HAND, a new terrain descriptor using SRTM-DEM: Mapping terra-firme rainforest environments in Amazonia

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1. Introduction

Tropical terrain covered by rainforest presents rich mosaics of very distinctive environments, often hidden from remote view. The overwhelming challenge of describing 5.5 million km² of such environments and associated dense, tall and closed-canopy vegetation in Amazonia has made its complete inventory a seemingly impracticable task. Passive optical remote sensing imagery (such as Landsat and CBERS) can reveal spectral properties of forest canopy with detail (e.g. Wulder, 1998), but rarely allows for finding accurate correspondence of canopy features with soils and local hydrology. In Amazonia non-floodable swampy forests can not be easily distinguished from non-floodable terra-firme forests using just bidimensional spectral data. Accurate topographic data are required for the understanding of land surface processes at finer scales. Topographic detail has now become available with the Shuttle Radar Topographic Mission (SRTM) data. This new digital elevation model (DEM) shows the feature-rich relief of lowland rain forests, adding to the ability to map rain forest environments through many quantitative terrain descriptors. In this paper we report on the development of a new quantitative topographic algorithm, called HAND (Height Above the Nearest Drainage), based on SRTM-DEM data. We tested the HAND descriptor for a groundwater, topographic and vegetation dataset from central Amazonia. The application of the HAND descriptor in terrain classification revealed strong correlation between soil water conditions, like classes of water table depth, and topography. This correlation obeys the physical principle of soil draining potential, or relative vertical distance to drainage, which can be detected remotely through the topography of the vegetation canopy found in the SRTM-DEM data.

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data that allowed for the digital reconstruction of the surface relief, producing the DEM. The SRTM-DEM data, with a horizontal resolution of 30′ (~90 m near the equator) and a vertical resolution of 1 m, constitutes the finest resolution and most accurate topographic data available for most of the globe. Detailed information on the accuracy and performance of SRTM can be found in Rodriguez et al. (2006). In contrast to the passive optical imagery, this new DEM shows the feature-rich relief of lowland rain forests, adding to the ability to identify and map rain forest environments through many quantitative terrain descriptors.

A range of topographic algorithms are available, which allow various quantitative relief features to be obtained from the DEM. Slope and aspect (e.g. Jenson and Domingue, 1988), and drainage network and catchment area (e.g. Curkendall et al., 2003) are a few classical descriptors. A range of hydrological parameters such as superficial runoff trajectories, accumulated contributing area and groundwater related variables (e.g. Tarboton, 2003) add to the suite of relief descriptors. Relief shape parameters such as curvatures and form factors can also be calculated (Valeriano et al., 2006). The third dimension in a DEM, height, is obviously the key parameter, used to some degree in the derivation of all of the previously mentioned descriptors. Absolute height (above sea level — ASL) can be used on its own as a relief descriptor, as large scale geomorphologic features tend to be associated with altitude relevant geological control (Goudie, 2004). Upon flooding a given catchment for hydro dam development, for example, the height ASL is the descriptor that will predict the reach of the impoundment. However, when local environments in the fine scale relief are considered, height ASL has little, if any, descriptive power. As a result, local scale environments, although of conspicuous importance and clearly defined by characteristic terrain topography that is clearly visible on the SRTM-DEM, have not so far had a good descriptor.

In this paper we present the development of a new quantitative topographic algorithm based on SRTM-DEM data. We crafted and tested the terrain descriptor, applying it for a groundwater, topographic and vegetation dataset from central Amazonia, using ground calibrated terrain classes for mapping the study area.

2. Algorithm development

2.1. Conditioning procedures

The new descriptor algorithm requires a hydrologically coherent DEM as input, with resolved depressions (sinks), computed flow directions for each grid point and a defined drainage network. The procedures to develop these are presented below.

2.1.1. Fixing DEM topology and computing flow directions

Topography is a hydrologic driver since it defines the direction and speed of flows. Flow directions define hydrological relations between different points within a basin. Topological continuity for the flow directions is therefore necessary for a functional drainage to exist. Hydrological connections by flow direction between two points on a surface are not the same as those based on Euclidian distances. As seen in Fig. 1, point A is spatially closer to C, but it is hydrologically connected to point B because superficial water (runoff) will flow towards the latter.

The flow directions can be represented using different approaches (Zhou and Liu, 2002). For a DEM represented by a grid, the simplest and most widely used method for determining flow directions is designated D8 (eight flow directions) initially proposed by O’Callaghan and Mark (1984). In this method, the flow from each grid point is assigned to one of its eight neighbors, towards the steepest downward slope. The result is a grid called LDD (Local Drain Directions), whose values clearly represent the link to the downhill neighbor. A pit is defined as a point none of whose neighbors has a lower elevation. For a pit, the flow direction is undefined.

Defining G as a set of pairs of Cartesian coordinates of a grid with c columns and r rows,

$$G = \{(i,j)| i \in [1,c] \land j \in [1,r] \land N \},$$  (1)

we can represent LDD as a function that associates to each grid point (i,j) the flow direction LDD(i,j) which can assume a value according to its orientation: N, NE, E, SE, S, SW, W, NW or null. The null value is assigned to all points with undefined flow direction (pits).

The real hydrological meaning of the LDD depends on the quality of the DEM. The C Band interacts strongly with the vegetation with the result that the actual topography represented in the SRTM data is roughly that of the upper canopy (Valeriano et al., 2006). Therefore, for areas where the soil surface is covered by dense or tall vegetation it must be expected that a variable degree of relief masking occurs in the SRTM data (Kellndorfer et al., 2004), producing pits and extensive unresolved flat areas. Some of these features can be real properties of the relief, but often they represent artifacts in the data. SRTM data, perhaps because of radar speckle (noise) or vegetation effects, have more spurious points than other DEMs (Curkendall et al., 2003). Besides, forests have characteristic sylvigenetic dynamics with a relatively high occurrence of tree gaps (Oldeman, 1990), which will appear in the SRTM-DEM as depressions. Such depressions, if they occur on a stream, for example, create false interruptions in the topological continuity of that drainage (apparent impounding).

Another particular feature of SRTM data is related to abrupt transitions of vegetation types or land uses where vegetation is suddenly absent, revealing the soil surface in a patchy manner.

According to Lindsay and Creed (2005), the depression artifacts arising from underestimation of elevation should be filled and the features caused by elevation overestimation should be corrected by breaching. In general, filling methods involve raising the inner area of a depression to the elevation of its outlet point, defined as a point through which water could leave the depression. The outlet is usually
defined as the lowest point along the border of the depression basin. On the other hand, breaching methods create an artificial channel lowering some points across a divide in order to connect two neighboring depressions.

In this work, both sink and flat areas were eliminated by using a process similar to depression breaching suggested by O’Callaghan and Mark (1984), Band (1986) and Jenson and Domingue (1988). Although depression breaching can create strong anomalies at the edge of the artificial drainage channels, it produces the least amount of change on most of the remaining points of the DEM. Fig. 2 exemplifies the approach used in the DEM fixing process. The first step is to delimit the sink area (or closed basin) to be corrected based on the LDD obtained from the original DEM. Note that there are two sink areas in this example (52 and 50 elevation, the pits in darker hues). Next, the outlets of these sinks, generally falling on a saddle in the relief, are identified (here, 55 for the first pit). This outlet point will be the neighbor of the lowest point along the limits of the adjacent sink area (54). A topological trajectory passing through the outlet and connecting the two pits is then generated. Taking into account the distance between the two extremities, the new elevation of every point along this trajectory for cutting the hill or breaching is calculated by a linear interpolation. The result is a new functional flow path that eliminates one sink. Finally, a coherent new LDD is obtained based on this corrected DEM.

2.1.2. Computing drainage network

Many methods of automatic extraction of drainage networks from DEMs have been developed. Soille et al. (2003) grouped the drainage extraction algorithms into two classes, the first based on morphological features and the second on hydrological terrain characteristics.

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**Fig. 2.** DEM fixing process. Red arrows indicate flow directions changed during correction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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The contributing area of point \((i,j)\), defined as \(A(i,j)\), is computed through an iterative process.

Let \(A^t(i,j)\) be the contributing area of point \((i,j)\) in the \(t^{th}\) iteration. In the first iteration \(t=1\)

\[
A^1(i,j) = \begin{cases} 
1 & \text{if } (k,l) \in G \\
0 & \text{otherwise}
\end{cases}
\]

(5)

where \(G\) represents the set of all upward points connected to any given point, that is

\[
G = \{ (k,l) : \forall (i,j) : (i,j) \in N((k,l)) \}. \quad (6)
\]

In this first iteration, the contributing area of all points that initiate a flow path is equal to one.

For the other iterations \(t>1\)

\[
A^t(i,j) = \begin{cases} 
A^{t-1}(i,j) & \text{if } A^{t-1}(i,j)>0 \\
1 + \sum_{(k,l) : (k,l) \in G \wedge (k,l) \neq (i,j)} A^{t-1}(k,l) & \text{if } A^{t-1}(i,j)=0 \\
0 & \text{otherwise}
\end{cases}
\]

(7)

where \(F^{-1}(i,j)\) represents a set of all neighbors of point \((i,j)\) that flow to it, that is

\[
F^{-1}(i,j) = \{ (k,l) : (k,l) \in N((i,j)) \}
\]

(8)

The iteration process stops \((t=n)\) when, for any point \((i,j)\), \(A^{n+1}(i,j)=0\), that is, \(A(i,j) = A^n(i,j)\).

The method based on the contributing area is very easy to implement and therefore widely used. Tarboton (2003) pointed out that a significant question with this method is the choice of contributing area threshold. The basic hypothesis is that channel heads, where there is a transition from convex to concave profiles, is also where concentrated fluxes begins to dominate over diffusive fluxes (Tarboton et al., 1991, 1992). Some authors have called for objective criteria to define channel heads, such as the relationship between slope and contributing area (Tarboton et al., 1991). Others use local curvatures to account for spatially variable drainage densities (Tarboton and Ames, 2001). Montgomery and Foufoula-Georgiou (1993) compared the constant contributing area with the slope-dependent contributing area. Although these approaches represent progress towards the automatic determination of channel heads, the tests we conducted for Central Amazonia showed that the application of these methodologies to SRTM data did not estimate drainage density properly. We suspect that vegetation masking ground topography may be the explanation. For this reason, we decided to use the contributing area threshold as one of the main criteria to define the drainage network, validating channel heads with field data. To define the channel heads we used an additional criteria based on simplifications of horizontal and vertical geomorphic curvatures.

Firstly, the channel head element should represent a convergent point, meaning it should have two or more overland flux paths converging to it (horizontal curvature). Secondly, the channel profile should be concave, i.e., where the channel head profile point has a smaller change of elevation than the mean of the elements located uphill and downhill of it (vertical curvature).

2.2. The height above the nearest drainage terrain descriptor

To quantify relevant parameters that could uniquely identify generalizable spatial properties of hill slopes there was the need to have a local frame of variable topographic reference that should be more useful than the all encompassing and generic height ASL, or the third dimension in the DEM. Horizontal distances of DEM grid points to connected drainage channels (slope length) have been computed by a number of approaches (e.g., Tucker et al., 2001). As the initial interest in this study was to predict potential hydrological properties for each DEM grid point, especially the depth to the permanently saturated zone, this approach wasn’t useful. The gravitational potential energy difference between any given grid point and the other extremity of the hill slope flow path, at the functional stream outlet (explicit in the LDD), defines a unique and permanent property of that grid point that we call draining potential. The vertical distance of a given grid point to its drainage outlet (which is hydrologically important) can in most cases be expressed as a relative height, or the height difference between those points. Thus there will be no gravitationally driven water movement between two hydrologically connected points that share the same height. Classifying all grid points according to their respective draining potentials allows them to be grouped into classes of equipotential (equivalent draining gravitational potential), defining environments or zones with inferred similar hydrological properties. The linking of every grid point to its outlet on the drainage system allows for the whole DEM to be normalized for the drainage network (adjusting point heights in relation to the drainage), which in this way becomes a distributed frame of topographic reference.

If \(D\) is a set of drainage network points, identified by a number through a bijective function in order that each point of the drainage...
network be identified by a unique identification number \(i \in \mathbb{N}^7\). We define that

\[
D(i,j) = \begin{cases} 
\lambda & \text{if } (i,j) \text{ is a drainage network point} \\
0 & \text{otherwise}
\end{cases}
\] (9)

and its inverse function as

\[
D^{-1}(\lambda) = \{(i,j) \in G | D(i,j) = \lambda\}. 
\] (10)

Following respective flow paths, each and every point in the grid is necessarily connected to a drainage point. Let \(I(i,j)\) be the function that identifies the drainage point connected to the point \((i,j)\). This function is computed through an iterative process and the result is a grid that associates the identification number of the drainage point that each point is connected to. If \(F(i,j)\) is the drainage identification number of the point \((i,j)\) in the \(t^{th}\) iteration. In the first iteration \((t=1)\),

\[
P(i,j) = D(i,j).
\] (11)

For the other iterations \((t>1)\)

\[
P'(i,j) = \begin{cases} 
P^{-1}(i,j) & \text{if } P^{-1}(i,j) \neq 0 \\
P^{-1}(F(i,j)) & \text{if } P^{-1}(F(i,j)) \neq 0 \\
0 & \text{otherwise} \end{cases}
\] (12)

The iteration process stops \((t=m)\) when, for any point \((i,j)\), \(F(i,j) \neq 0\), that is,

\[
I(i,j) = P^m(i,j). \] (13)

Assuming that all points belong to a flow path and that all flow paths are associated to respective drainage points, we define the HAND value of any given point \((i,j)\) as

\[
\text{HAND}(i,j) = \begin{cases} 
H(i,j) - H_0(i,j) & \text{if } H_0(i,j) < H(i,j) \\
0 & \text{otherwise} \end{cases}
\] (14)

where \(H(i,j)\) represents the height of the point \((i,j)\) given by the original DEM and \(H_0(i,j)\) is the height of drainage point hydrologically connected to point \((i,j)\) following the flow path, that is,

\[
H_0(i,j) = H(D^{-1}(I(i,j))). \] (15)

It is important to note that if the point \(i,j\) is a point belonging to the drainage, then

\[
I(i,j) = D(i,j) \] (16)

\[
D^{-1}(I(i,j)) = (i,j) \] (17)

\[
H_0(i,j) = H((i,j)) \] (18)

and so

\[
\text{HAND}(i,j) = H((i,j)) - H((i,j)) = 0. \] (19)

In other words, all grid points belonging to the drainage network are zeroed in height, which implies that the draining potential (according with the HAND definition) along the stream channel is disregarded. Although the drainage channel is also a flow path, which effectively drains, the HAND descriptor uses the whole channel as a flat relative topographic reference, the end of all non channel flow paths. By definition, the HAND drainage outlet grid point is the nearest draining point to itself, therefore it can only be subtracted from itself.

It is important to note that the breaching process, required to reach a topologically sound and accurate drainage network, introduces occasional canyon like artifacts into the DEM, as a result of aberrant height differences adjacent to the drainage network. These artifacts would be transferred to the HAND grid if it were computed from the corrected DEM. When using original SRTM data for the HAND grid computation, some associations prescribed by the corrected drainage connection grid result in small negative differences that could be interpreted as points
below their associated drainage points (impoundment). Considering the 1 m elevation accuracy of the SRTM and the disturbances caused by the forest canopy, these small negative differences fell within the noise in the data, and were zeroed. Therefore, in the HAND algorithm we combined the more meaningful need to reach a topologically coherent LDD (requiring the topological correction of the DEM, leading to an accurate drainage network), with the use of the original non-corrected DEM (which has dispersed sinks) for the computation of the final HAND grid, thus avoiding the canyon aberrations associated with the corrected DEM.

Fig. 3 shows an example of the HAND procedure. Based on a LDD grid, overlaid with the computed drainage network, all flow paths are coded according to the nearest associated drainage point. The marked point with height 72 in the DEM is connected to the drainage point with height 53 (both coded 2), resulting in a HAND of 19. This means that the marked grid point is 19 m above its corresponding drainage point. Fig. 4 summarizes all operations involved in obtaining the HAND grid.

3. Application

3.1. Study area

Data from a 37 km square study area located in the Cuieiras Biological Reservation (central Amazonia NW of Manaus, Fig. 6), was used to test the new HAND terrain descriptor. The area, representative of large areas in Amazonia and including the K34 LBA flux tower site (Araujo et al., 2002) and the Asu hydrological catchment (Waterloo et al., 2006; Tomasella et al., 2007; Cuartas et al., 2007), is covered by pristine, terra-firme (terrain not subject to flooding by the annual flood cycle of the Amazon and its major tributaries) rain forest vegetation, with the canopy height varying from 20 m to 35 m. Forest biomass in the vicinities is highly heterogeneous and has been reported ranging from 215 to 492 ton/ha (Laurance et al., 1999; Castilho, 2004). Details about the wet equatorial seasonal climate (annual rainfall larger than 2000 mm) can be found in Araujo et al. (2002) and Cuartas et al. (2007). The landscape in and around the Asu catchment (Fig. 5), is composed mostly of flat plateaus (90–105 m ASL) incised by a dense drainage network within broad swampy valleys (45–55 m ASL).

Ground truth data were collected in various field campaigns. A total of 120 points were visited in the Asu catchment for testing the HAND application. These points fell along a hydrological transect (site C1), across two 1st order sub catchments, and along two 2.5 km-long N–S and E–W orthogonal transects, crossing the catchment edge-to-edge. Field positions of streams and stream heads were also logged for verification of the calculated drainage network. Points beneath the forest canopy were located in the field using accurate geo positioning (obtained with a 30 m horizontal accuracy) in conjunction with
vegetation and soil pattern evaluation, aided by subsurface water table depth data (multiyear time series, logged by an irregular sampling network of 27 piezometers installed in valleys, major stream heads, and along a hillslope hydrological transect). Hydrological details about the Asu instrumented catchment can be found in Tomasella et al. (2007). Non-floodable local environments were clearly identified in the field through topography, vegetation, soils and hydrological cues.

3.2. Results

The SRTM data for the study area were corrected in order to produce the hydrologically coherent LDD. Using this corrected LDD, the contributing area grid was computed and with it the drainage network was derived, using a selected contributing area threshold. The HAND grid was then obtained using this drainage as reference. The results of these steps are presented below.

3.2.1. Drainage network sensitivity

Drainage density is an important parameter for the accuracy of the HAND descriptor. Fig. 6 shows networks extracted from the SRTM data using three different contributing area thresholds. For the HAND descriptor, the contributing area is the tunable parameter. Note that the lower the threshold, the higher the density of the resulting drainage network. Automatic extraction of the drainage network from a DEM still lacks competence to represent channel heads realistically and with robustness, which requires field verification for an appropriated representation of drainage density. The ground truth for channel heads carried out in this study indicated that the contributing area threshold of 50 grid points produces the most accurate drainage network density.

From an exploratory analysis of the relationship between drainage density and contributing area threshold, we found that varying thresholds within the range of 47 through 92 did not change channel hierarchy at a verification point in a 3rd order stream. Smaller or larger thresholds produced higher or lower orders respectively. Fig. 7 shows the impact of these three contributing area thresholds (47, 50 and 92), plus two chosen extreme points (5 and 500) on the HAND grid distribution of heights. The skewness in the HAND distribution of heights is directly proportional to the smoothness of the HAND grid. Higher frequencies of the small HAND values, for example, result in a smoother topography of the HAND grid, which implies a lower ability to distinguish and resolve contrasting local environments. If the calculated drainage network remains within the range that realistically captures the order hierarchy.
of the drainage network, then the effect of slightly varying channel heads on the HAND grid (and therefore on other estimations based on it), will not be significantly great. In a forthcoming paper we report this to be a robust result, verified for a wider area around the Asu catchment. But for other areas with distinct geomorphologies this finding still needs verification.

3.2.2. The HAND grid DEM

Fig. 8 shows a HAND grid shaded relief of the test area. Altimetric differences along the drainage channels are no longer visible as they were in the original DEM (Fig. 5b). The capacity of the HAND descriptor to make evident locally significant terrain-controlling factors is apparent.
The main difference between the original SRTM-DEM and the HAND grid DEM (Fig. 9) lies in the effect of the topographic normalization for the drainage network. In fact, the HAND grid converts into absolute the relative nature of the distributed frame of topographic reference in the drainage network. Thus, although the HAND grid loses the height reference to sea level, it enhances meaningful local relative variations in height. This local relevance is especially useful because height differences now found in the HAND grid have hydrological significance, and can potentially reveal previously hidden local environments.

### 3.2.3. Mapping local environments

The HAND algorithm can be applied to the SRTM-DEM of any terrain, producing HAND grid DEMs with implicit geomorphologic and hydrological meaning. However, the significance in practical applications is provided by finding HAND classes (ranges of heights) that match with relevant soil water and land cover characteristics. For this application, the most detailed field data was produced along the hydrological transect (Fig. 10), running orthogonally from the top of the K34 fluxtower plateau to the 2nd order Asu stream (Hodnett et al., in preparation). This transect encompassed and represented all topographic features for the area, containing measurement and sampling points for soil water, vegetation, soil and topographic ground truth verification.

The vertical cross-section of the hydrological transect (Fig. 10a), reveals the relation of the HAND grid profile with the surveyed ground topography and water table data. Note the convergence of the water table with the topography in the lowland, towards the stream. Note also that the HAND grid profile hovers above the ground topography by the distance of the forest vegetation height (the C-band radar data from the SRTM interacted strongly with the forest canopy). Local environments and their relative extents were defined by matching ground truth of vegetation and topography with groundwater data. These environments were easily recognized in the field by pattern observation, and were classified as waterlogged (considering only the zone where soil is perennially saturated to the surface), ecotone (shallow water table, usually covered by Campinarana - sensu, Anderson et al., 1975) or upland.

![Fig. 9. Profile comparing original SRTM data and the HAND grid normalized for the drainage network.](image1)

![Fig. 10. a) Cross-section of the Igarapé Asu hydrological hillslope transect (from A to A’) with HAND grid profile superimposed on ground topography and water table data. b) Overlay of ground truth points onto SRTM-based HAND grid DEM (grayscale, with top contour lines in red) along the hillslope hydrological transect (from A to A’).](image2)

(deep water table). The last category was arbitrarily split into slope (upland with slope > 3°) and plateau (flat upland).

The overlaying of the ground truth points onto the HAND grid (Fig. 10b) suggests a coherent matching between local environments identified in the field and corroborated by groundwater data, with drainage-normalized canopy-topography represented by the HAND grid. This coherence suggests that local environments can be associated with height classes in the HAND grid. An exploratory quantitative analysis matching the distribution of ground truth points in the Asu catchment with respective heights in the HAND grid (Fig. 11) suggests a compelling separation of HAND classes, especially between waterlogged, ecotone and upland environments.

Taking these into account, HAND grid values of 5 m and 15 m were selected as preliminary best-guess thresholds between the three classes. To optimize this separation (lessen errors on class inclusion) we applied the simplex algorithm (Cormen et al., 2001), finding 5.3 m and 15.0 m as the best thresholds between classes for the set of ground truth points available.

The upland class, in comparison to the other two lowland classes, represented well and in a relatively homogeneous way a single soil
water condition (well drained soil, deep water table). However there are many distinct substrate effects in the definition of an environment on a slope compared to one on a plateau. The waterlogged and plateau classes are quite well defined in that they share low slope angles, and are well separated from ecotone and slope. This analysis reveals that the HAND height is a good separator between the three soil water relevant classes. It also shows that, in the case of the Igarapé Asu catchment — with its fairly uniform plateau heights, it can also separate the upland class into slope and plateau. However, for other catchments with plateaus at variable HAND heights, it might not score so well. Slope angle, on the other hand, can be used to identify flat surfaces independently of HAND height. However the HAND height can still be useful to set aside plateaus from flat alluvial terrain in the valley bottoms. As both slope and aspect are terrain descriptors that do not require field verification, slope will be a better separator when applied exclusively for the upland class. The upland class (HAND > 15.0 m) was then split on the basis of slope, with the initial threshold value arbitrarily selected at 6.5% slope, and then optimized with the simplex algorithm to 7.6% (Fig. 12).

The ground truth survey was accurate in identifying the local environment for each chosen point, and as a result, for most points, the matching between field environments with HAND predicted environments was exceptionally good. Nevertheless, unavoidable localization errors were responsible for a few mismatches, which happened only to the extreme values. Area estimation indicates that the distinctive waterlogged plus ecotone environments (valley bottoms) occupied 43% of the surface, whereas slope and plateau occupied only 26% and 31% respectively (Fig. 13). The two valley bottom classes have been widely considered as a minor proportion of the landscape and as a result have been largely disregarded by most integrative studies of terra-firme. The HAND descriptor clearly and quantitatively reveals that the valley bottom classes are very important in this landscape. The HAND class test carried out in this study might suffer from some site specific bias, but as it uses site-independent gravitational potential as the main driver for its description of terrain, we expect that it will show robustness when applied in the Amazon outside the test area, and even anywhere else with a similar terrain covered by thick forests with a relatively uniform canopy height across the landscape.

4. Discussion

Topography in the SRTM shaded relief image is plainly discernible to the trained eye. When the computed drainage network is plotted on the SRTM image of a rainforest area, hidden local environments, such as riparian zones, appear to pop up out of the continuous canopy carpet. However this perception reveals an imaginary presence, which at best represents only a qualitative indication. An objective and quantitative descriptor of these hidden environments was lacking. Pure hypsometry, as that in the shaded relief, does not offer much. A given valley area at 200 m ASL, for example, might have a similar environment to another valley area at 650 m ASL, the latter lying kilometers upstream. Conversely, at 200 m ASL one can find a range of different local environments. Geographic Information System (GIS) buffer zoning is a common tool used for delineating local environments, most often in association with streams and other superficial waters or distinctive landscape features. Buffer analysis to define areas of riparian influence creates a zone of predefined width around the drainage, usually based on simple Euclidean distance (Burrough and McDonnell, 1998). However, without functional variables driving the buffer zoning process, geometric distances present little topographic, pedological and hydrological meaning or consistency. The uncertainty in this local environment delineation is especially troublesome for tropical rain forests (Bren, 2000; McGlynn and Seibert, 2003). The widely variable zone of floodable forests in Amazonia (Hess et al., 2003), for example, suggests that it would be grossly misrepresented if a simple geometric GIS buffer were applied. Therefore, geometric buffering zones also fail to provide a local environment descriptor, as the spatial extents of these perceived environments are highly irregular, and do not have extractable geometries that would correlate with the drainage network or other emergent feature in any easy way. Topographic patterns associated with contrasting environments, which are very evident from within the rain forest, needed to be rendered in quantitative manner.

Fig. 14. Comparison between the HAND (vertical distance do the nearest drainage) and horizontal distance to the nearest drainage (along water flow path) values, according to algorithm proposed by Tucker et al. (2001).

A porous medium (soil) presents a fine and interconnected network of void spaces and channels through which water can flow, following gradients of potential energy, always seeking equilibrium in the condition of least energy. This is a fundamental hydraulic principle. Flow routes from any given point on the terrain, or hill slope flow paths (overland or groundwater in the saturated zone), will seek trajectories of least resistance and will be propelled by gradients of gravitational energy (neglecting both matric and osmotic potentials for a saturated soil or for overland flow). These hill slope flow paths will invariably end somewhere on the drainage network, with the principle of least energy requiring a discharge into the nearest stream. Therefore, for each grid point in the SRTM-DEM, there must be a unique and topologically consistent flow path connecting it with its stream outlet. These connecting flow paths
bear all topological components, extractable from the SRTM-DEM, which allowed for the development of the new HAND terrain descriptor. The results of the test of the HAND descriptor reported here demonstrate its capacity to resolve meaningfully the delineation of local environments.

There are a host of generic terrain descriptors, e.g. topographic indexes, which could be compared to the HAND, but an exhaustive comparison is beyond the aim of the present work. The closest descriptor to the vertical distance along a flow path is the non-Euclidian horizontal distance along the same flow path (Tucker et al., 2001). To test the similarity between the two descriptors, 1000 independent points (pixels) were randomly drawn from the test area SRTM-DEM. According to the linear regression, the horizontal distance can only explain 55% of the total variance that can be explained by the HAND (Fig. 14).

There is an obvious relation between horizontal and vertical distances because it is expected that as one moves away from the drainage, the terrain will get higher. However, the other 45% of the variance is new information that only the HAND descriptor can give. Points with large horizontal distances but low HAND are indicative of great flat areas connected to the drainage (swampy areas). The innate swampy characteristic of these terrains, for example, would never be seen with horizontal distances alone. With a large HAND value (vertical flow path distance) and a small horizontal flow path distance, the terrain is quickly rising away from the stream, i.e. a well etched drainage valley. But, although the HAND has this evident advantage, the horizontal flow path distance is a great advance over plain Euclidian distances, because the latter may connect and relate points on the terrain that do not belong to the same catchment. Furthermore, horizontal flow path distances to the nearest drainage might have a bearing in terms of span of time spent in draining flows, determined by hydraulic conductivity and slope along the flow path. Height above the nearest drainage correlates directly with gravitational potential, and this fact alone sets this descriptor aside as unique.

5. Conclusions

The height above the nearest drainage algorithm was developed on top of the local drain directions and drainage networks, two well established and basic topographic descriptors. The HAND has added the height difference along flow paths, or draining potential, as a significant and unique terrain descriptor. The HAND terrain descriptor produces a normalized digital elevation model (HAND grid) that can be applied to classify terrain in a manner that is related to local soil water conditions. The HAND grid, a DEM all pixels have been mapped according to their draining potential, has a wide range of potential applications. The application of the HAND descriptor in classifying the terrain within a monitored hydrological catchment in Amazonia revealed strong correlations between soil water conditions, like classes of water table depth, and topography. This correlation obeys the physical principle of soil draining potential, or relative vertical distance to drainage, which can be detected remotely through the topography of the vegetation canopy found in the SRTM-DEM data. To our knowledge no previous study has noticed or reported the height above the nearest drainage as likely being a good terrain descriptor. It increases usability of the SRTM-DEM data and provides a new quantitative view on the steady state landscape, one that was missing in the repertoire of terrain descriptors.

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