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Mapping hydrological environments in central Amazonia: ground validation and surface model based on SRTM DEM data corrected for deforestation

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Abstract

One of the most important freely available digital elevation models (DEMs) for Amazonia is the one obtained by the Shuttle Radar Topography Mission (SRTM). However, since SRTM tends to represent the vegetation surface instead of the ground surface, the broad use of SRTM DEM as a framework for terrain description in Amazonia is hampered by the presence of deforested areas. We present here two datasets: (1) a deforestation-corrected SRTM DEM for the interfluve between the Purus and Madeira rivers, in central Amazonia, which passed through a careful identification of different environments and has deforestation features corrected by a new method of increasing pixel values of the DEM; and (2) a set of eighteen hydrological-topographic descriptors based on the corrected SRTM DEM. The hydrological-topographic description was generated by the Height Above the Nearest Drainage (HAND) algorithm, which normalizes the terrain elevation (a.s.l.) by the elevation of the nearest hydrologically connected drainage. The validation of the HAND dataset was done by in situ hydrological description of 110 km of walking trails also available in this dataset. The new SRTM DEM expands the applicability of SRTM data for landscape modelling; and the datasets of hydrological features based on topographic modelling is undoubtedly appropriate for ecological modelling and an important contribution for environmental mapping of Amazonia. The deforestation-corrected SRTM DEM is available at http://ppbio.inpa.gov.br/knb/metacat/naman.318.3/ppbio; the polygons selected for deforestation correction are available at http://ppbio.inpa.gov.br/knb/metacat/naman.317.3/ppbio; the set of hydrological-topographic descriptors is available at http://ppbio.inpa.gov.br/knb/metacat/naman.544.2/ppbio; and the environmental description of access trails is available at http://ppbio.inpa.gov.br/knb/metacat/naman.541.2/ppbio.

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1 Introduction

Environmental mapping in the 6 000 000 km^2 of the Amazon basin remains one of the major challenges in tropical research, since remote forests lack of reliable environmental datasets at scales that allow detailed studies due to difficulties to access, monitor and collect information. The apparent homogeneity of the forest canopy as seen from above comprises a mosaic of different environments, which detection can be done by the ongoing use of remote sensing data and geographic information system (GIS) metrics as descriptors for environmental variation in those remote areas. Among the descriptors, digital elevation models (DEMs) have shown to be a reliable data source for terrain description in Amazonia because terrain features derived from DEMs can be strongly correlated with soil properties (Daws et al., 2002; Pélissier et al., 2002; Luizão et al., 2004) and hydrology (Rennó et al., 2008; Nobre et al., 2011). Global elevation data at high spatial resolution (approximately 90 m) became easily available after the launch of the Shuttle Radar Topographic Mission (SRTM) in the year 2000. Since then, the SRTM-DEM has been widely used to map and classify environments in Amazonia (Salovaara et al., 2005; Valeriano et al., 2006; Bispo et al., 2009; Valeriano and Rossetti, 2010).

In dense tropical forests, the topographic detail provided by SRTM should be interpreted carefully because the C-band radar used to obtain the DEM interacts in a complex way with the dense forest canopy (Kellndorfer et al., 2004). Over Amazonian forests, the SRTM DEM should therefore be considered as a digital surface model, rather than an elevation model, resulting in a reduced detectability of important terrain features hidden by the dense canopy (Valeriano et al., 2012). An innovative method to extract hydrological features under the dense forests canopy was proposed by Rennó et al. (2008). The authors developed the Height Above the Nearest Drainage (HAND) algorithm which calculates a terrain descriptor that represent the vertical distance of each point of the terrain to the nearest drainage network. This terrain descriptor can be interpreted as the local drainage potential (Rennó et al., 2008; Nobre et al., 2011).

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The algorithm produces a new DEM where the values represent altitudes relative to the local drainages instead of the sea level. However, the applicability of the HAND approach for a large extent of Amazonia is hampered by the presence of deforested areas, where the original vegetation cover was either degraded or replaced by pasture and abandoned afterwards, converted in a mosaic of secondary forests with different regeneration ages. In practice, these areas are interpreted by HAND as depressions, generating false drainage channels and resulting in the misestimating of HAND values in areas around these channels.

In our dataset we provide a new SRTM DEM on which deforestation effects were corrected based on PRODES (Amazonian Deforestation Monitoring Project; INPE 2002) accumulated deforestation database. PRODES information was used to identify deforested areas in the original SRTM that could act as depressions to the HAND algorithm. We also present HAND grids using eighteen different drainage networks automatically extracted from the corrected DEM. The HAND algorithm was initially tested in topographically dissected areas in central Amazonia (Nobre et al., 2011), but also it proved to be useful in large flat areas (Moulatlet et al., 2014). The data set presented in this paper fills the lack of reliable data to be used as base for hydrological modelling for the interfluve between the Purus and Madeira rivers, two important tributaries of the Amazon River. This data set can also be broadly used for ecological modelling and is an important contribution for mapping Amazonian forests.

2 Data

2.1 Study site

The dataset covers a large area of dense tropical forests in Central Amazonia, delimited by the Purus river in the west, Madeira river in the east and Solimões river in the north (Fig. 1). The interfluve has flat terrains, with relatively low altitudes (27 m to 80 m a.s.l. on the corrected polygon-SRTM) and has seasonally imperfectly drained

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soils (Sombroek, 2000). Three geomorphologies are found: Alluvial Terraces, Mega-Slopes and Mega-Plateaus (IBGE, 1997), each of them with particular hydrological dynamics related to the soil type and proximity of the large rivers. Mega-plateaus and riverine terraces are subjected to flooding, caused by overflow of major tributaries of Amazon River, and by saturation of soil in the end of the rainy season (December–July), respectively. Mega-slopes are higher altitude and well-drained terrains. The main soil types are plinthosols on mega-plateaus and mega-slopes and fluvisols on alluvial terraces (Quesada et al., 2011).

2.2 Reducing deforestation features on the SRTM DEM

The deforestation-corrected SRTM DEM for the Purus–Madeira interfluve has the deforestation features (Fig. 2) replaced by non-deforested ones. The correction process consists in raising pixels values of the SRTM DEM at pre-selected areas and further evaluation of the results by the analysis of topographic profiles from non-deforested to the corrected areas (Fig. 1). The selection and delimitation of deforested areas were done by the use of the accumulated information available in the dataset of the PRODES project, which contains deforestation information collected by intense monitoring of Amazonia since 1988. This information is especially useful for the Purus–Madeira interfluve, where the identification of deforested areas is not obvious. After abandonment, deforested areas may become secondary forests at different regeneration levels, making the identification of these areas complex in the mosaic of forest types found on the interfluve between Purus and Madeira rivers. PRODES data is acquired from Landsat/CBERS imagery with a spatial resolution of 30 m.

The deforestation correction was done using the program DEM_CORR (Rennó 2009) implemented in IDL/ENVI, which provides tools to add or subtract elevation values of each pixel of the SRTM DEM. The criterion for adding values to the pixels is based on the height of the surrounding primary forests by the definition of elevation profiles. As a result, each pixel in deforested areas is assigned a new elevation, recovering the supposed original forest coverage. The original coverage of the patches

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of vegetation in variable regeneration stages was much more challenging to restore by our correction method than areas where forest was cut at ground level, since the variation of the pixels values on these large regenerating patches is higher.

The deforestation-corrected SRTM DEM product has a spatial resolution of 3 arcsec (approximately 90 m close to Ecuador), measuring 7200 columns by 6000 rows, and is available in geoTIFF format. The polygon including corrected areas (61°71′ W, 05°09′ S) is available in shapefile format. Areas outside the limits of the polygon were not corrected.

2.3 Drainage network extraction and hydrological modelling

The main aim of the correction in the SRTM DEM is to avoid the identification of false drainage channels by the HAND algorithm, caused by deforestation features (Fig. 2). Drainage extraction is a process dependent of the preceding determination of flow directions in a DEM, given that topographic features drive the directions of water flow on the terrain. Flow direction in a landscape is defined by the elevation difference between one point of the terrain and the nearest point in the drainage to which the focal point is hydrologically connected. The first stage of the drainage extraction is the definition of the local flow directions and the determination of the accumulated area, automatically extracted by computational procedures. Extractions made here followed the protocol described in Rennó et al. (2008). The following step is the definition of the contributing area threshold which indicates the number of contributing pixels necessary to initiate one drainage channel. The higher the threshold value is, the lower is the density of the drainage network. We selected eighteen thresholds (10, 20, 30, 40, 50, 100, 150, 200, 250, 300, 350, 400, 500, 600, 700, 800, 900, 1000) that provided different densities of drainage networks. Then, for each of the eighteen drainage networks we calculated the vertical distance to the nearest drainage by the HAND algorithm, which resulted in eighteen HAND grids for the study area.

HAND normalizes pixel altitudinal values by changing their reference from sea level to the nearest drainage. This is the hydrologically connected nearest drainage, not nec-

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essarily the lower one with the lowest Euclidian distance. As a result, local drainages will have an elevation of zero meters, independent of their elevation a.s.l.. The pixels in the neighbourhood will be assigned new values according to the nearest drainage. HAND values close to zero indicate areas where the water table is close to the surface (saturated areas) whereas high values indicate a deep water table (well-drained areas). HAND is a stationary measure and does not vary according to seasonal variation. It represents the local draining potential of the terrain independent of the season and rainfall variations. The HAND normalization reveals heterogeneous landscapes hidden in the SRTM DEM based on the draining potential of each pixel (Fig. 3). HAND has been used as hydrological descriptor because of its capability to describe hydrological environments based on the distance of each pixel of a DEM to the water table (Nobre et al., 2011; Gharari et al., 2011).

The eighteen selected thresholds allowed the extraction of eighteen HAND grids. The use of different thresholds in an attempt to comprise the variety of terrain types found in the Purus–Madeira interfluve, because different geomorphologies may be sensitive for specific drainage thresholds. Therefore, the set of thresholds allows the choice of the most suitable data for different types of studies and environments.

2.4 Ground truth data

We also provided field data obtained along more than 110 km of walking trails inside the forest that contain a qualitative description of the environments along the trails (Table 1). We described environments categorizing the soil drainage conditions approximately every 90 m and recorded the presence of all small streams, which are usually undetectable in the SRTM DEM. The classification was done between August of 2010 and February of 2011 and includes eight classes of hydrological environments, from well-drained to inundated areas. For each description point we recorded the geographical coordinates in order to provide information to validate the choice of drainage thresholds.

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3 Limitations of the data use

The dataset provided here offers an important hydrological contextualization of topographic data from a deforestation-corrected SRTM by the provision of eighteen hydrological models based on different drainage networks. It also allows for a local adjustment of the hydrological models through field data validation. However, the dataset should be used with precaution in some applications for four reasons. First, deforestation correction for large deforested patches is complex because of the high variation in elevation in these areas. An attempt for correction of deforestation features in extremely deforested conditions can be seen in Rennó et al. (2009). Second, drainages may be either overestimated or underestimated for some areas depending on the chosen threshold, since there are no available methods for using more than one threshold in the same HAND grid. Further study is needed to provide methods for combination of thresholds in the calculation of the hydrological models. The eighteen HANDs provided here are attempts to overcome this problem. Additional environmental descriptors, such as soil drainage conditions and water table monitoring data might also clarify the choice of the most suitable drainage network for specific areas. Third, large areas of the Purus–Madeira interfluve are subject to flooding by the larger rivers of the basin. Flooding is an important environmental characteristic not taken into account in our hydrological modelling. HAND represents the local draining potential of each pixel of the SRTM DEM but for flooded areas this potential may be misinterpreted. Fourth, the resolution of the input data determines the scale for the HAND application. In this case, the model cannot be used at very local scales, where a resolution below 90 m is required.

4 Dataset location and format

All the data and meta-data presented here are available at the permanent repository of data maintained by the Brazilian National Program of Research in Biodiversity (PPBio)

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(Pezzini et al., 2011) hosted at the National Institute for Amazonian Research (INPA), in Manaus, Brazil (http://ppbio.inpa.gov.br/repositorio/dados). The new SRTM DEM and the set of eighteen HAND images are available in geoTIFF format. The field description data is available as a table in csv format, the delimitation of areas corrected on the SRTM-DEM is available as a shapefile.

5 Data Provenance and Structure

We presented here the products of deforestation corrections over the SRTM DEM using PRODES datasets. The effects of deforestation were minimized and allowed the application of a more reliable DEM for terrain modelling. The dataset explicitly expresses the role of hydrology on the surface of the landscape. The deforestation-corrected SRTM DEM was already used in Martins et al. (2014) as framework for extraction of topographic indexes. Cintra et al. (2013) and Moulatlet et al. (2014) extracted point values from the HAND with threshold of 50 as proxies for local hydrological conditions to describe woody biomass production and understory herbs species distribution, respectively. The great applicability of the deforestation-corrected SRTM DEM and the HAND dataset is not restricted to ecological studies, but it also allows any environmental modelling. The environmental description of the hydrological conditions is useful information to plan ecological studies on the central Amazonia and especially important for validation of remote sensing products. The data has large applicability and helps to fill the gap of environmental data for Amazonia. An extension of this methodology for other areas in Amazonia in the future would be an important step in the mapping of Amazonian forests.

Author contribution. G. M. Moulatlet prepared the manuscript with contribution of all co-authors; G. M. Moulatlet, T. Emilio and J. Schietti collected the data; C. D. Rennó developed the algorithm code and ran the analyses; all the authors evaluated and validated the models.

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Table 1. Structure of the table describing the geographical coordinates of the main hydrological features along 110 km of walking trails in the research plots of the Brazilian Program of Biodiversity (PPBio) and adjacent trails placed along the Interfluve Purus–Madeira. The field name columns contain the information taken along the trails. The original table is available in a excel sheet csv format at (http://ppbio.inpa.gov.br/repositorio/dados).

Field name	Description
Site	Sites name of plots along the Interfluve Purus–Madeira (http://ppbio.inpa.gov.br/sitios/br319)
Latitude	Latitudinal coordinate format in decimal degrees
Longitude	Longitudinal coordinate format in decimal degrees
Main_Hydro	Main hydrological feature. Hydrological features are represented either by one water body, such as streams, flooding areas or by a soil drainage condition.

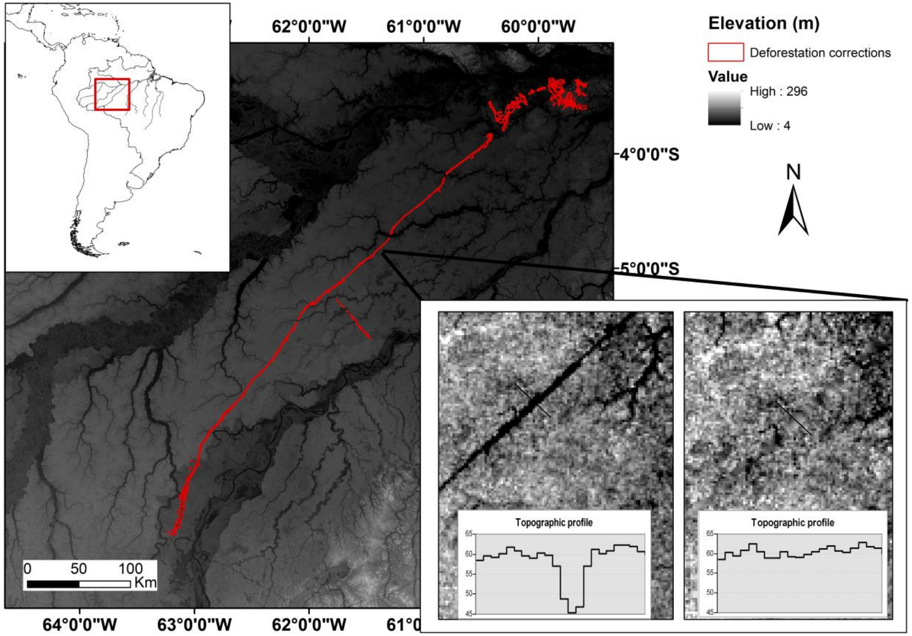

Figure 1. Study area. The gray scale represents the elevation values in meters from the SRTM-DEM data. The inner box shows the comparison between the original SRTM-DEM and the new SRTM-DEM with deforestation features corrected. Both topographic profiles are shown in the graphs. Red polygon indicates the areas where the deforestation correction was done.

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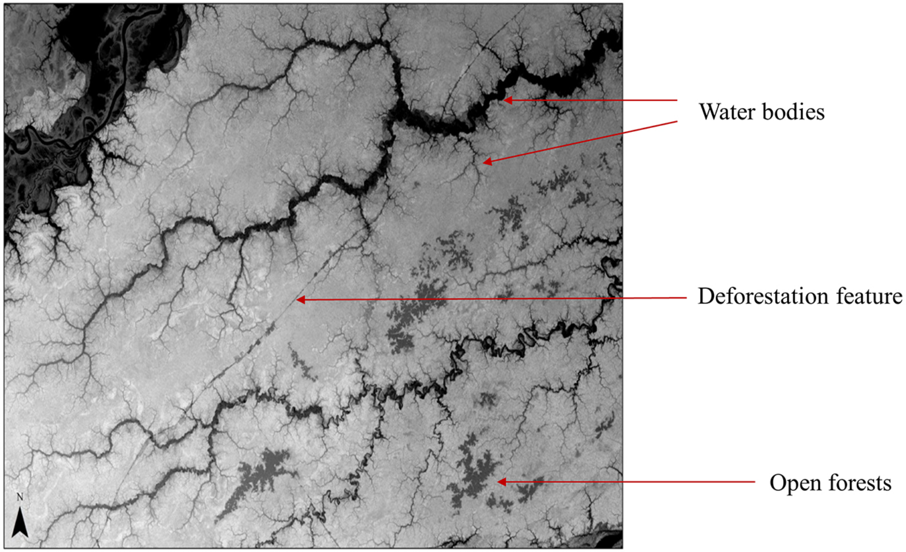

Figure 2. Arrows indicate three important terrain features for interpretation of the SRTM. The image shows that deforestation has the same gray color pattern than rivers and forests growing on podzolic soils.

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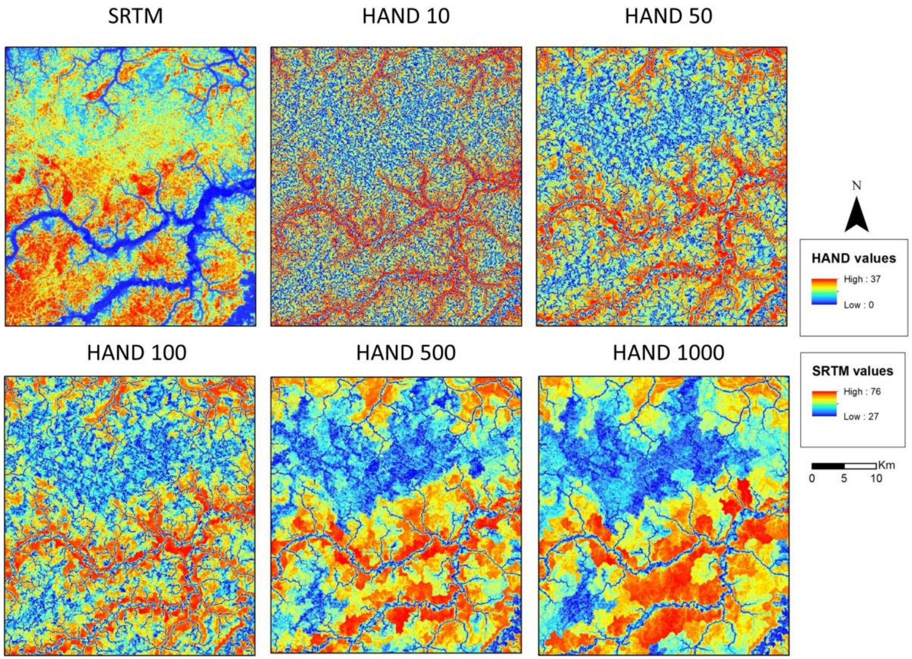

Figure 3. Comparisons among SRTM DEM and HAND DEM at five out of the eighteen drainage thresholds available. HAND values are indicators of the vertical distance of the terrain to the water table level and provide hydrological environments mapping, useful for ecological modeling over large extent areas. The thresholds (on the top of each HAND figure) were used during the application of the HAND method and indicate the density of the drainage network based on the number of pixels contributing to the drainage channel initiation (the higher the threshold the lower is the drainage density).

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