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Biomass, harvestable area, and forest structure estimated from commercial timber inventories and remotely sensed imagery in southern Amazonia

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Abstract

The purpose of this study was to determine if spatially-explicit commercial timber inventories (CTI) could be used in conjunction with satellite imagery to improve timber assessments and forest biomass estimates in Amazonia. As part of a CTI, all commercial trees ≥45 cm DBH were measured and georeferenced in 3500 ha of a logging concession in NW Mato Grosso, Brazil. A scientific inventory was conducted of all trees and palms ≥10 cm DBH in 11.1 ha of this area. A total of >20,000 trees were sampled for both inventories. To characterize vegetation radiance and topographic features, regional LANDSAT TM and ASTER images were obtained. Using a stream network derived from the ASTER-based 30 m digital elevation model (DEM), a procedure was developed to predict areas excluded from logging based on reduced impact logging (RIL) criteria. A topographic index (TI) computed from the DEM was used to identify areas with similar hydrologic regimes and to distinguish upland and lowland areas. Some timber species were associated with convergent landscape positions (i.e., higher TI values). There were significant differences in timber density and aboveground biomass (AGB) in upland (6.0 stems ha^{-1}, 33 Mg ha^{-1}) versus lowland (5.4 stems ha^{-1}, 29 Mg ha^{-1}) areas. Upland and lowland, and timber and non-timber areas could be distinguished through single and principal component analysis of LANDSAT bands. However, radiance differences between areas with and without commercial timber on a sub-hectare scale were small, indicating LANDSAT images would have limited utility for assessing commercial timber distribution at this scale. Assuming a 50 m stream buffer, areas protected from logging ranged from 7% (third order streams and above) to 28% (first order and above) of the total area. There was a strong positive relationship between AGB based on the scientific inventory of all trees and from the commercial timber, indicating that the CTI could be used in conjunction with limited additional sampling to predict total AGB (276 Mg ha^{-1}). The methods developed in this study could be useful for facilitating commercial inventory practices, understanding the relationship of tree species distribution to landscape features, and improving the novel use of CTIs to estimate AGB.

Keywords: Primary forest; Reduced impact logging (RIL); Selective logging; Biomass; GIS; LANDSAT; ASTER; PCA; Deforestation; Amazon; Brazil

1. Introduction

Record rates of deforestation in 2004 in the frontier regions of Amazonia, and an increasing trend since 1990 (INPE, 2005), indicate a need for management alternatives for forest resources. Selective logging, a compromise between preservation and complete deforestation, provides opportunities to sustain forest resources while encouraging economic development. Advances in selective logging through reduced impact logging (RIL) and certification of timber harvests can substantially reduce stand damage and carbon loss (Putz and Pinard, 1993; Johns et al., 1996; Pinard and Putz, 1996; Pereira et al., 2002; Feldpausch et al., 2005). Certification requires a commercial timber inventory (CTI) prior to initiating logging operations. Including the forest of this study, 17 Forest Stewardship Council (FSC) certified RIL operations are currently active in native forests in Amazonia, for a total of 12,812 km^2 (FSC, 2004). These georeferenced CTIs could potentially be used in combination with remotely sensed data and limited, more intensive in situ inventories to improve

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inventory practices, enhance understanding of the relationship of tree species distribution in the landscape, and generate estimates of tree aboveground biomass (AGB).

The *terra-firme*, non-inundated forest of the Amazonian landscapes can be a heterogeneous mix of tall, closed-canopy forest, *Caatinga* and *Campinarana* on sandy soils (Prance and Brown, 1987; Guillaumet, 1987), short stature palm, bamboo (Nelson and Irmão, 1998), and *cipozal* vine tangles (Pérez-Salicrup et al., 2001) with discontinuous canopies. Site factors such as poor drainage, steep slopes, and shallow soil can result in some areas with low biomass and low timber densities. This study addresses the issue of forest spatial heterogeneity by examining the relationship between a large (3500 ha), spatially-explicit inventory of individual trees (>20,000), and remotely sensed radiance and topographic characteristics. Several medium-scale studies in the Amazonian states of Amazonas and Pará have examined tree heterogeneity in ~100 ha plots (Lovejoy and Bierregaard, 1990; Laurance et al., 1997; Keller et al., 2001) and in small plots distributed across a large area (Pitman et al., 1999), but none at the scale of thousands of hectares.

If a strong relationship exists between commercial timber and AGB and other forest properties, a CTI could potentially serve as a tool to estimate differences in primary forest biomass and structure at the landscape level. Such relationships would aid estimation of carbon stocks and carbon loss by reduced impact logging in Amazonia (Johns et al., 1996; Pereira et al., 2002; Feldpausch et al., 2005).

Using satellite sensors to identify discontinuities in AGB following disturbance is now an established technique, having proven successful for identifying areas of deforestation (INPE, 2005), selective logging (Asner et al., 2005), and distinguishing stages in early secondary succession (Lucas et al., 1993; Foody and Curran, 1994; Steininger, 2000; Vieira et al., 2003; Lu et al., 2004). To date, however, efforts to detect differences in AGB and tree distribution in undisturbed, closed-canopy tropical rain forest using LANDSAT TM imagery have been largely unsuccessful in Amazonia (Foody and Curran, 1994; Steininger, 2000). The resolution of the LANDSAT TM data and saturation of normalized vegetation indices in closed-canopy forests makes differentiation of species or biomass difficult without the use of fine resolution or Light Detection and Ranging (LiDAR) remote sensing (Drake et al., 2003). LANDSAT TM is currently used by timber companies for low-tech visual estimates of timber potential. In this study, we utilize LANDSAT TM in conjunction with an Advanced Spaceborne Thermal Emission Reflection Radiometer (ASTER) based digital elevation model (DEM) to identify terrain components that could be important to tree distribution and density.

We assess the spatial heterogeneity of commercial timber, harvestable area, and the relationship between a large-scale (3500 ha) CTI of merchantable trees and a small-scale (11.1 ha) scientific inventory of both merchantable timber and non-commercial trees and palms (≥10 cm DBH). The primary objectives of our study were to (1) determine if there is a relationship between commercial timber vegetation (biomass, DBH, volume, basal area, and density) and radiance and landscape controls (2) determine how much forested area would be restricted to logging based on RIL mandated stream buffers (as characterized by the stream network generated from a ASTER DEM), and (3) evaluate if it is possible to estimate total aboveground biomass of all trees and palms (≥10 cm DBH) from trees sampled in the CTI alone (≥45 cm DBH).

2. Methods

2.1. Study site

The study was conducted at Fazenda Rohsamar in southern Amazonia, a 25,000 ha forest managed by Rohden Indústria Lígnea Ltda (S10°28′ W058°30′). The forest lies adjacent to the Rio Juruena in the northwestern region of the state of Mato Grosso, in the county of Juruena, Brazil. The regional climate is tropical humid, with 2200 mm of annual rainfall, a 3-month dry season from July to October and a mean annual temperature of 24.8 °C (IBGE, 2005). The soils, predominantly dystrophic acidic Oxisols and Ultisols, are classified as Kandistults and Haplustoxes according to USDA classifications (Soil Survey Staff, 1999) and as Acrisols and Ferralsols according to U.N. FAO classifications (FAO-UNESCO, 1987). The vegetation is closed canopy, humid primary forest. This research is part of the Large-scale Biosphere Atmosphere Experiment in Amazonia (e.g., Davidson and Artaxo, 2004; Keller et al., 2004).

Rohden Indústria divided the forest into twenty ~1200 ha management units, including one unit preserved as a control, and the remaining area protected as an ecological reserve. Logging began in 1992 using conventional selective logging methods (CL). In 2003, Rohden Indústria was certified by the Forest Stewardship Council and began harvesting certified timber.

Our research focused on three areas, Blocks 4 (1137 ha), 5 (1397 ha), and 18 (1037 ha), harvested in 2002, 2003, and 2004, respectively. A wooded mesa-rock outcrop is a dominant feature in the landscape which can easily be seen in the LANDSAT image, rising 300 m above the surrounding forest and running east-west, bisecting the forest (Fig. 1). The slopes and top of the outcrop are protected from logging as a reserve. Blocks 4 and 5 share a border with the outcrop. A rise between Blocks 4 and 5 is a drainage divide, with Block 4 draining to the east and block 5 draining south-west. Block 18 resides south of the mesa, shares no border with the mesa, is approximately 4 km from Blocks 4 and 5, and drains primarily to the north. The three blocks are *terra firme* forest. Block 5 has some distinctive features, such as an area with *campinarana* low-stature vegetation (aqua-colored in the LANDSAT color composite of bands 3, 5, 7) and more contiguous lowland areas (pink in the LANDSAT) than the other two blocks.

2.2. Commercial timber inventory

A CTI is a compulsory requirement for certified logging. Collection of these data involves measuring and mapping all merchantable trees based on established inventory criteria

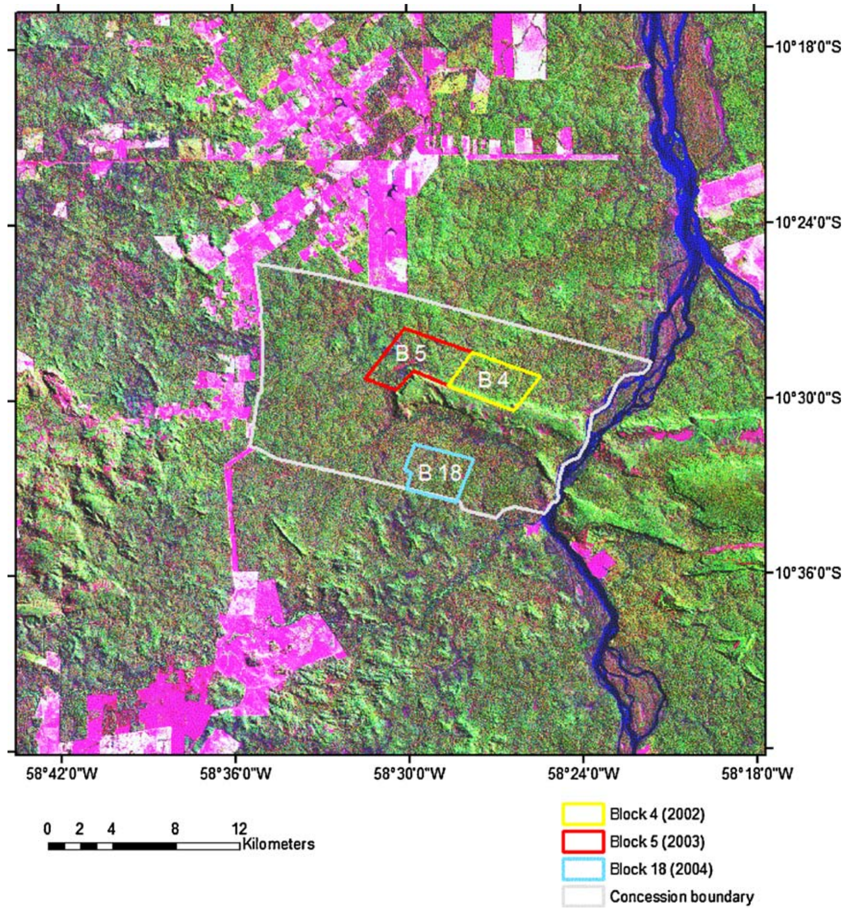

Fig. 1. LANDSAT TM image (acquired July 1996) showing the location of the Rohden logging concession at Fazenda Rosahmar adjacent to the Rio Juruena in the county of Juruena in southern Amazonia, MT Brazil. Boundaries are shown for Blocks 4, 5, and 18. Pink areas on the image indicate low-stature vegetation, or outside the concession are deforested and are most frequently pastures; aqua blue areas indicate low-lying areas or water; and green areas are native forest vegetation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

(Table 1) and broadly mapping stream location. These data facilitate pre-logging planning of road and log deck construction to avoid major streams and gain access to areas of greatest timber volume and trees of commercial value. Log decks are located along the roads at points that reduce the skidding distance for logged trees. CTI data, with each tree uniquely identified, also allow the logging company to establish a chain-of-custody for tracking individual trees from the forest to market. Measurements of logging rates, forest damage, and carbon export by selective logging in this forest were reported by Feldpausch et al. (2005).

The CTIs were conducted prior to harvesting by establishing parallel transects every 50 m and placing position markers every 25 m along the transects (20 transects per km, or 76–90 transects per block). This results in a 25 m × 50 m grid. A surveying team walked each transect and measured diameter at

Table 1
Commercial timber inventory methods used by Rohden Indústria Ltda

Survey parameter	Block 4 (2002)	Block 5 (2003)	Block 18 (2004)
Stream buffers (trees not measured)	50 m	50 m	50 m
Minimum DBH measured	≥30 cm DBH	≥30 cm DBH	≥45 cm DBH
Species measured	Hardwoods	Commercial species[a]	Merchantable commercial species[a]
Minimum DBH labeled "cut"	>45 cm DBH	>45 cm DBH	>45 cm, >60 cm DBH[b]
Preserved trees	30–45 cm DBH	30–45 cm DBH	Not measured
Seed trees	10% of measured trees	10% of measured trees	Not measured

For 3 years to measure and map timber of potential commercial value in three logging blocks in Fazenda Rohsamar in southern Amazonia. Data are stream buffer size where trees were not inventoried and were protected from cutting, minimum DBH measured, species measured, trees marked for cutting, trees measured, and preserved for the next logging cycle, and seed-source trees. For the analysis, data were standardized to inventory methods used in 2004.

[a] Commercial species are timber of potential value, while merchantable commercial species are 37 timber species currently sold on the timber market.

[b] Three species had a minimum harvest DBH of ≥60 cm DBH, as these species have a thick outer sap wood with no commercial value. Harvesting large diameter trees provides a greater heartwood volume.

breast height (DBH), commercial height (height from the ground to the first bifurcation—used to estimate commercial volume), species, tree location, and assigned each tree a unique number. The dominant commercial species recorded in this forest included Caucho/Borracheira (*Castilloa ulei*), Cupiúba (*Goupia glabra*), Cedro marinheiro (*Guarea dukei*), Caixeta (*Simarouba amara*), Angelim pedra (*Dinizia excelsa*), Angelim amargosa (*Vataeropsis speciosa*), and Caroba (*Jacaranda copaia*). Commercial height and tree location within the 25 m × 50 m grid were visually estimated; DBH was measured with a diameter tape. To georectify the location of trees, we collected GPS reference points for the location of a subset of transect stakes throughout each of the three blocks. The data were transferred to the GIS and the CTI tree *x* and *y* data georeferenced (UTM zone 21).

The CTI for Blocks 4 and 5, 1 year prior to and during the first year of forest certification, was comprised of measurement of trees ≥30 cm DBH, including both commercial and non-commercial species, seed trees, and preserved trees (30–45 cm DBH) (Table 1). For Block 18, the timber company revised their CTI criteria to reduce survey time. The DBH of trees sampled was increased to >45 cm DBH and the number of tree species sampled reduced to include only timber species currently sold on the commercial market. The minimum DBH recorded was also increased for a select set of five timber species because of their low heartwood to sapwood ratio. For these species, only individuals ≥60 cm DBH were measured. We standardized the Blocks 4 and 5 data set to the inventory methods used in Block 18 (2004) for timber trees, a total of 19,400 trees >45 cm DBH (≥60 cm for the five select species) in the three blocks (Fig. 2a).

2.3. Scientific inventory: aboveground biomass ≥10 cm DBH

Prior to logging in 2003, a scientific inventory was conducted in Block 5. Tree characteristics and AGB for all trees and palms ≥10 cm DBH was measured by stratified sampling across the block to account for differences in tree densities (trees/ha). Using the commercial timber inventory to identify tree density variation across the block, we located eight long (10 m × 1000 m) and eight short (10 m × 200–500 m) belt transects. Within each georeferenced transect we measured DBH of all trees and palms with trunks ≥10 cm DBH, lower and upper canopy height, species, and location of all individuals to the nearest 10 cm on an *x*–*y* grid. Canopy height was measured with a Haglöf Vertex III-60 ultrasonic hypsometer calibrated at ambient temperature to compensate for the effect of air density on transmission time. Data were transferred to the GIS and georeferenced to UTM coordinates.

2.4. Biomass and stand structure calculations

We calculated dry biomass (kg) for each individual tree in the belt transects and trees measured in the CTI using the allometric equation 3.2.3 from Brown (1997), with DBH (cm) at 1.3 m height (or immediately above prop-roots or buttresses) as the predictor (Eq. (1)). This equation was developed from measuring 170 Amazonian trees with a DBH range of 5–148 cm ($R^2 = 0.84$):

$$\text{tree biomass (kg)} = 42.69 - 12.80\,\text{DBH} + 1.24\,\text{DBH}^2 \qquad (1)$$

This equation was compared to others derived from Amazonian trees; although biomass estimates varied by size class, total biomass estimates varied little between the different equations (Keller et al., 2001). To estimate the area of the forest with and without commercial timber and produce estimates of stand structure on a per hectare basis from the CTI data, we generated maps with ArcMap (ESRI, 2005) based on absolute counts and tree properties of 100% of the stems within each cell (i.e., absolute estimate rather than interpolation). We generated continuous raster maps from the CTI data on a per hectare basis, including mean biomass, DBH, volume, basal area, and density. A search radius of 30 m was used to generate values on a per ha basis from the CTI data, which represents the mean distance between commercial trees plus one standard deviation calculated from the transect data and CTI data. We validated the search distance by comparing commercial tree density estimated by this search distance to the density estimated per block (total commercial tree count divided by the block area).

Forest spatial structure was computed for each block, including density (tree/ha), nearest neighbor (m), distance from each tree to the nearest stream (m), and spatial clustering using ArcMap. We calculated commercial timber characteristics by block from the CTI inventory of trees ≥45 cm DBH and forest structure for all trees ≥10 cm DBH (commercial and non-commercial trees, palms and vines) from the belt transect data: DBH (cm), canopy height (m), wood volume ($m^3\,ha^{-1}$), biomass (Mg) per tree, and biomass per ha. The CTI and scientific inventory data represent pre-harvest stand properties. Data for the CTI (commercial trees alone) and the scientific inventory (all trees and palms ≥10 cm DBH) were analyzed separately. Differences in the CTI stand properties were evaluated among the three ∼1200 ha blocks, with the block as the analysis unit. To determine differences in stand structure for the belt transect data for Block 5 alone, each transect was the analysis unit. The data were analyzed using a one-way analysis of variance (ANOVA). In the presence of significant differences, we tested for differences between individual means using a Tukey multiple comparison test ($p = 0.05$).

The distance between trees from the CTI was analyzed using the Point Distance nearest neighbor function of ArcMap as a measure of the distribution and clustering of trees. To determine if larger diameter trees are uniformly distributed or clustered throughout the forest, tree clustering as a function of DBH and distance, was analyzed using Moran's *I* in the ArcMap spatial analyst. Moran's *I* detects departures from spatial randomness, which for our analysis indicates clustering of trees. Values range from −1 (strong negative spatial autocorrelation) to 1 (strong positive spatial autocorrelation). Moran's *I* is defined as:

$$I = \frac{N\sum_i\sum_j W_{i,j}(X_i - \bar{X})(X_j - \bar{X})}{(\sum_i\sum_j W_{i,j})\sum_i (X_i - \bar{X})^2}$$

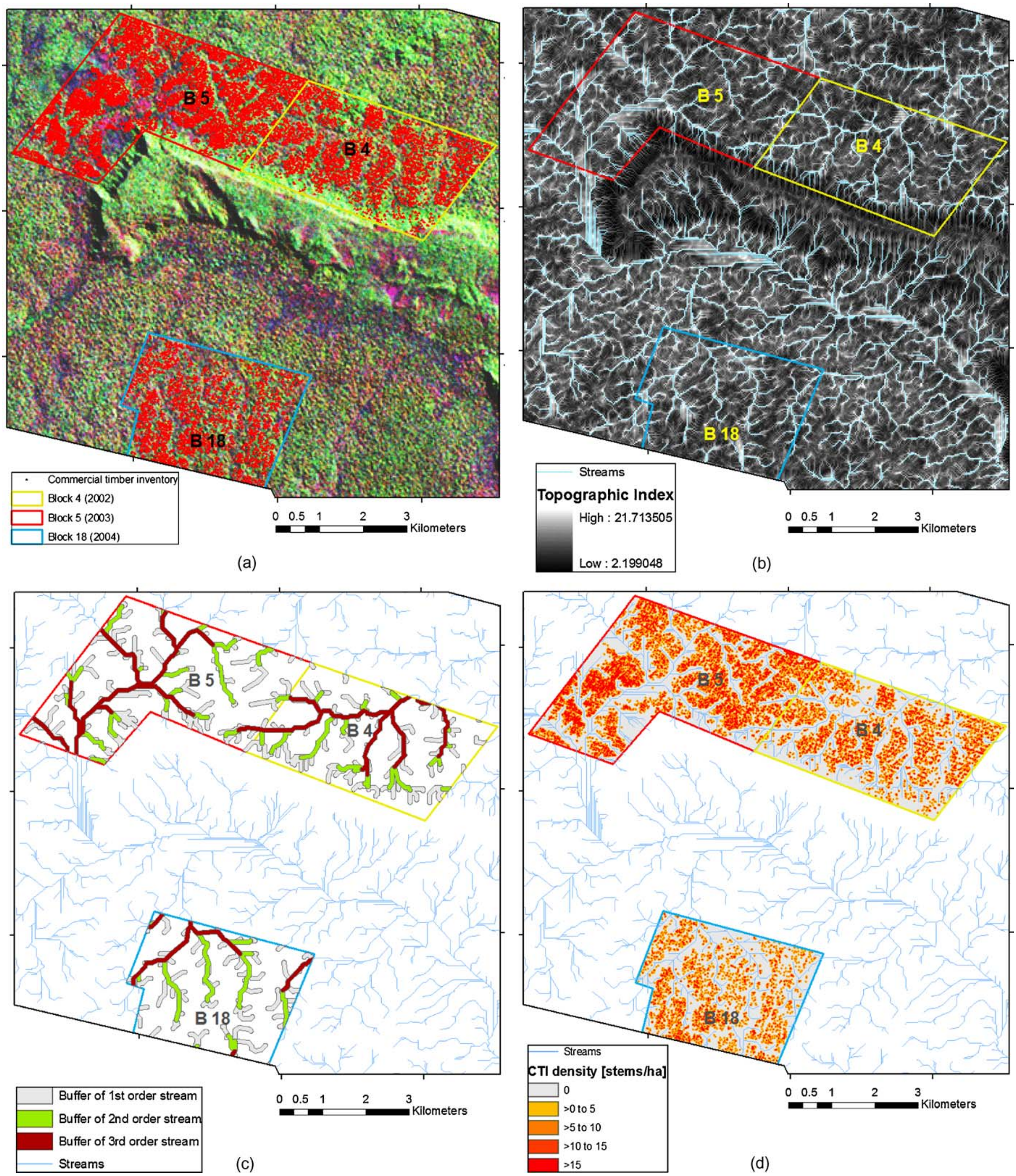

Fig. 2. (a) Georeferenced location of individual trees (●) from the CTI superimposed over a pre-harvest LANDSAT TM image; (b) topographic index and stream network generated from the ASTER DEM with boundaries for Blocks 4, 5, and 18; (c) area protected from harvesting as first to third order or greater stream buffers; (d) density of commercial timber in Fazenda Rohsamar in southern Amazonia, MT Brazil.

where N is the number of cases; X_i is the variable value at a particular location; X_j is the variable value at another location; X is the mean of the variable; and W_{ij} is a spatial weight of contiguity (1 if location i is contiguous to location j and 0 otherwise).

2.5. Predicting total forest biomass from commercial inventories

We evaluated the relationships between the biomass of all commercial timber and that of all commercial and non-commercial trees and palms with trunks ≥10 cm DBH. The AGB measured in the belt transects was the dependent variable and the predictor a subset of the belt transect data filtered for only commercial timber ≥45 cm DBH. Each transect was considered the sample unit. The data were tested for a normal distribution and equal variance to meet the assumptions of the analysis. The relationship between estimates of AGB (≥10 cm DBH) and commercial timber (≥45 cm DBH) was then calculated using simple linear regression.

2.6. Remotely sensed landscape assessment

A pre-logging, cloud-free LANDSAT Thematic Mapper (TM) image that covered the study area was acquired for July 1996. From the LANDSAT image, we extracted individual spectral bands 1–5 and 7 from each raster pixel for the three blocks. The LANDSAT bands 1–5 and 7, with a spatial resolution of 30 m, correspond to wavelengths blue (0.45–0.52), green (0.52–0.60), red (0.63–0.69), near infrared (0.76–0.90), short-wave infrared (1.55–1.75) and (2.08–2.35) μm, respectively. No atmospheric correction was applied to the image prior to pixel radiance extraction. Corrections are only required when comparing data from multiple images (Song et al., 2001). Simple band combinations and normalized vegetation indices were computed from the data extracted from each pixel. A principal component analysis (PCA) of radiance for bands 1–5 and 7 was conducted to determine the combination of bands that accounted for the most variation in radiance in the study area.

We also acquired an ASTER image for May 2002 (Global Land Cover Facility http://www.landcover.org). From the 30 m ASTER DEM, we derived a compound topographic index (TI) of the area with ArcMap. Topographic indices provide a measure of hydrologic similarity based on slope and contributing area (Moore et al., 1991). The TI was computed as:

$$\mathrm{TI} = \log\left(\frac{\alpha}{\tan\beta}\right)$$

where α is the upslope contributing area and β is the slope. A TI identifies areas of the landscape with similar hydrology. Highest values indicate the most poorly drained areas of the landscape (Fig. 2a). The TI computation used 30 m grid cells. The TI was left as continuous values for regression analysis or was reclassified into 2 TI classes, with values ≥8.6 corresponding to lowland vegetation. Lowland areas were defined through a comprehensive analysis of the relationship between vegetation and hydrology for the same logging block and georeferenced locations of transitions from lowland to upland (Jirka et al., in review). Separation between the two TI classes was accomplished by edge matching spectral shifts in the LANDSAT image with the TI raster layer at the georeferenced lowland to upland interface using ArcMap.

Using the hydrology tool pack in ArcMap, we generated a stream network with headwater locations that matched georeferenced stream headwater positions. By testing a range of contributing areas, we found that the minimum contributing area necessary to generate known stream headwaters was 50 cells (Fig. 2b). Under forest certification, logging is prohibited within 50 m of streams. We established a buffer to this distance for first, second, and third order streams and computed the reduction in the available harvestable area for each block.

2.7. Associations among radiance, topographic and stand properties

The relationship between the CTI (biomass, DBH, volume, basal area, and density) and satellite-derived data for radiance (LANDSAT single and combined bands) and topography (TI and slope) were first examined using simple linear regression on the continuous values. No linear relationship was found, so we classified the area into upland, lowland, and stream buffer and areas with and without commercial timber. Upland and lowland classes are not exclusive from the timber classification (i.e., commercial timber species may occur in either upland or lowland class). Areas were classified as having the presence (>0 commercial tree ha^{-1}) or absence (0 commercial tree ha^{-1}) of commercial timber based on density raster maps derived from the CTI, with areas of zero values assigned as non-timber (commercial) areas. Estimates of timber presence or absence and the 50 m stream buffer grid layer were spatially joined to the upland and lowland layer. To test for differences between the classes, values for every other pixel (60 m × 60 m sampling grid) were sampled and the classes subjected to a one-way analysis of variance (ANOVA). No transformations were necessary as the data were normally distributed. Differences between individual means were tested using a Tukey test ($p = 0.05$). Because of the large sample size, we used a random number generator to sub-sample half of the LANDSAT pixel values; ANOVAs were re-run on the subset to test the statistical significance using the smaller sample size.

3. Results

3.1. Assessing commercial and non-commercial timber in situ

3.1.1. Commercial species

Forest structure (e.g., density, spatial distribution) and tree characteristics from the CTI differed among blocks (Table 2). Density was defined as no commercial trees within a search radius of the mean separation distance between nearest neighbor trees plus one standard deviation (30 m). Using this

Table 2
Commercial timber inventory: forest structure, spatial patterns, and tree characteristics from the CTI (Blocks 4, 5, and 18) for Fazenda Rohsamar, southern Amazonia, MT Brazil*

	Block 4	Block 5	Block 18	Mean
Density (trees ha^{-1})				
Based on total block area†	5.4 a	8.6 b	4.0 c	6.2
Based on area outside stream buffer**	5.3	8.4	3.6	5.8
Nearest neighbor (m)				
Observed mean	16.3 a	14.0 b	22.3 c	16.1
Std. deviation	13	11	16	13
Expected mean	21.8	17.2	26.3	20.4
Ratio (obs./expected)	0.7	0.8	0.8	0.8
Z-score	−31.4	−32.3	−15.4	−49.8
p-Value	0.01	0.01	0.01	0.01
Spatial distribution	Clustered	Clustered	Clustered	Clustered
Spatial autocorrelation‡				
Predictors	DBH and distance	DBH and distance	DBH and distance	–
Moran's *I* index	0.04	0.13	0.08	
Variance	<0.001	<0.001	0.003	
Z-score	3.3	13.3	4.8	
p-Value	0.01	0.01	0.01	
Spatial distribution	Clustered	Clustered	Clustered	
Biomass (Mg ha^{-1})**				
Based on total block area	23.1	27.0	16.9	22.8
Based on area outside stream buffer	32.9	38.6	22.9	32.2
DBH (cm)				
Mean	73.1 a	62.8 b	73.5 a	67.6
S.E.	0.32	0.21	0.39	0.17
Median	67.0	57.3	67.0	
Maximum	255.0	197.4	296.0	
Commercial height (m)				
Mean	16.2 a	12.7 b	16.4 c	14.3
S.E.	0.05	0.03	0.07	0.03
Wood volume (m^3 ha^{-1})**				
Mean (based on area outside stream buffer)	21.6	20.5	15.3	19.3
Basal area (m^2 ha^{-1})**				
Mean (based on area outside stream buffer)	2.4	2.8	1.7	2.3

Data represent only commercial timber trees ≥45 cm DBH residing outside of 50 m stream buffers (see Table 1 for CTI inventory criteria).
* Values followed by different letters indicate significant differences between blocks (Tukey test; $p < 0.05$).
† Values extracted from a grid layer formed by density calculated using a search distance of the mean distance between trees plus one standard deviation.
** Values based on the total for each block divided by the area outside of stream buffers in each block—no ANOVA performed.
‡ Analysis of spatial clustering of trees within each block with DBH and distance as the predictors (Moran's *I* index values vary between −1 and 1); values indicate that trees with greater DBH are significantly more spatially clustered in the three blocks (high positive spatial autocorrelation); mean Euclidean search distance was the mean distance between trees plus one standard deviation.

radius results in tree density being calculated on a 0.28 ha basis. This was considered an appropriate area to distinguish nearest neighbor effects on tree distribution from landscape or other environmental factors that could influence commercial tree density. Block 5 had significantly higher mean tree density and biomass, and significantly lower distance to nearest neighbor, DBH, and canopy height than the other two blocks. That is, although there were more commercial trees available for harvest in Block 5, the trees were on average shorter and with smaller DBH than trees in the other blocks. Despite this, the greater number of stems in Block 5 was sufficient to result in nearly 1.4 times the commercial biomass than the other blocks. All blocks displayed significant clustering of commercial trees, indicating that the commercial timber was not uniformly distributed across the landscape.

3.1.2. Aboveground biomass ≥10 cm DBH

From the belt transects for the scientific inventory, there was significantly greater AGB in the small and intermediate DBH classes (10 to <45 and 45 to <80) than the large DBH class (≥80 cm) for all commercial and non-commercial trees and palms with trunks ≥10 cm DBH (Table 3). Approximately half of the 276 Mg ha^{-1} total dry biomass in all trees and palms ≥10 cm DBH was in stems 10–45 cm DBH. Stem density was significantly higher in the smallest diameter class than the two larger classes, constituting 95% of the total trees and palms ≥10 cm DBH. Canopy depth – from the first bifurcation to the top of the tree – ranged from 7.6 to 16.7 m for the three classes. Stems in the scientific inventory (≥10 cm DBH), unlike the CTI (≥45 cm DBH) (Table 2), were distributed randomly at each

Table 3
Total aboveground biomass: forest structure, spatial patterns, and tree characteristics by DBH class for all commercial and non-commercial trees and palms with trunks ≥10 cm DBH for 16 transects totaling 11.1 ha in Block 5 for Fazenda Rohsamar, southern Amazonia, Brazil

	DBH (cm)			Total
	10 to <45	45 to <80	≥80	
n	4535	246	54	4825
Density (no. trees ha^{-1})				
Mean	488.8	22.0	5.0	515.7
S.E.	16.1	1.3	1.0	15.4
Median	480.0	21.0	5.0	
Minimum	396.5	15.0	0.0	
Maximum	598.0	32.0	12.0	
Percentage of total	95	4	1	
Nearest neighbor (m)				
Observed mean	2.3	21.6	140.7	2.2
Expected mean	2.2	10.6	24.6	2.2
Ratio (obs./expected)	1.0	2.0	5.7	1.0
Z-score	3.6	27.5	53.3	3.6
p-Value	n.s.	n.s.	n.s.	n.s.
Spatial distribution	Dispersed	Dispersed	Dispersed	Dispersed
Biomass (Mg ha^{-1})				
Mean	153.1	74.7	48.3	276.2
S.E.	4.0	4.1	10.0	12.1
Median	155.7	74.1	41.4	
Minimum	128.6	48.7	0.0	
Maximum	180.2	101.3	116.4	
Percentage of total	55	27	17	
DBH (cm)				
Mean	26.2	56.7	93.2	–
S.E.	0.2	0.8	1.9	
Median	26.4	55.9	91.3	
Height to canopy (m)				
Mean	13.7	17.7	21.2	–
S.E.	0.5	0.6	1.0	
Median	13.7	17.5	21.8	
Tree height				
Mean	21.3	29.8	37.9	–
S.E.	0.5	0.8	1.7	
Median	21.7	30.2	38.9	
Volume (m^3 ha^{-1})				
Mean	110.4	56.7	43.3	210.4
S.E.	3.2	3.8	9.4	12.5
Basal area (m^2 ha^{-1})				
Mean	15.8	5.7	3.4	24.8
S.E.	0.4	0.3	0.7	0.9

individual diameter class level, with no significant clumping. There was no relationship between stem diameter and proximity to streams.

3.2. Landscape analyses

3.2.1. Stream buffers

Under RIL guidelines, trees within 50 m of streams are protected from logging. Applying these criteria to all first order or greater streams in each block excluded 28% of the total area from logging (Table 4; Fig. 2c). Limiting logging restrictions to third order streams or higher would exclude only 7% of the forest.

Table 4
Land distribution by 50 m stream buffer, timber density, and reduction of total available timber area for Fazenda Rohsamar in southern Amazonia, MT Brazil

	Block 4	Block 5	Block 18	Mean
Total area (ha)	1137	1398	1037	1191
Percent area as 50 m stream buffer including[a]				
≥First order streams	29	30	26	28
≥Second order streams	14	15	12	14
≥Third order streams	8	9	5	7
Percent of area with[b]				
No timber	29	18	35	27
>0–5 trees ha^{-1}	18	16	19	18
>5–10 trees ha^{-1}	11	13	11	11
>10–15 trees ha^{-1}	6	9	5	7
>15 trees ha^{-1}	7	14	4	8
Percent total harvestable area[c]	42	52	39	45

[a] Harvesting within 50 m of streams is prohibited. Stream network generated from ASTER DEM and 50 m stream buffers applied to first, second, and third order streams and greater.
[b] Values extracted from a grid layer formed by density calculated outside of ≥first order stream buffers using a search distance of the mean distance between trees plus one standard deviation.
[c] Difference between total block area and the area outside of stream buffers for ≥first order streams + area with no timber outside of buffers.

3.2.2. Timber distribution

An additional 27% of the forest had a commercial tree density of zero trees per hectare (Table 4, Fig. 2d). Based on the ASTER-derived TI estimate of upland and lowland areas, 8% of the area outside of buffers was defined as lowland (TI ≥ 8.6) (Table 5). Areas lacking commercial timber species were not restricted to lowland positions; on a landscape basis, 86% of the areas identified as having no commercial timber were in upland positions. Nevertheless, commercial timber biomass, density, volume, and basal area were significantly greater on upland than lowland positions (Table 6). The mean TI class for some commercial timber species was not significantly different from

Table 5
Mean percent of area as lowland, upland and buffer and with and without commercial timber for Blocks 4, 5, and 18 in Fazenda Rohsamar, southern Amazonia, MT Brazil

	Buffer	Lowland	Upland
TI classification (%)			
Total (no buffer)	–	13	87
Total (buffer included)	29	8	63
	Buffer	Non-timber	Timber
Mean percent of area	29	24	47
Percentage as lowland	15	14	10
Percentage as upland	85	86	90

Lowland area computed independently of the stream buffer based on LANDSAT radiance data and the topographic index (TI) derived from the ASTER data for known lowland areas.

Table 6
Mean biomass, density, and basal area for 37 commercial timber species ≥45 cm DBH in lowland and upland topographic positions estimated from the CTI in Fazenda Rohsamar, southern Amazonia, MT Brazil

	Lowland	Upland	*t*-Value	*p*
Biomass (Mg ha^{-1})	29.4 ± 0.57	32.5 ± 0.62	−4.36	<0.01
Density (stems ha^{-1})	5.4 ± 0.09	6.0 ± 0.09	−6.14	<0.01
Volume (m^3 ha^{-1})	18.9 ± 1.2	24.8 ± 0.5	−4.38	<0.01
Basal area (m^2 ha^{-1})	1.9 ± 0.12	2.4 ± 0.05	−4.41	<0.01

Mean area-based values calculated from 100% of individual trees with the variation as the standard error across rasters. Two sample *t*-test ($p = 0.05$).

the mean TI (Fig. 3). However, some timber species had significantly higher mean TI values than the landscape TI mean (areas become less well drained with increasing TI value), suggesting habitat preference based on hydrology. For example, the timber species Cupiúba (*G. glabra*), Caixeta (*S. amara*), and Angelim pedra (*D. excelsa*) occurred almost exclusively in more poorly drained sites where Cedro marinheiro (*G. dukei*) and Caroba (*J. copaia*) did not occur.

3.3. Distinguishing commercial timber remotely

As a result of the low range of radiance values in closed-canopy forests, LANDSAT radiance proved ineffective for estimating the magnitude of timber stocks (biomass, volume, density, and basal area). The individual LANDSAT bands, band combinations of simple ratios, and a PCA, however, provided some statistically significant separation among upland, lowland, timber, and non-timber categories, though the differences in radiance among categories were small (Table 7). Independent of timber presence, there were significant differences in radiance for single and band combinations between upland and lowland positions. Considering both topographic position and timber presence, upland areas with timber had radiance values that differed from upland without timber. The same was true for lowland areas with and without timber. For both cases, however, the absolute radiance differences were too small to be useful for remote inventory.

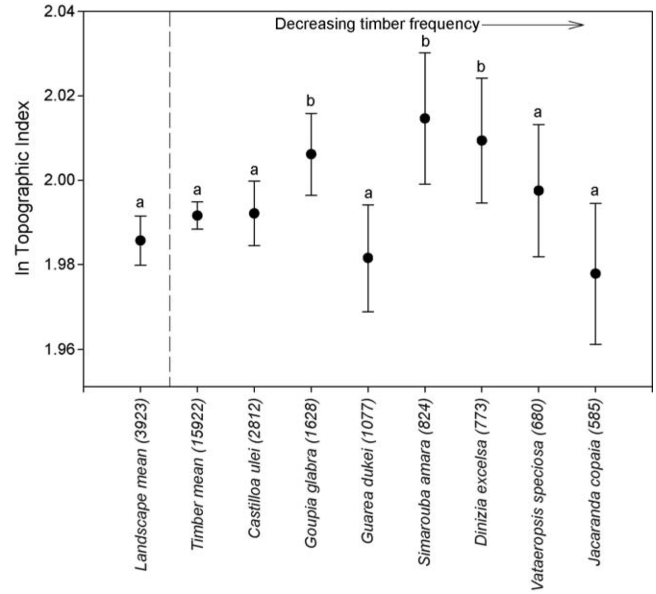

Fig. 3. Mean natural log of the topographic index for the landscape and commercial timber trees in Blocks 4, 5, and 18 in Fazenda Rohsamar, southern Amazonia, MT Brazil. Higher topographic index values indicate decreasing drainage. Timber species are ordered by decreasing frequency of occurrence. Values in parentheses indicate the sample size. Different letters indicate significant differences from the landscape topographic index mean (Dunnett's comparison to the control, $p < 0.05$; bars are 95% confidence intervals).

Table 7
Mean LANDSAT TM radiance for single and band combinations for areas classified as upland and lowland, and areas with and without commercial timber for Blocks 4, 5, and 18 in Fazenda Rohsamar, southern Amazonia, MT Brazil

LANDSAT TM bands	Upland	Lowland	*p*	Timber	Non-timber	*p*	Upland		Lowland		*p*
							Timber	Non-timber	Timber	Non-timber	
No. of pixels sampled	5797	775		4329	2243		3876	1921	453	322	
Single bands											
TM 4	64.08a	55.4b	<0.001	63.34a	62.50b	<0.001	64.23a	63.78b	55.76c	54.90c	<0.001
TM 5	43.04a	38.65b	<0.001	42.46a	42.65a	n.s.	42.93a	43.27b	38.43c	38.96c	<0.001
Band combinations											
TM 247	97.68a	87.31b	<0.001	96.70a	95.98b	<0.001	97.77a	97.48a	87.52b	87.03b	<0.001
TM 457	119.51a	105.28b	<0.001	118.02a	117.48b	<0.01	119.51a	119.53a	105.31b	105.24b	<0.001
TM 57	55.44a	49.87b	<0.001	54.68a	54.97b	<0.001	55.28a	55.75b	49.54c	50.33d	<0.001
TM 4/3	3.65a	3.26b	<0.001	3.63a	3.57b	<0.001	3.66a	3.63b	3.29c	3.21d	<0.001
TM 5/3	2.45a	2.27b	<0.001	2.43a	2.44a	n.s.	2.45a	2.46b	2.27c	2.28c	<0.001
Albedo	216.32a	200.63b	<0.001	214.64a	214.14a	n.s.	216.29a	216.37a	200.46b	200.85b	<0.001
Principal component analysis											
PCA 1	80.15a	70.32b	<0.001	79.21a	78.55b	<0.001	80.23a	79.98a	70.53b	70.03b	<0.001
PCA 2	21.09a	20.79b	<0.001	20.86a	21.43b	<0.001	20.92a	21.44b	20.40c	21.34b	<0.001

ANOVAs between upland, lowland, timber, and non-timber areas in upland and lowland areas with corresponding *p* significance values. Mean values with different letters are significantly different across rows (n.s. indicates non-significant difference; Tukey test; $p < 0.01$). Lowland and upland are not an exclusive class from presence or absence of timber, since timber occurs in both upland and lowland positions. Non-timber vs. timber areas were classified from the commercial timber inventory.

3.4. Estimating forest structure and AGB from the CTI

As commercial timber inventories become more widespread, these data may provide a basis for estimating AGB and density and to evaluate variability across the landscape. Using only commercial timber data from the belt transects (37 currently harvested species ≥45 cm DBH), biomass was predicted of all commercial and non-commercial trees and palms ≥10 cm DBH ($R^2 = 0.67$; $p < 0.01$). There was also a relationship between commercial timber and AGB in individual DBH classes. For example, the biomass for timber species alone (≥45 cm DBH) was related to the biomass of all trees and palms ≥45 cm DBH ($R^2 = 0.64$; $p < 0.01$) and large stems ≥80 cm DBH ($R^2 = 0.63$; $p < 0.01$). There was no relationship, however, between commercial timber and AGB in the 10 to <45 cm DBH class, nor between commercial timber and non-commercial and commercial stem density or basal area. This indicates that based on the CTI criteria for this forest (Table 1) biomass from the commercial timber inventory, 12% of the AGB, could be used to predict biomass for all stems ≥10 cm DBH. Predicting other stand properties and the biomass of only small stems (10 to <45 cm DBH) was not possible from the commercial timber data alone.

4. Discussion

4.1. Estimating harvestable area

Although certified RIL practices impose a 50 m stream buffer, and independent auditors field-verify adherence to the rules, the field interpretation of a ‘‘stream,’’ especially in upland headwater positions, is an uncertain process. Some of the headwater streams are dry at the time of harvesting since cutting occurs only during the dry season when rainfall drops to <50 mm/month. Hence in practice, first order streams may not be identified in the field if the inventory is also carried out during the dry season. These ephemeral streams could be mapped and excluded from harvesting with digital terrain analysis as demonstrated in this study.

The first order stream buffers are more likely to occupy upland landscape positions than those bordering second or third order streams. For example, 85% of the first order stream buffers occupied upland positions. Since commercial timber biomass, density, volume, and basal area were greater in upland positions (Table 6), protecting first order stream buffers (Table 4) would result in a proportionally higher reduction of timber than protecting second order or greater streams. Additional research is needed to examine the logging effect (tree-fall, skidder disturbance, etc.) on different order streams to determine if buffers are warranted around all streams at the low logging rates of RIL in this study.

4.2. Estimating timber distribution based on ASTER and LANDSAT imagery

Based on the ASTER-derived TI and using the TI value (≥8.6) as a cut-off to classify upland and lowland positions, nearly 90% of the forest area was upland. Areas without timber occurred with the same frequency as areas with timber on upland and lowland positions (Table 5). This is because timber species account for only a small fraction of the total tree species. Areas lacking timber species are forested by non-merchantable trees. We found that commercial timber species, which are determined by market criteria rather than ecological forces, span a large range of TI and topographic positions and as such, do not fall as a group into a distinct set of topo-edaphic conditions. However, individual commercial timber species obligate or facultative preference for specific hydrological conditions makes it possible to estimate species-specific timber distributions. For example, the timber species Caixeta (*S. amara*) will generally occupy less well drained areas and Cedro marinheiro (*G. duckei*) areas similar to the landscape TI mean (Fig. 3). Such species-specific growth preferences may help to estimate timber distribution for some species.

Though LANDSAT TM data are inexpensive, a disadvantage in their use is that canopy discontinuities are sometimes lost in the 30 m × 30 m resolution. Bands 4 and 5 alone and in PCA combination resulted in discernable differences in the mean radiance of lowland versus upland areas and in discerning timber from non-timber areas (Table 7). Other studies have found that canopy reflectance from primary forest can serve as a predictor of understory floristic and edaphic patterns, but not species richness (Tuomisto et al., 2003; Rajaniemi et al., 2005). This is similar to our work, where landscape units could be distinguished by spectral signatures, but predicting actual stand parameters such as commercial timber volume, basal area, etc. was not possible using LANDSAT imagery.

4.3. Predicting AGB

Amazon Basin-wide live AGB estimates for primary forests vary from 155 to 464 Mg ha^{-1} (Brown et al., 1995; Fearnside, 1997; Houghton et al., 2001; Keller et al., 2001) compared to our estimate of 276 Mg ha^{-1} for trees and palms ≥10 cm DBH. Many reported AGB estimates are from inventories of stems ≥30–45 cm DBH, with the assumption that most of the biomass resides in large-diameter trees. These studies then either sample a subset of stems <30–45 cm DBH or estimate the smaller diameter stems and extrapolate the values to the entire study area (e.g., Gillespie et al., 1992; Keller et al., 2001). Our results indicate that AGB would be underestimated by 30% if stems 10 to <30 cm DBH were excluded from the analysis and 55% if stems 10 to <45 cm DBH were ignored. We also found high AGB spatial variability across the landscape for commercial and non-commercial trees ≥80 cm DBH, with as little as zero and as much as 116 Mg ha^{-1} in large 1-ha sample plots (10 m × 1000 m) (Table 3), further indicating that timber species are spatially aggregated and large trees (≥80 cm DBH) are rare in some areas of the forest.

The large portion of biomass in small diameter classes and high biomass spatial variability indicates the need to sample smaller diameter classes and the importance of adequately dispersing sampling parcels for purposes of quantifying total AGB in Amazonian forests. We found that short belt transects (10 m × 200–500 m) produced a similar range of AGB estimates as long transects (10 m × 1000 m) for all stems ≥10 cm DBH, indicating that a sampling protocol that utilizes many short transects spread throughout the landscape is as effective as when a few long transects are used. These results were also reported by Keller et al. (2001), as they calculated that 21 small (0.25 ha) plots would have produced comparable stand-level biomass estimates to their estimate from four large plots totaling 392 ha. Long transects, however, do provide advantages to short transects since they are less susceptible to error in georeferencing and more representative of coarse-grained satellite imagery since they span many pixels.

Our estimates of AGB for all trees and palms with DBH ≥10 cm exclude coarse woody debris and do not account for hollow boles or biomass in vines, small (<10 cm DBH) trees or buttresses. Including these values would alter estimates of AGB, although the changes relative to the total biomass would be small since the allometric equations we used to compute biomass included a range of species, including some with hollow stems and trees with buttresses (Brown, 1997). Vine biomass in the same forest averaged 15 Mg ha^{-1} (Feldpausch et al., 2005).

4.4. Predicting AGB from CTIs

We make a case for the novel use of CTIs to estimate AGB. The expansive area currently included in Amazonian CTIs conducted under certified RIL provides a unique opportunity to expand Amazon basin-wide estimates of AGB. Based on our analysis using trees sampled in the CTI alone to estimate AGB, it would be necessary to conduct a scientific inventory for each forest where AGB would be estimated. This is a result of the regional differences in number of species included in the CTI, which is market dependent. Commercial timber (≥45 cm DBH) represented an average of 8–12% of the total biomass (≥10 cm DBH). The strong relationship between commercial timber alone and total biomass in trees and palms (≥10 cm DBH) suggests that commercial and non-commercial stand biomass is dependent on many of the same site characteristics. The weak relationship between the commercial timber density and stems 10 to < 45 cm DBH indicates that the population density of small stems is unrelated to the occurrence of large commercial trees.

4.5. Deforestation and forest management

In 2004, 4% of the total deforestation in Amazonia occurred in the county adjacent to our study site as the state of Mato Grosso continues to have both the highest rates of deforestation (48% of the basin-wide total) (INPE, 2005) and the largest soybean producer in the world (Economist, 2004). The recent surge in Amazonian deforestation indicates timber resources in selectively logged forests hold a lower value than converting the land to other uses. Improving forest management and adding value to standing forest could offset pressure to deforest for annual crops and pasture. At the local and regional scale, zoning of the frontier regions (Nepstad et al., 2002) through the use of improved tools for estimating available timber and harvestable area could facilitate forest conservation under RIL methods. Areas containing many streams have a lower harvestable area for timber with RIL-mandated buffer zones. By using remote methods to efficiently identify stream networks, road building, and unnecessary disturbance in areas with a high proportion of buffer exclusions could be avoided. This is especially important considering recent estimates of selective logging in Amazonia represent a 60–123% increase on previously reported estimates (Asner et al., 2005).

5. Conclusions

The methods developed in this study could be useful for estimating the harvestable area of stands prior to timber mapping and facilitating the novel use of CTIs to estimate AGB at the scale of thousands of hectares in the Amazon Basin. Individual timber species showed some preference for specific hydrological conditions, suggesting that determining a topographic index from an ASTER-derived DEM may be a useful approach for predicting the occurrence of some, but not all commercial species. However, since timber species in aggregate were present in both lowland and upland landscape positions, these topographic designations were not useful for delineating non-commercial areas. Buffers around first order and greater streams reduced the potential harvestable area by 28%. Dry season harvesting, however, may reduce the perceived buffer area for ephemeral headwater streams. These streams could be mapped and excluded from harvesting with a digital terrain analysis. There were significant differences in LANDSAT radiance between areas with and without commercial timber and timber and non-timber areas. With little separation, however, between mean spectral values for individual and band combinations for these classes, the differences will not be useful to predict the quantity of timber available nor presence or absence of commercial timber species in other forests on a sub-hectare scale. It was possible to estimate tree AGB (≥10 cm DBH) from an inventory of commercial timber alone (commercial species ≥ 45 cm DBH). This relationship suggests that biomass and carbon stocks can be estimated for other areas which have been inventoried for commercial timber. As a result of regional differences in species included in the CTIs, it is necessary to conduct small-scale stand-specific estimates of AGB in spatially dispersed areas of the forest to use the CTI to estimate AGB at the scale of thousands of hectares.

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