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Present and future loss of climate niches in the forested Brazilian Amazon

Bruce Walker Nelson [1]
Britaldo Silveira Soares Filho [2]
Ana Luisa Kerti Mangabeira Albernaz [3]

[1] Instituto Nacional de Pesquisas da Amazônia - INPA/Ecologia
Av André Araujo 2936 - 69060-001 - Manuas - AM, Brasil
bnelsonbr@yahoo.com.br

[2] Universidade Federal de Minas Gerais
Instituto de Geociências, Departamento de Cartografia
Av. Antônio Carlos, 6627 - Pampulha - 31270-900 - Belo Horizonte - MG, Brasil
britaldo@csr.ufmg.br

[3] Museu Paraense Emílio Goeldi, Coordenação de Ciências da Terra e Ecologia
Av. Perimetral 1901 - Terra Firme - 66077-530 – Belém - PA, Brasil
anakma@museu-goeldi.br

Abstract. A map of rainfall seasonality, using the Walsh Index, was taken as a spatial proxy for forest beta diversity across the Brazilian Amazon. Deforestation up to 2006 from Inpe (Prodes Digital) and projected up to 2036, were used to determine percent loss of the original forest cover in each consecutive slice of the Walsh index. A modified version of the SimAmazonia model, with Business-as-Usual infra-structure growth, was employed for the future scenario. By 2006, over 60% of the forest in some of the drier climate niches had been lost. Dry forest is of very limited natural extent in the Amazon and is more susceptible to degradation by fire -- thus a high conservation priority. Supporting only the presently established conservation areas and indigenous areas will not be sufficient for the protection of this habitat. Losses are projected to exceed 90% of the original area in some dry climate niche slices by 2036. The largest remnants of dry forest today are in Roraima, along the Transamazon Highway and in Maranhão. The Walsh Index appears to be a useful separate predictor of Amazon deforestation.

Keywords: Amazon, beta diversity, habitat loss, rainfall, Walsh index, deforestation model.

1. Introduction

Because seasonal and spatial variations in temperature are small across the Amazon forest, biologically relevant climate variability is largely a function of the amount and the seasonal distribution of rainfall. Monthly rainfall data were used to create a map of the Walsh Tropical Rainfall Index for the Brazilian Amazon. This index (Walsh, 1996) takes on high values where the dry season is shorter and/or wetter, low values where longer and/or drier. Distinct intervals of the gradient are therefore expected to define the niches of different plant species. Places with dissimilar Walsh Index values should have dissimilar plant communities. Using data from the Prodes Digital web site, the area of original forest extent was determined for regular intervals of this climate gradient. The percent of forest lost from each climate niche was determined for 2006 and predicted for 2036. We examined only the forested portion of each climate niche, because remote sensing allows a more accurate annual assessment of habitat loss in forested areas.

2. Methodology

2.1. Future Deforestation Scenarios: SimAmazônia

Spatial estimates of remaining forest in 2036 were derived from a modified version of the SimAmazonia model. The model ran for the 35 year period, 2001 to 2036. The spatial drivers of deforestation are the same across all of the Brazilian Amazon, but their strength varies in each of 39 subregions. For example, the influence of proximity to prior deforestation is greater in Mato Grosso than in the upper Rio Negro. To historical tendencies of deforestation advance, the model adds the effect of a timetable for paving the main highways. A road-growing algorithm is included, branching off from these highways. Further parameterization details are given in Soares-Filho *et al.* (2006) and on the SimAmazonia web site: <www.csr.ufmg.br/simamazonia/>.

Within 12 Landsat scenes Soares-Filho *et al.* (2006) had previously determined historical resistance to deforestation penetration for indigenous reserves and for federal and state conservation areas. For this study a new calibration was devised for conservation areas in two categories -- those where sustainable uses and habitation are permitted, and those with more strict conservation rules where habitation is not permitted.

Author BSSF further tailored the model to address strategic planning demands in 2006 from the ARPA (Amazon Region Protected Areas) program. Two deforestation models were considered – one where about 90 conservation areas presently supported by ARPA continue to offer an historical degree of resistance to the penetration of deforestation, and one in which these conservation areas present no resistance to deforestation during the simulation period. Both the 2036 scenarios were otherwise run under the "Business as Usual" road-building and governance levels. Forest losses predicted within each conservation area under the no-resistance scenarios allowed a ranking of threat levels in order to establish investment priorities for ARPA in 2006. Here we examine how the two Business as Usual scenarios – with and without effective conservation area protection – affect predicted percent loss of forest within the different climate niche intervals across the entire Brazilian Amazon.

The SimAmazonia model produced spatial predictions at 1 km resolution. Map cells take values from 0 to 36, where zero represents forest remaining in 2036, at the end of the simulation period. All positive values are the number of years prior to 2036 that deforestation is expected to occur. Cells with value 36 also include those deforested prior to the starting year of 2001. Natural non-forest (never forested) is identified by the no-data flag value.

2.2. Walsh Tropical Rainfall Index

Mean monthly precipitation (~1950 to 2000) was downloaded from the Worldclim web site at 10 minute resolution. A single index was derived for each cell according to the following rules (Walsh, 1996). A score of -2 was given to those cells with less than 50 mm of rain for a given month, -1 for cells with 50 to 100 mm, +1 for 100 to 200 mm, and +2 if monthly rain exceeds 200 mm. The 12 monthly maps of scores were summed. To this sum was added 0.5 for each month in the year that a cell has more than 100 mm following a month with less than 100 mm. This is a correction for how many times the dry season starts in each cell, because two short dry seasons are less stressful than a single long dry season. In the final product the index can take values between -24 (dry) and +24 (wet).

2.3. Geoprocessing Steps

The desired output is percent loss of each distinct Amazon forest habitat, that is, distinct slices of the climate attribute. Losses are reported for 2006 and for the two projected situations in 2036 from the modified SimAmazonia model.

1. Reclassify the two SimAmazonia Business as Usual model outputs of 2036 forest extent, such that remaining forest in 2036 = 1, all other cells = 0. Project both these boolean images of 2036 forest extent to Albers Equal Area Conic, and window out identical areas using a standard envelope.
2. Obtain from the Prodes Digital web site the 2006 deforestation data, file <PDigital2000_2006_AMZ_gtif.zip>. This includes two tiffs in GCS SAD69 projection, one with 60m cells, the other 90m. Use the 90m data. The Prodes site provides translations for all 56 thematic codes in the 60m data, but not for the 41 codes in the 90m data. By overlaying and comparing the two images, it was possible to identify the meaning of all 41 codes in the 90m thematic raster.
3. Reclassify Prodes 2006 90m image into two boolean images, each showing forest = 1, not forest = 0:
   a) [Original forest extent]
   b) [Remaining forest in 2006]
4. Project both Prodes boolean images to Albers Equal Area Conic and resample to 1000m resolution, using a function that preserves total area of each binary class. Without such a function bias can be very large. For example, in the state of Maranhão a simple nearest neighbor resampling of the "remaining forest", from 60m to 1000m cell size, increased the apparent area of remaining forest in the state by 83%. This same error for Maranhão was only 0.05% when using a compensating resample function. Window out the standard envelope.
5. Multiply the boolean image [original forest extent] by each of the 2036 forest extent images from the SimAmazonia model. Outputs are [Forested 2036 effective UCs] and [Forested 2036 ineffective UCs]. This confines the analysis, eliminating extra-Brazilian and extra-Amazonian areas of remaining forest in 2036.
6. Project the Walsh tropical rainfall index image to Albers Equal Area Conic, window out the standard envelope and resample to 1000m cell size.
7. The Walsh Index image takes values between -24 and +24. Offset the image by +30 to permit multiplication by boolean masks. Reset the no-data flag to zero.
8. Multiply the rainfall index image by the boolean image: [Walsh+30] x [original forest extent]. Output gives Walsh+30 values wherever there was past or present forest in the Brazilian Legal Amazon, zero elsewhere.
9. Multiply rainfall index by three boolean images:
   a. [Walsh+30] x [Forested 2006];
   b. [Walsh+30] x [Forested 2036 effective UCs];
   c. [Walsh+30] x [Forested 2036 ineffective UCs].
10. Comparing histograms of the four images output in steps 8 and 9, gives percent forest loss in each climate niche slice in 2006 and the two 2036 scenarios.

3. Results and Discussion

Across the originally forested area of the Brazilian Legal Amazon, Walsh index values range from a dry extreme of about -10 in northern Roraima and central Maranhão to the wet extreme of +24 in the northwest of Amazonas. Dry forests had a very limited extent in the pristine Legal Amazon. Only 170,000 km^2 existed with an index of +0.5 or less, only 13,000 km^2 with an index of -4.5 or lower.

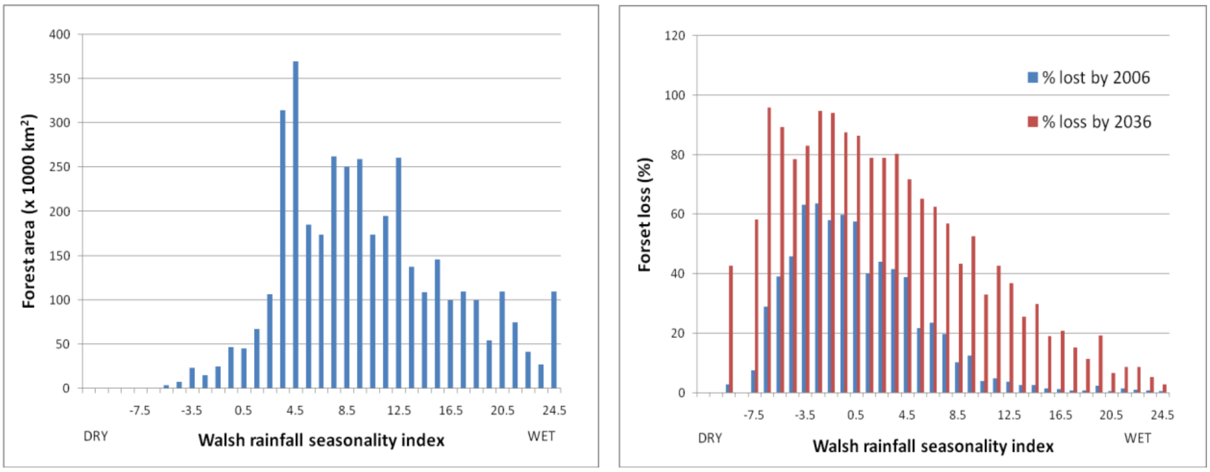

Figure 1. Left - extent of original forest in the Brazilian Legal Amazon within each slice of the Walsh climate index; Right - percent forest loss in each climate class by 2006 and projected for 2036.

3.1. Present Losses

By the year 2006, cumulative forest losses mapped by INPE's Prodes Digital project in the Brazilian Amazon had reached 676,000 km^2. (This does not include deforestation in all or part of three Landsat scenes in the eastern Amazon, totaling 41,000 km^2 of land area, for which Prodes Digital does not provide data.) This land cover alteration has occurred preferentially at the expense of drier forests. Some slices of the climate niche have already lost 60% of their forest area (Figure 1, right panel, blue columns). The remaining forest in each slice of the climate niche is simply the complement of each column in the right panel, i.e. between the top of the column and the 100% level.

Percent losses are progressively lower in the wetter portion of the climate gradient. Man's preference for land-cover conversion in areas occupied by dry forest is even more alarming when one considers that there was very little dry forest present in the pristine Legal Amazon (Figure 1, left panel). Percent losses as of 2006 also drop off very rapidly at the most extreme dry end of the climate gradient. This appears to be a consequence of indigenous reserves in Roraima and Maranhão that protect the very limited original area of these driest forests.

Figure 2 is a spatial representation of climate slices in the remaining forest (grey tones) and in the deforested area of Amazonia as of 2006 (colors). Note that there is a paucity of green color on the map, meaning there is very little deforestation in wet areas. Dry forests – red and orange colors – have been hardest hit. The few remaining dry forests are indicated by the darkest grey tones. The largest remnants of dry forest are in Roraima, along the Trans-Amazon Highway west of Altamira (PA) and in central Maranhão.

It is well known that deforestation is concentrated in the more seasonal areas along the southern and eastern edge of the Amazon forest, in close proximity to the well developed road networks of the Central and the Northeast regions. Accessibility rather than human preference for dry areas might therefore account for the loss of dry forest habitat. However, deforestation is also high in the dry forests of Roraima and on the north bank of the Amazon opposite Santarem, both disconnected from the main road network of the rest of the country (Figure 2). This suggests that dry climate is a separate and legitimate driver of deforestation, as argued by Laurance *et al.* (2002).

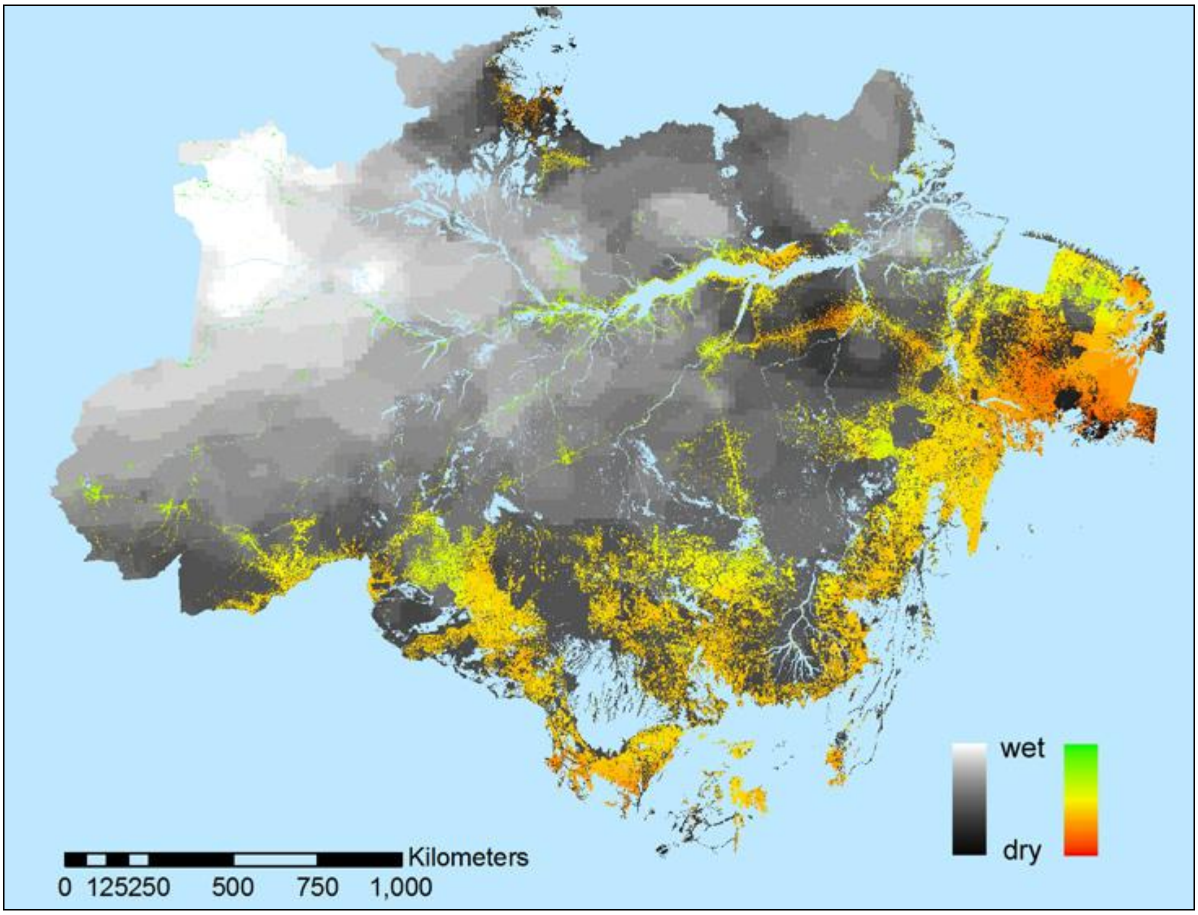

Figure 2. Walsh rainfall seasonality index values across the deforested (colors) and remaining forest (grey tones) areas of the Brazilian Amazon as of 2006. Deforestation pressure is highest in dry areas.

3.2 Future losses

By 2036, under Business as Usual road-building and law-enforcement levels and with the indigenous areas and the ARPA-supported conservation areas maintaining their historical resistance to deforestation, total deforestation is projected to reach 1,840,000 km^2.(47% of the original forest). Losses are predicted to exceed 75% of the original forest in the 11 climate niche slices with Walsh values between -6.5 and +3.5. Some intervals of the climate gradient are projected to lose more than 90% of their area (Figure 1, right panel, red columns).

Allowing conservation areas to resist or not to resist forest penetration (both under Business as Usual) had no effect on net deforestation by 2036. Total remaining forest by 2036 was predicted to be 2,070,000 km^2 in both cases, with differences only in the hundreds column. It also had no effect on the partitioning of deforestation into different climate niche intervals. Under the Business As Usual setup, the model in effect sets goals for the growth of autochthonous roads and other drivers of deforestation such that – in the time frame of this simulation – these drivers redirect deforestation pressure away from “closed” conservation units. In other words, the model allows compensatory deforestation (leakage) as long as alternative areas are available to be deforested outside conservation units. If the model were run under a better law-enforcement governance scenario, including a well-supported ARPA Program (Soares Filho *et al.* 2008), it would, however, predict substantially less deforestation and carbon emissions from the Amazon, relative to the Business as Usual setup.

4. Conclusions

Forests with a long and/or intense dry season are clearly the most threatened forest habitat in the Brazilian Amazon. Very high losses were already in place by 2006, even without counting degradation by ground fires and logging. By 2036, losses are projected to exceed 90% in some climate intervals. Though dry forests are clearly a critical conservation priority, few new conservation areas have been established there. One reason may be the policy-makers' tendency to avoid social conflict and high reparation costs. These areas tend to have high population density, good road infra-structure, more fertile soils and a climate more suitable for agriculture and cattle. The Walsh Index of tropical rainfall seasonality appears to be a useful predictor of Amazon deforestation. The historical relationship between percent of forest lost and the Walsh Index is not linear, but skewed and hump-shaped, probably a consequence of indigenous areas protecting the few very driest forests.

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