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METHODOLOGICAL INSIGHTS

Application of merged 1-m and 4-m resolution satellite data to research and management in tropical forests

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Summary

1. Until very recently there have been no digital data from satellites for studying events that occur at scales of 10–1000 m^2 over large areas (100–100 000 ha). Many phenomena of interest to ecologists, such as impacts of selective logging on forest processes, occur over large extents but at local scales. Here we report results from a pilot project to evaluate through visual interpretation the potential of newly available 1-m panchromatic and 4-m multi-spectral data from the IKONOS satellite, for studying forest structure, dynamics and logging impacts in logged and old-growth tropical moist forest.

2. The study area, the Mil Madeireira Itacoatiara Ltda site of Precious Woods Amazon, near Itacoatiara, Amazonas, Brazil, is managed using reduced-impact logging practices to minimize environmental impacts, and thus represents a lower bound for logging impacts in tropical rain forests.

3. The IKONOS image was georeferenced using uncorrected global positioning system (GPS) locations for 10 control trees whose crowns were clearly visible in the image. The root mean square error (RMSE) of the geometric transformation was 4 m, while the mean crown diameter of 50 randomly chosen trees in old-growth forest was 9·4 m. The fact that the RMSE was less than half the average crown diameter implies that it will usually be possible to locate from the ground crowns that are distinct on the image, given sufficiently accurate GPS locations.

4. IKONOS data are well suited for evaluating and monitoring logging impacts. Many impacts of logging were clearly observable in the image, including major and some minor roads, logging patios and larger logging gaps. Smaller extraction roads and logging gaps were not observable.

5. Many individual trees were distinct on the IKONOS image, indicating that it is now feasible to conduct demographic studies of tropical rain forest canopy trees based on repeated satellite observations. Linking these remotely sensed data to ground data will require improved GPS positions, because it is currently difficult to obtain accurate GPS readings in tropical rain forest understoreys.

6. *Synthesis and applications.* IKONOS 1-m and 4-m data were found to be useful for identifying individual trees as well as some logging management features in a tropical moist forest in central Amazonia. These data will have many applications for research and management of intervened and old-growth tropical forests, including planning and assessment of logging activities, as well as monitoring adherence to certification criteria such as those of the Forest Stewardship Council. Rapid development of these

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applications will come from building on existing data on forest structure and function, and by fostering collaborations between remote sensing scientists, ecologists and natural resource managers.

Key-words: Amazonia, georeferencing, IKONOS, reduced-impact logging, remote sensing, tropical moist forests.

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Introduction

Describing, understanding and monitoring tropical forests at regional and larger scales is important for many global issues, including sustainable management of natural resources, climate change detection and biodiversity conservation. While there is a need for studies of tropical forests at scales of 100s to 10 000s of hectares, many key processes operate at very small (local) scales and require fine-scale study done at the plot level. For decades remotely sensed data from satellites have provided researchers with landscape- to regional-scale environmental data sets with global and repeat coverage at pixel sizes of 10s to 1000s of metres. Aerial photography and other airborne sensors, on the other hand, have provided finer-resolution data sets of local areas but the data are generally expensive and logistically difficult to obtain, particularly in tropical areas. Only very recently have high-resolution satellite data become commercially available, making possible fine-scale studies over large areas. The commercial IKONOS satellite (Space Imaging, Thornton, Colorado, USA), one of several new satellites collecting high-resolution data, was launched in September 1999 and provides, on request, effectively global coverage of 1-m panchromatic data and four bands of 4-m multi-spectral data in the blue, green, red and near infra-red portions of the spectrum, respectively (Table 1) (Lillesand & Kiefer 2000).

To date, the most widely used satellite data include Landsat Multi-spectral Scanner (MSS; 80 m pixels), Landsat Thematic Mapper (TM) and Enhanced TM (ETM; 30-m multi-spectral pixels), Systeme Pour l'Observation de la Terre (SPOT; 20-m multi-spectral pixels) and Advanced Very High Resolution Radiometer (AVHRR; 1-km pixels) (Lillesand & Kiefer 2000). Much of the work aimed at characterizing and detecting changes in tropical forests has been done using Landsat TM data (but see Nagendra & Gadgil 1999) due to their affordability, seven spectral bands and relatively fine spatial resolution. Single date Landsat TM data have been found to be useful for studies of tropical forest extent and fragmentation, larger (> 1 ha) disturbance events (i.e. blowdowns, fire patterns and flood impacts), and detection of distinctive forest types (Skole & Tucker 1993; Tanner, Kapos & Adams 1998; Nepstad *et al*. 1999; Cochrane 2001; Cochrane & Laurance 2002). However, TM data have not been found to be good at differentiating between less distinctive forest types in the humid tropics or different forest age classes without the incorporation of field data and/or analysis of multi-temporal TM data (Tanner, Kapos & Adams 1998; Sader *et al*. 1989; Nelson *et al*. 2000; but see Steininger 1996). Studies of selective logging using TM data in the Amazon have found that TM and ETM data can be used to detect logging patios and the wider logging roads but generally lack the resolution necessary to detect gaps, skids and other roads (Asner *et al*. 2002; Read 2003). Stone & Lefebvre (1998) found evidence of selective logging difficult to detect using TM data, and the logging features to be undetectable on the imagery after 3 years.

Table 1. Band wavelengths for IKONOS data (source Space Imaging 2002)

Wavelength (μm)
0·445–0·516 (blue)
0·506–0·595 (green)
0·632–0·698 (red)
0·757–0·853 (near infra-red)
0·45–0·90 (panchromatic)

This paper presents findings of a pilot study to assess the potential of IKONOS satellite data for characterizing tropical forest structure and dynamics. Our goal was to link the satellite data with field measurements and observations of individual trees, gaps and logging management features, and to determine potential applications to management and monitoring of logging operations, as well as the potential for research in old-growth forests.

We carried out the work in a tropical moist forest reduced-impact logging (RIL) operation in Amazonia in both logged and unlogged (old-growth) areas. Reduced-impact logging operations seek to minimize logging impacts on soils and the remaining vegetation by carefully siting roads, controlling the amount and type of timber extracted and left in place, and reducing damage associated with cutting and extracting (Pinard & Cropper 2000; Sist 2000). Reduced-impact logging operations cover only a small fraction of tropical rain forests (Forest Stewardship Council Access 2001) and represent the lower bound of biological and physical impacts of logging in tropical forests. Most tropical logging occurs with much greater environmental impacts. We reasoned that if IKONOS data were successful in providing useful metrics of logging effects in the best-case reduced-impact logging scenario, they would also work in situations with much greater forest disturbance.

Methods

STUDY AREA

The study site was located in the Precious Woods Amazon (Mil Madeireira Itacoatiara Ltda) logging operation, north of the Rio Amazon near Itacoatiara, Amazonas (140 km east of Manaus, Brazil), at approximately 2°48′S, 58°48′W (Fig. 1). The site covers about 127 000 ha of lowland forests (tropical moist forest in the Holdridge system;, Holdridge 1947), spanning an elevational range of approximately 60–120 m above sea level with flat plateaux and plains separated by steep slopes. In this study we worked only on relatively level sites, thus avoiding image interpretation problems associated with shadows caused by steep slopes. The mean temperature of the area is 26 °C and annual rainfall is 2100 mm, with a pronounced dry season from July to October (RADAMBRASIL 1976).

Precious Woods Amazon (also known as Mil Madeireira) was the first reduced-impact logging operation in the Amazon (Precious Woods Amazon 2001). The company uses low-impact logging and selection techniques and was certified by the Forest Stewardship Council (FSC) in 1997 as complying with their environmental, social and economic criteria (Forest Stewardship Council Access 2001). The logging is carried out in several thousand-hectare contiguous sections each year, stopping during the wet months of February–April. The results we report here were obtained in a logging section that was cut from the end of 2000 until May 2001. We also worked in an unlogged, old-growth section of > 15 000 ha.

DATA

We used IKONOS satellite (Space Imaging™ processing level: standard geometrically projected) multispectral (4-m pixels) and panchromatic (1-m pixels) data for a 6500-ha area of logged and old-growth forest of the Precious Woods Amazon operation. The cost of the data was US \$29 km^{-2} each for the panchromatic and multi-spectral images (i.e. US \$58 km^{-2}); however, prices have since dropped and are currently at US \$37·50 km^{-2} for both the panchromatic and multi-spectral data, with a minimum required order of 100 km^2 (Space Imaging 2002). The data were acquired on 12 March 2001 (Table 2), thus all logging impacts visible in the image were < 1 year old. All ground-based data were gathered in July 2001.

We merged the 1-m panchromatic with the 4-m multi-spectral data to create a 1-m pan-sharpened image using a forward-reverse principal components

Fig. 1. The study site, the Mil Madeireira Itacoatiara Ltda logging operation located near Itacoatiara, Amazonas, Brazil.

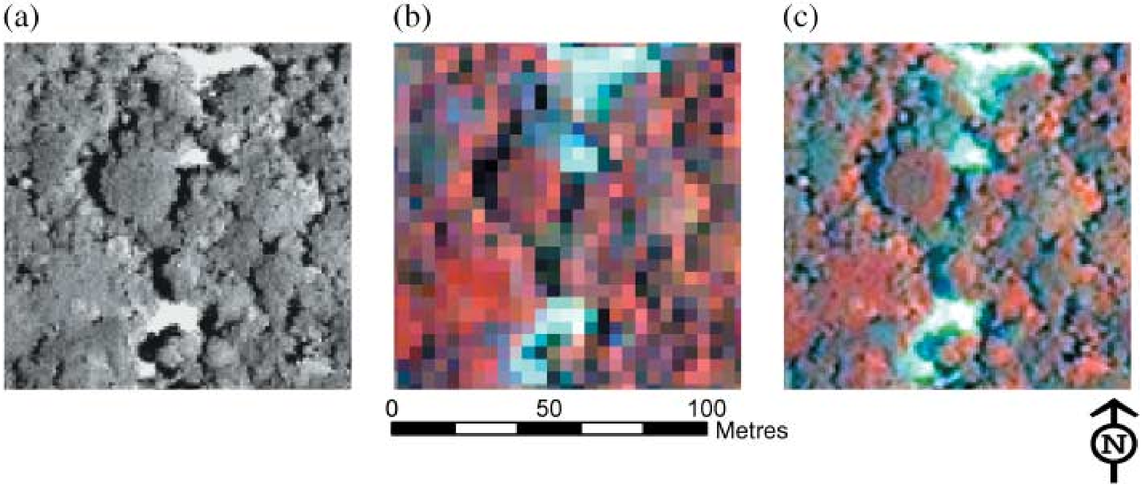

Fig. 2. IKONOS image subsets of an area of logged forest at Mil Madeireira Itacoatiara Ltda: (a) IKONOS 1-m panchromatic data; (b) IKONOS 4-m multi-spectral data (RGB display of bands 4, 2, 1); and (c) IKONOS 1-m pan-sharpened data (RGB display of bands 4, 2, 1).

Table 2. IKONOS data acquisition attributes

Date	12 March 2001
Time	14:10
Sun azimuth	91·38
Sun elevation	61·30
Collection azimuth	83·45
Collection elevation	73·34
Source	Space Imaging Co. (Denver, CO)

transform described by Chavez, Sides & Anderson (1991). In this transformation the principal components of the 4-m multi-spectral image were calculated, and the histogram of the panchromatic image stretched to the same numeric range as the first principal component (PC1) of the multi-spectral data. The stretched panchromatic band was then substituted for PC1 and an inverse principal components transform calculated. The result was a 1-m resolution data set of four multi-spectral bands containing the same thematic information as the four original multi-spectral bands, respectively. This was accomplished using the Resolution Merge function in Erdas IMAGINE image processing software (ERDAS 1999).

In the field we used hardcopy false-colour printouts of the 1-m pan-sharpened image, in combination with global positioning system (GPS) technology, to identify and locate corresponding features on the image and on the ground. On this false-colour image the blue, green and near infra-red bands were assigned to blue, green and red colours, respectively. This band combination was preferred as it gave the most contrast between the bare soil and forest canopy. We found the pan-sharpened image to be more useful for identifying features than the 1-m or 4-m images alone (Fig. 2). Two GPS units with external antennae were used, a Magellan™ GPS Pro MARK X (Santa Clara, California, USA) and a Trimble™ Pro-XL (Sunnyvale, California, USA), which were found to agree to approximately 25-cm horizontal position under optimal conditions. The data were not differentially corrected.

IMAGE GEOREFERENCING

Ground control points for georeferencing the image to Universal Transverse Mercator coordinates were selected based on tree crowns that were clearly identifiable on the image. In all cases these represented trees left standing isolated in logging patios (cleared areas in the forest for temporary storage of cut logs) or trees at the edges of patios and logging roads that were distinctive from their neighbouring trees. Locations of the trees were recorded either from direct GPS measurements or calculated from angle and distance offsets from GPS positions gathered in adjacent, more open locations.

Because we wanted to work at the spatial scale of individual tree crowns, we needed to know how average crown sizes compared with the transformation error. Average crown size was estimated by selecting a 1250-ha area of old-growth forest on the image and using a random number generator to select 50 points. At each point, the area of the nearest identifiable crown was determined by digitizing the crowns from the IKONOS image. An assessment of the error associated with digitizing tree crowns was made by repeatedly ($n = 5$) digitizing crowns of nine trees and calculating the associated crown diameters. The mean coefficient of variation of the measures was < 5%.

LINKING GROUND-BASED MEASUREMENTS WITH IKONOS DATA: CROWN–AREA RELATIONSHIPS

A ground-based index of crown area was calculated for nine trees (including eight of the trees used for georeferencing the image plus a well-identified tree for which we did not have a good GPS position) and correlated with the crown area of those same trees digitized from the IKONOS image. The crown area index for each tree was calculated by measuring four crown radii measured from the centre of the trunk to the edge of the canopy at approximately 90° intervals; we sought to measure the longest crown axis possible as well as the longest radii more or less perpendicular to the first axis. A clinometer was used to determine the position on the forest floor of the vertical projection of the canopy edge. The crown area index was calculated as the area of the polygon formed by the four radii.

For the same set of trees, trunk diameter, measured to ±1 cm using a diameter tape or tree callipers as high as possible above the ground without using a ladder, was correlated with the digitized crown area for each tree.

Results

IMAGE GEOREFERENCING

Ten control points, concentrated in the logged section of the image but with some points extending into old-growth forest along new roads, were used to georeference the image, resulting in a root mean square error (RMSE) of 4 m. All field measurements were made within, or close to, the area bounded by the georeference control points. It was not possible to conduct an independent check of georeferencing accuracy because all high-quality ground control points were used in calculating the original transformation. All 10 control points used in the calculation of the transformation equations were canopy-level and emergent trees, and in the majority of cases it was assumed that the centre of the crown in the image corresponded to the centre of the trunk on the ground. Unless detailed crown mapping is done for each control point tree, the accuracy of image rectification by this method is unlikely to improve significantly. Another implication of this result is that it will be possible to georectify images of continuous forest to high precision using none of the usual control point features (road intersections, building edges), provided that accurate GPS readings can be taken under distinctive tree crowns.

The average crown diameter in the old-growth forest was 9·5 m, more than double the RMSE. This order of locational accuracy is sufficient for locating individual trees and gaps, assuming accurate GPS locations can be obtained.

LOGGED AREAS

Major logging management features were readily recognizable on the image (Fig. 3), including (i) primary roads approximately 20–25 m wide, used by logging trucks for transporting logs from the major logging patios to the sawmill; (ii) logging patios (temporary storage areas), approximately 1000–3000 m^2; and (iii) minor roads ranging from 10 to 20 m wide, used for extracting logs from forest to the patios. Single-vehicle width roads, used for extracting trees to minor roads, were identifiable on the ground but were frequently not

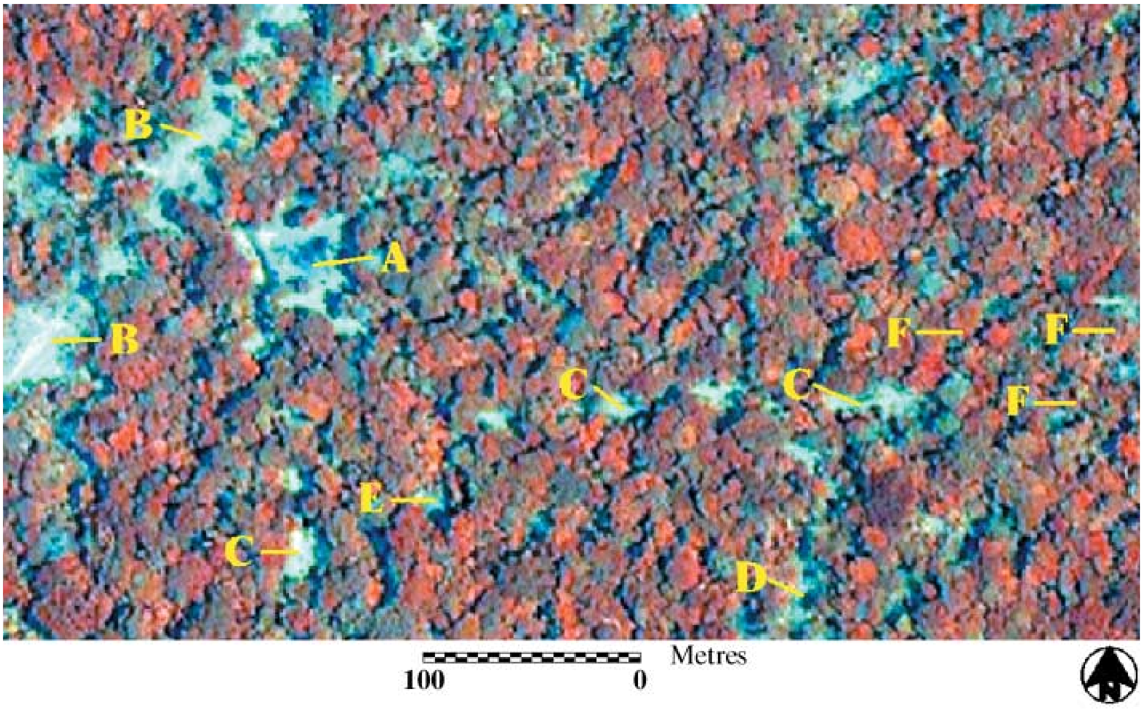

Fig. 3. Merged 1-m panchromatic and 4-m multi-spectral IKONOS image (RGB display of bands 4, 2, 1) showing logged tropical moist forest at the Mil Madeireira reduced-impact logging site near Itacoatiara, Amazonas State, Brazil. Visible logging management features include logging patio, approximately 1500 m^2 (A); primary road, 25-m wide (B); minor roads, 10–15-m wide (C); multiple-tree gap, 400 m^2 (D); and single-tree gap, 150 m^2 (E). Areas that were identified on the ground as gaps but not identifiable on the image are identified as F.

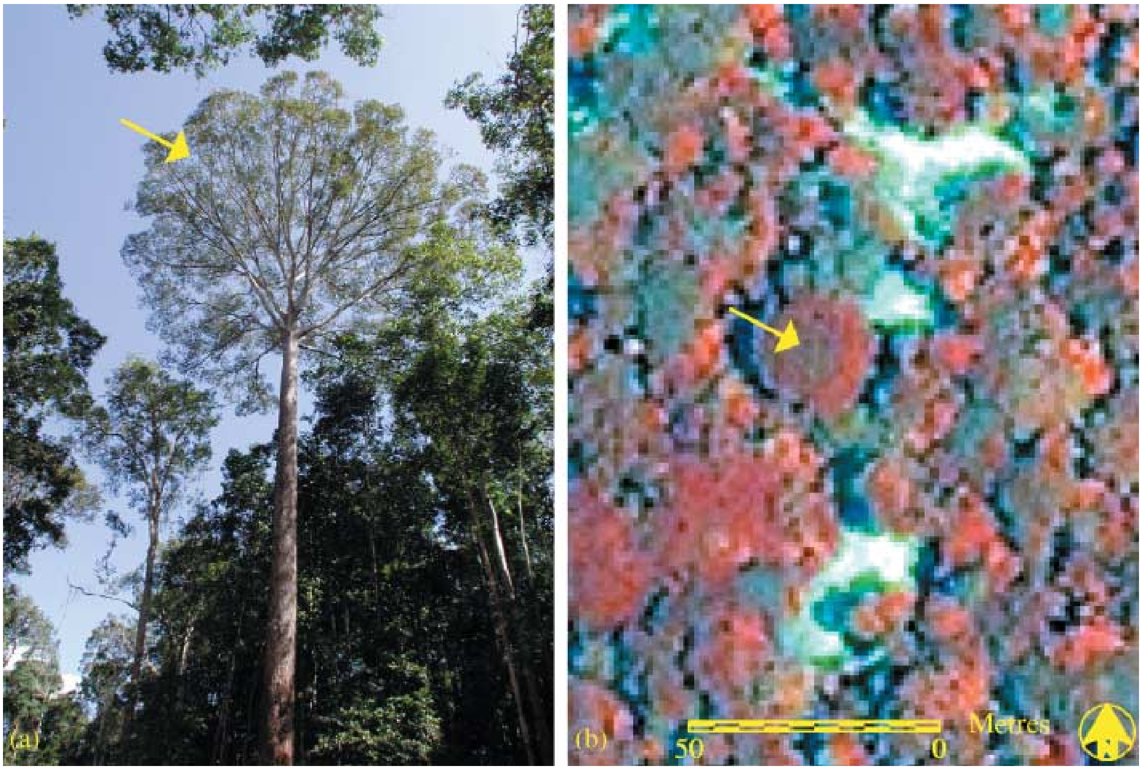

Fig. 4. Emergent tree (crown diameter 22 m, height approximately 40 m, trunk diameter 1·24 m at breast height), located on the edge of a road cut (A) that was clearly visible on the image (B), and identifiable with certainty on the ground using GPS and maps from the imagery (RGB display of bands 4, 2, 1).

distinguishable on the image. Some logging gaps, including single-tree gaps, were visible on the image, although others were not. Vertically projected clearings or gaps of less than 200 m^2 were apparent in some cases. It was not clear to us why some gaps were more distinctive on the image than others. However, shadows cast by surrounding vegetation and post-image-acquisition logging activity, which modified the forest structure we observed in the field, were contributing factors.

Individual tree crowns were clearly distinguishable on the image in many cases (Fig. 4). However, locating corresponding trees on the ground proved difficult unless the spatial context was clearly unique (i.e. proximity to gaps or clearings) and/or highly accurate GPS positions were available. Improving techniques or technology for obtaining accurate GPS readings under closed canopy will significantly increase the range of applications for IKONOS imagery in tropical forests.

OLD-GROWTH FOREST

Figure 5 shows a 11·5-ha block of unlogged old-growth forest (compare with Fig. 3). It is possible to distinguish many individual crowns, particularly those of emergents. However, there are also many areas where it is not possible to determine how many crowns were in the canopy, and this is true at all display magnifications. Determining the percentage of crowns in the canopy that are visible will require analysing IKONOS data over forest inventory plots.

Many natural gaps in the canopy are evident, but they do not contrast with the forest matrix as clearly as the logging patios and larger felling gaps. We attempted to examine the relationship between ground-based gap characteristics and IKONOS imagery by obtaining GPS locations in six gaps in old growth. Even in the largest natural gaps we were only able to obtain GPS readings by using an antenna raised *c.* 4–8 m above the forest floor. For five of the six gaps the mapped GPS locations were within the georeferencing error distance (approximately 4 m) of an area that we interpreted as low canopy on the IKONOS image (Fig. 5). However, we found that it was not possible to unequivocally locate these gaps on the image due to the combination of the geolocational error and the relatively high frequency of occurrence of low-canopy areas in the forest. Future studies should use multiple measurements per gap to ensure unequivocal geolocation, as well as provide information on the minimum size of gaps identifiable on the image. These results suggest that, given sufficient ground-based data at a site, it may be possible to use IKONOS for forest turnover measurements.

CROWN AREA RELATIONSHIPS

A major potential application of high-resolution data is to predict forest basal area and biomass from tree crown size. To do this, it will be necessary to compare information derived from the satellite image with ground-based data on individual trees and stands. We

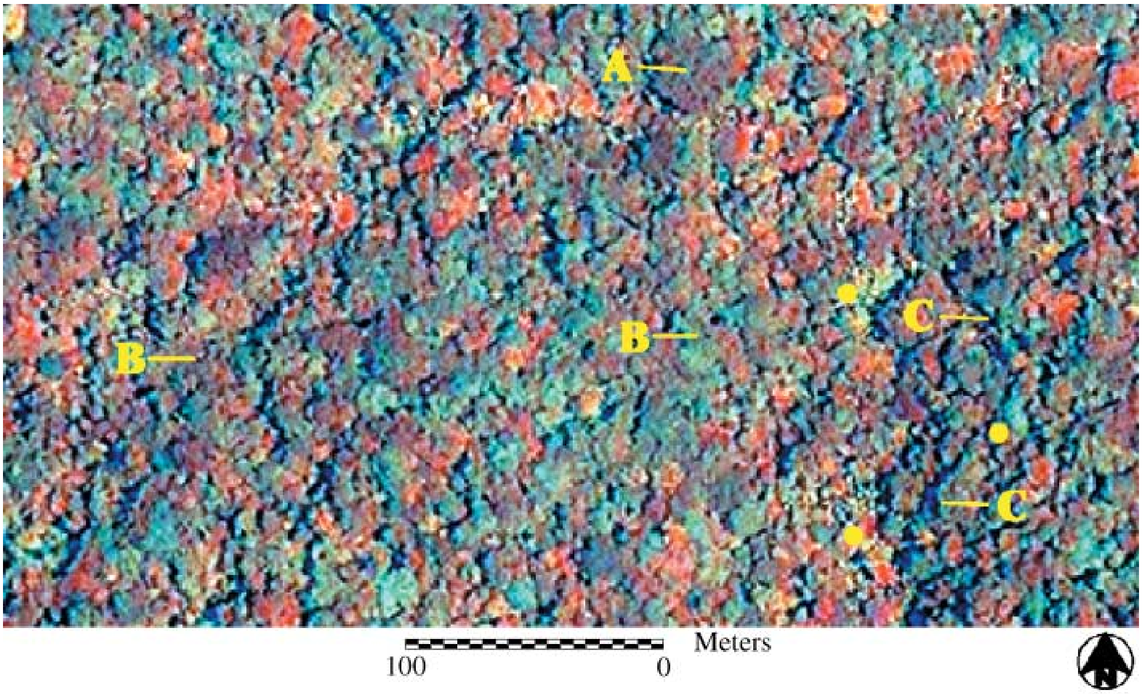

Fig. 5. Merged 1-m panchromatic and 4-m multi-spectral IKONOS image (RGB display of bands 4, 2, 1) showing old-growth tropical moist forest at the Mil Madeireira reduced-impact logging site near Itacoatiara, Amazonas State, Brazil. Some large emergents are clearly visible (A) but there are also large areas where individual crowns cannot be distinguished (B). Some areas of lower canopy are obvious (C) but the relationship between smaller gaps, lower canopy sites and shaded areas are not clear. Dots indicate the GPS locations taken in three forest gaps.

found that crown area digitized from the IKONOS image was very significantly correlated with trunk diameter ($r^2 = 0{\cdot}84$, $P < 0{\cdot}001$, $n = 9$). This suggests that it may be possible to use crown size information derived from IKONOS imagery to predict canopy tree diameter distributions and therefore an important portion of forest biomass (Clark & Clark 2000). We emphasize that the trees we worked on were all on or close to edges associated with the logging operations, and consequently were easier to see clearly than the average tree on this landscape (compare Fig. 4b with Fig. 5). We also found that ground-based measurements of the index of crown area were significantly correlated with the digitized crown area of the same trees ($r^2 = 0{\cdot}51$, $P < 0{\cdot}02$, $n = 9$). Given that these crowns were all clearly distinguishable, the low r^2 of this relationship suggests that it may be challenging to correlate ground-based stand-level data on crown size with similar data derived from digitizing canopy areas from an IKONOS image.

Discussion

Our findings show that IKONOS satellite data have potential for studies of tropical forest structure and function in both logged and old-growth areas. These 1-m and 4-m resolution data open new avenues for using satellite data to investigate processes that occur at the 10–1000 m^2 scale (such as logging impacts or mature-forest treefall gaps) but that are of interest to evaluate over landscapes ranging from 100s to 10 000s of hectares. The ability to identify individual trees and some logging management features (major and some minor roads, patios, some extraction gaps) in a reduced-impact logging operation indicates that in other higher-impact operations it will be possible to identify and quantify a higher percentage of the logging impact. Although the full extent of logging impacts will not be identifiable solely from these data (e.g. single-use skid roads and smaller and older gaps are not readily visible), it should be possible to assess the relative impact based on what is visible. This makes the use of IKONOS satellite data a valuable tool for forest managers for both planning and assessing logging activities. Furthermore, given the ever-increasing number of certified logging operations (Forest Stewardship Council Access 2001), these data could be used for monitoring adherence to certification criteria, such as limits on the area of land converted to roads, and location of logged trees in relation to number per area and proximity to streams.

Although we used the multi-spectral data merged with the panchromatic data for identifying features visually, in this pilot study we did not conduct additional data transformations or classifications with the data sets. Future studies exploring the spectral and spatial characteristics of the data will be likely to reveal additional information and patterns that may have direct research and management applications, such as mapping species composition and diversity.

Our results show that it is possible to locate precisely some proportion of individual canopy and emergent trees in IKONOS images of tropical forests. This means it is now feasible to conduct demographic studies over large areas on at least the larger canopy trees by using repeated IKONOS images through time. This is particularly valuable for tropical forests, where whole-forest studies have been hampered by small plot areas, unrepresentative site selections, and logistical difficulties of many sorts in establishing and recensusing plots. More study is needed to determine what proportion of the canopy trees are visible in IKONOS imagery, and that proportion will certainly vary among different forest types, across environmental gradients such as rainfall, topography and probably through succession. In addition to studying canopy trees as a class, without regard to species, it may be possible to work at the species level for species with distinctive canopy architecture and/or reflectance characteristics.

Another major application will be to study forest gap formation and recovery rates over large areas. This will involve considerable ground research over each landscape to determine how canopy height, gap size, canopy reflectances and shadow effects interact. One way to make rapid progress in this understanding would be to assess the same landscape using both IKONOS and a lidar sensor (cf. Laser Vegetation Imaging Sensor; Drake *et al.* 2002). The three-dimensional representation of radiation-reflecting surfaces provided by a lidar mapper would provide a unique way to assess the relationship between IKONOS data and independently measured canopy height and structure at landscape scales.

We think that IKONOS data will be particularly valuable in sites where they can be linked to field data on forest structure and function. Many such data already exist, and rapid progress in understanding the potential of IKONOS imagery will come from building on these resources. Good sources for such data include industries that control large land areas, such as timber and oil companies, as well as government natural resources management agencies, non-governmental organizations and academically affiliated research sites. A major limitation to the potential widespread adoption of IKONOS data for the applications described above, however, is their current high costs.

Lastly, many of the results presented here resulted from interactions, in the field and in the laboratory, within a multi-disciplinary team. In our case this team consisted of a remote sensing/GIS expert, three ecologists with very different backgrounds, and an experienced local woodsman. We suggest that future studies on the application of high-resolution imagery to landscape-scale ecological patterns and processes should consider collaborations that include both remote sensing/GIS scientists as well as terrestrial ecologists.

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