Revista Brasileira de Cartografia (2015) N^0 67/3 691-700
Sociedade Brasileira de Cartografia, Geodésia, Fotogrametria e Sensoriamento Remoto
ISSN: 1808-0936

HAND TERRAIN DESCRIPTOR FOR MAPPING REGIONAL SCALE ECO-HYDROLOGICAL UNITS OF AMAZON TERRA FIRME

Descritor de Terreno HAND para Mapeamento em Escala Regional das Unidades Eco-Hidrológicas de Terra Firme da Amazônia

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Recebido em 10 de Janeiro, 2014/ Aceito em 10 de Fevereiro, 2015
Received on January 10, 2014/ Accepted on February 10, 2015

ABSTRACT

The HAND (Height Above the Nearest Drainage), a quantitative topographic descriptor, is used to classify terrain in a manner that is related to local soil water conditions, providing hydrological meaning to the SRTM DEM. The HAND was calibrated in a small basin (37km²) of similar topographical characteristics. In this paper, we applied HAND descriptor for classifying Terra Firme environment (plateau, slope, ecotone and waterlogged) in an area of 19 000 000 km^2, characterized by heterogeneous relief, in the Eastern Amazon, Brazil. We propose calibration technique for applying HAND descriptor for large areas and heterogeneous relief, and we show how to attenuate the canopy effects of the SRTM DEM for the boundary between forested and deforested areas, in order to produce coherent data for hydrological modeling.

Keywords: Shuttle Radar Topography Mission (SRTM), Terra Firme Land Mapping, HAND Quantitative Topographic Descriptor.

RESUMO

HAND (*Height Above the Neareast Drainage*) é um descritor topográfico quantitativo utilizado para classificar o terreno de acordo com as condições hidrológicas locais do solo, proporcionando significado hidrológico ao DEM do SRTM. O HAND foi calibrado para uma pequena bacia (37km²), de similar característica topográfica. Neste artigo, nós utilizamos o descritor topográfico HAND para classificar os ambientes de Terra Firme (platô, vertente, ecótono e baixio) de uma área de 19 000 000 km^2, caracterizada por relevo heterogêneo, na Amazônia Oriental, Brasil. Nós propomos um método de calibração do HAND para grandes áreas e relevos heterogêneos, e mostramos como atenuar os efeitos da vegetação no DEM do SRTM para os limites entre áreas florestadas e desflorestadas, a fim de produzir dados coerentes para a modelagem hidrológica.

Palavras chaves: Shuttle Radar Topography Mission (SRTM), Mapeamento Ambientes de Terra Firme, Descritor de Terreno

HAND.

1. INTRODUCTION

The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) provides landform details that are not visible in optical satellite images. That increased the number of studies that use the SRTM data as input for geomorphological studies (FERNANDES; VALERIANO, 2013; SANTOS; JUSTINA; FERREIRA, 2012) and hydrological and environmental modeling (CURKENDALL *et al*., 2003; KELLNDORFER *et al*., 2004; SAATCHI *et al*., 2008; SESNIE *et al*., 2008).

Nevertheless, the use of SRTM DEM presents constraints to hydrological and environmental modeling. SRTM altimetry is referred to sea level. This reference may not be a good predictor of eco-hydrological units, waterlogged, ecotone, slope and plateau (Ribeiro *et al*., 1999), because SRTM DEM does not assure that the association between altitude and occurrence of eco-hydrological is comparable in a large and heterogeneous surface (NOBRE, 2011; RENNÓ *et al*., 2008).

The Height Above the Nearest Drainage (HAND) is a promising topographic descriptor that was developed to normalize the SRTM DEM by using the nearest drainage network as a reference rather than sea level (RENNÓ *et al*., 2008). This drainage network normalization in the HAND algorithm is an important improvement over other algorithms (GHARARI *et al*., 2011; NOBRE *et al*., 2011; SAVENIJE, 2010; ZOU *et al*., 2009). Firstly, this algorithm creates topographic gradient which is comparable over regional scale. Secondly, it potentially enhances previously hidden drainage network. Finally, the HAND algorithm is applied to classify terrain considering local soil water, which gives the HAND algorithm high prediction power in ungauged basins (SAVENIJE, 2010).

HAND model has been calibrated to undisturbed forest landscape, located in a small watershed entirely characterized by one specific landform type (CUARTAS *et al*., 2012; GOMES DE FREITAS *et al*., 2012; NOBRE *et al*., 2011; RENNÓ *et al*., 2008). However, landscapes that are characterized by distinct landforms other than the one where HAND was tested require distinct calibration parameters. But to do that, field campaign is needed, which represents one of the main obstacles to research in Amazon region. Because conducting field campaigns in the Amazon region is time-consuming and expensive, we propose a new HAND grid calibration technique based on a geomorphological map. We hypothesized that the geomorphological map is capable of representing the dominant hydrological processes in the landscape.

In cases of fragmented forest landscape, an extra image processing in SRTM DEM is required before applying HAND algorithm. Because SRTM DEM is sensitive to Earth's surface elements, the boundary between forest and deforested area can be expressed as depressions, creating false channel drainage (VALERIANO *et al*., 2006). This is referred as Canopy Effects and represents one of the main limitation for drainage modeling, because it prevents the interpretation of the attributes extracted of SRTM DEM (VALERIANO *et al*., 2006). In this article, we present a straightforward method for reducing SRTM DEM Canopy Effects using land cover thematic maps.

Finally, we showed how to use HAND algorithm in a heterogeneous terrain and disturbed landscape calibrating it for a 19 000 000 km^2 area of *terra firme* rainforest environments in the Eastern Amazon.

2. STUDY AREA

The test site encompasses 19 000 000 km^2 along BR-163, named Sustainable Forestry District BR-163 (SFD BR-163), located in Southwest Pará State, Brazil, (Fig. 1). The average annual rainfall in this region is 1920 mm with the heaviest rains occurring between December and May and a short dry season occurring between August and October. The average monthly temperatures vary from 24.3ºC to 25.8ºC (EMBRAPA, 2008). Geologically, the study area is formed by two tectonic domains: the Phanerozoic sedimentary basin in the north, characterized by flat relief; and the Protherozoic lithologic units in the south, characterized by irregular terrains (CPRM, 2008). The region is covered by the non-flooded Terra Firme forest. The canopy height of the forest ranges from approximately 30 to 40 m, with occasional emergent species reaching approximately 50 m. The anthropogenic landscape is dominated by pasture, agriculture, mining and urban areas (EMBRAPA, 2008).

3. METHODS

The study has employed data from field campaign and from satellite image. The method involves the steps presented bellow.

3.1 Ground truth data

Field campaign was conducted during the early weeks of September, which coincided with the dry season in the region. Observed accumulated precipitation for September was around 60mm, without rainfall during the field campaign (CPTEC, 2008). We collected a total of 441 points, 269 points from soils with a water table near the surface (wet areas) and 172 points from soils with deep water tables (dry areas). We avoided taking points in disturbed areas like pastures, agricultural, clear-cut and mining areas. The presence of intermittent drainage and the conversion process of forest to pasture, which makes the springs water dry, were observed.

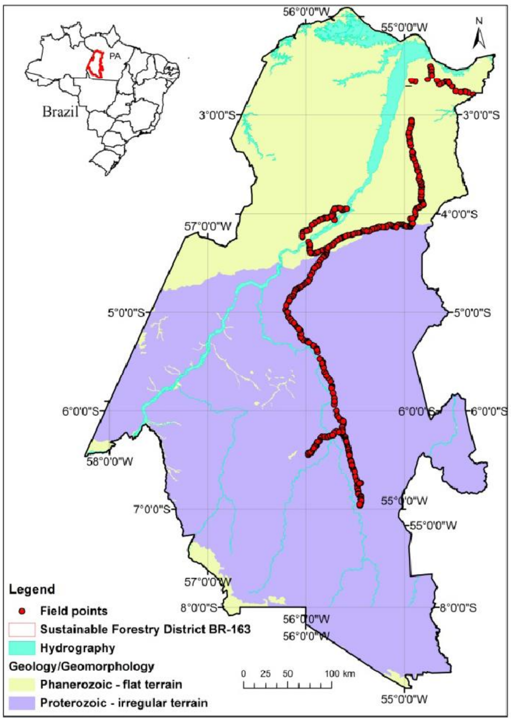

Fig. 1 – Study area: Sustainable Forestry District BR-163 (SFD BR-163), Pará (PA), Brazil.

Thus, to confirm these features, we verified the context around the point, observing the presence of drainage features and wet areas. A Global Positioning Satellite (GPS) was used to register the geographic coordinates for each inspected point, representing the classified areas by the algorithm. Elevation data were not collected, since the objective of this field work was to verify the accuracy of eco-hydrological classes (area) mapped by HAND, and not the elevation points, which would be very inaccurate using a common GPS. Each point collected represented a class mapped by the algorithm.

3.2 Drainage network extraction

Contributing area threshold is an important parameter for the accuracy of the HAND algorithm. Based on contributing area threshold, drainage network is derived, which in turn, is used to produce HAND grid representing the eco-hydrological units (for full description of the Hand algorithm procedures see Rennó *et al.* (2008).

We defined drainage network using ground truth data and geomorphologic map (1:1.000.000) (CPRM, 2008) (see Fig. 1). We plotted points of dry and wet areas on contributing area grid, and we interactively adjusted drainage network density. Note, the lower the threshold, the higher the density of the resulting drainage network. Geomorphological map was used to identify the flatter and the irregular terrain, which is na important information to define drainage network. We hypothesized that geomorphological homogeneous regions match areas with similar hydrological characteristics. Based on geomorphological map, we extrapolate the threshold to the whole study area.

Next, terra firme was quantitatively partitioned into the following eco-hydrological units, according to Ribeiro *et al.* (1999): waterlogged (water table perennially at the surface), ecotone (shallow water table) and upland (deep water table). We used thresholds for identifying each class, according to Rennó *et al.* (2008): waterlogged (HAND<5.3m), ecotone (5.3≤HAND≤15m), slope (HAND<15m and slope≥7.6%) and plateau (HAND>15 and slope<7.6).

3.3 Fixing the Canopy Effects in the SRTM DEM

The false channels drainage caused by Canopy Effects (Fig. 2) were eliminated by using the DEM_CORR software, which was developed in an IDL environment (RENNÓ, 2009). Method involves a process in which certain values are subtracted from forested areas to equalize the terrain between forest and deforested area. This is a tunable parameter. Procedure essentially removes the vegetation, which makes the SRTM DEM closer to the real surface. For this, we used binary mask representing forest and non-forest areas. We qualitatively determine suitable value to be subtracted, looking at improved quality in the corrected image, and also comparing drainage network extracting from corrected and original image.

For this procedure, we assume canopy height uniformity for the whole area. We masked forested areas using the Amazon Forest Monitoring System data (INPE, 2001), for the year in which the SRTM mission was held (2000).

3.4 Analysis

The values of the SRTM-DEM and HAND algorithms were computed for points collected during field campaign and were compared in a box plot. With this analysis, we investigated whether HAND algorithm could map local environments better than the original SRTM DEM. We used 286 samples for accuracy assessment of HAND grid, based on confusion matrix and Kappa Coefficient (COHEN, 1960).

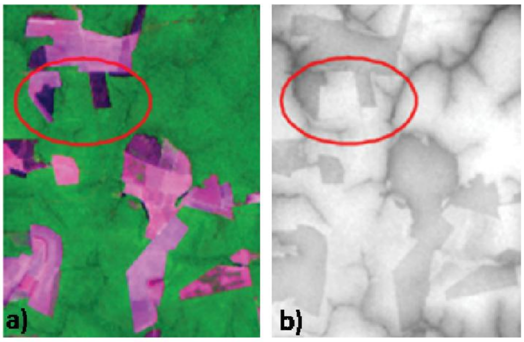

Fig. 2 - (a) LANDSAT TM image (RGB composite, bands 5,4,3) shows clear-cut areas in magenta and forest in dark green; (b) SRTM-DEM, of the same area, shows false depressions caused by abrupt transitions between forest (light grey areas) and deforestation (dark grey areas).

4. RESULTS

The Canopy Effects of SRTM data for the study area were corrected using land cover thematic maps. Using this corrected data, the contributing area grid was computed and with it the drainage network was derived, using a selected contributing area threshold. The HAND grid was obtained using this drainage as reference. The results of these steps are presented below.

4.1 Fixing Canopy Effects in the SRTM DEM

From an exploratory analysis, we found that the suitable parameter for reducing Canopy effects in the SRTM DEM was to subtract 10 meters from the forested area. Figure 3 shows the effect of false depressions on the drainage network extracted from the SRTM DEM before and after correcting the linear artifacts. From this, we observe a smoother transition from terrain after image correction.

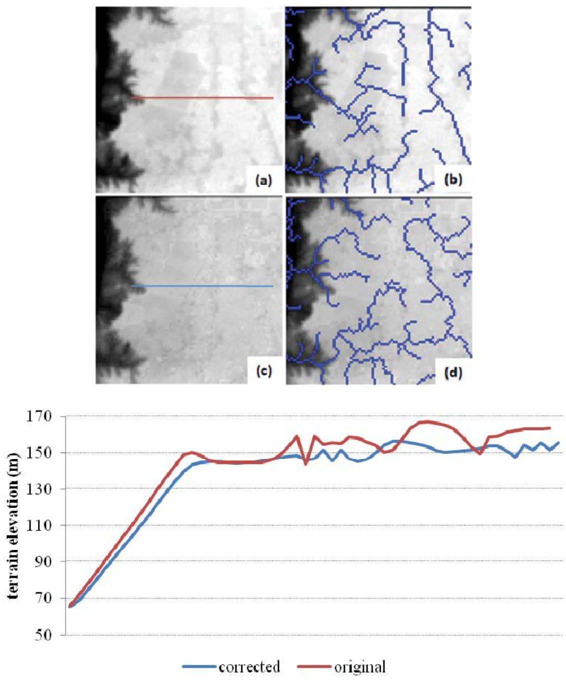

Fig. 3 - Deforestation effect on the drainage network: (a) original SRTM DEM, (b) drainage network extracted from the original SRTM DEM, (c) corrected SRTM DEM and (d) drainage extracted from the corrected SRTM DEM. Red and blue line represent SRTM elevation profile before and after image correction, respectively.

4.2 Drainage network sensitivity

We found that the best drainage network result for the south part of SFD BR-163, characterized by undulating and poorly-drained areas, was obtained by applying a contributing area threshold of 50 grid points. We defined drainage network using ground truth data and geomorphologic map. We plotted points of dry and wet areas on contributing area grid, and we interactively adjusted drainage network density. Based on geomorphological map, we extrapolate the threshold to the whole study area. We hypothesized that geomorphological homogeneous regions match areas with similar hydrological characteristics. The topography in this area is undulated and composed of swampy areas with a dense drainage network. In contrast, the best drainage network result for the north part, characterized mostly by flat and well-drained areas, was obtained with a contributing area threshold of 150 grid points. The topography of the north region of the District is smoother and is mainly composed of flat plateaus that are incised by a sparse drainage network.

4.3 Mapping *Terra Firme* environments

The SFD BR-163 *Terra firme* was divided into the following eco-hydrological classes: 17.4% (32.7km^2) waterlogged, 18.3% (34.5km^2) ecotone, 31.4% (59.2km^2) slope and 32.9% (62km^2) plateau (Fig. 4). Fig. 5 (a)-(c) contain details regarding the HAND grid with different geomorphologic units. Accuracy rate between classification and ground data was estimated at 90% and Kappa coefficient at 87% (Table 1).

The eco-hydrological classes are not distributed uniformly in the district. In the north part of the SFD BR-163 (34 km^2), plateau occupied 11.1% (20 km^2) of the surface, whereas waterlogged, slope and ecotone occupied 2.2% (4 km^2), 2.4% (4 km^2) and 3.2% (6 km^2), respectively. In the central part of the SFD BR-163 (106 km^2), on the other hand, surface is comparatively steeper and predominantly occupied by eco-hydrological class "slope" (41%, 43 km^2). The eco-hydrological classes waterlogged, plateau and ecotone occupied 15% (16 km^2), 26% (27 km^2) and 18.5% (19.5 km^2) of this region, respectively. Finally, in the southern SFD BR-163 (42 km^2), slope and plateau occupied 28.3% (12 km^2) and 35% (15 km^2) of surface, respectively. In contrast, waterlogged and ecotone occupied 16% (7 km^2) and 21% (9 km^2) of area, respectively.

4.4 HAND grid ground truth verification

The box plot graphs display the relationships between the normalized drainage data, which are represented by the HAND grid, the absolute SRTM-DEM height and the surveyed ground data (Fig. 6). The wet and dry point distributions are clearly distinguishable in the normalized drainage network. HAND grid uses the same reference, *i.e.,* the nearest drainage, to represent terrain gradient over study area. In this grid, the lowest elevations indicate humid areas and the highest elevations indicate dry areas. In contrast, the absolute height of the SRTM-DEM confuses local hill slope gradients with landscape-scale gradients.

Thus, SRTM-DEM may fail in predicting occurrence of dry and wet surfaces over large and heterogeneous landscape, since those environments occur, regardless of absolute height.

We selected two regions along the SFD BR-163 district to illustrate this point (Fig. 7). The north part of study area, areas located between 172 and 192 m above sea level (a.s.l.) were classified as plateau by using the HAND algorithm. In the southern part of district, the same range in absolute height represents waterlogged class, according to the HAND algorithm classification. Thus, using the height above sea level, dry and wet areas are not well differentiated.

Using the HAND algorithm we established two distinct models, based on geomorphological characteristics, to better represent the topographic gradient from the upper to the lower study area. This method allowed the topographical gradients defined in the north part of district, which is relatively flatter than the southern region, to be physically applied in the southern part of the district and vice versa. However, a fuzzy zone was detected between the wet and dry points even when a normalized height was used. This fuzzy zone was likely related to the slope areas.

5. DISCUSSION

We showed that the inappropriate use of

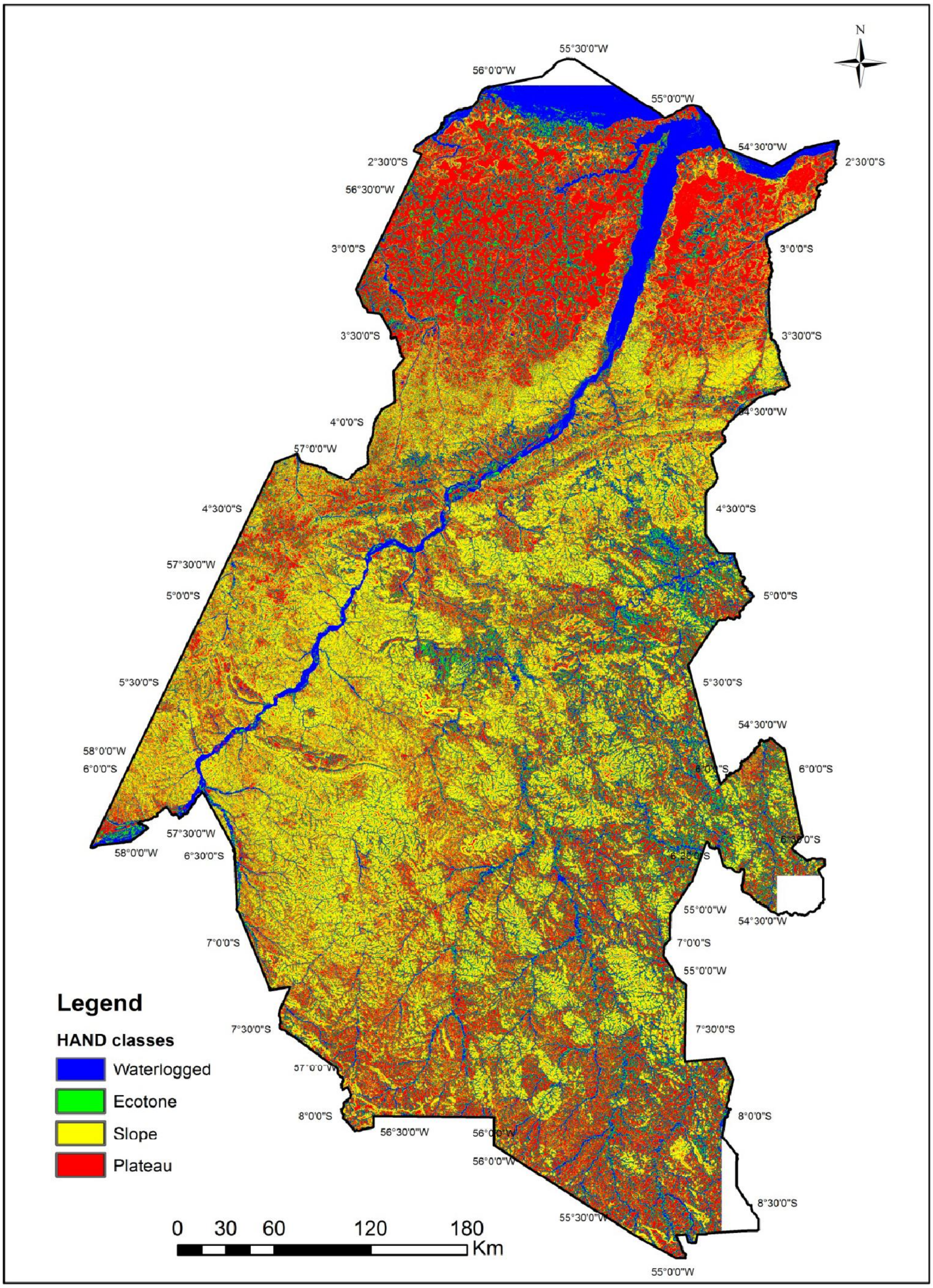

Fig. 4 - Four-class HAND map of the BR-163 Sustainable Forestry District.

SRTM data in local scale topographic analysis can hinder or create unusable results when applied to broad scales. SRTM DEM has little to no hydrological meaning at broad scales. Because a unique hydrological model was not applied to the entire Amazon region, the HAND model became an important tool for dealing with landscape heterogeneity in the Amazon region.

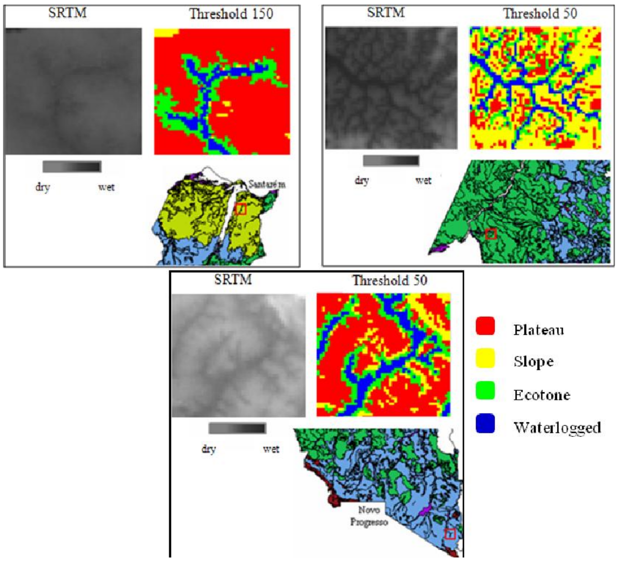

Fig. 5 - HAND grid with the geomorphologic unit of Plateau.

Table 1: Confusion matrix for accuracy assessment

		Ground data				
		plateau	slope	ecotone	waterlogged	total
HAND	plateau	84	0	7	0	91
	slope	0	49	18	0	67
	ecotone	0	2	46	0	48
	waterlo-gged	0	0	0	80	80
	total	84	51	71	80	286

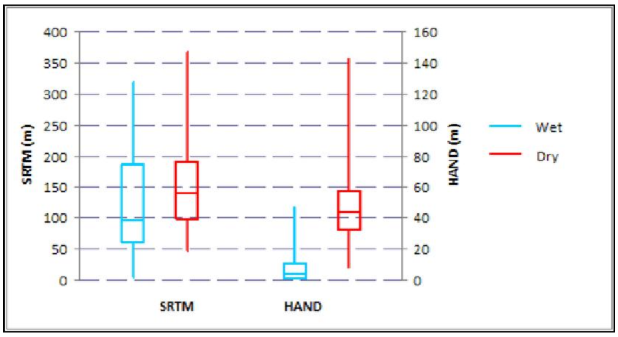

Fig. 6 - Box plot summary of the SRTM-DEM and HAND grid estimates (The top and bottom of each rectangular box denote the 75th and 25th percentiles, respectively, with the upper and lower limits and the median shown inside the box).

The inherent ecological and hydrological sensibility makes HAND metrics especially suitable for handling the reduction of uncertainties in the aboveground biomass estimation, and the assessment of geographic species distributions, the two core environmental issues in the Tropical Rainforest. Ambiguity in biomass estimation

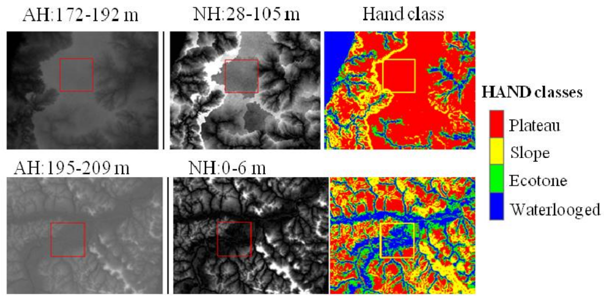

Fig. 7- Relationship between the absolute height (AH) of the SRTM DEM and the normalized height (NH) of the HAND grid.

is responsible for much of the uncertainty in carbon emission models (HOUGHTON, 2003, 2005). Castilho *et al*., (2006) show that local altitude, rather than absolute altitude, can be used as a proxy for soil characteristics. These characteristics make the HAND grid an important tool for improving current biomass stock estimates over large areas in the Amazon. The HAND algorithm can also be used to refine models for the spatial prediction of species and to subsidize conservation management. Topography and soil water conditions play a dominant role in controlling species occurrence (BOHLMAN *et al*., 2008; LAURANCE *et al*., 2010; POULSEN *et al*., 2006; TUOMISTO *et al*., 2003; VORMISTO *et al*., 2000; ZUQUIM *et al*., 2009). However, Willis & Bhagwat (2009) indicated that most of biodiversity models fail to capture topographic heterogeneity and have unreliable results because they do not use a detailed data set.

Large and heterogeneous areas, like the Sustainable Forestry District of BR-163, distinct terrain models need to be conceptualized, for which new calibration parameters are needed. Traditionally, data collection in the Amazon region is time-consuming and is not feasible in large areas such as the BR-163 Sustainable Forest District (19.000.000 Km^2). Here, an alternative method to calibrate models based on a geomorphologic map was used to draw inferences regarding landforms. However, the validity of a model must be checked before it is applied, the presented method may reduce the required field campaign effort for large areas.

Interpretability of the SRTM DEM and of the eco-hydrological units of the HAND model depends of the attenuation of Canopy Effects. We showed a straightforward method to the reduction of these artifacts.

5. CONCLUSION

The main goal of this study was to map *terra firme* environments at a broad scale. In doing so, we emphasized the advantage of using the normalized HAND grid instead of the absolute SRTM DEM height to classify *terra firme* environments. Broad scale studies require unavoidable attention to spatial heterogeneity, which was achieved by using the HAND topographic descriptor. The normalized HAND model was able to predict soil water conditions at local and regional scales, which confirmed the eco-hydrological function of the topographic classes.

A wide array of disciplines can use the HAND model to overcome their own challenges. The HAND grid results are available at http://www.dpi.inpe.br/pime.php. We encourage tests in a variety of phytophysionomies and at different scales. Due to the lack of detailed topographic data in the Amazon region, the HAND algorithm is potentially an important and useful source of data for studies in different Amazon regions.

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