Canopy shadow in IKONOS satellite observations of tropical forests and savannas

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Abstract

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 in multispectral observations from satellites (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.

We used 44 IKONOS images from the Large-Scale Biosphere–Atmosphere Experiment in Amazonia (LBA) data archive to quantify the spatial variation of canopy shadow fraction across a broad range of forests in the Brazilian Amazon and savannas in the Brazilian Cerrado. Forests had substantial apparent shadow fractions as viewed from the satellite vantage point. The global mean (± S.D.) shadow fraction was 0.25 ± 0.12, and within-scene (e.g., forest stand) variability was similar to interscene (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. 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 near-infrared (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. A 10% increase in shadow fraction resulted in a 3% and 10% decrease in red and NIR channel response, respectively. The normalized difference vegetation index (NDVI) of tropical 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 to no relationship occurred between shadow fraction and either NIR reflectance or the NDVI of savannas. Quantitative information on shadowing is needed to validate or constrain radiative transfer, spectral mixture, and land-surface models used to estimate material and energy exchanges between the tropical biosphere and atmosphere.

Keywords: Amazon; Brazil; Canopy shadow; Cerrado; IKONOS; Savanna; Shade; Shadow; Tropical forest

1. Introduction

The high species diversity of tropical forests and savannas leads to concomitant spatial variation in canopy structure and biochemistry. From a remote sensing perspective, tropical forests are often considered mosaics of highly foliated trees in dense stands that form a ‘green carpet.’ This perspective has served the remote sensing community in a variety of ways, such as in using these forests as dark calibration targets for global studies (Kaufman & Sendra, 1988; Liang, Fang, & M.Z., 2001). However, it is becoming increasingly apparent that the green carpet assumption is invalid for even the most dense tropical forest regions of the world (Asner, Townsend, & Braswell, 2000; Bohlman, Adams, Smith, & Peterson, 1998). Compared to our understanding of tropical forests, there is broader recognition that savannas are complicated mixtures of herbaceous and
woody plant lifeforms that result in strong spatial variations of biophysical structure (Asner, Wessman, Schimel, & Cole, 1998; Cole, 1986; Menges, Hill, & Ahmad, 2001). Nonetheless, there are relatively few observations pertaining to the three-dimensional structure of savannas and its relation to remotely sensed data. Indeed, the spatial variability of canopy structure remains poorly understood in tropical forests and savannas, leading to persisting uncertainty with respect to their ecological, biogeochemical, and climatological function (Morley, 2000; Turner, 2001).

The major structural factors contributing to reflectance variability in tropical forests include leaf optical properties, leaf area index, leaf angle distribution, and crown dimensions and spacing (Bohlman et al., 1998; Gastellu-Etchegorry et al., 1999; Guillevic & Gastellu-Etchegorry, 1999). These factors are also major drivers of reflectance variation in savannas, although canopy fractional cover (or bare soil extent) and water stress are often dominant in these environments (McGuire, Friedl, & Estes, 1993; Roberts et al., 1998). Independent of the scale-dependent sources of structural variation—leaf, canopy or landscape levels—combinations of these factors result in spatial variations of apparent shadow as observed from remote sensors (Gerard & North, 1997). In fact, changes in shadowing allow some remote sensing approaches, such as with multiglase observations, to estimate the structural attributes of ecosystems (Diner et al., 1999; Gobron et al., 2000).

Because shadowing is closely linked to the biophysical characteristics of plant canopies, it is a major contributor to the radiance or reflectance properties of tropical forests and savannas. A few studies have highlighted this issue using radiative transfer models (e.g., Asner, Bateson, Privette, & Wessman, 1998; Gastellu-Etchegorry et al., 1999), but almost no information has been collected to better understand shadow variability in the environment or to test the models. The “green carpet” assumption for tropical forests persists, due in part to the remote sensing observations having too low spatial resolution to directly observe shadows. The common observations made of tropical forests using Landsat, AVHRR, and similar resolution instruments (tens to thousands of square meters in pixel size) are likely to be affected by intra- and inter-canopy shadowing. These effects are present in the observations, but our ability to quantify them has been limited or nonexistent.

The IKONOS satellite (Space Imaging, Thornton, CO, USA) was launched into low Earth orbit in September 1999. IKONOS provides the first operational meter-scale resolution satellite observations of Earth for use by the civilian sector. The instrument has a panchromatic band (0.45–0.90 μm) with a 1-m spatial resolution, as well as four multispectral bands, each with 4 m spatial resolution. The panchromatic data provide an opportunity to observe plant canopies at spatial scales approaching the size of individual crowns and vegetation clusters (Asner et al., 2002; Franklin, Wulder, & Gerylo, 2001). The global coverage of IKONOS provides a new means to observe vegetation crowns and shadowing anywhere worldwide, and its application to remote tropical forests and savannas is only now being realized.

We report on a study designed to improve our understanding of remotely sensed shadow in tropical forests and savannas. Utilizing the Large-Scale Biosphere–Atmosphere Experiment in Amazonia (LBA) IKONOS satellite data archive, we quantified the spatial variation of canopy shadow fraction across a broad range of forests in the Brazilian Amazon and savannas in the Brazilian Cerrado. In doing so, we sought to understand (1) how shadow fraction varies locally or within apparently homogeneous forest stands; (2) how shadow fraction varies regionally across a range of known forest and savanna types; (3) the contribution of shadow fraction variation to visible and near-infrared (NIR) wavelength observations from Landsat-like instruments; and (4) the contribution of shadow fraction to vegetation index measurements, with particular focus on the normalized difference vegetation index (NDVI).

2. Methods

2.1. IKONOS satellite data

The IKONOS satellite data were acquired for the LBA program (www.eosdis.ornl.gov/lba_cptec) as part of a NASA Scientific Data Buy Project (www.esad.ssc.nasa.gov). The data were delivered in a geo-registered, UTM projection with 11-bit radiometric resolution. Wavelength bands at full-width, half-maximum (FWHM) are (1) panchromatic: 0.45–0.90 μm; (2) blue: 0.45–0.52 μm; (3) green: 0.51–0.60 μm; (4) red: 0.63–0.70 μm; and (5) NIR: 0.76–0.85 μm.

A total of 44 images (or image sub-scenes) were available from the LBA archive, including 29 tropical forest, 10 tropical savanna, and 5 tropical pasture images (Fig. 1). All images were collected in 2000 or 2001. The goal was to quantify shadow fraction for particular vegetation types; thus, each scene was subset to an 840 × 840-m area to avoid cloud cover, water bodies, and areas containing steep terrain, and to maximize land-cover uniformity. These homogeneous areas were first located in the panchromatic images then visually inspected using the multispectral images to confirm uniformity. Panchromatic and multispectral images (red and NIR bands) were subset for each site and date. The 29 forest subset images were selected to ensure no apparent land-use disturbance or regrowth patterns. The five savanna IKONOS images were subset into 10 scenes spanning low-, medium-, and high-density classes based on visual estimates of <25%, 25–75%, and >75% woody vegetation cover, respectively.

Five scenes were duplicate acquisitions, providing an opportunity to analyze shadow fraction of the same areas under changing viewing and solar geometry conditions.
Four of these paired scenes were of tropical forest, and one was of a savanna.

2.2. Image analysis

Histograms were used to determine a shadow threshold DN value in each IKONOS panchromatic image. A ‘break’ in the histogram was visually selected as the threshold between shadows and sunlit features (Fig. 2). A digital mask was created for the derived shadow area in each scene and compared to the original scene to ensure that the threshold was set properly. The number of shade pixels per $28 \times 28$ m (Landsat-like) area was calculated. The multispectral IKONOS images were then resampled to $28 \times 28$-m pixels to be compared with the panchromatic shadow fraction count results. Regression statistics were generated showing relationships between shadow fraction, IKONOS multispectral bands 3–4 (red, NIR), and the NDVI in the $28 \times 28$-m grid cells. These procedures were repeated with the shadow fraction threshold varied by $\pm 5\%$ and $\pm 10\%$ in order to quantify the sensitivity of the analysis to different shadow-DN thresholds. Kruskal–Wallis one-way analysis of variance on Ranks and Tukey Tests were performed to determine differences in the results as the shadow threshold was varied.

The IKONOS scenes, while radiometrically calibrated, were not converted into units of radiance for this study. Therefore, to compare scenes, the IKONOS bands 3–4 DN values were mean-minimum normalized for comparison between scenes. This was done by computing a mean band DN value for all scenes containing a particular vegetation or land-use type (forest, savanna, pasture). The minimum, mean value was then subtracted from the mean value of each scene. This value was subsequently subtracted from

![Fig. 1. Map of Brazilian states showing centerpoint locations of forest, savanna, and pasture IKONOS images used in this study.](image1.png)

![Fig. 2. Examples of image-shadow digital number (DN) threshold selections in four panchromatic IKONOS images employed in this study.](image2.png)
each DN. This approach removed the effect of variable sensor gain settings from the overall analysis.

3. Results and discussion

3.1. Threshold sensitivities

Selection of image DN values for shadow threshold calculations is an inherently subjective process. However, increasing or decreasing the DN threshold by 5% (≈ 28–36 DN) did not result in shadow fraction differences from the IKONOS panchromatic image set (Kruskal–Wallis ANOVA, \( p > 0.05 \); Table 1). A 10% change did lead to a significant difference in shadow results relative to the actual threshold values used in the study, but this range represented 100–140 DN values. This was a very wide range that was easily accommodated while working with the DN histogram distributions and by visual checks of the image shadow classification results. We thus assert that the sensitivity of the shadow results to threshold selection was within the limits required for further investigation and comparison to multispectral data.

3.2. Forest shadow fractions

Examples of the panchromatic IKONOS images for forests, savannas, and pasture are shown in Fig. 3. There was substantial variation in tree crown shapes and densities across the 29 forested scenes, as depicted in the Ituqui and Santarem km-67 sites shown in this figure. This variation resulted in a wide range of image shadow fractions, with a minimum (mean ± standard deviation [S.D.]) value of 0.14 ± 0.06 and a maximum of 0.35 ± 0.14 within a given scene (Table 2). In general, the within-scene variance (standard deviation) in shadow fractions increased as the mean shadow fraction increased. The overall mean (± S.D.) shadow fraction for all 28 × 28-m grid cells in the 29 forested scenes combined was 0.25 ± 0.12 (n = 39,600 grid cells). Minimum and maximum shadow fraction for any given 28 × 28-m grid cell was 0.0 and 0.99, respectively.

The distribution of shadow fraction values was somewhat skewed, as roughly 30% and 12% of grid cells had values greater than 0.30 and 0.40, respectively (Fig. 4). These results indicate the substantial shadow component present in tropical forest images. They also highlight both the inter- and intra-scene variability of shadow fractions. Variation at the interscene level (0.06 < S.D. < 0.14; Table 2) was of similar magnitude to that at the intra-scene scale (S.D. = 0.12; Fig. 4). From a remote sensing perspective with Landsat-type instruments, shadow fractions exert major control over spatial variability in canopy reflectance, at both the local and regional levels.

It is apparent from the image analyses that a generalized or ‘global’ estimate of tropical forest shadow fraction is not possible; the pronounced variation in fractional shadow cover indicates substantial variation in top-of-canopy biophysical structure. Photon transport modeling studies must account for this variation to accurately simulate canopy reflectance at pixel scales (Pinty & Verstraete, 1998). Theoretically, this can be achieved by explicitly representing spatial variations in crown dimensions, spacing, LAI, leaf angle distributions, and other vegetation structural properties (e.g., Knyazikhin, Martonchik, Myneni, Diner, & Running, 1998; Li, Strahler, & Woodcock, 1995; Myneni, Nemani, & Running, 1997). However, this information does not currently exist for humid tropical forests, and thus, spatially explicit simulations of vegetation structure are not possible. An alternative method is to replicate the spatial and statistical distribution of apparent shadow fractions throughout a simulated image. Our results provide the input to constrain such a modeling approach. Landscape structural parameters such as crown size and spatial density could be adjusted to fit the observed shadow fractions like those shown in Fig. 4 and Table 2. Additional work is needed in this area, as the radiometric properties of the shadows also require analysis (Roberts, Smith, & Adams, 1993).

3.3. Savanna and pasture shadow fractions

Mean (± S.D.) shade fractions for all 28 × 28-m grid cells in the high-, medium-, and low-density savannas were 0.16 ± 0.05, 0.12 ± 0.04, and 0.0 ± 0.01, respectively (Fig. 5). These were each statistically different from the forest fractional shadow results (t-tests, \( p < 0.05 \)). In contrast to the forest images, the high- and medium-density savannas had near-normal shadow fraction distributions (Fig. 5a and b). These two savanna groups did not have statistically different means (t-test, \( p < 0.05 \)) or distributions (Kolmogorov–Smirnov Test; Sokal & Rohlf, 1995). Like the forest images, shadow fraction values within the grid cells varied widely in these two savanna groups, with a minimum value of 0.0 (no shadow in a ‘Landsat’ pixel) to a maximum of 0.39 (nearly half the pixel in shadow).

Table 1

<table>
<thead>
<tr>
<th>Threshold selection</th>
<th>Difference of ranks</th>
<th>( q )</th>
<th>( p &lt; 0.05 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual vs. − 5%</td>
<td>31</td>
<td>3.521</td>
<td>no</td>
</tr>
<tr>
<td>+5% vs. actual</td>
<td>31</td>
<td>3.521</td>
<td>no</td>
</tr>
<tr>
<td>Actual vs. − 10%</td>
<td>62</td>
<td>7.043</td>
<td>yes</td>
</tr>
<tr>
<td>+10% vs. actual</td>
<td>62</td>
<td>7.043</td>
<td>yes</td>
</tr>
<tr>
<td>−5% vs. − 10%</td>
<td>31</td>
<td>3.521</td>
<td>no</td>
</tr>
<tr>
<td>+10% vs. +5%</td>
<td>31</td>
<td>3.521</td>
<td>no</td>
</tr>
</tbody>
</table>

The first column shows comparison of the actual threshold employed in the study, ± 5% or ± 10% of image DN range. The remaining columns indicate statistical results of Kruskal–Wallis one-way ANOVA on ranks. If \( p \)-value < 0.05, test indicates statistically significant differences in the final shade fraction results among all IKONOS scenes combined.
landscapes. Similarly, the pasture images had near-zero shadow fractions and a highly skewed statistical distribution for all grid cells \((n = 4500)\). The low-density savanna and pasture sites were statistically different \((t\)-test and Kolmogorov–Smirnov Test).

The savanna results indicate the wide variation of shadow fractions across the studied landscapes. All three savanna classes were derived from a region of the Brazilian Cerrado near the capital of Brasilia. However, pronounced spatial gradients in savanna physiognomy are common in the Cerrado (Teixeira de Oliveira-Filho, Sheperd, & Stubblebine, 1989), allowing for a comparison of shadowing effects by approximated woody vegetation density. Our results show that as the density of woody vegetation decreases from high (>75%) to low (<25%), the fractional shadow cover decreases as well (Fig. 5a–c). However, the distribution of shadow fractions does not change substantially when values are greater than 25%.

Fig. 3. Example IKONOS subset images of forest, high/medium/low-density savanna, and cattle pasture. Image names and dates match those provided in Table 2.
That is, both high- and medium-density savanna groups had similar statistical distributions of shadow fraction (Fig. 5a vs. b). This implies that woody vegetation, which is the source of most shadowing in these regions, varies in a spatially random pattern. If this were not the case, then shadow fraction distributions would become skewed at higher vegetation densities due to clumping of canopies. Another possibility is that woody vegetation occurs in a nonrandom (uniform) pattern on the savanna landscape, although we have not observed this in the field or in other studies.

### 3.4. View–solar geometry effects

The assertions presented above are based on results from over 39,600 ‘Landsat’ 28 × 28-m grid cells containing the IKONOS shadow-threshold data in 44 images. As shown, the sensitivity of our analyses to threshold selection could be accommodated within limits imposed by the goals of the study. However, the effects of viewing and solar geometry are also important, as shadow fractions can change with observation angles (Adams et al., 1995; Peddle, Hall, & LeDrew, 1999). Because the spacecraft is highly maneuver-
Fig. 4. Histogram of shadow fractions from 29 IKONOS panchromatic images of Amazon tropical forests. Descriptive statistics are provided in upper right (μ = mean; σ = standard deviation).

Fig. 5. Histogram of shadow fractions from IKONOS panchromatic images of (A) high-density savanna; (B) medium-density savanna; (C) low-density savanna; and (D) cattle pastures. Descriptive statistics are provided in upper right corners of each graph (μ = mean; σ = standard deviation).
able, IKONOS images have the potential to be acquired under widely varying view zenith and azimuth geometries.

In general, view zenith for our 44-scene data set ranged from 10° to 25°, with a few images acquired closer to nadir (Table 2). In contrast, view azimuth angles varied from 6° to 360°, indicating that the instrument was actively pointed about its orbital path. Despite this wide range of viewing geometries, there was little evidence of a generalized shadow fraction dependence on these changing conditions (Fig. 6). Similarly, changes in solar zenith and azimuth angles had no apparent systematic effect on shadow fraction results (Fig. 6).

Acquisition of duplicate IKONOS scenes with differing view–sun geometry affords the opportunity to further test the sensitivity of shadow fraction estimates to changing observation conditions. Among five pairs of scenes spanning forest and savanna land covers, only one image pair in Mato Grosso showed a substantial difference in shadow fraction between the two collection dates (Table 2). This pair had a mean (+ S.D.) shadow fraction of 0.20 ± 0.07 on May 19, 2001 and 0.36 ± 0.10 on April 30, 2000. The other paired images (delineated by asterisks in Table 2) had shadow fraction differences of only 0.0–0.04 between acquisition dates. Further analysis of the Mato Grosso images indicated that while the solar zenith and azimuth angles were very similar between acquisition dates, the view azimuth direction did change substantially from 262° in 2000 to 79° in 2001. Thus, the 2001 observations were collected closer to the solar plane (solar azimuth = 40°), which decreased the apparent shadow visible from the sensor vantage point. This would explain the nearly twofold difference in shadow fraction between the two scenes.

This pronounced view azimuth effect on shadow fractions was surprising, but it is most obvious in the imagery when comparing a single emergent tree crown and the shadow that it casts on the surrounding forest (Fig. 7). We conclude that changing view azimuth can be important to studies of vegetation shadow and structure using high spatial resolution sensors. Sensors such as IKONOS and Quickbird (DigitalGlobe, Longmont, CO, USA) must be highly maneuverable to acquire data over requested targets, but to do so can introduce significant changes in scene reflectance characteristics due solely to observation geometry.

3.5. Multispectral sensitivity to shadow fraction

There was substantial variation in observed shadow fractions within ‘Landsat’ 28 × 28-m grid cells derived the IKONOS panchromatic imagery (Figs. 4 and 5). The shadow fraction results were higher than anticipated given that stand density and LAI are high and forest gap fraction is very low in Amazon tropical forests (McWilliam et al., 1993). However, shadows are a function of canopy structure, part of which involves the top-of-canopy ‘topography’ that is now observable from spaceborne sensors such as IKONOS (Fig. 3). Combined with multispectral observations, there is an opportunity to better understand the role of shadowing on other types of remotely sensed data. How do the measured shadow fractions affect multispectral observations of tropical forest, savanna, and pasture canopies using Landsat-like sensors?

IKONOS bands 3 (red) and 4 (NIR) signal response was highly sensitive to shadow fraction in tropical forest scenes from the LBA Amazon archive (Fig. 8).
typical scenes are shown for red and NIR bands (Fig. 8a and b). Both the slope and data-scatter varied by image, likely due to differences in view–solar geometry and forest structural characteristics. Normalizing all the data from 29 forest images provided a means to summarize the relationship between shadow fraction and multispectral response, independent of these image-to-image variations (Fig. 8d and e). The normalized data indicated that a 10% increase in canopy shadow fraction results in 3% and 10% decreases (absolute) in red and NIR sensor response, respectively. Thus, over the range of fractional shadow values that occurred in the forest scenes, red and NIR responses varied by roughly 35% and 95%, respectively (Fig. 8d and e).

The effects of apparent shadows on sensor response (DN, radiance, reflectance, etc.) depend upon both the materials present in the image and the measurement wavelength. For live vegetation, photons are efficiently absorbed in the red spectral region, whereas scattering dominates in the NIR (Curran, 1989). The relative impact of shadowing is lower at visible wavelengths because the vegetation is already dark and multiple scattering of radiation is minimal. In contrast, shadow effects are most dramatic in the NIR because each scattering element in the pixel (e.g., leaves) is very bright, resulting in a disproportionate effect of changing shadow fraction on image pixels. Independent of wavelength, we conclude that changing shadow fraction exerts substantial control over pixel response in multispectral data of tropical forests.

Relationships between shadow fraction and the NDVI of forested pixels were weaker than those for individual channel responses. While there were negative correlations for specific scenes in the LBA IKONOS archive (Fig. 8c), no general relationship emerged following normalization of the NDVI data across scenes (Fig. 8d). On a scene-by-scene basis, we conclude that NDVI is sensitive to shadow fraction albeit less so than either the red- or NIR-channel responses.

The negative correlation between shadow fraction and IKONOS red-channel response was generally similar for the high-, medium-, and low-density savanna image sets (Fig. 9a–c). For all three savanna types, a 10% increase in apparent shadow resulted in a 5–7% decrease in red-wavelength response. In contrast, there was almost no
relationship between shadow fraction and NIR response (Fig. 9d–f). This occurs because savanna images are mostly comprised of exposed soil and senescent herbaceous vegetation, with low densities of greener woody vegetation. Soil, senescent vegetation and green foliage are each very bright in the NIR spectral region (Asner, 1998); therefore, a small change in shadowing does not exert strong control over NIR pixel reflectances since it is compensated for by the concomitant increase in green (bright) foliage that casts the shadows. This is not the case in the visible spectral region, where green foliage is dark and both soil and senescent vegetation are bright. Small changes in green foliage cover—and thus, shadows cast by woody plants containing this foliage—exert substantial control over red-channel reflectance properties of savannas (Fig. 9b).
Among savannas, there was little evidence of a relationship between shadowing and the NDVI, with the exception of the medium-density savanna for which a 10% increase in shadowing resulted in a nearly equal percentage increase in NDVI. This result trends oppositely to those derived for forest and high-density savanna (Figs. 8f and 9g). This occurs because increasing woody plant cover in a low vegetation setting (e.g., sparse savanna, pasture) leads to increased red-wavelength absorption (Fig. 9b), while NIR scattering remains relatively constant.

In general, shadows accounted for ~30–50% of the variance in red and NIR channel responses in forested images collected by IKONOS (Fig. 8d and e). Other important factors likely include leaf area index, crown architecture, and leaf optical properties. In savannas, shadows exerted much greater control over IKONOS red-channel response than in the NIR. Shadows accounted for about 15–50% of the red-channel responses, depending upon the densities of woody plants across the landscape (Fig. 9a–c). There was much less of a response in the NDVI to shadow fraction variation, with weak trends even changing in sign based on vegetation density (Fig. 9g–i).

4. Conclusions

This study demonstrates the magnitude and variability of apparent shadow fraction in remotely sensed observations of tropical forests, savannas, and pastures. The shadow fractions are substantial and increase with vegetation density (pasture < savanna < forest). Once the canopy reaches ~100% cover (forested scenes), variations in shadow fraction are dominated by variations in crown size and dimensions, stand density, crown architecture, leaf area index, leaf optical properties, and viewing and solar geometry (Gilabert, Garcia-Haro, & Melia, 2000; Li & Strahler, 1992). Although the biophysical attributes of the canopies were not explicitly addressed in this study, these sources of shadow variation are relatively well known (Asner, 1998; Gascellu-Etchegorry et al., 1999; Li et al., 1995; Myneni, Ross, & Asrar, 1989). However, the extent of such canopy structural effects on remotely sensed shadow has not been quantified, especially in tropical ecosystems. High spatial resolution satellite sensors such as IKONOS provide the capability to probe these issues anywhere in the world. Using shadow analysis techniques with 1-m panchromatic and 4-m multispectral IKO-
NOS data of 44 forest, savanna, and pasture areas, we draw the following conclusions:

- Amazon tropical forests have substantial apparent shadow fractions as viewed from the satellite vantage point. The global mean (± S.D.) shadow fraction is 0.25 ± 0.12, and within-scene (e.g., forest stand) variability is similar to interscene (e.g., regional) variation. The distribution of shadow fractions for tropical forest stands is skewed, with 30% of pixels having fractional shadow values above 0.30.

- Tropical savannas have observable shadow fractions as viewed from satellite sensors. These shadow fractions increase from 0.0 ± 0.01 to 0.12 ± 0.04 to 0.16 ± 0.05 for savannas with woody vegetation at low (<25% cover) to medium (25–75%) and high (>75%) density. As woody vegetation density decreases (e.g., more sparsely distributed), the distribution of shadow fractions becomes increasingly skewed toward very small values.

- The maneuverability of high spatial resolution sensors such as IKONOS leads to substantial variation in viewing and solar geometry during imaging. In particular, viewing azimuth is highly variable and can occasionally result in changed shadow fractions between image acquisitions.

- In Amazon tropical forests, multispectral observations using both red (0.63–0.70 μm) and NIR (0.76–0.85 μm) wavelength regions are highly sensitive to sub-pixel shadow fractions. At wavelengths in which vegetation efficiently absorbs photons (e.g., red), each 10% increase in shadow fraction results in a 3% decrease in pixel reflectance (or DN response). The same incremental increase in shadowing leads to a 10% decrease in NIR response. Shadows accounted for ~30–50% of the variance in red and NIR channel responses in forested images collected by IKONOS.

- The NDVI of tropical forests is relatively insensitive to changes in shadow fraction, but weak negative correlations do exist for specific forests.

- Savannas show substantial sensitivity to shadow fraction in the visible (e.g., red) wavelength region of the spectrum. For low-, medium-, and high-density savanna systems, a 10% increase in shadow fraction results in a 5–7% decrease in red-channel response. Overall, shadows accounted for ~15–50% of the red-channel responses, depending upon the densities of woody plants across the landscape. Little to no relationship occurs for reflected NIR radiation or for the NDVI.

Spatial patterns of observed shadow fractions from IKONOS are rich in information on the structural properties of tropical forests and savannas. Most of this information remains underutilized by the remote sensing, climate, ecological, and biogeochemical research communities. For example, shadow fraction variations are indicative of top-of-canopy roughness, which is an important variable controlling energy and material transport within the planetary boundary layer (Chen & Coughenour, 1994). Shadow fraction also exerts control over surface albedo (Barnes et al., 2000), which affects mesoscale climate, particularly in humid tropical regions (Dirmeyer & Shukla, 1994). Spatial variations in observed shadow (and thus canopy structure) also result in concomitant patterns of fractional solar energy absorption and primary productivity. Asner, Bateson et al. (1998) showed that changes in woody vegetation cover exerted strong control over carbon uptake by both the overstory and understory (herbaceous) vegetation in a temperate savanna. It is likely that such variations occur at the top of humid tropical forest canopies as well, although no quantitative information was found in our literature surveys on this topic. In addition, recently developed radiative transfer and carbon cycle models utilize statistical or explicit representations of canopy structure to simulate shading effects on canopy energy absorption and plant growth (e.g., Asner et al., 2001; Moorcroft, Hurtt, & Pacala, 2001). The development of these newer models implies that the three-dimensional context within which light is scattering and absorbed does matter for land-surface studies. Shadowing is an inherent component of these studies.

Remote sensing studies of tropical forests and savannas have largely ignored the three-dimensionality of vegetation structure and the resulting shadowing effects. Efforts to determine spatial and temporal patterns of land-cover change, carbon cycling and hydrology would benefit from a more explicit interpretation of the vegetation structure (Asner, 2000; Miller & Stoner, 1979). Understanding the basic properties and statistics of shadowing is a step toward developing this understanding.

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References

