroforestry areas and in the definition of vegetation regrowth stages.

4. Discussion and conclusions

IKONOS tasking for the Large Scale Biosphere–Atmosphere Experiment in Amazonia has focused on the acquisition of imagery at a set of key study sites. The data acquired to date are currently being used by a number of researchers to address a set of earth science applications that can benefit from high-resolution. These applications are of high priority to the international scientific community and the LBA project in particular and include strategies for improving estimates of terrestrial carbon stocks and fluxes as well as estimates of land-use and land-cover changes (Cerri et al., 1995; Prentice et al., 2001; The LBA Science Planning Group, 1996).

As LBA moves forward, it is necessary to consider the adequacy of the current set of holdings and potential strategies for future tasking of high-resolution instruments.

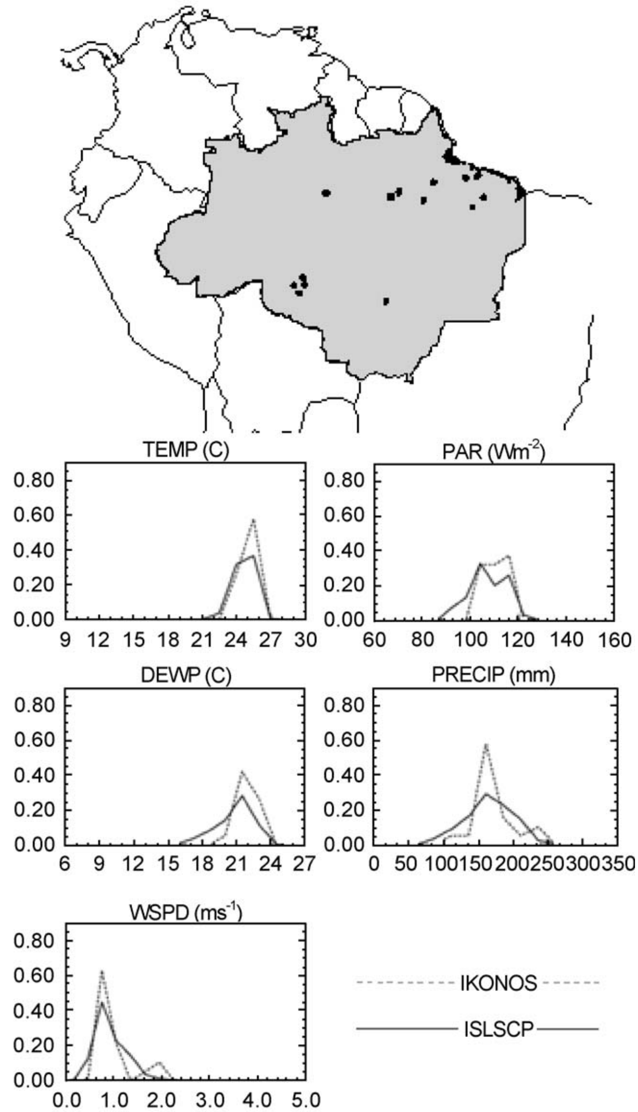


Fig. 8. (a) Brazilian Legal Amazon (Grey), and IKONOS sample locations (dots). (b) IKONOS sample distributions (dotted curves) and region-wide distributions (solid curves) of average annual conditions for several ecologically important environmental conditions. Conditions displayed include temperature (TEMP), dew point (DEWP), wind speed (WSPD), photosynthetically active radiation (PAR), and precipitation (PRECIP). Environmental conditions are the average of statistics for 1987 and 1988 complied in ISLSCP I (Meeson et al., 1995; Sellers et al., 1995).

One way to begin to assess the adequacy of current holdings is to calculate statistics on the representativeness of current holdings. For example, Fig. 8 presents sample distributions of several ecologically important climate variables defined by locations with IKONOS imagery, compared to those of the entire Brazilian Legal Amazon domain. As expected from a limited sample, these distributions tend to over-represent relatively common climatic conditions and under sample rare climatic conditions. Adding factors to this analysis such as soil type, topography, biogeography, and land-use history is likely to dilute the representativeness of the current set of holdings even further. With a current unique sample of approximately 3300 km^2 in an area of nearly 5,000,000 km^2, current IKONOS holdings represent a small and incomplete sample of this study area (< 0.1%).

Given the usefulness of IKONOS data and the limited size of the current set of holdings, how should future tasking be planned? Collecting imagery over the entire domain of Amazonia is prohibitive. For example, at current prices a single coverage of the area of the size of Amazonia would cost nearly US$1 billion and contain on the order of 10^4 GB of data. To make matters worse, repeat imagery are needed for change detection, inflating these potential costs and data volumes even more. The current strategy for tasking IKONOS data has been to focus on key study sites. To qualitatively improve the tasking strategy, an effort is needed to design and implement an objective and efficient sampling strategy. Objective and efficient sampling methods have been used in the context of ground-based sample measurements (e.g. USDA Forest Service, 1992). They are also necessary in high-resolution remote sensing.

Understanding the importance of fine-scale heterogeneity over large geographical areas is a central challenge in earth sciences that arises in many sub-disciplines (Ehleringer & Field, 1993; Hurtt, Moorcroft, Pacala, & Levin, 1998; Moorcroft et al., 2001). Toward this goal, new models that formally address issues of scaling are being developed (Moorcroft et al., 2001), and new technologies for obtaining high-resolution data remotely, such as IKONOS, are being developed and deployed. A critical challenge ahead will be in managing model complexity and efficiently organizing high-resolution information. Remote-sensing technologies that provide needed information are perhaps nowhere more important than in remote regions such as Amazonia, where ground-based infrastructure and access are limited.

Acknowledgements

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Appendix A. Database of IKONOS Tower Site images for LBA (http://www.eos-webster.sr.unh.edu)

Map ID	Name	Country	lat nw	lat sw	lat ne	lat se	lon nw	lon sw	lon ne	lon se	area (km^2)	Date acquired
1	Águas Emendadas	Brazil	– 15.52	– 15.58	– 15.52	– 15.58	– 47.63	– 47.63	– 47.57	– 47.57	49.06	6/23/2000
2	Águas Emendadas	Brazil	– 15.52	– 15.58	– 15.52	– 15.58	– 47.63	– 47.63	– 47.57	– 47.57	49.57	6/23/2001
3	Águas Emendadas	Brazil	– 15.50	– 15.60	– 15.50	– 15.60	– 47.65	– 47.65	– 47.54	– 47.55	123.71	6/1/2001
4	Brasília East	Brazil	– 15.62	– 15.72	– 15.62	– 15.73	– 47.99	– 47.99	– 47.89	– 47.89	124.10	6/1/2001
5	Brasília West	Brazil	– 15.58	– 15.68	– 15.58	– 15.68	– 48.08	– 48.07	– 47.97	– 47.97	124.17	6/1/2001
6	Caxiuanã	Brazil	– 1.72	– 1.78	– 1.72	– 1.78	– 51.49	– 51.49	– 51.42	– 51.42	49.06	6/7/2000
7	Caxiuanã	Brazil	– 1.72	– 1.78	– 1.72	– 1.78	– 51.49	– 51.49	– 51.42	– 51.42	48.83	9/3/2001
8	Cerrado	Brazil	– 21.63	– 21.70	– 21.64	– 21.70	– 47.65	– 47.65	– 47.58	– 47.58	49.03	5/29/2000
9	Cerrado	Brazil	– 21.63	– 21.70	– 21.63	– 21.70	– 47.65	– 47.65	– 47.58	– 47.58	50.43	5/29/2001
10	Fazenda Nossa Senhora	Brazil	– 10.73	– 10.79	– 10.73	– 10.79	– 62.39	– 62.39	– 62.33	– 62.33	49.03	8/2/2000
11	Fazenda Nossa Senhora	Brazil	– 10.73	– 10.79	– 10.73	– 10.79	– 62.39	– 62.39	– 62.33	– 62.33	49.43	8/2/2001
12	IBGE Campo Sujo	Brazil	– 15.92	– 15.98	– 15.92	– 15.98	– 47.90	– 47.90	– 47.84	– 47.84	49.06	5/29/2000
13	IBGE Campo Sujo	Brazil	– 15.92	– 15.98	– 15.92	– 15.99	– 47.90	– 47.90	– 47.84	– 47.84	49.64	5/29/2001
14	Jaru Tower	Brazil	– 10.03	– 10.13	– 10.03	– 10.13	– 61.98	– 61.98	– 61.88	– 61.88	110.29	4/6/2000
15	Jaru Tower	Brazil	– 10.05	– 10.11	– 10.05	– 10.11	– 61.97	– 61.96	– 61.90	– 61.90	49.06	5/17/2000
16	Jaru Tower	Brazil	– 10.05	– 10.11	– 10.05	– 10.11	– 61.96	– 61.96	– 61.90	– 61.90	48.43	5/28/2001
17	Manaus 1	Brazil	– 2.56	– 2.62	– 2.56	– 2.62	– 60.15	– 60.15	– 60.08	– 60.08	49.06	7/22/2000
18	Manaus 1	Brazil	– 2.56	– 2.62	– 2.56	– 2.62	– 60.15	– 60.15	– 60.08	– 60.08	49.13	8/2/2001
19	Manaus 2	Brazil	– 2.58	– 2.64	– 2.58	– 2.64	– 60.24	– 60.24	– 60.18	– 60.18	49.03	8/24/2000
20	Manaus 2	Brazil	– 2.58	– 2.64	– 2.58	– 2.64	– 60.24	– 60.24	– 60.18	– 60.18	49.11	10/7/2001
21	Santarém Kilo 67	Brazil	– 2.83	– 2.89	– 2.83	– 2.89	– 54.99	– 54.99	– 54.93	– 54.93	49.06	6/21/2000
22	Santarém Kilo 67	Brazil	– 2.83	– 2.89	– 2.83	– 2.89	– 54.99	– 54.99	– 54.93	– 54.93	49.03	11/3/2001
23	Santarém Kilo 83	Brazil	– 2.99	– 3.05	– 2.99	– 3.05	– 55.00	– 55.00	– 54.94	– 54.94	49.03	8/29/2000
24	Santarém Kilo 83	Brazil	– 3.01	– 3.05	– 3.01	– 3.05	– 55.00	– 55.00	– 54.94	– 54.94	33.06	11/14/2001
25	Santarém Kilo 83	Brazil	– 2.99	– 3.05	– 2.99	– 3.05	– 55.00	– 55.00	– 54.94	– 54.94	49.03	11/19/2001
26	Santarém Kilo 83	Brazil	– 3.04	– 3.07	– 3.04	– 3.07	– 55.01	– 55.01	– 54.94	– 54.94	25.86	8/29/2000
27	Santarém Kilo 83	Brazil	– 3.05	– 3.08	– 3.05	– 3.08	– 55.00	– 55.00	– 54.94	– 54.94	23.54	7/5/2002
28	Santarém Pasture	Brazil	– 2.99	– 3.05	– 2.99	– 3.05	– 54.92	– 54.92	– 54.86	– 54.86	49.00	6/13/2000
29	Santarém Pasture	Brazil	– 2.99	– 3.05	– 2.99	– 3.05	– 54.92	– 54.92	– 54.86	– 54.86	49.02	7/27/2001
30	Sinop Mato Grosso	Brazil	– 11.38	– 11.44	– 11.38	– 11.44	– 55.36	– 55.36	– 55.29	– 55.29	49.03	4/30/2000
31	Sinop Mato Grosso	Brazil	– 11.38	– 11.44	– 11.38	– 11.44	– 55.36	– 55.36	– 55.29	– 55.29	49.73	5/19/2001
32	Sinop Mato Grosso	Brazil	– 11.38	– 11.44	– 11.38	– 11.44	– 55.36	– 55.36	– 55.29	– 55.29	49.42	7/5/2002
33	Sugarcane	Brazil	– 21.07	– 21.13	– 21.07	– 21.13	– 48.10	– 48.10	– 48.03	– 48.03	49.03	6/12/2000
34	Sugarcane	Brazil	– 21.07	– 21.13	– 21.07	– 21.13	– 48.10	– 48.10	– 48.03	– 48.03	50.80	6/12/2001

Appendix B. Database of IKONOS Field Site images for LBA (http://www.eos-webster.sr.unh.edu)

Map ID	Name	Country	lat nw	lat sw	lat ne	lat se	lon nw	lon sw	lon ne	lon se	Area (km^2)	Date acquired
35	Altamira East	Brazil	– 3.17	– 3.31	– 3.17	– 3.31	– 52.26	– 52.26	– 52.17	– 52.17	171.32	10/14/2000
36	Altamira West	Brazil	– 3.17	– 3.31	– 3.17	– 3.31	– 52.35	– 52.35	– 52.26	– 52.26	162.14	10/14/2000
37	Alto Paraíso 1	Brazil	– 9.65	– 9.73	– 9.65	– 9.73	– 63.19	– 63.19	– 63.15	– 63.15	45.03	7/25/2002
38	Alto Paraíso 2	Brazil	– 9.42	– 9.50	– 9.42	– 9.50	– 63.35	– 63.35	– 63.30	– 63.30	50.63	7/14/2002
39	Alto Paraíso 3	Brazil	– 9.61	– 9.70	– 9.61	– 9.70	– 63.29	– 63.29	– 63.25	– 63.25	50.19	7/17/2002
40	Apeu	Brazil	– 1.27	– 1.34	– 1.27	– 1.34	– 48.00	– 48.01	– 47.94	– 47.94	49.06	7/10/2001
41	Cangussu	Brazil	– 9.95	– 10.01	– 9.95	– 10.01	– 50.04	– 50.04	– 49.98	– 49.97	49.00	7/7/2002
42	Cauaxi	Brazil	– 3.69	– 3.82	– 3.69	– 3.82	– 48.33	– 48.33	– 48.27	– 48.27	91.51	11/2/2000
43	Cauaxi	Brazil	– 3.69	– 3.82	– 3.69	– 3.82	– 48.33	– 48.33	– 48.27	– 48.27	91.51	6/18/2002
44	Cauaxi C	Brazil	– 3.61	– 3.65	– 3.61	– 3.65	– 48.50	– 48.50	– 48.39	– 48.39	48.76	7/7/2002
45	Cauaxi R (Scene A)	Brazil	– 3.71	– 3.75	– 3.71	– 3.75	– 48.43	– 48.43	– 48.37	– 48.37	28.10	8/9/2002
46	Cauaxi R (Scene B)	Brazil	– 3.71	– 3.75	– 3.71	– 3.75	– 48.43	– 48.43	– 48.37	– 48.37	28.10	8/20/2002
47	Cauaxi R (Scene C)	Brazil	– 3.71	– 3.75	– 3.71	– 3.75	– 48.43	– 48.43	– 48.37	– 48.37	28.10	8/23/2002
48	Ecuador 1 East	Ecuador	0.21	0.09	0.21	0.09	– 76.84	– 76.84	– 76.82	– 76.82	23.74	1/13/2002
49	Ecuador 1 West	Ecuador	0.21	0.09	0.21	0.09	– 76.94	– 76.94	– 76.82	– 76.82	76.97	1/5/2002
50	Ecuador 2 East	Ecuador	0.19	0.07	0.19	0.07	– 76.28	– 76.28	– 76.18	– 76.18	154.42	1/10/2002
51	Ecuador 2 West	Ecuador	0.19	0.07	0.19	0.07	– 76.30	– 76.30	– 76.20	– 76.20	152.19	2/15/2002
52	Ecuador 3 East	Ecuador	– 0.19	– 0.31	– 0.19	– 0.31	– 76.92	– 76.92	– 76.82	– 76.82	146.04	10/25/2000
53	Ecuador 3 West	Ecuador	– 0.19	– 0.31	– 0.19	– 0.31	– 76.94	– 76.94	– 76.91	– 76.91	34.84	10/25/2000
54	Ecuador 4	Ecuador	– 0.21	– 0.33	– 0.21	– 0.33	– 76.60	– 76.60	– 76.49	– 76.49	160.59	8/26/2001

Appendix B (*continued*)

Map ID	Name	Country	lat nw	lat sw	lat ne	lat se	lon nw	lon sw	lon ne	lon se	Area (km^2)	Date acquired
55	Ecuador 4 East	Ecuador	− 0.21	− 0.33	− 0.21	− 0.33	− 76.51	− 76.51	− 76.49	− 76.49	34.35	8/26/2001
56	Ecuador 4 West	Ecuador	− 0.21	− 0.33	− 0.21	− 0.33	− 76.61	− 76.61	− 76.51	− 76.51	154.75	8/26/2001
57	Fazenda Nova Vida	Brazil	− 10.11	− 10.17	− 10.11	− 10.17	− 62.84	− 62.84	− 62.75	− 62.75	60.64	8/16/2001
58	Fazenda Vitória	Brazil	− 2.93	− 3.00	− 2.93	− 3.00	− 47.45	− 47.45	− 47.37	− 47.37	74.22	7/29/2001
59	Igarapé-Açu 2	Brazil	− 1.15	− 1.22	− 1.15	− 1.22	− 47.61	− 47.61	− 47.54	− 47.54	55.00	9/19/2001
60	Igarapé-Açu 2	Brazil	− 1.15	− 1.22	− 1.15	− 1.22	− 47.61	− 47.61	− 47.54	− 47.54	55.00	10/3/2001
61	Igarapé-Açu 2	Brazil	− 1.15	− 1.22	− 1.15	− 1.22	− 47.61	− 47.61	− 47.54	− 47.54	55.00	8/31/2002
62	Igarapé-Açu 2	Brazil	− 1.15	− 1.22	− 1.15	− 1.22	− 47.61	− 47.61	− 47.54	− 47.54	55.00	9/19/2002
63	Igarapé-Açu 2	Brazil	− 1.12	− 1.21	− 1.12	− 1.21	− 47.62	− 47.63	− 47.54	− 47.54	92.92	10/22/2002
64	Ituqui, Brazil scene A	Brazil	− 2.51	− 2.68	− 2.51	− 2.68	− 54.33	− 54.32	− 54.22	− 54.22	211.80	7/27/2001
65	Ituqui, Brazil scene B	Brazil	− 2.51	− 2.68	− 2.51	− 2.68	− 54.24	− 54.24	− 54.19	− 54.19	100.94	8/7/2001
66	Ituqui, Brazil scene C	Brazil	− 2.51	− 2.68	− 2.51	− 2.68	− 54.39	− 54.39	− 54.28	− 54.28	227.15	8/7/2001
67	Ituqui, Brazil scene D	Brazil	− 2.51	− 2.68	− 2.51	− 2.68	− 54.50	− 54.50	− 54.37	− 54.37	261.12	10/6/2001
68	Ituqui, Brazil scene E	Brazil	− 2.51	− 2.68	− 2.51	− 2.68	− 54.50	− 54.50	− 54.49	− 54.48	35.40	10/9/2001
69	Machadinho	Brazil	− 9.43	− 9.54	− 9.43	− 9.54	− 62.11	− 62.11	− 62.00	− 62.00	154.47	5/28/2001
70	Mato Grosso	Brazil	− 9.57	− 9.63	− 9.57	− 9.63	− 55.97	− 55.97	− 55.90	− 55.90	49.00	7/5/2002
71	Medicilândia	Brazil	− 3.42	− 3.47	− 3.42	− 3.47	− 52.92	− 52.92	− 52.86	− 52.86	36.02	10/17/2002
72	Mil Madeiras	Brazil	− 2.79	− 2.89	− 2.79	− 2.89	− 58.84	− 58.84	− 58.76	− 58.76	96.99	7/25/2002
73	Pastaza	Ecuador	0.07	− 0.05	0.07	− 0.05	− 77.14	− 77.14	− 77.07	− 77.07	105.22	1/16/2002
74	Pilche	Ecuador	− 0.26	− 0.32	− 0.26	− 0.32	− 76.27	− 76.27	− 76.22	− 76.22	40.63	1/10/2002
75	Ponta de Pedras East	Brazil	− 0.19	− 0.31	− 0.19	− 0.31	− 76.92	− 76.92	− 76.82	− 76.82	146.04	12/19/2000
76	Ponta de Pedras West	Brazil	− 1.34	− 1.45	− 1.34	− 1.45	− 48.92	− 48.92	− 48.82	− 48.82	138.07	12/19/2000
77	Rohden East	Brazil	− 10.53	− 10.56	− 10.53	− 10.56	− 58.52	− 58.52	− 58.42	− 58.42	41.63	7/8/2002
78	Rohden Northeast	Brazil	− 10.44	− 10.52	10.45	− 10.52	− 58.47	− 58.48	− 58.40	− 58.40	68.79	10/1/2002
79	Rohden West	Brazil	− 10.53	− 10.56	− 10.53	− 10.56	− 58.59	− 58.59	− 58.50	− 58.50	35.60	7/8/2002
80	Rurópolis East	Brazil	− 4.06	− 4.09	− 4.06	− 4.09	− 54.83	− 54.83	− 54.72	− 54.72	39.90	7/8/2002
81	Rurópolis West	Brazil	− 4.06	− 4.09	− 4.06	− 4.09	− 54.85	− 54.85	− 54.74	− 54.74	40.95	7/5/2002
82	Santarém FLONA Tapajós	Brazil	− 2.99	− 3.08	− 2.99	− 3.08	− 55.00	− 55.00	− 54.94	− 54.94	76.55	7/5/2002
83	São Francisco do Pará East	Brazil	− 1.07	− 1.20	− 1.07	− 1.20	− 47.82	− 47.82	− 47.72	− 47.72	175.55	7/18/2001
84	São Francisco do Pará East	Brazil	− 1.07	− 1.20	− 1.07	− 1.20	− 47.83	− 47.83	− 47.72	− 47.72	191.10	12/30/2001
85	São Francisco do Pará West	Brazil	− 1.07	− 1.20	− 1.07	− 1.20	− 47.83	− 47.83	− 47.80	− 47.80	53.28	7/18/2001
86	Sewaya	Ecuador	− 0.15	− 0.20	− 0.15	− 0.20	− 76.20	− 76.20	− 76.14	− 76.14	35.86	2/4/2002
87	Tiguano	Ecuador	− 0.42	− 0.48	− 0.42	− 0.48	− 76.51	− 76.51	− 76.45	− 76.45	35.86	1/13/2002
88	Tomé-Açu East	Brazil	− 2.34	− 2.46	− 2.34	− 2.46	− 54.21	− 54.20	− 54.17	− 54.17	49.60	7/27/2001
89	Tomé-Açu West	Brazil	− 2.34	− 2.46	− 2.34	− 2.46	− 54.29	− 54.29	− 54.18	− 54.18	151.69	7/27/2001
90	Zabalo	Ecuador	− 0.19	− 0.24	− 0.19	− 0.24	− 75.43	− 75.43	− 75.37	− 75.37	35.86	2/9/2002

References

Araujo, T. M., Higuchi, N., & Carvalho, J. A. (1999). Comparison of formulae for biomass content determination in a tropical rainforest site in the state of Pará, Brazil. *Forest Ecology and Management*, *117*, 43–52.

Asner, G. P., Keller, M., Pereira, R., & Zweede, J. (2002). Remote sensing of selective logging in Amazonia: Assessing limitations based on detailed field measurements, Landsat ETM+ and textural analysis. *Remote Sensing of Environment*, *80*(3), 483–496.

Asner, G. P., Palace, M., Keller, M., Pereira Jr., R., Silva, J. N. M., & Zweede, J. C. (submitted for publication). Estimating canopy structure in an Amazon forest from laser rangefinder and IKONOS satellite observations. *Biotropica*.

Asner, G. P., & Warner, A. S. (submitted for publication). Canopy shadow in IKONOS satellite observations of tropical forests and savannas. *Remote Sensing of Environment*.

Bishop, C. (1995). *Neural networks for pattern recognition*. New York: Oxford University Press (504 pp.).

Boardman, J. W. (1989). Inversion of imaging spectrometry data using singular value decomposition. *IEEE International Geoscience and Remote Sensing Symposium, Vancouver, BC* (pp. 2069–2072).

Boardman, J. W. (1992). Sedimentary facies analysis using imaging spectrometry: A geophysical inverse problem. PhD Thesis, University of Colorado, Boulder, CO, 212 pp.

Braswell, B. H., Linder, E., Hagen, S., Xiao, X., Frolking, S., Moore III, B., & Liu, J. (2000). A Bayesian unmixing algorithm for retrieving land-cover distributions using global reflectance data. *American Geophysical Union Fall Meeting, San Francisco, CA.*

Bradshaw, G. A., & Spies, T. A. (1992). Characterizing canopy gap structure in forests using wavelet analysis. *Journal of Ecology*, *80*, 205–215.

Brienza Júnior, S. (1999). Biomass dynamic of fallow vegetation enriched with leguminous trees in the Eastern Amazon of Brazil. PhD Thesis, Goettingen Goettinger Beitrage zur Land- und Forstwirtschaft in den Tropen und Subtropen, 133 pp.

Brondízio, E. S., Moran, E. F., Mausel, P., & Wu, Y. (1994). Land use change in the Amazon estuary: Patterns of Caboclo settlement and landscape management. *Human Ecology*, *22*(3), 249–278.

Brondízio, E. S., Moran, E. F., Mausel, P., & Wu, Y. (1996). Changes in land cover in the Amazon estuary: Integration of thematic mapper with botanical and historical data. *Photogrammetric Engineering and Remote Sensing*, *62*(8), 921–929.

Brown, S. (1997). Estimating biomass and biomass change of tropical forests: A primer. FAO Forestry Paper 134, United Nations Food and Agriculture Organization, Rome, Italy.

Cerri, C., Niro, H., Melillo, J., Krug, T., Fernandes, E., Forsberg, B., Houghton, R., Keller, M., Martinelli, L., Nepstad, D., Nobre, A., Richey, J., Reynaldo, V., Crill, P., Davidson, E., De Mello, W., Melack, J., Mozeto, A., Skole, D., Soares, J. V., Sterberg, L., & Trumbore, S. (1995). The ecological component of an integrated Amazon study (also known as LBA): The effects of forest conversion. Workshop Report, Manaus, Brazil, 55 pp.

Clark, D. B., Read, J. M., Clark, M., Cruz, A. M., Dotti, M. F., & Clark, D. A. (submitted for publication). Application of 1-m and 4-m resolution satellite data to studies of tree demography, stand structure and land-use classification in tropical rain forest landscapes. *Ecological Applications*.

Cohen, W. B., & Spies, T. A. (1992). Estimating structural attributes of Douglas-fir/western hemlock forests stands from Landsat and SPOT imagery. *Remote Sensing of the Environment*, *41*, 1–17.

Cohen, W. B., Spies, T. A., & Bradshaw, G. A. (1990). Semivariograms of digital imagery for analysis of conifer forest structure. *Remote Sensing of the Environment*, *34*, 167–178.

Cressie, N. (1991). *Statistics for spatial data*. USA: Wiley-Interscience (900 pp.).

Cross, A. M., Settle, J. J., Drake, N. A., & Paivinen, R. T. M. (1991). Subpixel measurement of tropical forest cover using AVHRR data. *International Journal of Remote Sensing*, *5*, 1119–1129.

de Sá, T. D. A. & Alegre, J. (2001). Práticas agroflorestais visando o manejo de vegetações secundárias: Uma abordagem com ênfase em experiências amazônicas. In CONGRESSO BRASILEIRO DE SISTEMAS AGROFLORESTAIS, 3., 2000, Manaus, AM. Embrapa Amazônia Ocidental. *Documentos*, *17*, 102–115.

de Sá, T. D. A., de Oliveira, V. C., Coimbra, H. M., de Carvalho, C. J. R., Dias-Filho, M., Sommer, R., & Brienza Júnior, S. (1998). Diurnal and seasonal patterns of leaf water relations in spontaneous and enriched secondary vegetation components: Tools to understand water exchange and water stress behavior, Abstracts of the Third SHIFT Workshop, Manaus—AM. March 15–19, p. A14.

de Sá, T. D. A., de Oliveira, V. C., de Araújo, A. C., & Brienza Júnior, S. (1997). Biophysical aspects of enriched fallow with leguminous fast growing trees in Northeastern Pará, Brazil: Spectral composition of light and water vapour. In International Symposium on the Science and Practice of Short-term Improved Fallows, Lilongwe, Malawi, 1997, Abstracts, Lilongwe, IUFRO/ISSS-AISS-IBG/ICRAF.

de Sá, T. D. A., Vielhauer, K., Denich, M., Kanashiro, M., & Vlek, P. L. G. (1998). Towards improving natural resources use in Eastern Amazonia through a modified sequential agroforestry system. In Resumos Expandidos: II Congresso Brasileiro em Sistemas Agroflorestais, 25.11.1998, pp. 95–100.

Drake, J. B., Dubayah, R. O., Clark, D. B., Knox, R. G., & Blair, J. B. (2002). Sensitivity of large-footprint lidar to canopy structure and biomass in a neotropical rainforest. *Remote Sensing of Environment*, *81*, 378–392.

Drake, J. B., Dubayah, R. O., Clark, D. B., Knox, R. G., Blair, J. B., Hofton, M. A., Chazdon, R. L., Weishampel, J. F., & Prince, S. (2002). Estimation of tropical forest structural characteristics using large-footprint lidar. *Remote Sensing of Environment*, *79*, 305–319.

Ehleringer, J. R., & Field, C. B. (Eds.) (1993). *Scaling physiological processes leaf to globe*. San Diego, CA: Academic Press, 388 pp.

Fearnside, P. M. (1990). The rate and extent of deforestation in Brazilian Amazon. *Environmental Conservation*, *17*, 213–226.

Foody, G. M., Lucas, R. M., Curran, P. J., & Honzak, M. (1997). Nonlinear mixture modeling without end-members using an artificial neural network. *International Journal of Remote Sensing*, *18*, 937–953.

Harding, D. J., Lefsky, M. A., Parker, G. G., & Blair, J. B. (2001). Laser altimeter canopy height profiles: Methods and validation for closed-canopy, broadleaf forests. *Remote Sensing of Environment*, *76*, 283–297.

Hurtt, G. C., Moorcroft, P. R., Pacala, S. W., & Levin, S. A. (1998). Terrestrial models and global change: Challenges for the future. *Global Change Biology*, *4*, 581–590.

INPE (2000). *Monitoring the Brazilian Amazon Forest by Satellite 1999–2000*. Amazon Institutional Program, General Coordination of Earth Observation, National Institute of Space Research, Brazil.

Keller, M., Palace, M., & Hurtt, G. C. (2001). Biomass estimation in the Tapajós National Forest, Brazil: Examination of sampling and allometric uncertainties. *Forest Ecology and Management*, *154*, 371–382.

Lefsky, M. A., Harding, D., Cohen, W. B., Parker, G., & Shugart, H. H. (1999). Surface lidar remote sensing of basal area and biomass in deciduous forests of Eastern Maryland, USA. *Remote Sensing of Environment*, *67*, 83–98.

Means, J. E., Acker, S. A., Harding, D. J., Blair, J. B., Lefsky, M. A., Cohen, W. B., Harmon, M. E., & McKee, W. A. (1999). Use of large-footprint scanning airborne lidar to estimate forest stand characteristics in the Western Cascades of Oregon. *Remote Sensing of Environment*, *67*, 298–308.

Meeson, B. W., Corprew, F. E., McManus, J. M. P., Myers, D. M., Closs, J. W., Sun, K. J., & Sunday, D. J. (1995). *ISLSCP Initiative I-global datasets for land-atmosphere models, 1987–1988*. Washington, DC: American Geophysical Union, Available on CD-ROM.

Moorcroft, P., Hurtt, G., & Pacala, S. (2001). A method for scaling vegetation dynamics: The ecosystem demography model (ED). *Ecological Monographs*, *71*(4), 557–586.

Myneni, R. B., Hall, F. G., Sellers, P. J., & Marshak, A. L. (1995). The interpretation of spectral vegetation indices. *IEEE Transactions on Geoscience and Remote Sensing*, *33*, 481–486.

Nepstad, D. C., Verissimo, A., Alencar, A., Nobre, C., Lima, E., Lefebvre, P., Schlesinger, P., Potter, C., Moutinho, P., Mendoza, E., Cochrane, M., & Brooks, V. (1999). Large-scale impoverishment of Amazonian forests by logging and fire. *Nature*, *398*, 505–508.

Pereira, R., Zweede, J., Asner, G. P., & Keller, M. (2002). Forest canopy damage from conventional and reduced impact selective logging in Eastern Amazon, Brazil. *Forest Ecology and Management* (In press).

Prentice, I. C., Farquhar, G. D., Fasham, M. J. R., Goulden, M. L., Heimann, M., Jaramillo, V. J., Kheshgi, H. S., Le Quéré, C., Scholes, R. J., Wallace, D. W. R., Archer, D., Ashmore, M. R., Aumont, O., Baker, D., Battle, M., Bender, M., Bopp, L. P., Bousquet, P., Caldeira, K., Ciais, P., Cox, P. M., Cramer, W., Dentener, F., Enting, I. G., Field, C. B., Friedlingstein, P., Holland, E. A., Houghton, R. A., House, J. I., Ishida, A., Jain, A. K., Janssens, I. A., Joos, F., Kaminski, T., Keeling, C. D., Keeling, R. F., Kicklighter, D. W., Kohfeld, K. E., Knorr, W., Law, R., Lenton, T., Lindsay, K., Maier-Reimer, E., Manning, A. C., Matear, R. J., McGuire, A. D., Melillo, J. M., Meyer, R., Mund, M., Orr, J. C., Piper, S., Plattner, K., Rayner, P. J., Sitch, S., Slater, R., Taguchi, S., Tans, P. P., Tian, H. Q., Weirig, M. F., Whorf, T., & Yool, A. (2001). The carbon cycle and atmospheric carbon dioxide. In J. T. Hougton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, & C. A. Johnson (Eds.), *Climate Change 2001: The Scientific Basis. Contribution of the Working Group I to the Intergovernmental Panel on Climate Change* (pp. 183–238). Cambridge, UK: Cambridge University Press.

Quarmby, N. A., Townshend, J. R. G., Settle, J. J., & White, K. H. (1992). Linear mixture modeling applied to AVHRR data for crop area estimation. *International Journal of Remote Sensing*, *3*, 415–425.

Read, J. M. (in press). Spatial analyses of logging impacts in Amazonia using remotely-sensed data. *Photogrammetric Engineering and Remote Sensing.*

Read, J. M., Clark, D. B., Venticinque, E. M., & Moreira, M. P. (submitted for publication). Application of merged 1-m and 4-m resolution satellite data to research and management in tropical forests. *Journal of Applied Ecology.*

Sellers, P. J., Dickinson, R. E., Randall, D. A., Betts, A. K., Hall, F. G., Berry, J. A., Collatz, G. J., Denning, A. S., Mooney, H. A., Nobre,

C. A., Sato, N., Field, C. B., & Henderson-Sellers, A. (1997). Modeling the exchanges of energy, water, and carbon between continents and the atmosphere. *Science*, *275*, 502–509.

Sellers, P. J., Meeson, B. W., Closs, J., Collatz, J., Corprew, F., Dazlich, D., Hall, F. G., Kerr, Y., Koster, R., Los, S., Mitchell, K., McManus, J., Myers, D., Sun, K. J., & Try, P. (1995). *An overview of the ISLSCP-I Global datasets. On: ISLSCP Initiative I- Global datasets for land-atmosphere models, 1987-1988, vol. 1–5*. Washington, DC: NASA (Published on CD).

Shugart, H. H., Bourgeau-Chavez, L., & Kasischke, E. S. (2000). Determination of stand properties in boreal and temperate forests using high-resolution imagery. *Forest Science*, *46*(4), 478–486.

Skole, D. L., & Tucker, C. J. (1993). Tropical deforestation and habitat fragmentation in the Amazon: Satellite data from 1978 to 1988. *Science*, *260*, 1905–1910.

Smith, M. O. (1990). Vegetation in deserts: A regional measurement of abundance from multi-spectral images. *Remote Sensing of Environment*, *31*, 1–26.

Sommer, R. (2000). Water and nutrient balance in deep soils under shifting cultivation with and without burning in the Eastern Amazon, Göttingen, Cuvillier, 240 pp.

The LBA Science Planning Group (1996). The Large Scale Biosphere–Atmosphere Experiment in Amazonia (LBA): Concise Experimental Plan. LBA Project Office, CPTEC, Brazil, http://yabae.cptec.inpe.br/lba.

USDA Forest Service (1992). Forest service resource inventories: An overview, Washington, DC.

Vielhauer, K., Denich, M., de Sá, T. D. A., Kato, O. R., Kato, M. d. S. A., Brienza Jr., S., & Vlek, P. L. G. (2001). Land-use in a mulch-based farming system of small holders in the Eastern Amazon. *Proceedings of the Deutscher Tropentag* (Conference on International Agricultural Research for Development) "One World: Research for a better quality of life", Bonn, Germany, October 9–11 2001, pp. 1–9.

Vourlitis, G. L., Priante-Filho, N., Hayashi, M. M. S., de Souza Nogueira, J., Caseiro, F. T., & Campelo Jr., J. H. (2002). Seasonal variations in the evapotranspiration of a transitional tropical forest of Mato Grosso, Brazil. *Water Resources Research*, *38*(6), 30–31.

Vourlitis, G. L., Priante-Filho, N., Hayashi, M. M. S., de Souza Nogueira, J., Caseiro, F. T., Raiter, F., & Campelo Jr., J. H. (in press). The role of seasonal variations in meteorology on the net CO_2 exchange of a Brazilian transitional tropical forest. *Ecological Applications*.