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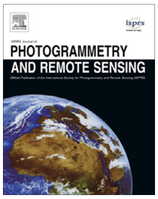

Remotely sensed biomass over steep slopes: An evaluation among successional stands of the Atlantic Forest, Brazil

Jomar Magalhães Barbosa[a,*], Ignacio Melendez-Pastor[b], Jose Navarro-Pedreño[b], Marisa Dantas Bitencourt[a]

[a] Department of Ecology, Institute of Biosciences, University of São Paulo, Brazil
[b] Department of Agrochemistry and Environment, University Miguel Hernández of Elche, Spain

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ABSTRACT

Remotely sensed images have been widely used to model biomass and carbon content on large spatial scales. Nevertheless, modeling biomass using remotely sensed data from steep slopes is still poorly understood. We investigated how topographical features affect biomass estimation using remotely sensed data and how such estimates can be used in the characterization of successional stands in the Atlantic Rainforest in southeastern Brazil. We estimated forest biomass using a modeling approach that included the use of both satellite data (LANDSAT) and topographic features derived from a digital elevation model (TOPODATA). Biomass estimations exhibited low error predictions (Adj. $R^2 = 0.67$ and RMSE = 35 Mg/ha) when combining satellite data with a secondary geomorphometric variable, the illumination factor, which is based on hill shading patterns. This improved biomass prediction helped us to determine carbon stock in different forest successional stands. Our results provide an important source of modeling information about large-scale biomass in remaining forests over steep slopes.

1. Introduction

Defining the spatial distribution of forest biomass enables us to evaluate how forested areas respond to human impact (Tangki and Chappell, 2008; Asner et al., 2010) and environmental conditions (Saatchi et al., 2007; Asner et al., 2009). Forest biomass is important to the carbon cycle (IPCC, 2006, 2010) because the rates of deforestation and forest regrowth determine the dynamics between carbon sources and sinks from the atmosphere (Freedman et al., 2009; Eckert et al., 2011). In this context, aboveground biomass (AGB) estimated at landscape scale presents an attractive tool for use on the evaluation of how forested regions influence the atmospheric carbon balance (Lu, 2006; Tangki and Chappell, 2008; Anaya et al., 2009; Li et al., 2010; Hall et al., 2011; Hudak et al., 2012). Regional or global AGB estimations have been largely done using a combination of field and remotely sensed data. Despite increasing interest in AGB data, some forest types, such as the Brazilian Atlantic Forest (BAF), have few studies that model their biomass using remote sensing methods (Freitas et al., 2005).

The BAF is one of the largest biodiversity centers in the world (Myers et al., 2000; Dirzo and Raven, 2003). However, 86% of its original area was deforested, which represents a reduction of approximately 129 million ha of forest area (SOS Mata Atlântica/INPE, 2012). This deforestation process occurred within multiple economic cycles (Dean, 1996). Some researchers have reported the regrowth of secondary forests in the BAF (Baptista and Rudel, 2006; Baptista, 2008; Lira et al., 2012). Although these studies are restricted both spatially and by scale, this tendency for regrowth has been explained by agricultural displacement from the BAF to the Amazon region (Pfaff and Walker, 2010; Walker, 2012).

The difficulty accessing steeply sloped areas helped maintain the remaining Atlantic forest in Brazil (Munroe et al., 2007; Teixeira et al., 2009). Similar de facto access restriction occurs in numerous other tropical mountain forests (Southworth and Tucker, 2001). Surveying the biomass in these mountainous regions is laborious, expensive and time consuming (Lu, 2006). Some success has been reported with estimating the AGB of steep-slope areas using remote sensing methods (Soenen et al., 2010; Sun et al., 2002; He et al., 2012). However, the estimation error remains high due to the difficulty of minimizing satellite data distortion in areas with heterogeneous topography (Liu et al., 2008). The combined difficulties of field surveys and satellite data processing in mountainous regions create the need for alternative field survey

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* Corresponding author. Address: Rua do Matão, 101, travessa 14, 05508-900 São Paulo, SP, Brazil. Tel.: +55 1193383359; fax: +55 1130918096.

E-mail addresses: jomarmbarbosa@gmail.com (J.M. Barbosa), imelpas@gmail.com (I. Melendez-Pastor), jonavar@umh.es (J. Navarro-Pedreño), tencourt@usp.br (M.D. Bitencourt).

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strategies and new statistical approaches to modeling biomass (Soenen et al., 2010).

In this study, we investigated how topographical features affect biomass estimations from remotely sensed data using different modeling steps. We also evaluated the accuracy of the biomass estimations through forest successional stands. The topographic information was included on the modeling steps to analyze its influence on the biomass estimation. In addition, we compared the spatial pattern of the modeled biomass among the successional forest stands. The results provided both a straightforward framework and a novel method for determining forest biomass in steep slope regions.

2. Materials and methods

2.1. Study area

The study area is located in Vale do Ribeira at São Paulo State, southern Brazil (24°33′S and 48°39′W; Fig. 1). It covers approximately 15,000 ha and encompasses elevations from 100 m to 900 m, slopes ranging from 0° to 40°, and a full variety of terrain aspects. This area is a representative portion of the topographic characteristics of the largest remaining Brazilian Atlantic Forest. The climate is characterized by consistent rainfall throughout the year, with an average annual rainfall about 2000 mm and a mean annual temperature of over 21 °C. The vegetation consists of ombrophilous tropical forests, which have approximately 100–160 species per hectare (Tabarelli and Mantovani, 1999) and a complex biophysical structure (Guilherme et al., 2004; Marques et al., 2009). Steep slopes within the study area have reduced deforestation required for intensive land use practices (Teixeira et al., 2009). Historically, major forest disturbances occurred through the slash and burn agriculture system, which was practiced by small farmers (Adams, 2000; Peroni and Hanazaki, 2002). This historical land management formed forest mosaics that include primary and secondary forests in different stages of regrowth.

2.2. Vegetation field data

Vegetation field data were collected in November 2010. A first survey (S1) of 170 points was distributed inside 17 plots of 0.36 ha. This number and area of calibration plots (totaling 6.12 ha) is similar to previous biomass mapping of tropical forests (Cutler et al., 2012). For each plot, 10 non-overlapping sample points were randomly selected and surveyed via the point-centered quarter method (PCQ) (Cottam and Curtis, 1956). The center of each sample point was divided into four quadrants. Subsequently, the nearest tree with a diameter at breast height (DBH) of over 4.9 cm in each quadrant was selected, and its total height, DBH and distance to the sample point were measured, totaling 40 trees for each plot (Fig. 2). Distance and tree height measurements were taken with a laser distance meter (Leica DISTRO A5). The stand density at each plot (S) was calculated as follows:

$$S_i = 4/(d_1^2 + d_2^2 + d_3^2 + d_4^2) \quad (1)$$

$$S = \Sigma S_i/n \quad (2)$$

where S_i is a tree density estimate for the ith sampled point; d_1, d_2, d_3 and d_4 are the distances (m) from the central point to the nearest tree in each quadrant; n is the number of points. S is the mean tree

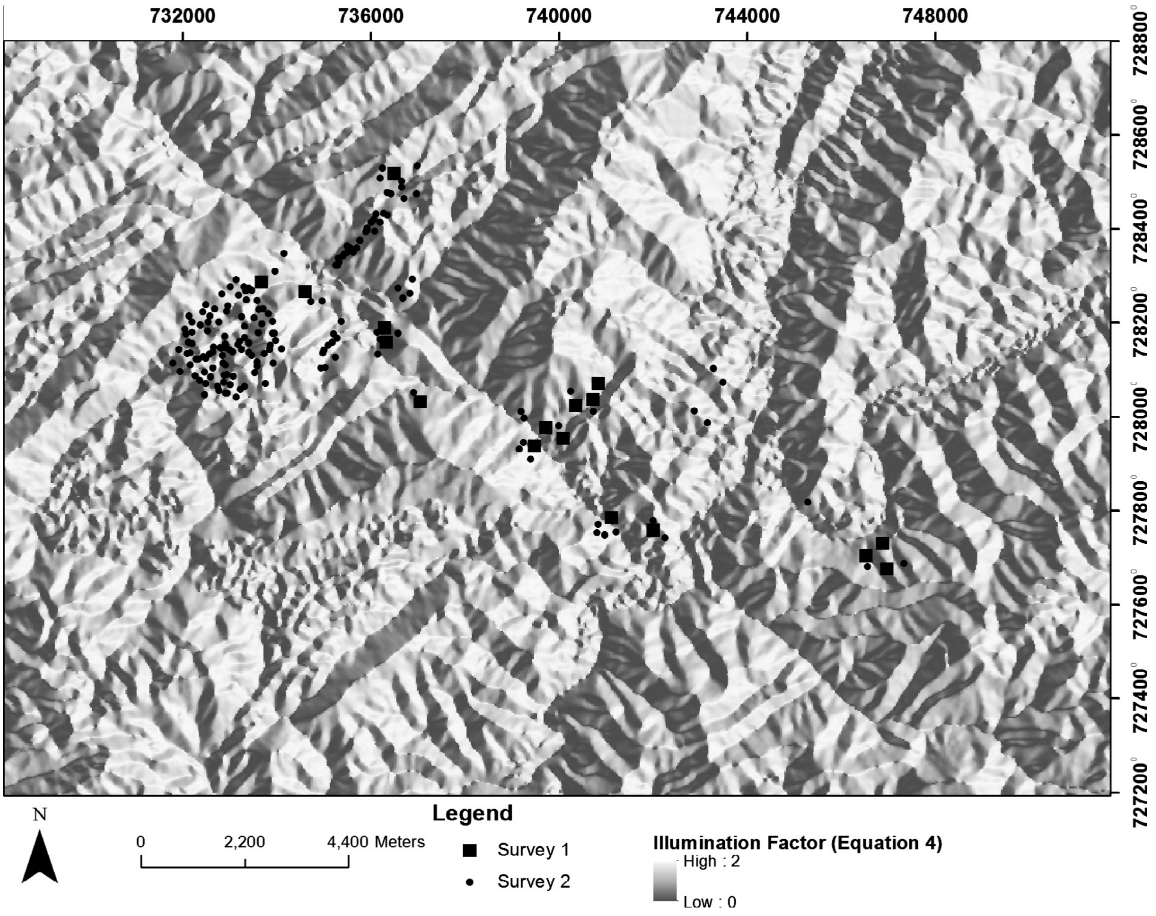

Fig. 1. Study area and surveyed points. The Illumination Factor represents a relief enhancement of solar illumination differences between mountainsides.