Remote Sensing of Environment 112 (2008) 3469–3481

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

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

Camilo Daleles Rennó [a,*], Antonio Donato Nobre [b], Luz Adriana Cuartas [a], João Vianei Soares [a], Martin G. Hodnett [c], Javier Tomasella [a,b], Maarten J. Waterloo [c]

[a] Instituto Nacional de Pesquisas Espaciais, Av. Astronautas, 1758, São José dos Campos, SP, 12227-010, Brazil
[b] Instituto Nacional de Pesquisas da Amazonia, Escritório Regional do INPA, INPE Sigma, Av. dos Astronautas, 1758, São José dos Campos, SP, 12227-010, Brazil
[c] Vrije Universiteit Amsterdam, De Boelelaan 1105, 1081 HV Amsterdam, The Netherlands

ARTICLE INFO

Article history:
Received 29 May 2007
Received in revised form 24 March 2008
Accepted 29 March 2008

ABSTRACT

Optical imagery can reveal spectral properties of forest canopy, which rarely allows for finding accurate correspondence of canopy features with soils and 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.

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 km^2 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 even seasonally flooded tropical forests could not be easily spotted and distinguished from non-floodable terra-firme forests using this type of data (Novo et al., 1997). The usually flat optical imagery can hint at relief through either bright or shadow reflection artifacts on the slope pixels of steeper areas, or where spectral signatures of the vegetation are distinctive because of local environmental effects (Guyot et al., 1989; Novo et al., 1997; Nobre et al., 1998), but without stereo images it lacks the ability to describe relief quantitatively. Optical stereo images (e.g. obtained from ASTER or SPOT) can be used to produce digital elevation models (DEM). However, the cost and difficulty of obtaining cloud-free coverage for many areas of the world, compounded with the requirement of sun angles below 25° (from Nadir) to avoid long shadows (Jacobsen, 2003), has limited the possibilities for producing DEMs of large, continuous areas (Hirano et al., 2003). In addition, because ground truth accessibility to large areas is limited, many aspects of landscape complexity in those vast tropical surfaces remain shrouded in mystery.

However, some of these drawbacks are quickly being overcome with imagery from active space borne sensors, such as synthetic aperture radars (SAR). Canopy penetrating L-Band SAR imagery from the Japanese Earth Resources Satellite (Siqueira et al., 2000) revealed with unprecedented detail patches of flooded vegetation (Barbosa et al., 2000; Melack and Hess, 2004). Careful mapping of such previously hidden seasonally flooded biomes has suggested their occurrence over a far wider area than formerly believed (Siqueira et al., 2003; Hess et al., 2003). Accurate topographic data are required for the understanding of land surface processes at finer scales. Topographic detail has now become available on a global scale through the C-Band SAR imagery (van Zyl, 2001) of the Shuttle Radar Topographic Mission (SRTM). The spaceborne SRTM circled the globe over a wide swath covering all the tropics and more, generating radar

* Corresponding author. Tel.: +55 12 39456521; fax: +55 12 39456468.
E-mail address: camilo@dpi.inpe.br (C.D. Rennó).

0034-4257/$ – see front matter © 2008 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2008.03.018

data that allowed for the digital reconstruction of the surface relief, producing the DEM. The SRTM-DEM data, with a horizontal resolution of 3" (~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,

$$G = \{\langle i,j \rangle | i = [1,c] \subset N, j = [1,r] \subset N\}, \quad (1)$$

we can represent LDD as a function that associates to each grid point $\langle i,j \rangle$ the flow direction LDD($\langle i,j \rangle$) 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

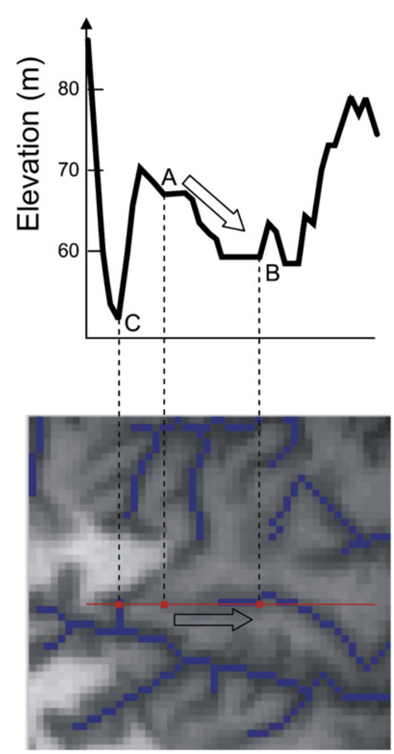

Fig. 1. Hydrological connection between points A and B. Red line indicates the profile shown above, blue lines represent the drainage network and the arrows indicate flow direction. B and C are points on streams. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)