Use of Remote Sensing to assess Ecosystem Integrity of the Brazilian Amazon rainforest – A Bayesian approach

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Abstract. Biodiversity supports many ecosystem services that are very important for climate change mitigation and adaptation. There is a functional link between the tropical forest ecosystem biodiversity and their capacity for carbon uptake and storage as well as regulation of evapotranspiration flux. Nevertheless, land use changes and agriculture expansion reduce the ecosystems integrity modifying the functions related directly to the ecosystem services. The relationship between biodiversity loss and the impacts on ecosystem services of tropical forests, in face of the ongoing global climate change needs to be better quantified. In this work, we considered the concept of Ecosystem Integrity (EI), which represents the connection of biodiversity with the ability of ecosystems to sustain the processes of self-organization. Bayesian Networks (BBN-Bayesian Belief Network) can provide metrics for the generation of Ecosystem Integrity Index, from the training of probabilistic relationships of evidence obtained through Remote Sensing data. The objective of this work is to present the methodological approach and the results of EI mapping, elaborated at the regional scale for different patterns of phyto-ecologic landscape of the Brazilian Amazon. The modelling was based on learning from the parameters (data-driven model) through the use of the Expectation Maximization algorithm. For the validation of this probabilistic model, an evaluation was carried out in controlled areas with field observation by experts. Results showed that it is possible to generate an Ecosystem Integrity Index at regional scale using a probabilistic model based on Bayesian Belief Networks (BBN), and totally free web-available satellite products.

Key words: Biodiversity; Bayesian Belief Networks (BBN); spatial models; land use changes

Introduction

The concept of Ecosystem Integrity (EI) is heavily discussed and a huge amount of definitions are used. Jorgensen and Müller (2000) describe EI as a balanced, integrated adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of a natural habitat of a region. Ecosystem integrity can be defined as a state of equilibrium of a natural system that is able to self-regulate through various functional processes. Ecosystem Integrity (EI) is also used as a synonym for intactness, completeness and integration of ecosystems.

The Ecosystem Integrity can be understood as a dynamic state of natural ecosystems in which it's observed maximum capacity of resilience and self-organization of its original components that maintains many ecosystem processes related to most terrestrial biogeochemical cycles. In this way the concept of IE this strongly related to biogeochemical cycles. By this, indicators used to assess EI are e.g. sun energy input (radiation balance, production of biomass) and export (respiration, transpiration), storage capacity of plants, biotic water flow (evapotranspiration), nutrient flows (mineralization) and biotic diversity (species number). However, the full understanding about the causality relations between these indicators and the EI state are not fully clear. Especially when ecosystems are altered by human actions, enhancing greatly the degree of uncertainty

Bayesian Belief Networks (BBN) are models that probabilistically represent correlative and causal relationships among variables. BBNs have been successfully applied to natural resource management to address environmental management problems and to assess the impact of alternative management measures. By training the probabilistic relationships using field data, remote sensing data and GIS data, related to the vegetation cover, the BBN can provide information on the ecosystems integrity state. Thus it becomes possible to establish the likelihood of ecosystems integrity of a given forest area and their likely response to climate change or alternative management actions.

In this study, we propose an approach to map Ecosystem Integrity based, exclusively, on the use of free web-available satellite products, for regions where there is a lack of updated systematic mapping or organized data collected in the field. In this way, this methodology is particularly important for countries with no or low field data availability.

2. Methodology

The methodological approach of this work consists in the generation of an "Ecosystem Integrity spatial model" based on probability distribution of evidence parameters (Bayesian theory - Lindley 1972). The modeling was based on learning process (dada-driven model) using the Expectation Maximization algorithm (Buntime 1994). Bayesian network has been established from an expert conceptual model that related different spatial data (Thematic maps and Remote Sensing data): (i) Biomass (MODIS/ USGS – NASA); (ii) EVI; (iii) LAI-Leaf Area Index (MODIS/ USGS – NASA); (iv) Tree Cover (MODIS/ USGS – NASA); (v) GPP- Gross Primary Productivity (MODIS/ USGS – NASA).

Several models were carried out using different Bayesian Belief Networks (BBN) and variables. This work presents the last BBN configuration developed (Figure 1). For the improvement of model and to get the best response to different phytophysiognomics features, it would be necessary to run the model independently for each Potential Phytoecological Zone of the Brazilian Legal Amazon region (Figure 3), allowing a more precise definition of the limits of each variable. The network structure was designed so that the node "Integrity" represented a direct cause of the evidence, that are the ecosystem attributes obtained freely from satellite products (EVI, VCF, LAI, and GPP). Thus, the change of state of each of the ecosystem attributes entail directly in Ecosystem Integrity probability.

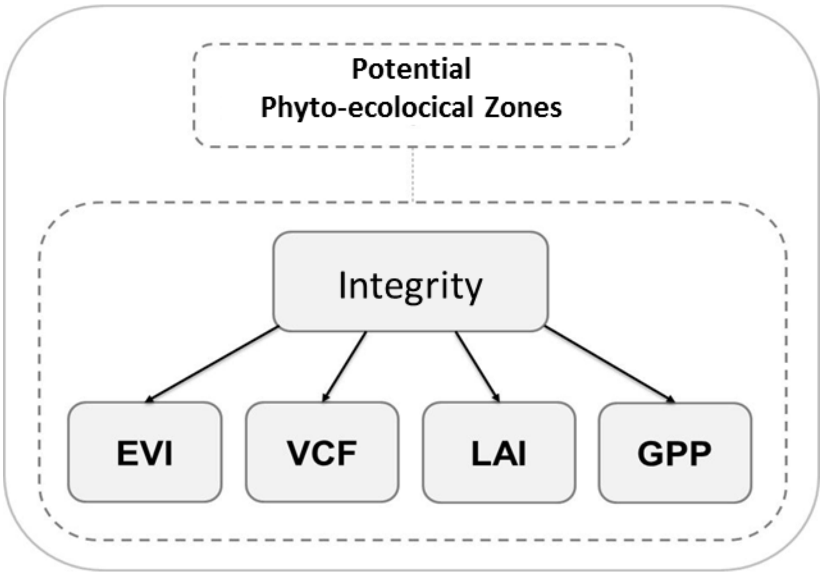

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Figure 1 –Bayesian network applied for each Phyto-ecological Potential Zone

For the network modeling, the data of each evidence were discretized in two classes (low and high integrity Integrity), using as a reference the previously defined thresholds. After the modeling stage, following the model shown in Figure 2, the networks were performed using the learning algorithm. Figure 2 shows an example of the network created.

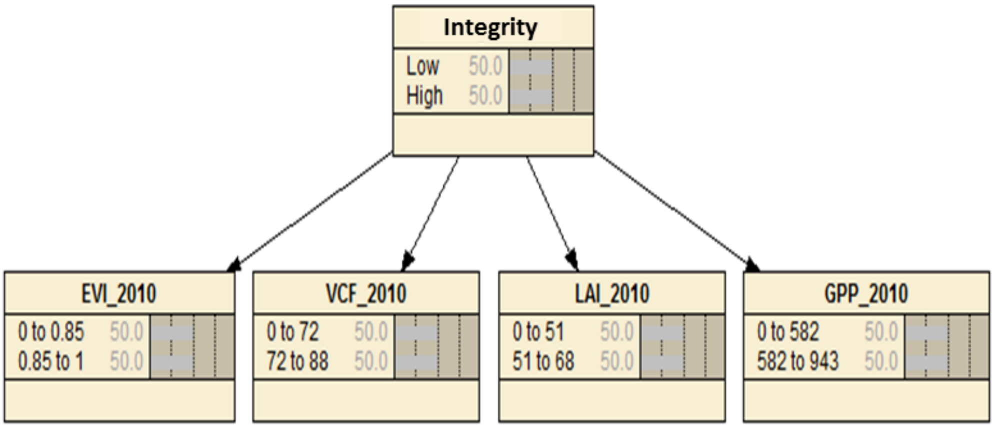


Figure 2 – Bayesian Belief Networks (BBN) modeled

Phyto-ecologic Potential Zones (Figure 3) have been used as conditions of EI, separating the areas in zones according to their phytofisionomics characteristics, topography features (relief) and climate in order to decrease the environmental heterogeneity and allow better adjustment of the model. The data of Brazil's Conservation Units were used in the definition of thresholds of evidence. The limit of the Legal Amazon was used as a mask to cut the data in raster format. The State administrative boundaries were only used as reference data for policy analysis.

The remote sensing data used as evidence of the model are presented and described in Table 1

Table 1 - Data used as evidence of the model

EVI-Enhanced Vegetation Index (Enhanced Vegetation Index)
▪ product: MODIS-3,005 MOD13A (Monthly L3 Global 1 km); ▪ Frequency: monthly; ▪ date: 1/1/2010; ▪ Pixel: 1 km; ▪ format of the file: HDF; ▪ Subdataset 1 | Variable: "1_km_monthly_EVI"; ▪ Source: USGS-NASA; ▪ General information: https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod13a3
LAI – index of leaf area (Leaf Area Index)
▪ product: MODIS-MOD09A1; ▪ Periodicity: 8 days; ▪ date: 1/1/2010 to 1/8/2010;

- Pixel: 1 km;
- format of the file: HDF;
- Subdataset 0 | Variable: "LAI";
- source: LIANG and XIAO, 2012/USGS-NASA;
- General information: "http://glcf.umd.edu/data/lai/"

VCF – percentage of tree cover (Vegetation Continuous Fields-Percent tree cover

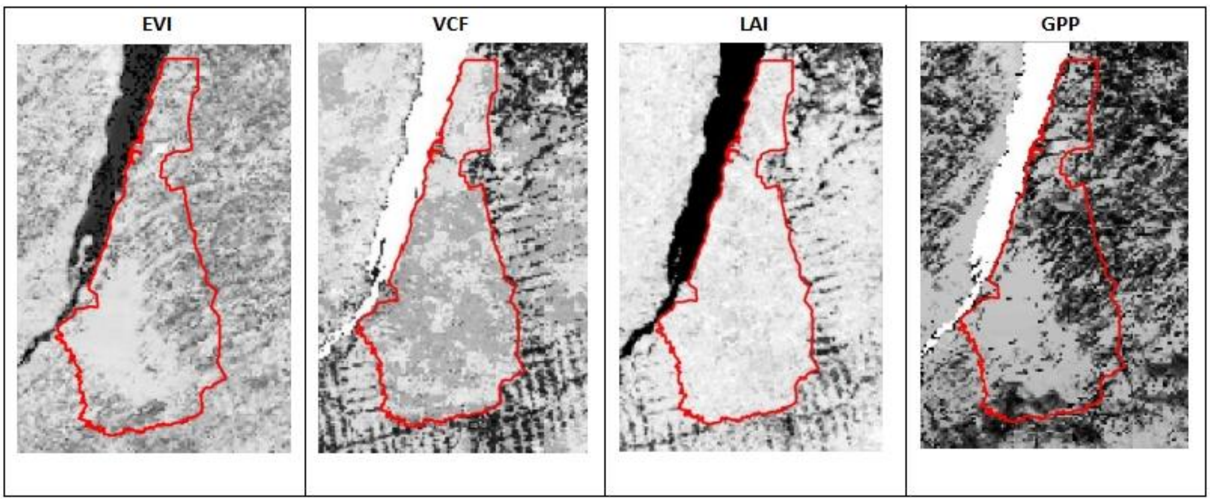
- product: MODIS-MOD44B_V5;
- Periodicity: Annual;
- date: 2010;
- Pixel: 250 m;
- file format: GEOTIF;
- Subdataset: TRE-Percent tree cover;
- source: DIMICELI et al., 2011-USGS/NASA;
- General information: "http://glcf.umd.edu/data/vcf/"

GPP-Gross Primary Productivity (Gross Primary Productivity)

- product: MODIS-2,005 MOD17A (8-Day L4 Global 1 km);
- Periodicity: 8 days;
- date: 1/1/2010 to 1/8/2010;
- Pixel: 1 km;
- format of the file: HDF;
- Subdataset 0 | Variable: "Gpp_1km";
- Source: USGS-NASA;
- General information:

"https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod17a2"

It is important to note that although some evidence mentioned appear to provide similar results and correlated, they provide different spectral responses for a particular area and, also, for different types of physiognomies, allowing a good differentiation of regions. The Figure 3 presents an example of this distinction to the Tapajós national forest area.



a b c d

Figure 3 - Example of the difference of spectral response to the evidence used
Note: Tapajós National Forest. (a) EVI, year 2010; (b) VCF, year 2010; (c) LAI, year 2010; GPP, year 2010.

Due to the global importance of the Amazon rainforest ecosystem and in order to carry

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out an analysis on a regional scale, the methodological approach was applied to the area of the Brazilian Legal Amazon, which includes nine Brazilian States: Acre (AC), Amazonas (AM), Amapá (AP), Maranhão (MA) (partially), Mato Grosso (MT), Pará (PA), Rondônia (RO), Roraima (RR) and Tocantins (TO). It is important to note also, that we took into account the various phytophysiognomics characteristics presented in this region showed in Figure 4 and table 2, allowing evaluating the methodological approach in bio-diverse regions.

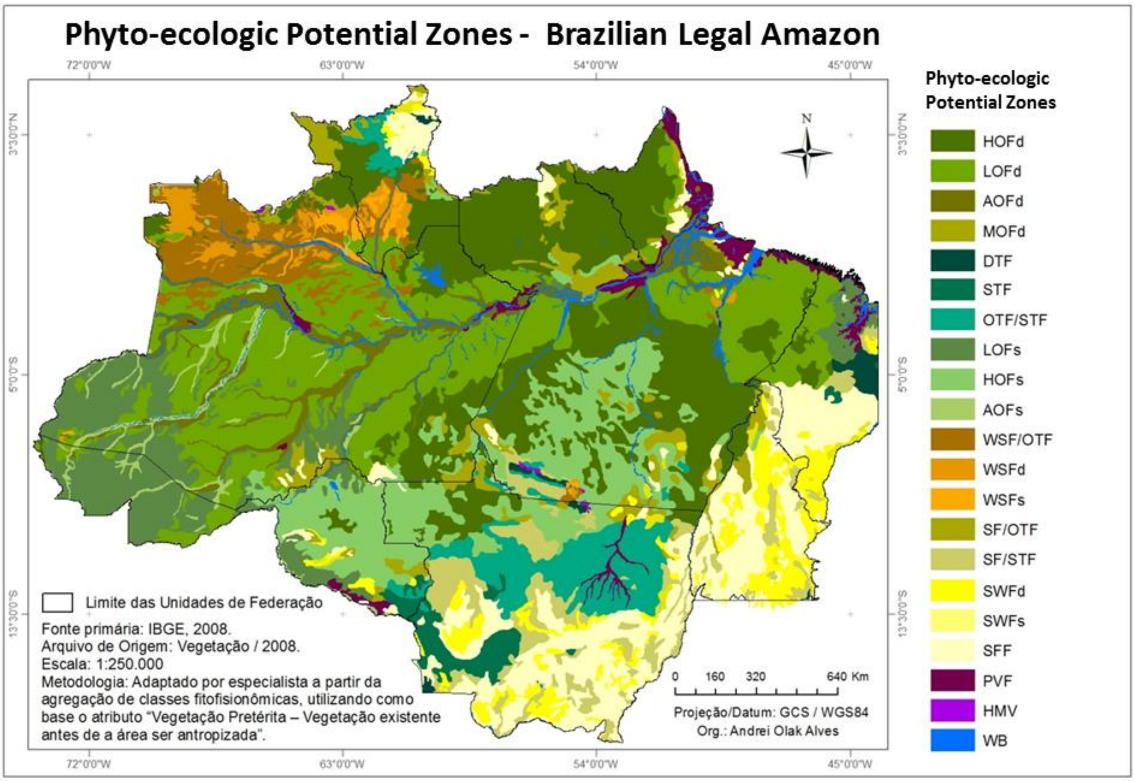

Figure 4. Phyto-ecologic Zones of the Brazilian Legal Amazon map.

Table 2. Phyto-ecologic Zones of the Brazilian Legal Amazon

HOFd	High Ground Ombrophylous Tropical Forest with Dense Canopy
LOFd	Low Ground Ombrophylous Tropical Forest with Dense Canopy
AOFd	Alluvial Ombrophylous Tropical Forest with Dense Canopy
MOFd	Mountain Ombrophylous Tropical Forest with Dense Canopy
DTF	Deciduous Tropical Forest
STF	Semi-Deciduous Tropical Forest
OTF/STF	Ombrophylous Tropical Forest / Semi-Deciduous Tropical Forest
LOFs	Low Ground Ombrophylous Tropical Forest with Sparse Canopy
HOFs	High Ground Ombrophylous Tropical Forest with Sparse Canopy
AOFs	Alluvial Ombrophylous Tropical Forest with Sparse Canopy
WSF/OTF	White-Sand Forest / Ombrophylous Tropical Forest
WSFd	White-Sand Forest with Dense Canopy
WSFs	White-Sand Forest with Sparse Canopy
SF/OTF	Savannah Formations / Ombrophylous Tropical Forest
SF/STF	Savannah Formations / Semi-Deciduous Tropical Forest
SWFd	Savannah Woody Formations with Dense Canopy
SWFs	Savannah Woody Formations with Sparse Canopy
SFF	Secondary Forest Formations

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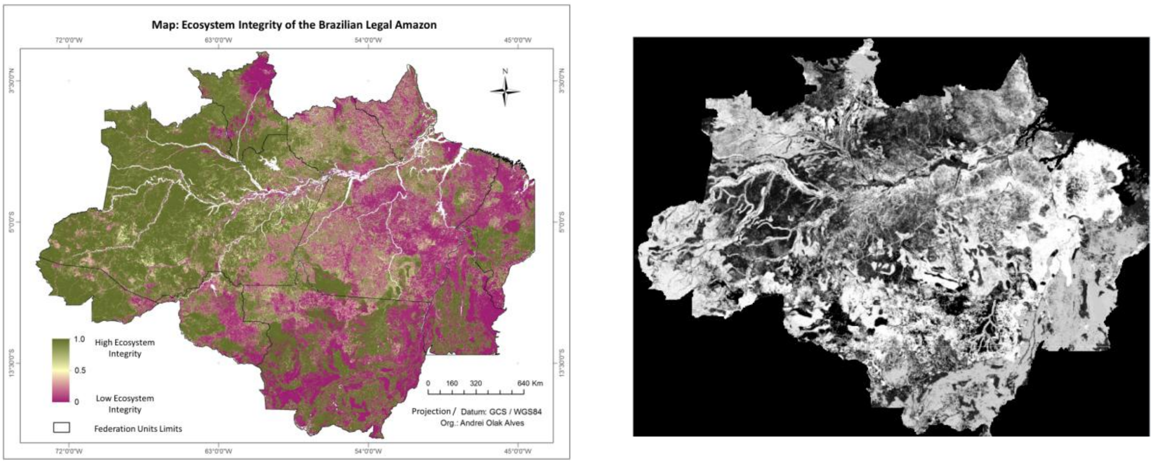
PVF	Pioneer Vegetation Formations
HMV	Hideaways Montano Vegetation

The validation of the Ecosystem Integrity model derived from probabilistic Bayesian Model (data driven) was assessed through the evaluation of controlled areas, field observation made by experts. Others validation methods are still being studied (expert knowledge model (knowledge driven) comparison and statistics analyses).

3. Results

The Figure 5 presents the map of Ecosystem Integrity generated by using the methodological approach proposed. To be possible to quantify the areas presenting high or low integrity, the outputs were classified into 3 classes: 0.00 to 0.35 – Low EI; 0.35 to 0.60 – Intermediate EI; 0.60 to 1.00 – High EI. The results showed that 53.22% of the Legal Amazon features IE High, 15.21% have Intermediate and 31.57% have IE Low.



a   b = EI loss = EI $_{actual}$ – EI $_{Pristine}$

Figure 5. (a) Ecosystem Integrity map (b) Loss of Ecosystem Integrity in 2010

Table 3 presents the percentage of EI per State of Brazilian Amazon region, taking into consideration the total area of the Legal Amazon.

Table 3. EI percentage by State considering the total area of the Brazilian Legal Amazon

States	% IE High	% IE Intermediate	% IE Low
AM	45,24	26,55	7,76
MT	16,50	12,92	25,59
PA	14,23	40,87	33,45
RR	5,32	1,23	4,53
AC	5,18	1,84	1,08
RO	4,49	5,29	5,27
TO	4,08	2,81	9,37
MA	3,56	3,77	8,77
AP	1,40	4,73	4,18

Note: States: AM - Amzônia; MT - Mato Grosso; PA – Pará; RR – Roraima; AC – Acre; RO – Rondônia; TO – Tocantins; MA – Maranhão; AP - Amapá

4. Conclusion

The preliminary results show that the methodological approach proposed was able to establish an Ecosystem Integrity spatial index. The forest physiognomies (Ombrophylous) achieved more accurate results when compared to the more sparse vegetal features as the savanna formations.

5. Final Considerations

This work presented a methodological approach developed for the generation of an index denominated Ecosystem Integrity on a regional scale, for different phyto-ecological zones using a probabilistic model based on Bayesian Networks (BBN) and Remote sensing products. Updating the satellite data using the same Bayesian network makes it possible to monitor the Ecosystem Integrity over time as well as monitor the EI loss. The methodological approach may serve to establish a protocol for monitoring the EI changes in tropical forest at regional scale. Finally, it is worth mentioning we propose an approach based, exclusively, on the use of free web-available satellite products, for regions where there is a lack of updated systematic mapping or organized data collected in the field. In this way, this methodology is particularly important for countries with no or low field data availability. Updating satellite data, it becomes possible to monitor the EI over time.

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