Relationships among slope, canopy height and vegetation greenness over coastal wet tropical forests in Australia and Brazil

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Abstract. The factors that determine the occurrence, composition and structure of tropical forests and their functional responses to climate change are still not well understood. Remote sensing provides valuable tools for investigating these factors at multiple temporal and spatial scales. This paper aims to 1) explore the influence of topography on canopy height over complex terrain coastal tropical forest sites in Australia and Brazil; and 2) examine the relationship between vegetation greenness and canopy height at these forests. We used canopy height and terrain slope data derived from airborne lidar observations and Enhanced Vegetation Index (EVI) and Normalized Difference Vegetation Index (NDVI) from Landsat 8 imagery. Our results revealed different relationships between canopy heights and local topography. Over the Brazilian site, canopy height was significantly lower over flat slopes ($0\text{-}10^0$), intermediate for gentle slopes ($10\text{-}30^0$) and higher for steep slopes ($>30^0$). Such relationship, however, was not observed over the Australian tropical forest site. Meanwhile, the Brazilian site showed significant differences in canopy greenness associated to different slope ranges, while the Australian site showed significant differences only for NDVI in two slope comparisons. We found no strong correlations between vegetation greenness and canopy height. Our results indicated site-specific relationships amongst canopy height, topography and VIs values, which might be attributed to distinct disturbance regimes and local environmental conditions, as well as bidirectional reflectance distribution function (BRDF) effects. Our findings thus highlight the influence of local context on the sensitivity of vegetation greenness to canopy structural properties.

Keywords: terrain slope, canopy height, vegetation greenness, airborne lidar, Landsat.

1. Introduction

Global tropical rainforests carbon stocks are in the order of 375 Pg (Avitabile et al. 2016), and their protection represents a critical component of global climate change mitigation. However, major knowledge gaps exist in the understanding of functional responses of tropical forests to global change and the determinants of their occurrence, composition and structure.

Understanding how environmental and abiotic factors control forests' biomass, structure and functioning is relevant to interpreting predicted alterations in disturbance regimes and forest dynamics resulting from global change. Abiotic properties and disturbance regimes create heterogeneous environments in tropical forests (Yang et al.

2016), and methods such as satellite remote sensing and field inventory plots are too coarse or present limitations for sampling large areas, and are therefore insufficient to characterize the fine scale structural properties. Airborne lidar can bridge this gap because it captures small scale properties and can cover relatively large areas (Asner et al. 2010). More specifically, scaling up approaches with different sensors can provide integrated mapping of phenological, chemical and structural traits that help to infer functional vegetation responses (Abelleira Martínez et al. 2016).

Existing research recognises the critical role played by topography in vegetation composition and structure (Clark & Clark 2000). In this study, we aim to perform a biome intercomparison and assess how vegetation height varies within elevation gradients, and the sensitivity of vegetation greenness to these differences, by combining observational data from two sources. We selected two sites of complex terrain at coastal tropical forests in two different continents, comprising different elevation ranges and precipitation regimes. We employed laser scanning (airborne lidar) and optical remote sensing (OLI sensor onboard Landsat 8) to investigate: a) how terrain slope affects forest height along elevation gradients in Australia and Brazil, and b) whether vegetation indices can detect fine-scale differences in tropical forests canopies.

2. Materials and methods

2.1. Study sites

Our study sites included two tropical forest sites: Serra do Mar in Brazil, and Robson Creek in Australia (Figure 1, Digital Terrain Models (DTM) included). Both have great altitudinal gradients, but comprise different elevation ranges, which precludes the terrain elevation comparison. Also, we did some exploratory analysis on slope aspect, considering four aspect directions (north, east, south and west), and we found generally no significant effects of aspect on canopy height. Thus, we focused only on terrain slope as a topographic variable, as it can deliver a consistent comparison between the two sites.

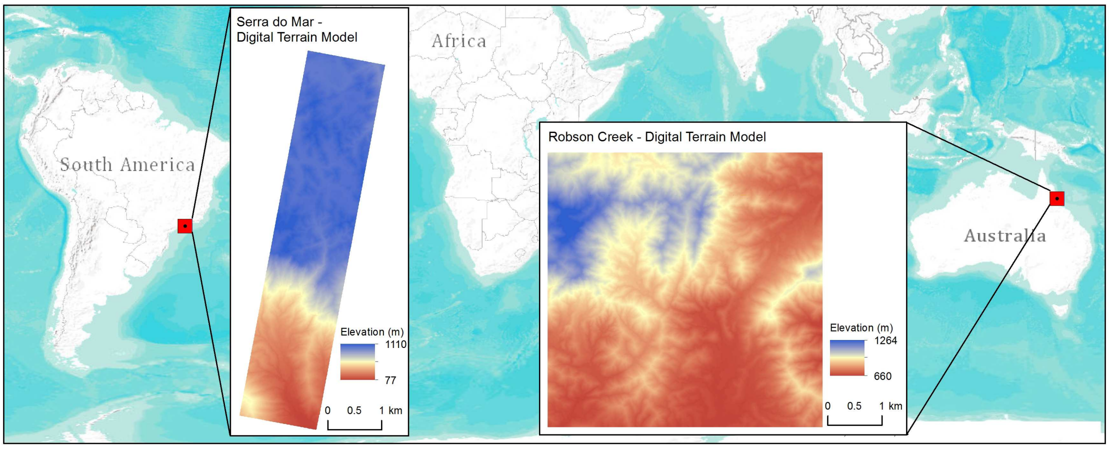

Figure 1. Location and altitudinal gradients of the study areas (Serra do Mar in Brazil, coordinates: -45.07, -23.35; and Robson Creek in Australia, coordinates: 145.62, -17.10).

The Serra do Mar (SM) site is located within the State Park of Serra do Mar, in São Paulo State. It is characterized by a great altitudinal gradient (0-1100 m a.s.l.) and is covered by the dense Atlantic Forest. The terrain slope is steepest at intermediate elevations (200‑900 m a.s.l), and the remaining area consists of relatively flat lowland forests just above sea level and the montane forest region on flatter sites over the plateau (900‑1100 m a.s.l). The precipitation is approximately 2500 mm annually, without strong seasonality (Alves et al. 2010).

The Robson Creek (RC) site lies in the Wet Tropics Bioregion of Australia, situated in the Danbulla National Park, along the north-eastern coast of the State of Queensland (Figure 1). The climate is seasonal, with approximately 60% of rain falling between January and March and mean annual precipitation of 2000mm. The landform is characterized by several altitudinal gradients, including flat to highly inclined areas, and an elevation range of 660 to 1200 m a.s.l. The region is mostly covered by rainforest, and is among one of the highest biomass forests in Australia. Occasional cyclonic disturbances affect the area (Terrestrial Ecosystem Research Network 2016).

2.2. Lidar data

The data for the SM mission was collected as discrete returns, while the data from the RC mission was collected as full waveforms. In the latter, in order to generate equivalent discrete return samples from the recorded raw waveforms, the data was post-processed using the RiAnalyze 4.1.2 program package. The acquisition parameters for both missions are described in Table 1.

Table 1. Lidar acquisition characteristics

Characteristic	**Robson Creek**	**Serra do Mar**
Equipment	Riegl Q560	Optech ALTM 3100
Acquisition date	13-14 September 2012	08-11 April 2012
Field of view (degrees)	variable (up to 45)	11
Scanning frequency (kHz)	240	59.8
Average return density (points/m²)	50.9	22
Area (ha)	2550	998

We resampled the lidar DTM for both sites from the original 1m to 30m spatial resolution, to be compatible with the Landsat images. We generated terrain slope data from the DTM and reclassified it on three slope categories: Flat ($0\text{-}10^0$), Gentle ($10\text{-}30^0$) and Steep ($> 30^0$). For canopy height information, we used the point clouds to generate Canopy Height Models (CHM), depicted by the 95th percentile of height, also at 30m resolution. The terrain elevation derived from the DTM was subtracted from each return to remove the topographic influence on the forest height. Data were processed using the FUSION package, version 3.50 (McGaughey 2015).

2.3. Landsat images and vegetation indices

As 2012 (year of the lidar campaigns) Landsat data of Climate Data Record (CDR) surface reflectances did not provide complete images due to "SLC-off" issues of ETM + sensor (Landsat 7), we used CDR images acquired by the Operational Land Imager (OLI) sensor onboard the Landsat 8 satellite, which were downloaded from USGS. We selected the first cloud free images for each site: (i) for Robson Creek, the Path/Row 96/72 from 2-Jul-2013; and (ii) for Serra do Mar, the Path/Row 218/76 from 6-Jun-2013.

To assess the sensitivity of vegetation greenness to differences in canopy height and terrain slope, we tested the Enhanced Vegetation Index - EVI (Huete et al. 2002) and the Normalized Difference Vegetation Index – NDVI (Rouse 1973). These indices show distinct responses to chlorophyll content, biomass, and canopy structural variations (Gao et al. 2000).

2.4. Data analysis

We randomly selected samples of 250 pixels in each slope class and extracted their canopy height and VI values. Then, the Student t-test was used to evaluate the differences in canopy height and VI among the categorical slope classes. We assumed that our canopy height and VI distributions were normal and independent.

Linear regression models were established between canopy height and the VI values at the pixel level. The adopted confidence level was 95%.

3. Results and discussion

The forest at the Robson Creek site has higher canopy height (mean 33.18m, SD 4.97m) than that at Serra do Mar site (mean 23.93m, SD 5.76m) (Figure 2). These results are in accordance with those found by Alves et al. (2010) for the Atlantic Forests. Regarding the RC site, Liddell et al. (2007) reported, for a tropical forest site also inside the Danbulla National Park, irregular canopy varying in height from 25 to 33m with indistinct stratification of the subcanopy.

The Serra do Mar site has a naturally occurring shorter canopy, compared to Robson Creek and other tropical forest regions. A potential explanation is that it is a highly fragmented region and a mosaic of gap-phase regeneration of different stages due to human-induced and/or natural disturbances (Ribeiro et al. 2011). The histogram shape shows higher frequency of low vegetation in the SM site than that observed in the Australian site, typical of regenerating forests.

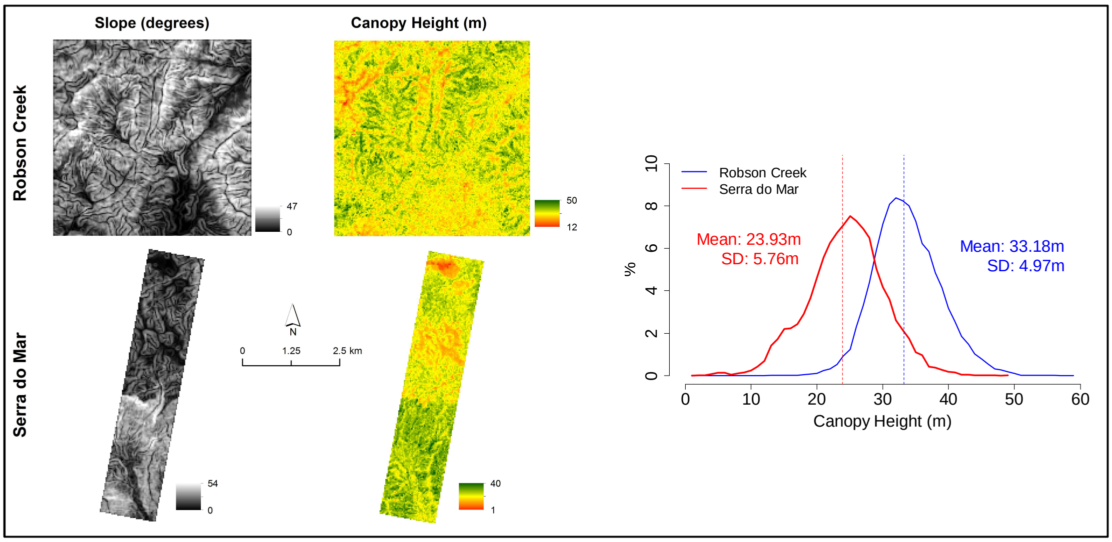

Figure 2. Terrain slope and canopy height maps (left), and canopy height histograms (right) for both sites. Dashed lines in the histograms indicate mean canopy height values.

3.1. Variations in canopy height according to terrain slope

Both sites showed greater canopy heights with steeper slopes (Figure 3). However, the canopy height sensitivity to slope variations was much more pronounced at the Brazilian site. Canopy height differences among all the slope classes were significant at Serra do Mar (*p*-value<0.001). At Robson Creek, the differences between flat and gentle and flat and steep slopes were significant (*p*-value<0.001), but not between gentle and steep slope (*p*-value = 0.109).

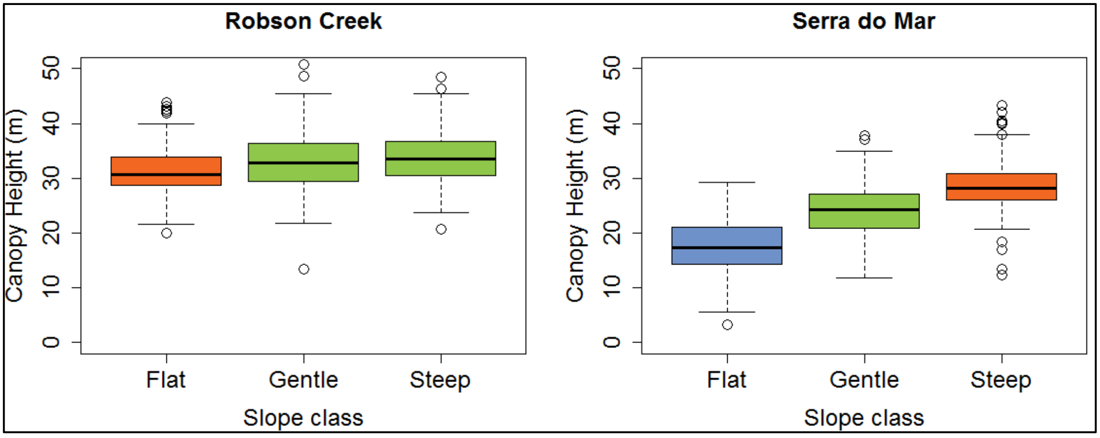

Figure 3. Canopy height according to slope class at both sites (n = 250 per slope class). Boxes colored with the same color are not significantly different. Slope classes are: flat (0-10^0), gentle slopes (10-30^0) and steep (>30^0).

The adopted slope thresholds produced evident distinction in canopy heights at SM. Our observations agree with Alves et al. (2010), who found, based on field inventories in this region, that steeper slopes support more large trees with higher biomass than flat and gentle areas. On the other hand, the Australian site has a more heterogeneous landscape, and may not present differences in canopy heights at steeper slopes, or still, the slope thresholds we adopted were not able to capture the existing environmental heterogeneity. Unequal local environmental conditions, and mostly importantly, different levels of anthropogenic disturbances are the most likely causes of these differences.

3.2. Vegetation greenness variability and its association with canopy height

We observed some pixels with abnormally low EVI values in these tropical forests (0.29 at RC and 0.03 at SM), mainly attributed to low reflectance and EVI values in relief shadow from the steepest areas at both sites. Thus, we adopted an EVI threshold of 0.4, reported in the literature as the low limit of EVI range at the Amazon tropical forests (Galvao et al. 2011) and only included in our study pixels whose EVI values were greater than 0.4.

The variation presented by EVI values was much higher than that for NDVI values (Figure 4). The EVI dynamic range at RC was 0.40-0.64, whilst at SM it ranged from 0.40 to 0.83. In contrast, the NDVI values were higher but the dynamic range was smaller for both sites (RC: 0.80-0.89 and SM: 0.83-0.92). These results were in line with previous reports of NDVI saturation issues at high biomass biomes (Gao et al. 2000; Huete et al. 2002).

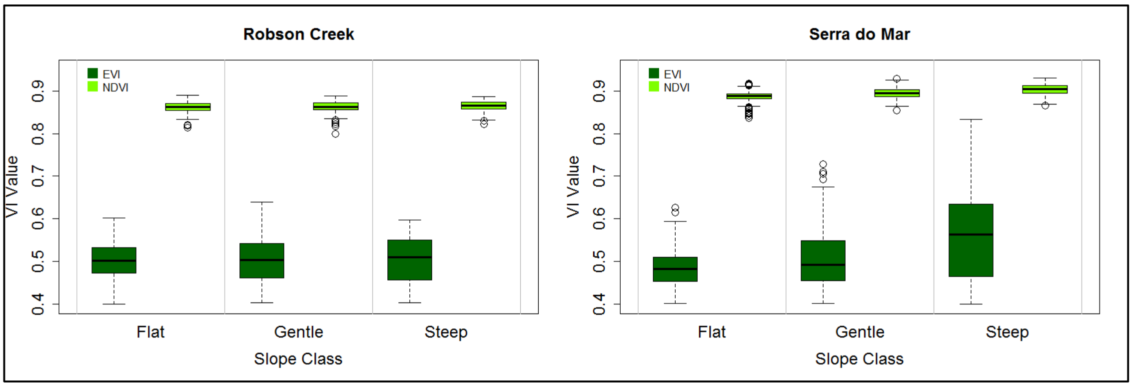

Figure 4. VI values according to slope class at both sites (n = 250 per slope class).

At the RC site, the differences in EVI among all slope classes were not significant (*p*-values > 0.51); NDVI differences were not significant between flat and gentle slope classes (*p*-value = 0.36); marginally significant at the 95% confidence level between gentle and steep (*p*-value = 0.045) and significant between flat and steep slopes (*p*-value = 0.002). For the SM study area, the differences were statistically significant amongst all slope classes for both EVI and NDVI (*p*-values < 0.001).

Although the VIs have shown to discriminate different canopy heights that occurred in the SM site at different slope ranges, they were not a good explanatory variable when fitted with canopy height in linear regression models (Figure 5). We observed very low R^2 values for the models at the RC site (0.003 for EVI, not significant, and 0.025 for the NDVI, significant). The R^2 results for the SM site were slightly better (0.155 and 0.330 for EVI and NDVI, respectively, both significant). Overall, the models were not consistent across sites and VI (EVI regressions show greater errors due to its greater dynamic range and possible bidirectional reflectance distribution function (BRDF) effects, and EVI at Serra do Mar seems to present a bias of larger residuals towards higher canopy heights).

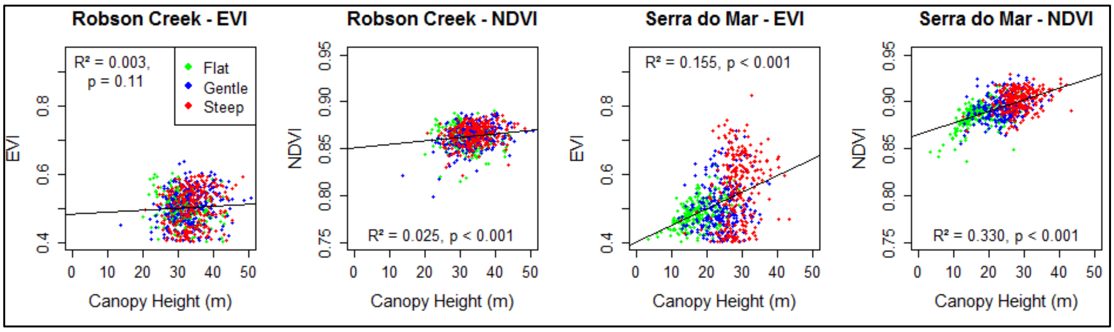

Figure 5. Scatterplots of VI values as a function of canopy height, colored according to terrain slope category. The regression lines are also shown as solid black lines.

Rugged terrains affect optical satellite images through variations they produce in both irradiance and BRDF (Li et al. 2012). Moreover, illumination effects and the proportion of sunlit and shaded leaves can exert influence on EVI values, as confirmed by Galvao et al. (2011). It may be the case that the interplay of these effects contributed to the differences in VI responses we found between our two study sites, and that EVI and NDVI variations may contain some artefacts due to BRDF effects.

4. Conclusions

This study investigated the influence of a topographic variable on the canopy height of tropical forests. Also, we assessed the sensitivity of two widely used VIs to differences in canopy height. The obtained results were not consistent across the two sites, indicating site-specific relationships. We found that slope has strong influences on canopy height in the Serra do Mar site, but a weaker effect in the Robson Creek site.

We also observed that vegetation greenness (represented by EVI and NDVI) varies across different terrain slopes at the SM site, but it was only marginally affected in the RC site. In addition, NDVI performed better in both sites to discriminate differences in canopy height, despite its smaller range. Notwithstanding, VIs showed limited explanatory power regarding canopy height, as shown by the low coefficients of determination we found at the linear regression models.

To develop a full picture of the associations among topographic variables, vegetation structural variables and vegetation greenness, additional studies are needed to: 1) further elucidate the underlying mechanisms influencing the results obtained here, such as interactions between elevation and slope (e.g. slope may affect differentially vegetation height at distinct elevation ranges); 2) investigate whether additional biophysical variables that lidar data can provide, such as canopy cover and density and LAI, show higher correlation with vegetation greenness. These variables indirectly include information about soil background, which are likely to influence VI variability (Gao et al. 2000); 3) address the effect of different lidar acquisition parameters (e.g. view angle, flight height, and point density) in the vegetation height. The very high point density of the RC dataset might be overestimating the canopy height at this site, as the mean canopy height value we found is the upper limit of the interval reported by Liddell et al. (2007); 4) land cover and land use history may be have played a fundamental role in our results, thus disturbance regimes should be also investigated as an important factor of local heterogeneity.

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