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# SPATIAL ASSESSMENT OF DATA GAPS FOR ESTIMATING BIOMASS ACROSS THE BRAZILIAN AMAZON

Graciela Tejada Pinell

Doctorate Thesis of the Graduate Course in Earth System Science, guided by Drs. Jean Pierre Henry Balbaud Ometto, and Eric Bastos Görgens, approved in June 29, 2017.

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Tel.:(012) 3208-6923/6921
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Dr. Celso von Randow

***Presidente / INPE / São José dos Campos - SP***

Dr. Jean Pierre Henry Balbaud Ometto

***Orientador(a) / INPE / São José dos Campos - SP***

Dr. Eric Bastos Görgens

***Orientador(a) / UFVJM / Diamantina - MG***

Dra. Thelma Krug

***Membro da Banca / INPE / SJCampos - SP***

Dr. Luiz Carlos Estraviz Rodriguez

***Convidado(a) / ESALQ - USP / Piracicaba - SP***

Dr. Marcos Longo

***Convidado(a) / EMBRAPA / Campinas - SP***

***Este trabalho foi aprovado por:***

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***(X) unanimidade***

***São José dos Campos, 29 de junho de 2017***

*“There is still a window of time. Nature can win If we give her a chance.”*

- Dr. Jane Goodall -

*(In Portuguese)*

*Alex, meu amor, porque juntos iluminamos nosso caminhar.*

*Luciana e Lara, minhas filhas, que são a razão para que a vida se renove e se torne mágica, plena e doce.*

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*(In Portuguese):*

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## ABSTRACT

Amazon forest provides fundamental ecosystem services such as biodiversity conservation, water cycling and carbon sequestration. Given the large extent of Brazilian forests, 75% of the Amazon Basin, there is great uncertainty in the storage of aboveground biomass (AGB) carbon stocks. There is a significant difference between AGB estimates and an urgent need to improve AGB estimates to support the National Communications (NC) of Brazil to the United Nations Framework Convention on Climate Change and Reducing Emissions from Deforestation and Degradation (REDD+). Whether for NC, REDD+ or for the carbon emissions modeling, stakeholders, policy makers and scientists have to decide which AGB product, dataset or combination of data to use, according to its availability, scale and coverage. The purpose of this study was to assess forest AGB spatial data gaps across the Brazilian Amazon. To achieve this goal, we conducted an extensive review and analysis of the AGB datasets coverage. AGB stakeholders connections were made through a social network analysis. Also, AGB maps variability within different environmental factors maps (soil, vegetation, topography and climate) were analyzed. Using difference and statistical analyses of AGB maps and, through a spatial multicriteria evaluation, we obtained a forest AGB spatial data gaps map for the Brazilian Amazon. The spatial coverage of AGB field and airborne LiDAR data shows great areas without AGB data and, even though stakeholders have connections, few datasets are available. By quantifying AGB maps and field data variability within multiple environmental factors, we provide valuable elements for understanding the current AGB data in function of climate, soils, vegetation and geomorphology. The main differences between AGB maps are found next to the rivers (mainly the Amazon River), in Amapá, northeast of Pará and central and north Amazon States, these areas coincide with areas of higher AGB. The forest AGB spatial data gaps map, which refers to places with no field or LiDAR data and where AGB maps differ the most, show the priority areas for further AGB assessments in the Brazilian Amazon. This study can be a useful tool for policy makers and different stakeholders working on AGB on which to base their decisions to choose AGB data or products for National Communications, REDD+, or carbon emissions modeling.


Key-words: Amazon. Tropical rain forest. Carbon**.** Aboveground biomass. REDD+. Environmental factors.

**AVALIAÇÃO ESPACIAL DAS LACUNAS DE DADOS PARA AS ESTIMATIVAS DE BIOMASSA DA AMAZÔNIA BRASILEIRA**

## RESUMO

A floresta amazônica fornece serviços ecossistêmicos fundamentais, como conservação da biodiversidade, ciclagem a água e sequestro de carbono. Dada a grande extensão das florestas brasileiras, 75% da Bacia Amazônica, existe uma grande incerteza nos estoques de carbono da biomassa acima do solo (AGB) armazenados na região. As estimativas de AGB existentes diferem significativamente entre si e há uma necessidade urgente de melhorá-las, uma vez que podem dar suporte às Comunicações Nacionais (NC) do Brasil para a Convenção-Quadro das Nações Unidas sobre Mudanças do Clima (UNFCCC) e Redução das Emissões por Desmatamento e Degradação florestal (REDD+). Seja para NC, REDD+ ou para a modelagem de emissões de carbono, as partes interessadas, os tomadores de decisão e os cientistas devem decidir qual produto, conjunto de dados ou combinação de dados de AGB usar, de acordo com sua disponibilidade, escala e cobertura. Com o objetivo de suprir esta demanda, neste estudo, avaliamos as lacunas de dados espaciais de AGB da floresta na Amazônia brasileira. Para isso, fizemos uma extensa revisão e análise da cobertura dos conjuntos de dados disponíveis. As conexões entre as partes interessadas foram feitas usando a *social network analysis*. Além disso, analisamos a variabilidade dos mapas de AGB em função de diferentes fatores ambientais (solo, vegetação, topografia e clima). Foram feitas também análises estatísticas e das diferenças entre os mapas de AGB e, com uma avaliação espacial multicritério, produzimos um mapa das lacunas de dados de AGB para a floresta amazônica brasileira. A cobertura espacial de AGB e os dados LiDAR aéreos mostram grandes áreas sem informação e, mesmo que as partes interessadas tenham conexões, poucos conjuntos de dados estão disponíveis. Ao quantificar os mapas de AGB e a variabilidade dos dados de campo em múltiplos fatores ambientais, fornecemos elementos valiosos para a compreensão dos dados de AGB atuais em função do clima, dos solos, da vegetação e da geomorfologia. As principais diferenças entre os mapas são encontradas ao lado dos rios (principalmente o rio Amazonas), no Amapá, no nordeste do Pará e nos estados amazônicos do centro e norte, coincidindo com áreas de maior AGB. O mapa de lacunas de dados espaciais de AGB da floresta, que se refere a locais sem dados de campo ou LiDAR e também onde os mapas da AGB diferem mais, mostram as áreas prioritárias para futuras avaliações de AGB na Amazônia brasileira. Este estudo é uma ferramenta útil para os formuladores de políticas e as diferentes partes interessadas que trabalham na AGB, que terá que devem decidir quais dados ou produtos da AGB devem usar para Comunicação Nacional, REDD + ou modelagem de emissões de carbono.

Palavras-chave: Amazônia. Floresta tropical úmida. Carbono**.** Biomassa acima do solo. REDD+. Fatores ambientais.

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# LIST OF ABBREVIATIONS AND ACRONYMS

AGB: Aboveground biomass

ALS: Airborne laser scanning

ATTO: Amazon Tall Tower Observatory

CCST: Earth System Science Center

CFI: Continuous Forest Inventory

DBH: Diameter at breast height

EBA: Estimativa de Biomassa na Amazônia, subproject 7 of Remote Sensing Environmental Monitoring of the Amazon Project

Embrapa: Brazilian Agricultural Research Corporation

FAO: Food and Agriculture Organization of the United Nations

GHGs: Greenhouse gases

INPA: National Institute of Amazon Researches

INPE: National Institute for Space Research of Brazil

IPCC: Intergovernmental Panel on Climate Change

LAI: Leaf area index

LBA: Large Scale Biosphere-Atmosphere Experiment in Amazonia

LiDAR: Light Detecting and Ranging

MRV: Monitoring and Measurement, Reporting and Verification

MCT: Minister if Science and technology of Brazil

MMA: Minister of Environment

NC: National Communication on Greenhouse gases to the UNFCCC

NDVI: Normalized Difference Vegetation Index

NFI: National Forest Inventory

PRODES: Deforestation Calculation Program

RAINFOR: Amazon Forest Inventory Network

REDD+: Reducing Emissions from Deforestation and Forest Degradation, and the Role of Conservation of Forest Carbon Stocks, Sustainable Management of Forests and Enhancement of Carbon Stocks

SMCE: Spatial multicriteria evaluation

SNA: Social Network Analysis

SRTM: Shuttle Radar Topography Mission

TEAM: Tropical Ecology, Assessment, and Monitoring Network

TREES: Tropical Ecosystems and Environmental Sciences Laboratory

UNFCCC: United Nations Framework Convention on Climate Change

CONTENTS

# 1 INTRODUCTION

The Amazon forest is a region of global interest from various perspectives, including biodiversity content and distribution, ecosystem services, climate change, biosphere-atmosphere interactions, agricultural production, socio-economic alternatives and indigenous knowledge. In the late 1980s, Brazil, as host of almost 2/3 of the Amazon forest area, implemented a remote sensing survey strategy to map changes in land use and land cover in the region as a policy mechanism and as a strategy to enforce environmental legislation and reduce deforestation and also as a tool to support social-environmental advances in the region. The Amazon Deforestation Calculation Program (PRODES) (INPE, 2015) was implemented as a yearly mapping of clear-cut forest clearing and has provided the longest series of tropical forest monitoring in the world to date. This historical series has supported the Brazilian position in international forums and opportunities, such as the Intended National Determined Contributions (UNFCCC, 2015) and the Reducing Emissions from Deforestation and Degradation (REDD+) mechanism (UNFCCC, 2014a). One critical piece of information for several of these actions, that is associated with mapping the land cover change, is forest biomass (AGUIAR et al., 2012; HARRIS et al., 2012b).

Accurate biomass estimates are relevant information for National Communications (NC) under the United Nations Framework Convention on Climate Change (UNFCCC), and for carbon emission estimates from deforestation (BACCINI et al., 2012; MCT, 2016). Nonetheless, biomass quantification has many methodological challenges, such as: accessibility, long distances and high costs on biomass measurements. Considering the complexity of structure diversity, wood density and dynamics of tropical forest, allometry get very complex and variable (SAATCHI, 2015).

Obtaining carbon and biomass estimates in the Brazilian Amazon is quite challenging. The large extension and particularities of its forest had determined that most of the existing biomass estimates differ significantly between each other. Carbon content estimates vary from 39 Pg C to 93 Pg C (HOUGHTON et al., 2001; SAATCHI et al., 2011; NOGUEIRA et al., 2015). There is also a large variation in aboveground biomass

(AGB) across the Brazilian Amazon Basin (FEARNSIDE, 1997; HOUGHTON et al., 2001; MALHI et al., 2006; SAATCHI et al., 2007) and between ground plots and remote sensing data (MITCHARD et al., 2014; SAATCHI et al., 2015). The lack of accessibility to most of the data from ground plots (forest inventories at the local level) and local-scale environmental data (soil and climate information), may be pointed as one of the key factors that determines the markedly divergent estimates of Amazon forest carbon density patterns visible in different AGB maps.

In the Brazilian Amazon, the total stock of AGB has been estimated from several sources, including forest inventory plots and remote sensing approaches (SAATCHI et al., 2011, 2015; BACCINI et al., 2012). Given the complexity and diversity of landscapes in tropical forest areas, remote sensing is one of the best tools for estimating AGB properties at large scales and in inaccessible areas, such as the scale of the Amazon (SAATCHI et al., 2011, 2015). Remote sensing methods have been used successfully in the tropics; but these techniques are still limited by the number and distribution of available plots of forest inventory data, to be able to ensure a proper validation and calibration of remote sensing products and spatial extrapolation methods (MITCHARD et al., 2014; SAATCHI et al., 2015).

Differences in remote sensing products and ground data have resulted in great discrepancies in the spatial distribution in different AGB maps (MITCHARD et al., 2014; OMETTO et al., 2014), showing the existence of considerable spatial uncertainties in the biomass estimates, highlighting the need to study these aspects (OMETTO et al., 2014). In order to tackle the uncertainty associated to biomass estimates, the IPCC guidelines on GHGs (IPCC, 2006) suggest to use environmental factors maps to find classes or stratums were the AGB is similar (stratification). Nonetheless, stratification has many methodological challenges, such as choosing, the proper environmental factors maps in function of the scale, classification schemes and quality (IPCC, 2006; ANGELSEN et al., 2012).

Considering all these, we can see that there is an urgent need to improve biomass estimations to support the recent Brazilian commitments in the context of climate change. These aspects are a growing concern in the scientific and political community and a progressive evolution is expected (MMA, 2015; FEARNSIDE, 2016). However, immediate decisions are made by using the current and available AGB databases and environmental factors maps. Whether for NC, REDD+ or for the carbon emissions modeling, stakeholders, policy makers and scientist have to decide which AGB product, dataset or combination of data to use, based on its availability, scale and coverage.

In this study, we assessed coverage of AGB datasets, and variability, similitudes and differences between the AGB maps. Complementarily to this, relations between different stakeholders working on AGB in the Brazilian Amazon were identified. Also, by quantifying the AGB maps and RadamBrasil field data variability within different environmental factors, we provide valuable elements for understanding the current AGB data in function of climate, soils, vegetation and geomorphology maps. Thus, joining these previous analyses we have obtained a forest AGB spatial data gaps map, which refers to places with no ground or LiDAR data, where the AGB maps differ the most. In other words, we assessed priority areas for further AGB assessments in the Brazilian Amazon.

## 1.1 Objectives

### 1.1.1 General objective

The aim of the study is to assess forest aboveground biomass spatial data gaps across the Brazilian Amazon

### 1.1.2 Specific objectives

- Evaluate the coverage of existing AGB data across the Brazilian Amazon forest.
- Analyze the AGB maps variability within different environmental factors maps.
- Assess the differences between AGB maps.
- Produce a spatial AGB data gaps map for the Brazilian Amazon forest.

## 1.2 Research questions

- Is the coverage of the AGB datasets sufficient for estimating the Brazilian Amazon forests biomass?
- Is there any relation between the AGB maps and the environmental factors maps?
- Where are the main differences between the AGB maps?
- Where are the AGB spatial data gaps in the Brazilian Amazon forests?

# 2 HOW MUCH IS KNOWN ABOUT BIOMASS IN THE BRAZILIAN AMAZON FOREST

## 2.1 Quantifying Amazon forest biomass

Forest biomass is estimated from *in situ* sampling (field surveys) and remote sensing. *In situ* sampling can be divided *in situ* destructive direct biomass measurements and *in situ* non-destructive biomass estimates. The first consists in harvesting trees, drying them, and weighting the biomass (GTOS, 2009). While the second, also known as biomass plots design, refers to stem (and sometimes crown) measurements in a number of plots and its conversion to biomass by using particular equations or conversion factors (GTOS, 2009), examples of the second are Brown and Lugo, (1992) and Brown, (1997). Remote sensing biomass estimation is based in the amount of microwave, optical or infrared radiation reflected or scattered by the vegetation (GTOS, 2009).

Biomass maps are derived from field data estimates, sometimes combined with remote sensing data (calibrated and validated with field biomass data) or expansion factors (Baccini et al., 2012; Saatchi et al., 2011).

### 2.1.1 *In situ* sampling and allometry

*In situ* sampling refers to a destructive direct biomass measurement which consists in harvesting the tree, dry the samples, and weight the biomass for each tree compartments (GTOS, 2009). This intensive and costly labor work is necessary to develop the biomass allometry equations (BROWN, 1997; HIGUCHI et al., 1998; CHAVE et al., 2005), to extrapolate the biomass sample data (*in situ* and remote sensing) to larger areas with similar characteristics (e.g. stratums) (GTOS, 2009).

Also, allometry refers to statistical relationships to estimate forest biomass that includes data from destructive sampling (tree parameters as volume, density etc.) and the development of equations or expansion factors to get biomass from measurable tree parameters as the diameter at breast height (DBH) and/or height. For example: The equation of AGB developed by Higuchi et al., (1998), used a database of 315 destructive sampling trees also considering dominant height, according to Lima, (2010), who used fallen trees to developed local volume equations in other sites of the Brazilian Amazon; The highly known below ground biomass (BGB) equations of Silva, (2007), used more than 130 trees roots measurements to get an equation which relate AGB and BGB; At tropical scale, Brown, (1997) developed an AGB equation for broadleaf forests using data from 371 harvested trees; Chave et al. (2005) developed equations using 2410 trees from the tropics (5 sites in Brazil). These equations are employed in many biomass maps (SAATCHI et al., 2011; BACCINI et al., 2012). Also, the height-diameter relationships, considering environmental factors, geographic location, and forest structure, were explored by Feldpausch et al. (2011) and the incorporation of tree height as relevant variant in AGB estimations to reduce uncertainty in (FELDPAUSCH et al., 2012). Finally, FAO has been gathering the worldwide forest allometry online database (www.globallometree.org) (HENRY et al., 2013).

### 2.1.2 *In situ* non-destructive biomass estimates (sampling plots)

Biomass non-destructive *in situ* estimates, consist in measuring tree parameters as DBH in sampling plots, and using allometric equations and expansion factors to extrapolate the biomass data to unit ground area, or stratum (PEARSON; WALKER; BROWN, 2005; GTOS, 2009). The sampling plot design is the most common method used to estimate forest biomass data collected from trees, (DBH) in several of plots; then this data is extrapolated to a larger area (e.g. vegetation stratum) (PEARSON; WALKER; BROWN, 2005). Depending on the objectives of the measurements (i.e. forest inventory, REDD project, etc.) the type, number and location of plots will vary (PEARSON; WALKER; BROWN, 2005).

Stratification is recommended to reduce sampling cost and efforts, and increase the statistical robustness of a forest biomass assessment. Stratification consist of dividing the project area into subpopulation (stratums) that form homogenous units according to the variable of interest. In the case of forest, the variable is AGB (PEARSON; WALKER; BROWN, 2005; IPCC, 2006). For example, to measure forest carbon content (≈50% of the AGB biomass), the IPCC (2006) recommends to stratify forest area into homogenous units, considering environmental factors maps as climate, soil, vegetation and relief with similar biomass content.

According to the IPCC, (2006), there are five carbon pools to consider when quantifying biomass in forest: AGB, BGB, dead wood, litter, and soil organic matter. Most of the forest inventories take into account only woody AGB and the rest of the carbon pools are inferred, from allometric equations and expansion factors (RADAMBRASIL, 1983). Other forest inventories and REDD+ projects, measure all the carbon pool in the plots (NFI, 2016).

### 2.1.3 Field plots networks in the Brazilian Amazon

AGB plots have been established by many institutions and networks in the Brazilian Amazon. The RadamBrasil project conducted one of the first large-scale forest inventories aiming at commercial trees between 1973 to 1983 (NOGUEIRA et al., 2015). The project measured all the trees greater or equal to 31.83 cm of DBH. RadamBrasil dataset is widely used for generating biomass maps (MCT, 2004, 2010; NOGUEIRA, 2008; NOGUEIRA et al., 2015).

The National Institute of Amazon Researches (INPA) aims to promote scientific knowledge of the Brazilian Amazon region, focusing on tropical forest management (between many other science topics) (LIMA, 2010; HIGUCHI, 2015). INPA`s Tropical Forestry Department has been monitoring Amazon forest since the 1980`s, with many large projects such as LBA, Jacaranda, Bionte, Carbon Dynamics of Amazonian Forests Project (CADAF), etc. Also, INPA administrates the Forest Experimental Station (Estação Experimental de Silvicultura Tropical EEST) that includes the Cuieiras biological reserve in the ZF-2 and also studies the Ducke forest reserve in Manaus. INPA is working in a continuous forest inventory (CFI) of the Amazonas State that started with the CADAF project, with permanent and temporal plots. In these plots, all trees with more than 10 cm DBH and between 5 and 10 cm DBH (natural regeneration) are measured; common tree names, epiphytism presence and stem quality are documented (LIMA, 2010). Many of the INPA´s plots are part of the Amazon Forest Inventory Network (RAINFOR) and Tropical Ecology, Assessment and Monitoring Network (TEAM) networks.

Since 2002, RAINFOR has been monitoring forest biomass structure and dynamics in the Amazon Basin and gathering these data to understand the relationship with environmental factors such as soil and climate (MALHI et al., 2002; PEACOCK et al., 2007). RAINFOR network, gathered plots across the Amazon Basin with a field protocol systematic measurements of DHB, tree status and tree death, with some plots varying from 10 to 30 years old (PEACOCK et al., 2007). The TEAM network works on tropical forest ecosystem services, biodiversity, climate and land cover change in tropical forest, with plots in two sites in the Brazilian Amazon: LBA site managed by INPA and Ferreira Penna Scientific Station in Caxiuanã, where AGB is measured periodically in all stems larger than 10 cm DBH (trees, lianas, palms, and tree ferns) (TEAM NETWORK, 2016). The average AGB per plot of RAINFOR and TEAM networks are available online at (http://www.forestplots.net/).

Since 2013, the Brazilian National Forest Service is in charge of the National Forest Inventory (NFI) directed at generating information on forest resources (natural and plantations) every 5 years (NFI, 2016). The NFI started its systematic sampling design (forest and other land use classes), with the establishment of sampling units (or plots) in a grid of 5 x 5 km for the Amazon biome (20 x 20 km grid for other biomes). In each sampling unit, all trees with more than 10 cm of DBH were measured in sub-sampling units (20 x 50m) and trees with more than 40 cm of DBH in other subsampling units. The NFI collected data also from trees from 5-10 cm of DBH, herbaceous vegetation, litter and soils (30 to 50 cm of deep). However, few areas will not be considered in this inventory due to accessibility (NFI, 2016).

Another network with biomass plots, conceived with the objective of assessing the impacts of environmental changes on tropical ecosystems using remote sensing and field surveys, is the Tropical Ecosystems and Environmental Sciences Laboratory (TREES) located in the National Institute for Space Research (INPE).

The Sustainable Landscapes Brazil project, focused on airborne LiDAR and degraded forest, uses ground plots to calibrate the empirical relations between Airborne Laser Scanning (ALS) and Aboveground Biomass (AGB) in the Brazilian Amazon (LONGO et al., 2016; SATO et al., 2016). They collect field data from many networks (DOS-SANTOS; KELLER, 2016a; SUSTAINABLE-LANDSCAPES, 2016); plots have been monitored and some re-measured. Other institutions and networks working with forest biomass plots are the Emílio Goeldi Museum of Pará, with the Ferreira Penna scientific station in the Caxiuanã National Forest, with forest biomass measuring plots and a Flux tower, also related to the LBA and constantly monitored by networks as TEAM and RAINFOR between others. Since 1973, the Brazilian Agricultural Research Corporation (Embrapa), part of the Ministry of Agriculture, Livestock, and Food Supply, has a wide range of activities and projects related to tropical agriculture in all Brazilian biomes at different scales (EMBRAPA, 2016). Embrapa has been monitoring also managed forests through the Tropical Managed Forests Observatory. Embrapa Acre has also biomass plots and LiDAR experiences. Redeflor has permanent plots in the Amazon using the same measuring and monitoring methods and works with institutions, networks, universities, and forest concessions that have permanent plots in the Amazon.

### 2.1.4 Remote sensing AGB estimates

Remote sensing satellite methods have been used to determine forest cover at coarse scale through optical sensors, as Landsat and MODIS, calculating vegetation index as Normalized Difference Vegetation Index (NDVI), and Leaf area index (LAI). However, the advent of active airborne remote sensing techniques at intermediate scale brings the possibility to acquire tridimensional information about the vegetation. Airborne remote sensing like Radar and LiDAR allows to quantify changes in three dimensional forest structure and canopy functional traits in tropical forest at landscape scale (ASNER; MASCARO, 2014; HENRY et al., 2015). Radar data has been used in the Brazilian Amazon (SANTOS et al., 2003; BISPO et al., 2014; TREUHAFT et al., 2015) and, the RadamBrasil project used airborne radar images and photographs (RADAMBRASIL, 1983). As mentioned above, since 2012 the Sustainable Landscapes project has been working with LiDAR airbone biomass data, also the Earth System Science Center (CCST)/INPE has implemented the Improving Biomass Estimation Methods Project under the Amazon Fund and it already has 612 transects off LiDAR flights all along de Brazilian Amazon Biome.

Terrestrial LiDAR (or ground-based LiDAR) is opening a new way of getting allometry from nondestructive estimates through the laser pulses transmitted from an active sensor installed in a tripod. TLS can assess the forest structure in a three-dimensional way, it enables direct estimates of complete tree volume (CALDERS et al., 2014). There are some experiences using TLS in tropical forest in Brazil (PALACE et al., 2016).

### 2.1.5 Forest AGB maps

Forest biomass maps are a combination of field data, allometry, and sometimes remote sensing data and modeling. The decisions on each of these components and the scale (level of detail and study area) influence the final AGB quantity and distribution within the map (OMETTO et al., 2014).

There are many AGB maps covering the Brazilian Amazon forests. The first attempt to get a ABG came from Houghton et al., (2001), which analyzed if biomass estimates yield similar spatial patterns of quantity and distribution of biomass, finding that the biomass estimates vary by more than a factor of two and no patterns of agreement are found on the regions of high and low biomass. One of the first biomass maps that considered basal area and AGB interpolation was from Malhi et al., (2006), with 227 forest plots accounting for variations in basal area and wood density combined with environmental factor maps.

Since 2004, Brazil has been preparing AGB maps to report GHGs in the NC of Brazil to the UNFCCC, which is now in its third version. The MCT (2010) AGB map, employed in the second NC of Brazil and in the REDD + baseline, was an improvement of the initial NC (MCT, 2004); both AGB maps were based on 1682 RadamBrasil project plots (RADAMBRASIL, 1983). There were few differences between the methods, expansion factors and equations used to estimate AGB in the first and second NC (TEJADA, 2014). The vegetation map used in the NC (MCT, 2010) was based on reclassification of the IBGE, (2004) and MMA, (2006b) vegetation maps without transition vegetation classes. The average biomass for each forest vegetation physiognomy was estimated (using literature references for vegetation physiognomies without field data) and the biomass values per vegetation class were extrapolated in each of the RadamBrasil volumes. The AGB extrapolation of the RadamBrasil volumes sheets lead to a highly questioned biomass distribution in quadrants in the resulting AGB map (OMETTO et al., 2014; TEJADA, 2014). Therefore, for the third NC (MCT, 2016), Brazil prepared another biomass map (MCT, 2015, 2016) also based in RadamBrasil plots (1682), but using the biomass equations of BROWN, (1997) instead of Higuchi et al., (1998). The expansion factors of Nogueira, 2008 were used to include tress with DBH smaller than 31.83 cm and the method to extrapolate biomass was the Inverse Distance Weighting (MALHI et al., 2006).

One of the first biomass maps published, and available online was the map of Saatchi et al., (2007), which reports a biomass extrapolation method using field plots data and remote sensing for the Amazon basin. Then, Saatchi et al., (2011) published a biomass map at tropical scale for the year 2000 modeling the spatial distribution of biomass, with a combination of global forest height data, several remote sensing databases, field data and more than 3 million LiDAR shots. The authors used 4079 AGB plots at pan tropical scale (707 in the Brazilian Amazon) to calibrate GLAS (spaceborne LiDAR) height to AGB and for the BGB they used diverse equations and expansion factors. After processing field data and GLAS LiDAR observations (to sample AGB) and developing a relationship of both: Lorey's heigh and AGB and AGB to BGB; they mapped the biomass stratifying forest structure using a data fusion model based on Maximum Entropy (MaxEnt) at 1 km spatial resolution (SAATCHI et al., 2011). To stratify forest types, they used LAI to developed landscape data (forest structure and seasonality), NDVI and backscatter metrics, resulting in a carbon density map. Saatchi et al., (2011) carbon map has been widely used as it is available online been the base of the carbon emission estimates from deforestation map of Harris et al., (2012).

Baccini et al., (2012) carbon density map, also available online at pan tropical scale, is focused on C density estimates of AGB live woody vegetation using remote sensing multispectral surface reflectance, and 483 field plots co-located with LiDAR "footprints (the number of plots in the Brazilian Amazon are not mentioned). They used an specifically designed protocol for the optimal integration of field and satellite data and modeled ABG with RandomForest approach and biomass equations. The carbon map, for the years 2007-2008, have a spatial resolution of 500 m. Baccini et al., (2012) and Saatchi et al., (2011) biomass maps has been compared in many publications (MITCHARD et al., 2013, 2014; SAATCHI et al., 2015; AVITABILE et al., 2016), as an interactive web application that compares both maps (http://carbonmaps.ourecosystem.com).

The comparison of Mitchard et al., (2014) of Saatchi et al., (2011) and Baccini et al., (2012) maps has generate controversy, due to the comparison of remote sensing measurements with field plots of RAINFOR network (SAATCHI et al., 2015). To compare both maps, they created a field data based AGB map using kriging to allow a spatial comparisons (MITCHARD et al., 2014). AGB was calculated using parameters of the moist tropical forest model (CHAVE et al., 2005), height estimated from the region specific Weibull models (FELDPAUSCH et al., 2012) and wood density (CHAVE et al., 2009).

The biomass map of Nogueira et al., (2015) is based on a stratification approach, as well as the previous AGB map experiences (NOGUEIRA et al., 2008), but in this case, they consider more plots (2702 plots instead of 2317) from RadamBrasil project (RADAMBRASIL, 1983), assigning the average biomass value to 29 vegetation classes or stratums (IBGE, 2012). For this map, Nogueira et al. (2015) used the vegetation map of SIVAM, (2002), employing allometric equations for bole-volume estimates for dense and open forests (NOGUEIRA et al., 2008). They covered the Legal Amazon and the Amazon biome without using any remote sensing product or data, employing only allometric equations, expansion factors of previous studies

Finally, the biomass pan tropical map published by Avitabile et al., (2016), a combination of Saatchi et al., (2011) and Baccini et al., (2012) maps, resulted in a fuse pant-tropical AGB biomass map at 1 km resolution. They used a data fusion approach with bias removal and weighted linear averaging, which spatializes the biomass pattern of a reference data set, including reference biomass maps and reference plots in the Brazilian Amazon. They also used RAINFOR network (http://www.forestplots.net/) and Sustainable Landscapes project (SUSTAINABLE-LANDSCAPES, 2016) field data.

The AGB maps of MCT, (2004, 2010) and Nogueira et al., (2008, 2015) are maps that pretend to represent the potential biomass, not considering degradation and secondary vegetation. On the other hand, the AGB maps of Saatchi et al., (2007, 2011), Baccini et al. (2012) and Avitabile et al., (2016) are maps which represent current biomass for specific years, which consider forest degradation and secondary vegetation.

## 2.2 Environmental factors and forest biomass

Forest biomass is influenced by forest distribution, structure and environmental factors such as climate, soil and relief and various processes (QUESADA et al., 2012; PAN et al., 2013). The main environmental factors to be considered in biomass estimates will depend on the scale of analysis; for example, climate is determinant in forest distribution and structure at global scale. At landscape scales the topography and soil type can modify the climate influence forming local microclimates (PAN et al., 2013). At global scale, climate has been used as the main environmental indicator of forest distribution, due to correlation between forest geographical patterns and climate (as the well-known Holdrige`s life-zone system) (IPCC, 2006; PAN et al., 2013). At regional scale, the influence is more complex. According to Saatchi, (2015), a roboust relationship between soil and climate and forest biomass for predicting regional variations does not exist yet. In tropical latitudes, the range in temperature is low, so the biomass is influenced by the precipitation, sometimes expressing a relationship between forest and rain.

At the Brazilian Amazon scale, precipitation could be a better forest indicator than temperature, but as in other scales, climate is a strong indicator of forest biomass distribution (PAN et al., 2013). Soil type has enormous influence in growth and stem turnover rates of forest biomass productivity, according to the nutrient availability gradient, mainly phosphorus and nitrogen along the Amazon (DAVIDSON et al., 2004; QUESADA et al., 2012). In the case of topography, mountains influence local climate affecting the wind circulation and precipitation (PAN et al., 2013). The gradients of elevations are strong related to forest structure and functioning (ASNER; MASCARO, 2014).

The environmental factors maps such as climate, soil, ecological zone, are the base for forest biomass stratification according to the IPCC (2006). The stratifications can be made under 3 levels of methodological complexity called tiers (IPCC, 2006). Tier 1, used at global level, requires IPCC default assumptions, methods and data (SIMONS et al., 2001). Tier 2, used at regional scale, requires default assumptions and methods, and country specific data (IBGE, 2001; MMA, 2006b). The high complexity level of tier 3 used at regional or local scales, requires country specific assumptions, methods and data (MMA, 2006a).

There are many maps of environmental factors related to climate, soils, topography and vegetation in the Brazilian Amazon. CPTEC from INPE is the Brazilians Institution that provides climate data. Many climate maps can also be downloaded from the PMM: Precipitation Measurement Missions (https://pmm.nasa.gov/trmm) from the NASA, and WorldClim - Global Climate Data (www.worldclim.org/). Soil, vegetation, climate, and relief maps at national scale (Brazil) and regional scale (for the Brazilian Amazon) are available online on the IBGE and MMA websites (www.ibge.gov.br and http://mapas.mma.gov.br/i3geo/datadownload.htm). MMA has also a page online where the maps can be visualized (http://mapas.mma.gov.br/i3geo/mma/openlayers.htm?3j668cndkqi2p9e6hqr6d8tni5).

## 2.3 Forest biomass and international climate agreements

The emissions from land use and cover change (LUCC), especially from deforestation and forest degradation, are the second source of total $CO_2$ emissions responsible for climate change (IPCC, 2014). The most known climate change mitigation mechanism under the UNFCCC, related to forest, is REDD+. The idea behind REDD+ is that countries that are willing and able to reduce emission from deforestation should be financially compensated for doing so (UNFCCC, 2014b). Under the first commitment period of the Kyoto Protocol (2008-2012) of the UNFCCC, REDD had not been credited, REDD was first established as a separate climate change mitigation mechanism in 2005 during the COP[1] 11 and in 2007 at the COP 13 in Bali (thus not accessible for existing internationally regulated carbon markets) (UNFCCC, 2014b). The urgent need to take further meaningful action to REDD in developing countries in the post-2012 international climate policy was also acknowledged (UNFCCC, 2014a; MMA, 2015). Since then, in every COP the REDD political and methodological issues were addressed, until reaching REDD plus which has a broader scope, including forest conservation and enhancement of carbon stocks.

The expected agreement on the post-2012 negotiations for a post Kyoto Protocol in the COP 15 did not succeed. Only the COP 19 in Warsaw (2013) had a significant breakthrough, referring to reducing emissions from deforestation and forest degradation, the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries (REDD+), providing guidance on a variety of

[1] Conference of the Parties (COP) is the supreme decision-making body of the is the supreme decision-making body of the Convention (UNFCCC) (http://unfccc.int/bodies/body/6383.php)

measures related to REDD (UNFCCC, 2015). Finally, in 2016 the Paris Climate agreement was signed highlighting the political support for the existing internationally agreed frameworks as the Warsaw Framework for REDD+. Other great advances of the Paris agreement were mitigation, finance and international markets were part of the Paris agreement between other great advances (MMA, 2015).

Brazil as a part of the UNFCCC, has been participating actively in REDD+ in its different phases. Brazil was the first country to implement the Warsaw Framework and has already submitted the Forest Reference Emission Levels (FREL) for the Amazon and Cerrado biomes, which are under review by the UNFCCC. After approval and publishing of FREL in the Lima REDD+ Information Hub (online platform where are all the official documents submitted by country referring REDD+ activities), FREL will start Fundraising for results based on payments (MMA, 2015). Also, Brazil has been presenting the NC for the UNFCCC (MCT, 2004, 2010, 2016) and right now is preparing the fourth NC.

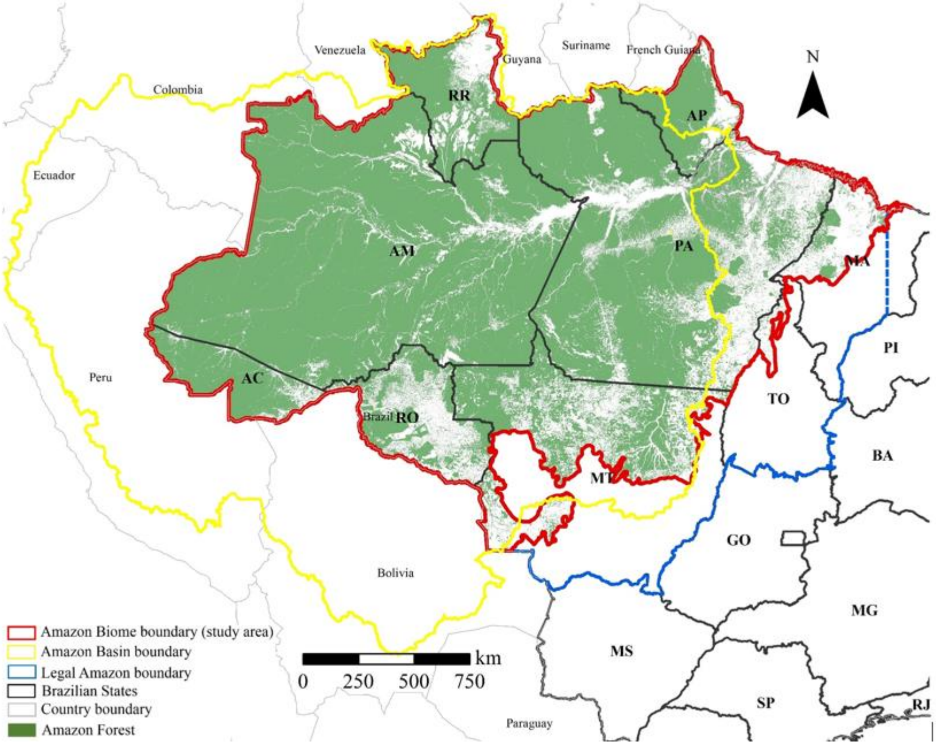
# 3 METHODS AND MATERIALS

## 3.1 Study area

The Brazilian Amazon Basin has an area of 3,869,653 $km^2$ and covers 60% of the entire Amazon Basin, which is shared with six other countries (Fig. 3.1). In Brazil, the Amazon can also be referred by using the term Brazilian Legal Amazon, which refers to a legally designated border surrounding an area with a similar ecological structure and economic, political and social conditions, totalizing more than 5 million $km^2$. Another term used in this context is the Brazilian Amazon biome, corresponding to an area of 4,196,943 $km^2$ covered by similar vegetation and fauna, defined by physical conditions such as geography, lithology and climate that generate unique biological diversity (IBGE, 2004a).

This study focuses only on the forest area considered as intact by PRODES in 2014 (~3,139,172 $km^2$) (INPE, 2015) within the Brazilian Amazon biome (IBGE, 2004a). This definition covers nine Brazilian States: Acre, Amapá, Amazonas, Pará and Roraima States, 98.8% of Rondônia, and 54% of Mato Grosso, 9% of Tocantins, and 35% of Maranhão States (Fig. 3.1). The scale of the study will be regional (Amazon biome scale).

Figure 3.1 - Study area, covering forests in the Brazilian Amazon biome.

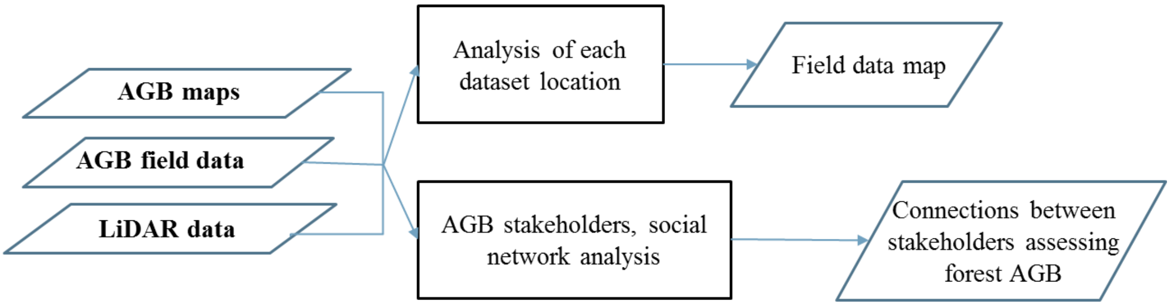



Source: The 2014 forest mask data are from INPE (2015) and the Brazilian Biomes from (IBGE, 2004a).

## 3.2 Existing AGB data distribution

This section is divided into three different components: (1) extensive review of existing AGB datasets; (2) social network analysis to establish the links and interrelations between the identified stakeholders; and (3) identification of the coverage of the AGB datasets. These components are shown in Figure 3.2.

Figure 3.2 - Coverage analysis of AGB data flowchart.




Source: by the author.

### 3.2.1 Review of existing AGB datasets

We performed an extensive review of the available datasets related to AGB (such as data from forest inventories, field plots, AGB maps, remote sensing products and maps of environmental factors) in the Brazilian Amazon. Scientific literature, institutional web pages, and reports were used, but also institutions and researchers were contacted. All data were organized in a georeferenced dataset in a geographic information system environment.

### 3.2.2 Social network analysis between the AGB stakeholders

During the review and interviews, the links between institutions, programs and stakeholders were mapped and analyzed through social network analysis (SNA) (SCOTT, 2012). The SNA counted the number of connections between the stakeholders, placing more weight on stakeholders with more connections. Table 3.1 shows all the stakeholders connections identified during the review.

Table 3.1 - AGB stakeholders connections of the social network analysis.

| Id | Label | Attribute | Number of total connections | Connections | |
|---|---|---|---|---|---|
| 1 | UFRA | National Universities | 1 | 14 | 15 |
| 2 | ESALQ | National Universities | 1 | 15 | 58 |
| 3 | UFOPA | National Universities | 3 | 58 | 40 |
| 4 | UFMT | National Universities | 1 | 58 | 36 |
| 5 | UFAM | National Universities | 1 | 40 | 16 |
| 6 | UFCG | National Universities | 1 | 40 | 17 |
| 7 | USP | National Universities | 2 | 40 | 19 |
| 8 | Leeds | International Universities | 1 | 40 | 20 |
| 9 | UNICAMP | National Universities | 2 | 40 | 18 |
| 10 | New Hampshire | International Universities | 1 | 40 | 21 |
| 11 | Landcaster | International Universities | 2 | 40 | 22 |
| 12 | Oxford | International Universities | 1 | 40 | 23 |
| 13 | Exeter | International Universities | 1 | 40 | 24 |
| 14 | RadamBrasil | Projects | 4 | 40 | 25 |
| 15 | LBA | Projects | 11 | 58 | 25 |
| 16 | CADAF | Projects | 1 | 36 | 24 |
| 17 | Tacape | Projects | 1 | 36 | 23 |
| 18 | Chichuá | Projects | 1 | 41 | 38 |
| 19 | Pronex | Projects | 1 | 41 | 36 |
| 20 | INCT-Madeiras | Projects | 1 | 42 | 41 |
| 21 | PPOPE | Projects | 1 | 42 | 28 |
| 22 | Piculus | Projects | 1 | 42 | 36 |
| 23 | Bionte | Projects | 2 | 42 | 38 |
| 24 | Jacaranda | Projects | 2 | 56 | 54 |
| 25 | Geoma | Projects | 2 | 14 | 56 |
| 26 | AMAZONICA | Projects | 1 | 55 | 39 |
| 27 | ESECAFLOR | Projects | 1 | 15 | 37 |
| 28 | PPBio | Projects | 2 | 15 | 36 |
| 29 | FATE-Amazonia | Projects | 2 | 15 | 48 |
| 30 | Go Amazon | Projects | 2 | 15 | 51 |
| 31 | EBA | Projects | 9 | 15 | 26 |
| 32 | Amazon FACE | Projects | 2 | 15 | 38 |
| 33 | ATTO | Projects | 4 | 15 | 39 |
| 34 | Silva Carbon project | Projects | 1 | 15 | 33 |
| 35 | Sustainable Landscapes | Projects | 18 | 39 | 28 |
| 36 | EEST-INPA/ZF2 (Manaus-Amazonas) | Main sites | 9 | 14 | 46 |
| 37 | Humaita Forest Reserve (Acre) | Main sites | 2 | 14 | 54 |
| 38 | Floresta Nacional Tapajós (Santarem-Pará) | Main sites | 5 | 57 | 38 |
| | | | | 35 | 36 |
| | | | | 53 | 38 |
| | | | | 53 | 42 |
| | | | | 54 | 39 |
| | | | | 30 | 39 |
| | | | | 27 | 39 |
| | | | | 43 | 1 |
| | | | | 43 | 2 |
| | | | | 43 | 3 |
| | | | | 43 | 4 |
| | | | | 43 | 5 |
| | | | | 43 | 44 |
| | | | | 43 | 55 |
| | | | | 43 | 37 |
| | | | | 53 | 30 |
| | | | | 51 | 53 |
| | | | | 51 | 31 |
| | | | | 53 | 12 |

| Id | Label | Attribute | Number of total connections |
|---|---|---|---|
| 39 | Caxiuanã national forest (Belen-Pará) | Main sites | 6 |
| 40 | Amazon State Forest Inventory | Main networks | 11 |
| 41 | TEAM | Main networks | 7 |
| 42 | RAINFOR | Main networks | 22 |
| 43 | Redeflor | Main networks | 9 |
| 44 | National Forest Inventory | Main networks | 14 |
| 45 | FAO FRA | Institutions | 3 |
| 46 | National Forest Service | Institutions | 5 |
| 47 | TNC | Institutions | 1 |
| 48 | NASA | Institutions | 3 |
| 49 | IPAM | Institutions | 2 |
| 50 | IMAZON | Institutions | 1 |
| 51 | INPE | Institutions | 8 |
| 52 | IBAMA | Institutions | 1 |
| 53 | TREES | Institutions | 10 |
| 54 | Embrapa | Institutions | 7 |
| 55 | Emilio Goeldi Museum | Institutions | 4 |
| 56 | IBGE | Institutions | 3 |
| 57 | ICMBio | Institutions | 1 |
| 58 | INPA | Institutions | 10 |
| 59 | SDS | Institutions | 1 |
| 60 | US Forest Service | Institutions | 2 |
| 61 | UFRN | National Universities | 1 |
| 62 | UFPR | National Universities | 1 |
| 63 | UNIR | National Universities | 1 |
| 64 | UNEMAT | National Universities | 2 |
| 65 | IDEFLOR | Institutions | 1 |
| 66 | Conservation International | Institutions | 1 |
| 67 | UFAL | National Universities | 1 |
| 68 | UFAC | National Universities | 1 |
| 69 | Tropical Managed Forests Observatory | Main networks | 1 |

Connections

| | |
|---|---|
| 53 | 13 |
| 31 | 35 |
| 31 | 11 |
| 31 | 53 |
| 31 | 58 |
| 31 | 54 |
| 31 | 46 |
| 31 | 36 |
| 31 | 44 |
| 35 | 48 |
| 35 | 34 |
| 35 | 10 |
| 35 | 31 |
| 35 | 53 |
| 35 | 50 |
| 35 | 54 |
| 35 | 49 |
| 35 | 51 |
| 35 | 47 |
| 35 | 60 |
| 35 | 46 |
| 35 | 9 |
| 35 | 8 |
| 35 | 7 |
| 35 | 6 |
| 41 | 66 |
| 44 | 56 |
| 44 | 60 |
| 44 | 51 |
| 44 | 58 |
| 44 | 54 |
| 44 | 61 |
| 44 | 62 |
| 44 | 63 |
| 44 | 64 |
| 44 | 65 |
| 44 | 67 |
| 44 | 8 |
| 44 | 68 |
| 45 | 44 |
| 45 | 46 |
| 51 | 30 |
| 69 | 54 |

National Universities · International Universities · Projects · Main sites · Main networks · Institutions

The Label column is the name of the stakeholder; Attribute is the type of stakeholder; Number of total connection is the sum of the connection; while Connections show each connection between two stakeholders using their respective Id. Acronyms are in A1.
Source: by the author.

### 3.2.3 Coverage of AGB field data

To analyze the coverage of the AGB plots (that we had access) over the Brazilian Amazon forest we calculated a distance from the current field plots map.

It is difficult to determine the area covered by the AGB plots since different protocols result in different plot sizes, and not all networks have this information available. To estimate the sampled area by plots in the Brazilian Amazon forest, a regular plot size of 1 ha of the plots with no sampled area was assumed. In the case of sampled area of LiDAR transects, we used available information from EBA and Sustainable Landscapes projects (EBA, 2016; SUSTAINABLE-LANDSCAPES, 2016).

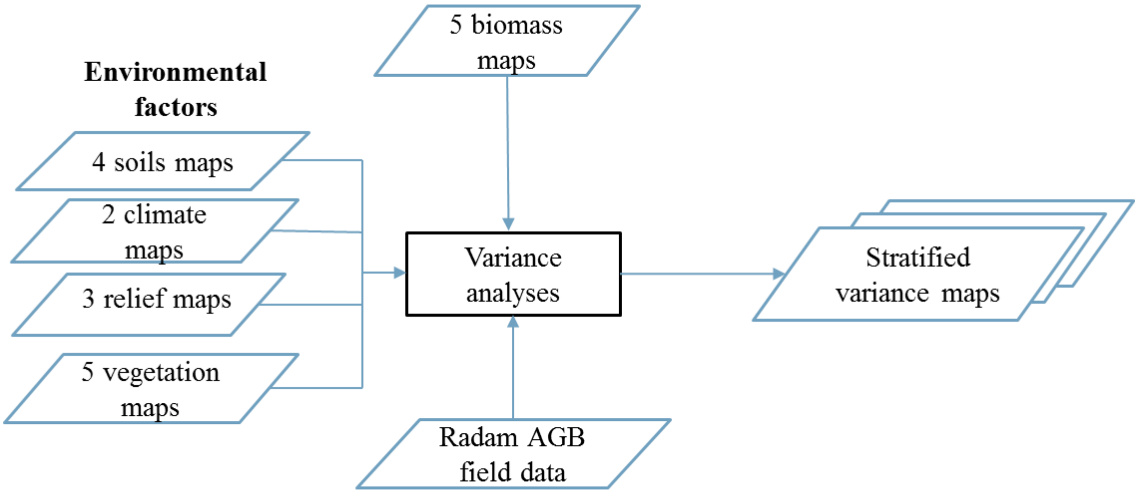
## 3.3 Forest AGB variability and environmental factors analyses

In order to achieve this objective, we chose five of the nine AGB maps, selecting the latest map of authors with more than one map (SAATCHI et al., 2011; NOGUEIRA et al., 2015; MCT, 2016), assuming improvements in methods and data quality are shown in the latest version. Also, we included maps from Baccini et al., (2012) and Avitabile et al., (2016). Mitchard et al., (2014) map was not considered for the analysis, since their purpose was not to produce a biomass map itself, but a kriging extrapolation of RAINFOR AGB plots to compare with remote sensing data.

The biomass maps of Saatchi et al., (2011), Baccini et al., (2012) and Avitabile et al., (2016) considered only AGB and not BGB. MCT, (2016) and Nogueira et al. (2015) considered both AGB and BGB. In order to compare these maps, we subtracted BGB using the expansion factor and ratios by class of vegetation, methodology used in both maps, according to Nogueira et al., (2008) (Fig. 3.3).

The AGB maps variability within the different environmental factor maps (soil, vegetation, topography and climate) was measured in terms of population variance (considering every environmental factor map –Eq. 1) and stratified variance (considering the different classes or stratums of each environmental factor map -Eq 2) (Fig. 3.3). The stratified variance of RadamBrasil field plots were also calculated in every environmental factor map, as a way to compare the variance of field data versus the variance of AGB maps as shown in Figure 3.3.

Figure 3.3 - Forest biomass variability and environmental factors analysis flowchart.




Source: by the author.

**Equation 1. Global variance**

$$\sigma^2 = \frac{\sum (X_i - \mu)^2}{N}$$

Where: $X_i$ is an observation; $\mu$ is the population mean; and $N$ is the population size

**Equation 2. Stratified variance**

$$s^2 = \sum_{i}^{n} \left( {n_j}/{N} \right)^2 * s_j$$

Where: $s^2$ is the total stratified variance, $n$ is the stratum $j$ size, $N$ is the population size and $s_j$ is the sample variance of the stratum $j$

The logic behind using the variance, is that in each class of an environmental factor map, there is an homogenous class or stratum. Therefore, the AGB should be more similar in a class than in the entire map. Stratify could help reduce cost and efforts in sampling large areas, calculating the number of AGB plots needed to represent each class (PEARSON; WALKER; BROWN, 2005; IPCC, 2006).

We carried out the stratified variance analysis to identify in which environmental factors maps (and classes) the AGB maps and RadamBrasil have less variance. Considering that an environmental factor class with low AGB variance (more similar) represent better the AGB classes.

Since multiple sources of information, regarding environmental factors maps, are available, after a preliminary analysis, the following maps were chosen (Table 3.2).

Table 3.2 - Environmental factors map used in the analyses.

| Environmental factor | Maps | Description | N° of classes* | Scale | Spatial resolution | Download site |
|---|---|---|---|---|---|---|
| **Vegetation** | Vegetation map of Brazil (IBGE; USGS, 1992) | Vegetation map, digitalized by the U.S. Geological Survey | 36 | National | 1: 5,000,000 | http://mapas.mma.gov.br/mostratema.php?temas=vegetacao |
| | Vegetation map (SIVAM, 2002) | Based on RadamBrasil project map, actualized by SIVAM project | 80 | National | 1: 250,000 | http://mapas.mma.gov.br/i3geo/datadownload.htm |
| | Vegetation map of Brazil (IBGE, 2004b) | Includes forest, non-forest formations according to plant physiognomies, also used remote sensing | 38 | National | 1: 5,000,000 | ftp://geoftp.ibge.gov.br/informacoes_ambientais/ |
| | Brazilian Biomes Vegetation Cover (MMA, 2006b) | PROBIO project gather all the other vegetation mapping initiatives with more detailed satellite images analysis | 298 | Regional | 1: 250,000 | ftp://geoftp.ibge.gov.br/mapeamento_sistematico/banco_dados_georeferenciado_recursos_naturais/amazonia_legal/ |
| | Vegetation Physiognomies of Brazil (MCT, 2010) | Map used in the National Communications of Brazil, grouping the transition classes of IBGE (2004) and PROBIO vegetation maps | 28 | Regional | 1: 250,000 | http://sirene.mcti.gov.br |
| **Soils** | Soil map of Brazil (IBGE, 2001) | The soil map used the new Brazilian system of soil classification of EMBRAPA and published by IBGE and EMBRAPA. | 32 | National | 1: 5,000,000 | http://mapas.mma.gov.br/i3geo/datadownload.htm |
| | Soils of Legal Amazon (MMA, 2006a) | This map is part of the Environmental and Ecological Zoning (ZEE) of the Legal Amazon | 26 | Regional | 1: 250,000 | http://mapas.mma.gov.br/mapas/aplic/zee/atlas_zee_openlayers.htm?1c421f54qsjnqii3frjqj03vq2 |
| | Soil carbon stocks (BERNOUX; VOLKOFF; CERRI, 2002) | Soil carbon stocks is a combination of IPCC global soils with vegetation classes | 42 | National | - | - |
| | Soil map (QUESADA et al., 2011) | Soil maps with particular reference to RAINFOR sites. Basin wide distributions of soils under forest vegetation | 13 | Regional | 1: 5,000,000 | - |
| **Climate** | Water deficit (FONSECA et al., 2016) | Cumulative water deficit (1988-2014) calculate using TRMM data. | 14 | Global | 0.25° | https://mirador.gsfc.nasa.gov |
| | Climate Map of Brazil (IBGE, 2002) | Thematic map of Brazil, data from 1978 with adaptations in 2002, dry months | 5 | National | 1: 5,000,000 | http://www.ibge.gov.br/english/geociencias/default_prod.shtm |
| **Topography** | Relief map 2002 (MMA, 2002) | Relief map 2002 (Compartimentos do relevo do Brasil – 2002) | 32 | National | 1: 250,000 | http://mapas.mma.gov.br/i3geo/datadownload.htm |
| | Relief units map of Brazil (IBGE, 2006) | Temathic map, based on RadamBrasil project and improved with remote sensing products | 69 | National | 1: 5,000,000 | ftp://geoftp.ibge.gov.br/informacoes_ambientais/geomorfologia/vetores/brasil/ |
| | Geomorphology of the Legal Amazon (MMA, 2006a) | This map is part of the Environmental and Ecological Zoning (ZEE) of the Legal Amazon | 64 | Regional | 1: 250,000 | http://mapas.mma.gov.br/mapas/aplic/zee/atlas_zee_openlayers.htm?1c421f54qsjnqii3frjqj03vq2 |

* The number of classes refers the study area and the classification chose in each map.
Source: by the author.

The climate map of Brazil is an update of a previous 1978 climate map (NIMER, 1979) that reflects the climate zones, thermic regions and wetness expressed by dry months (IBGE 2002). The information taken from this map is the number of dry months within a year that reflect the precipitation occurrence and distribution. Another map that also considers many climate attributes is the water deficit map, that shows the cumulative water deficit from 1988 to 2014 calculated by Fonseca et al. (2016), using TRMM data. In both maps, climate data represents the average and not inter-annual variability.

The Soil map of Brazil (IBGE, 2001), is part of the IBGE wall-to-wall maps at 5 million scale, use the Embrapa soil classification and it was made converting the RadamBrasil, (1983) data in a digital format. The Soils of the Legal Amazon map was produced by the Ministry of Environment of Brazil (MMA) with the Environmental and Ecological Zoning project (ZEE), in the context of the Scenarios for the Legal Amazon project and the IBGE (MMA, 2006a). The ZEE produced a geographic database for the legal Amazon at 1: 250,000. This map was made taking into account soil texture and relief. At the Amazon basin scale, the Soil map of QUESADA et al. (2011) was made with references of RAINFOR forest sites with soil data. The Soil Carbon Stocks map of Bernoux et al. (1997) links vegetation and global soil classes (IPCC, 2006) for the Brazilian Amazon, so this map has already a relationship with vegetation.

The Relief map, is part of the 4$^{th}$ IBGE Atlas with 32 relief units (MMA, 2002). The Relief Units map, based on geomorphology classes at 5 million scale, includes new mapping techniques using remote sensing images (Landsat and Radar) of SIVAM project for the Legal Amazon, to improve the original classification (IBGE, 2006). Also in the context of the ZEE project, you find the Geomorphology map of the Legal Amazon (MMA, 2006a) at 1: 250 000, which also used satellite images.

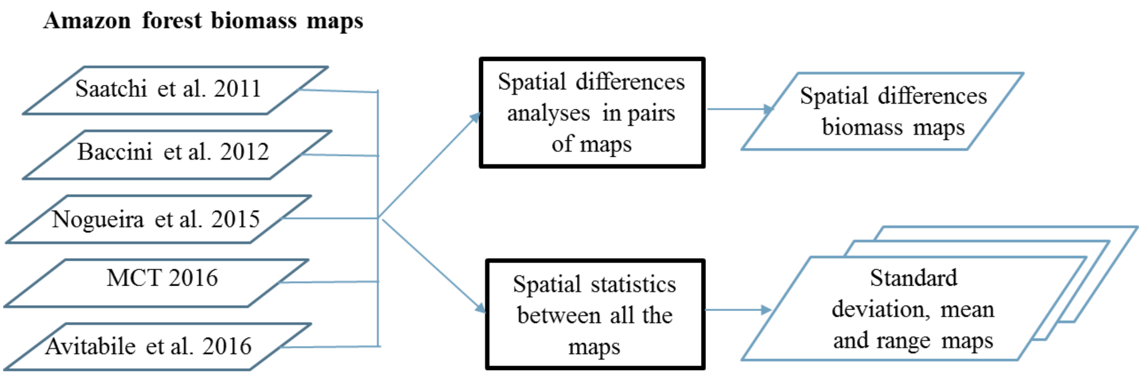
The first large-scale vegetation mapping based on Radar images and field work was accomplished during the RadamBrasil project (RADAMBRASIL, 1983) that was later updated based on the SIVAM (Sistema de Vigilância da Amazônia) project in 2002.

In 2004, IBGE published a wall-to-wall map series at 5 million scale including the Vegetation Map of Brazil (IBGE, 2004b) to reconstruct the original vegetation cover using the phytoecology-region bibliography and remote sensing (Landsat 5-TM) parameters which evidence relief, hydrology and vegetation cover to delimit better the stratums or classes. The Brazilian Biological Diversity Project (PROBIO) gathers all the previous efforts of SIVAM, Radambrasil, PRODES and IBGE (between many others) with more satellite images and SRTM data in order to generate a unique geographic database for the Amazon biome with IBGE and the MMA (MMA, 2006b). The PROBIO map with 298 vegetation classes is an excellent choice for local-scale studies. Finally, for the Brazilian NC, the vegetation map of IBGE (2004) and the PROBIO maps were used disregarding vegetation transition classes resulting in a reclassified vegetation physiognomies map.

### 3.4 AGB maps differences analysis

In this section, we performed the differences analyses of five of the AGB maps (SAATCHI et al., 2011; BACCINI et al., 2012; NOGUEIRA et al., 2015; AVITABILE et al., 2016; MCT, 2016), in pairs of maps as shown in Figure 3.4. We generated 10 AGB differences maps. Then, we calculated the cell statistics of all the AGB together, to obtain the average, standard deviation and range, in order to summarize and map the tendencies of all the AGB maps (Fig. 3.4). The main result of this stage, is a map of the standard deviation along with all the inputs maps, showing most of the AGB differences that was used for further analysis.

Figure 3.4 - Differences analysis between AGB maps flowchart.



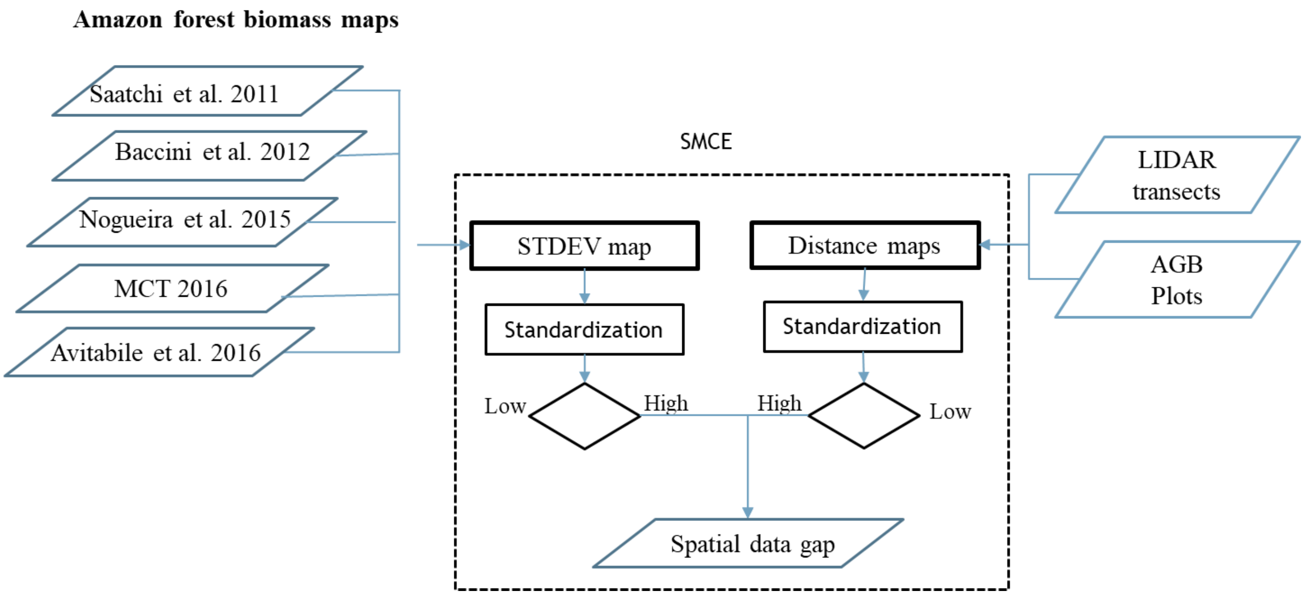

Source: by the author.

## 3.5 Forest AGB spatial data gaps map

Our final product is a forest AGB data gaps map. For this, we performed a spatial multicriteria evaluation (SMCE) in the GIS ILWIS environment (ALLARD M.J.; CARLOS R; ANN, 1988), using as inputs the distance maps from the LiDAR transects and AGB plots and the standard deviation map (Fig. 3.5). For the SMCE, all the input maps were previously standardized in order to make them fully comparable, converting the original values in a range from 0 to 1.

The distance and the standard deviation maps were conceived as a benefit factor, which, under the ILWIS-SMCE criterion means that the higher the value the more it contributes to the goal. In this case, the goal is to map the gaps of representativeness of AGB, including AGB maps and plots. Thus, areas with higher distance to sampling plots or LiDAR transect and with higher standard deviation are much likely to be considered as a gaps.

Figure 3.5 - Forest AGB spatial data gaps map flowchart, using a spatial multicriteria evaluation (SMCE)




Source: by the author.

# 4 RESULTS

## 4.1 AGB data coverage

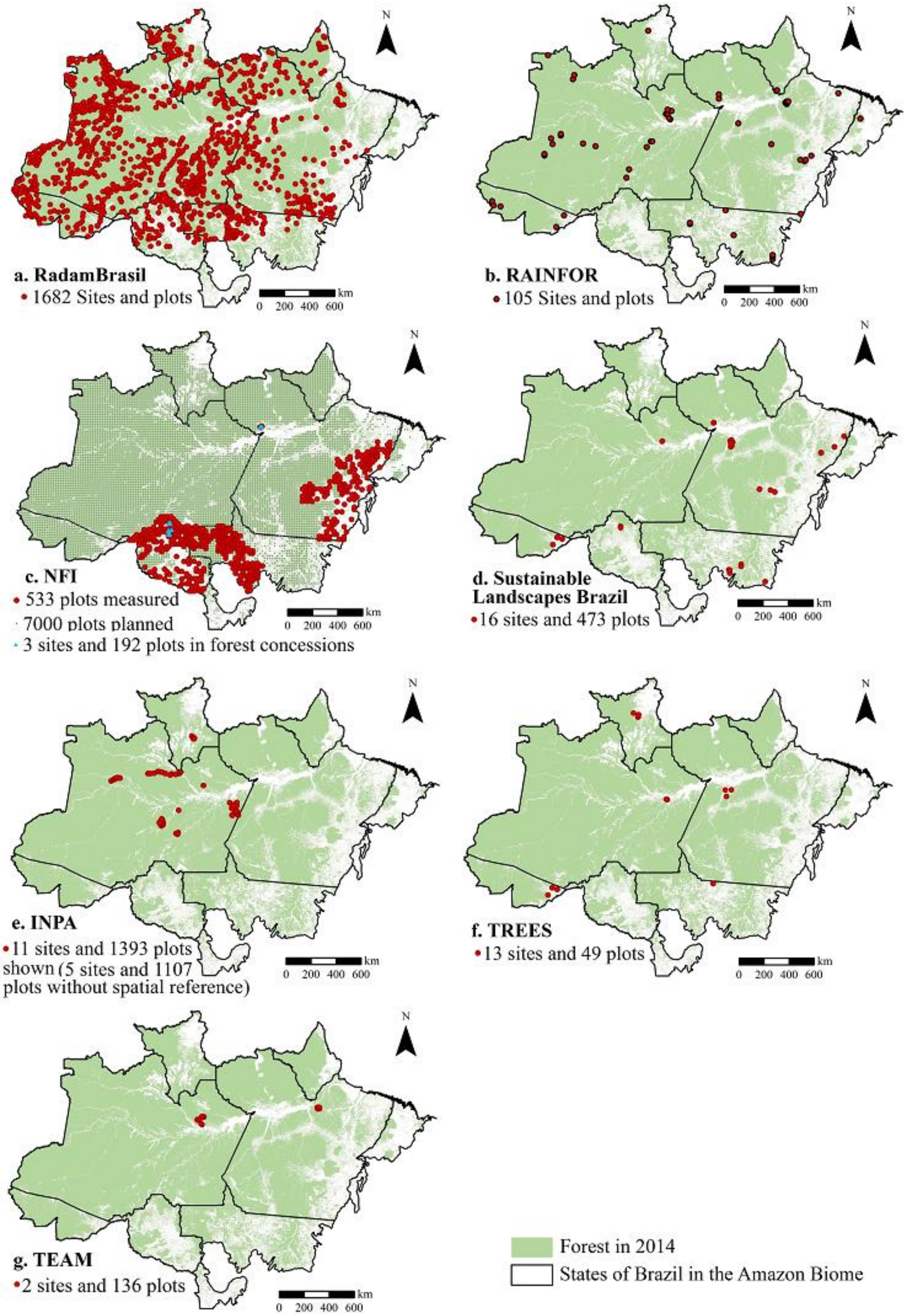
### 4.1.1 AGB datasets

Here we present the results of the AGB datasets assessment, which were systematized in figures and tables. This assessment helps us get the AGB field plots and LiDAR plots distribution and to understand the relationship within the stakeholders working with AGB.

#### 4.1.1.1 Field data

There are many forest AGB sampling plots and networks in the Brazilian Amazon, differing in their objectives, scale, type of data acquired, distribution, and the number of measurement sites. Five of these networks have regularly monitored data in these AGB plots (i.e. RAINFOR, Sustainable Landscapes, INPA, TREES and TEAM) while one performed measurements once between 1973-1980 (RadamBrasil), and the other one is currently performing measurements (NFI). The main characteristics of these networks are presented in Table 4.1 while the distribution of each network is shown in Figure 4.1.

Figure 4.1 - Distribution of forest AGB plots.




Red dots indicate the location of measurement sites, not representing its area.
(a) RadamBrasil; (b) RAINFOR; (c) National Forest Inventory; (d) Sustainable Landscapes Brazil; (e) INPA; (f) TREES; and (g) TEAM.
Source: (a) RADAMBRASIL, 1983; (b) http://www.forestplots.net/; (c) NFI, 2016; (d) SUSTAINABLE-LANDSCAPES, 2016; (e) personal communication; (f) TREES, 2016; and (g) TEAM NETWORK, 2016.

The RadamBrasil project (1973-1983) is composed of 2702 plots and focused on only commercial trees (RADAMBRASIL, 1983) (Fig. 4.1a). Despite the date of measurement (almost 30 years ago) and no biomass re-measurements, this dataset is widely used, for its extensive plots coverage (MCT, 2004, 2010, 2016, NOGUEIRA et al., 2008, 2015).

INPAS´s Forest Management Laboratory, also has extensive forest inventory and now is working on a Continuous Forest Inventory (CFI) of the Amazonas State, including more than 2500 forest AGB plots. Only those joining the RAINFOR network and TEAM are available online (HIGUCHI, 2015). The RAINFOR network monitors AGB in the Amazon Basin (413 plots), including 141 plots in the Brazilian Legal Amazon and only 105 in the Amazon Biome forest (Fig. 4.1b) (MALHI et al., 2002; PEACOCK et al., 2007). Also, the TEAM network has two sites in the Brazilian Amazon: one in Manaus and the other in Caxiuanã, with 136 plots (Fig. 4.1g). The INPE´s TREES laboratory has 49 plots, 17 of which are used to measure AGB (Fig. 4.1f) (the other plots are to measure fire impacts on forest), and the AGB data will be available through the RAINFOR website. The Sustainable Landscapes Brazil project focuses on airborne LiDAR data, using 473 AGB plots (DOS-SANTOS; KELLER, 2016a; SUSTAINABLE-LANDSCAPES, 2016) some their own and those from other networks to calibrate airborne laser scanning (ALS). The main advantages of the Sustainable Landscapes Brazil project are that their plots are new and the data is completely available online, allowing collaborations and partnerships (EBA project, Brazilian National forest service, among many others). Another network evaluating AGB is Redeflor, which has permanent plots in the Amazon (the spatial locations of the plots are unavailable), bringing together institutions such as Embrapa, networks, universities, and forest companies. Furthermore, the Amazon Tall Tower Observatory (ATTO) project has inventoried 12 plots (of 1 ha) in Manaus using also old AGB data from INPA and LBA (ANDREAE et al., 2015).

Finally, the Brazilian Forest Service is in charge of the NFI, where extensive and systematic sampling is performed in a grid of 5 x 5 km (in the Amazon biome). As of December of 2016, 533 sample plots (of 0.2 ha) have been completed among 7000 planned units for the Amazon Biome. Until now is not clear how the NFI data will be released (Fig. 4.1c) (NFI, 2016). The Brazilian Forest Service also has 192 permanent plots in forests concessions (Fig. 4.1c) (NFI, 2016).

Table 4.1 - Main sources of Brazilian Amazon AGB field data (networks and projects).

| Networks | Scale | Initial measurements/ Re-measurements | Total plots/Brazilian plots | Plots in the study area/ sampled area (ha) | Carbon pools measured | Availability | Web page |
|---|---|---|---|---|---|---|---|
| **Amazon Forest Inventory Network (RAINFOR)** | Amazon Basin | ~1960/ Yes | 413/ 141 | 105/ 405 | AGB | Yes, online | http://www.forestplots.net/ |
| **RadamBrasil** | Brazilian Amazon | 1973-1983/ No | 2702/ 2702 | 1682/ 1682 | AGB | Yes, online | http://sirene.mcti.gov.br |
| **Tropical Ecology Assessment and Monitoring (TEAM) Network** | Pantropical | 2002/ Yes | 1021/ 136 | 136/ 136 | AGB | Yes, online | http://www.teamnetwork.org/ |
| **Sustainable Landscapes Brazil** | Brazilian Amazon/ local (São Paulo, Santa Catarina) | 2012/ Yes | >500 | 473/115 | AGB | Yes, online | https://www.paisagenslidar.cnptia.embrapa.br/webgis// |
| **INPA-Amazonas Estate Forest Inventory** | Regional (Amazonas State), local (Acre, Pará, Roraima) | 1980/Yes | ND/2503 | 2503 plots/ND | AGB, few trees of BGB | No | https://www.inpa.gov.br |
| **Brazilian Forest Service:** | | | | | | | |
| **National Forest Inventory** | Brazil | 2013 -2017/ Yes | 15000/ 15000 | 533 (of 7000 planned)/ 107 | AGB, litter, soil, dead wood | No | http://ifn.florestal.gov.br/ |
| **Permanent plots in forest concessions** | Local (Rondônia and Pará) | 2010 | 192 | 192/ND | AGB | ND | http://www.florestal.gov.br/monitoramento |
| **Redeflor** | Brazil | ND | 800 | ND/ ND | ND | No | http://redeflor.net/ |
| **Tropical Ecosystems and Environmental Sciences Laboratory (TREES)** | Local (Acre, Rondônia, Alta floresta, Pará, Manaus) | 2012/ Yes | 60 | 49/ 17 | AGB | No | http://trees-research.weebly.com/ |

ND: No data; AGB: Aboveground biomass; BGB: Belowground biomass.
Source: by the author.

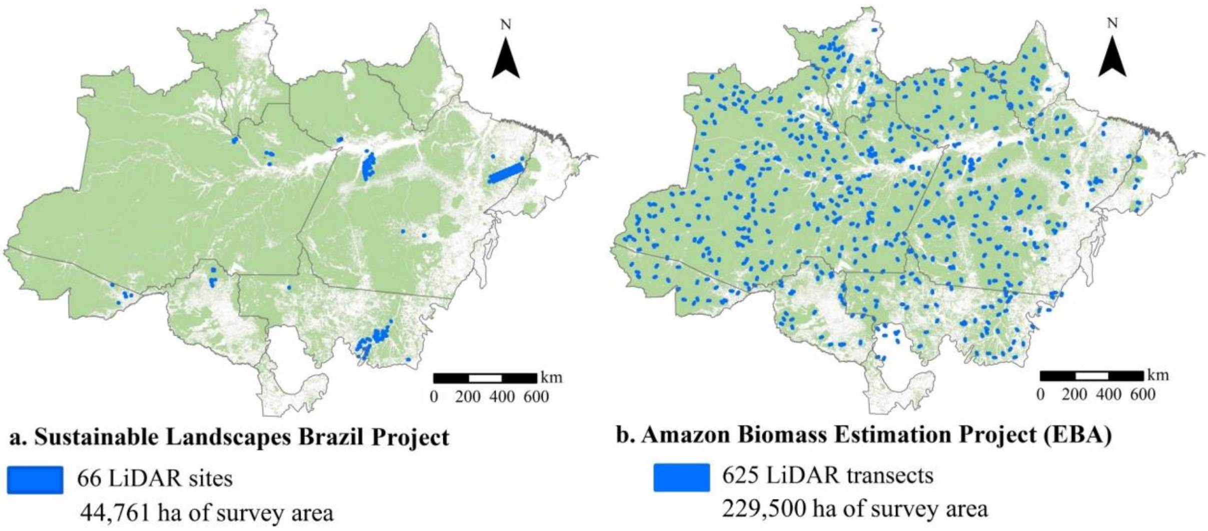
#### 4.1.1.2 Remote sensing data

The main remote sensing products using optical sensors such as Landsat and MODIS at the global level are Vegetation Tree Cover (HANSEN et al., 2003), GlobCover 2009 (ARINO et al., 2010) and GLC 2000 (BARTHOLOMÉ; BELWARD, 2005). There are also products that examine forest cover change at the pantropical scale (HANSEN et al., 2013), while PRODES addresses the scale of the Brazilian Amazon using Landsat, giving the official annual deforestation rate (INPE, 2015). Active sensors from satellite platforms, such as GLAS-LiDAR, have been used to generate AGB maps at a pantropical scale (SAATCHI et al., 2011; BACCINI et al., 2012).

The RadamBrasil project (RADAMBRASIL, 1983) also used airborne radar images and photographs to quantify natural resources, these information registries are available in 550 radar mosaics at a 1: 250,000 scale at the IBGE site (see Table 3.2).

Two projects are currently working with airborne LiDAR. The Sustainable Landscapes Brazil project has airborne LiDAR data (available at: https://www.paisagenslidar.cnptia.embrapa.br/webgis//) (DOS-SANTOS; KELLER, 2016b; SUSTAINABLE-LANDSCAPES, 2016). The total LiDAR survey area has reached 160,000 ha, and employed more than 470 field inventory plots until 2015 (Fig. 4.2a). The EBA project has 612 transects of 300 m x 12.5 km (375 ha) with LiDAR data in the first campaign in 2016 (Fig. 4.2b), with more 500 transects planned for 2017, EBA will use field data from many networks (between INPA, TREES, Sustainable Landscapes, NFI for calibration and validation (EBA, 2016) (EBA, 2016).

Figure 4.2 - LiDAR datasets

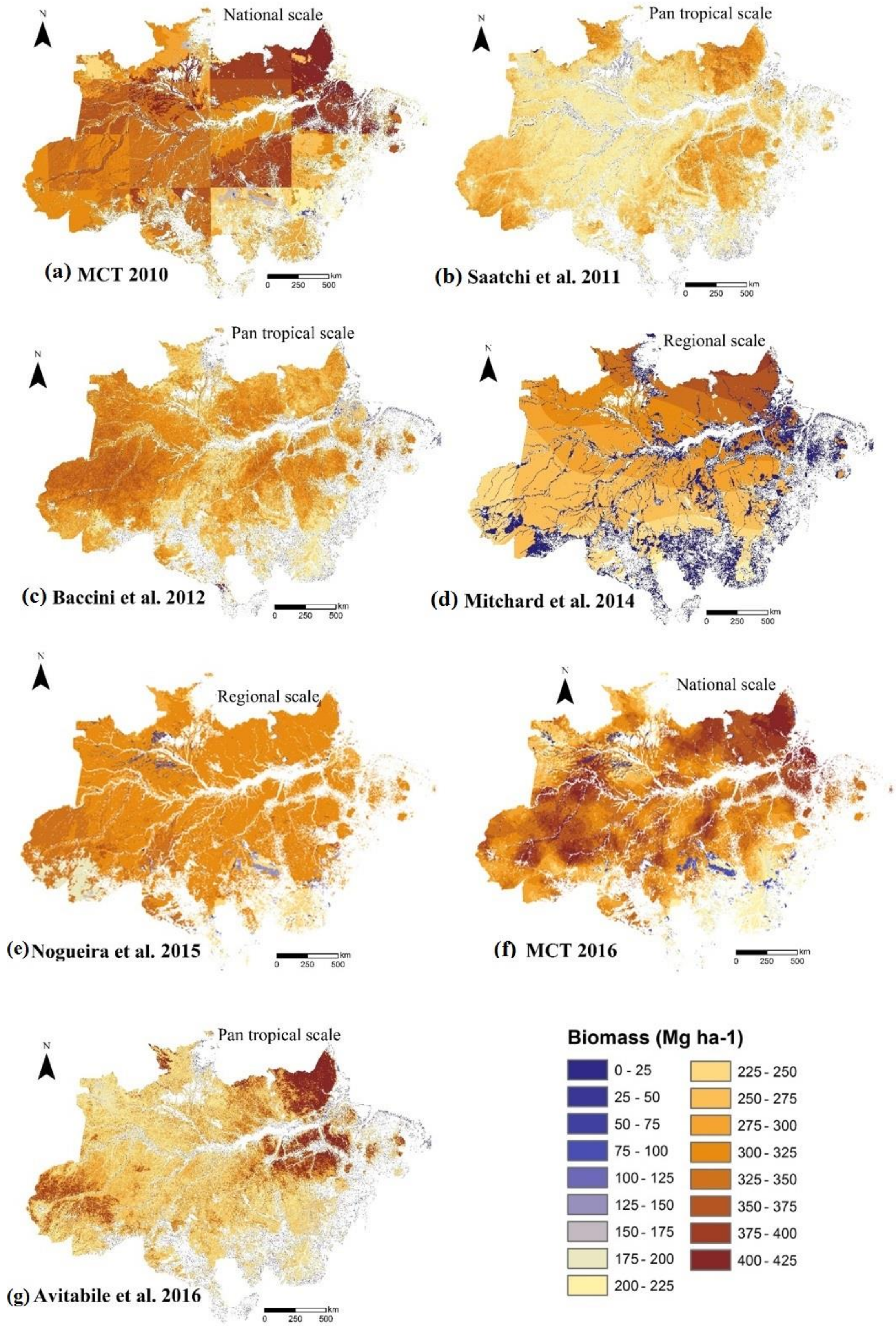



Source: (a) Sustainable Landscapes Brazil (DOS-SANTOS; KELLER, 2016b; SUSTAINABLE-LANDSCAPES, 2016); (b) Amazon Biomass Estimation subproject 7 (EBA, 2016).

#### 4.1.1.3 Forest AGB maps

The AGB maps for the Brazilian Amazon, show significant differences in both quantity and distribution (Table 4.2 and Fig. 4.3). For example, the AGB maps for NC of Brazil, differ a lot from the second to the third NC (Fig. 4.3a and 4.3f). In the second NC, the AGB map is the result of the aggregation of the mean AGB values per vegetation class, which were extrapolated in RadamBrasil volume sheets, leading to a gross quadrant-like AGB distribution, that do not represent the AGB distribution (OMETTO et al., 2014; TEJADA, 2014). For the third NC, different extrapolation methods, equations and expansion factors have been used leading to a different distribution of AGB (MCT, 2016). Nogueira et al., (2015), is another AGB map employing RadamBrasil field data also based on a stratification approach using mean AGB for a vegetation map classes (Fig. 4.3e, Table 4.2). These maps (MCT, 2004, 2010; NOGUEIRA et al., 2015), represent the potential biomass per vegetation class, without considering degraded or growing forests.

Figure 4.3 - AGB maps for the Brazilian Amazon using the same visual scale.




Source: by the author.

At the pantropical scale, because of its availability on line, the map of Saatchi et al. (2011), have been widely used (Fig. 4.3b, Table 4.2) and was employed as the basis for determining carbon emissions from the deforestation map of Harris et al., (2012). Another map constructed at the pantropical scale and available online (see Table 4.2) is the carbon density map of Baccini et al., (2012), which is based on multispectral surface reflectance and established field plots co-located with LiDAR footprints.

Many comparisons and combinations resulted from the maps of Saatchi et al., (2011) and Baccini et al., (2012) (MITCHARD et al., 2013, 2014; SAATCHI et al., 2015; AVITABILE et al., 2016). Mitchard et al., (2014) compared both maps with a kriging extrapolation of RAINFOR AGB field plots. Additionally, the fused pantropical AGB map of Avitabile et al., (2016) (Fig. 4.3g), a combination of 2 maps (SAATCHI et al., 2011; BACCINI et al., 2012) was obtained using a data fusion approach including field data from RAINFOR and the Sustainable Landscapes Brazil project (see Table 4.1).

Table 4.2 - Main characteristics of the Amazon forest AGB density maps.

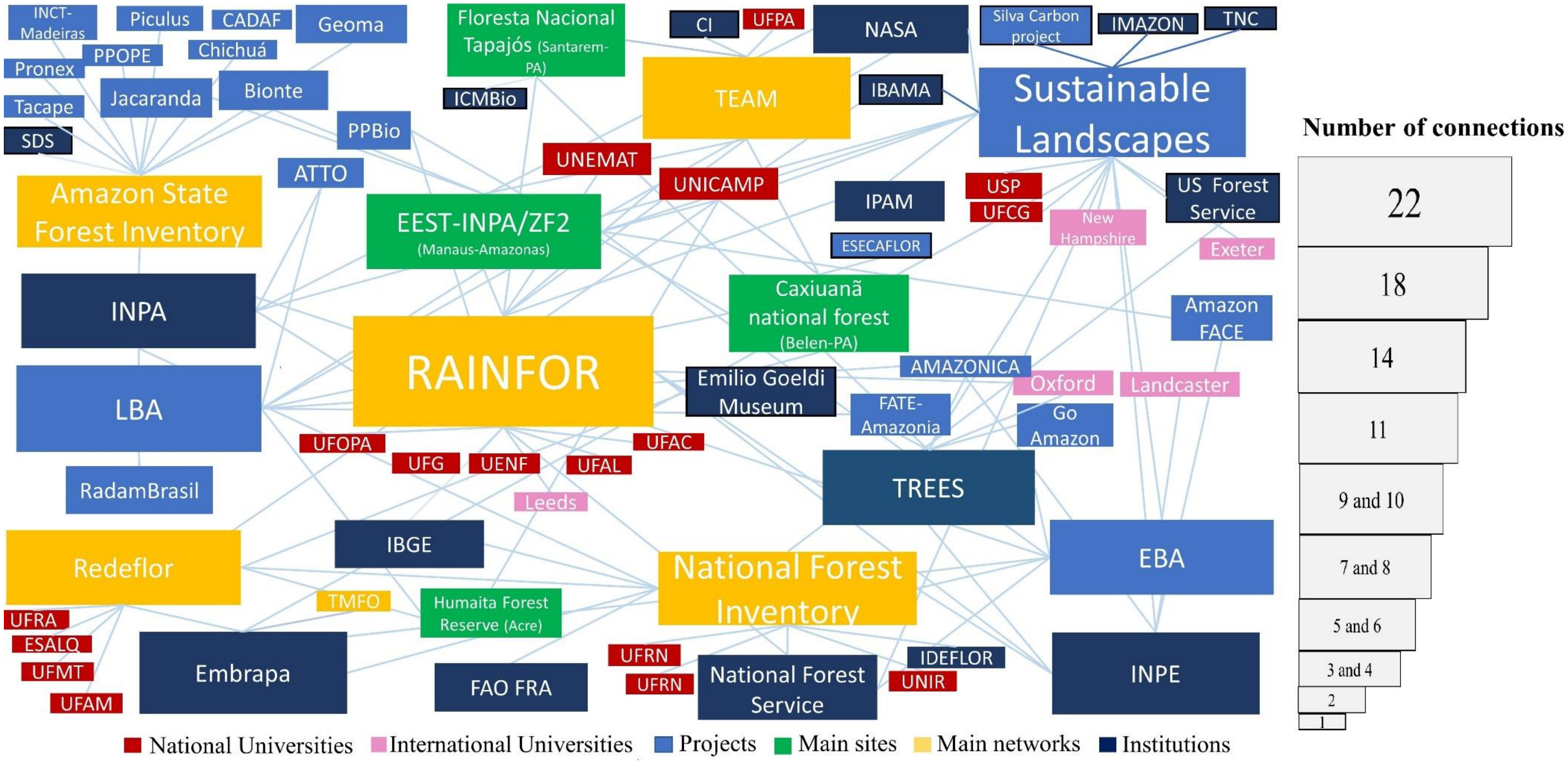
| Map | Scale | Spatial resolution | Temporal scale (year) | Field forest plots/ Source | Study area plots/ Sampled area (ha) | Remote Sensing products/ Other inputs | Model |
|---|---|---|---|---|---|---|---|
| Saatchi et al. (2007) | Amazon Basin | 1 km | 2000-2004 | 544/ Many Sources | ~361/ ~1633[d] | MODIS (NDVI, LAI, % tree cover), JERS-1 Radar, SRTM/ Vegetation map, Climate data (WorlClim) | Biomass classification approach |
| Nogueira et al. (2008) | Brazilian Amazon | 1 km (landscape level) | Only 1976 | 2879/ RadamBrasil and literature | 2879/ 2879 | No/ Vegetation map (IBGE, 2012) | None |
| MCT (2010) | Brazilian Amazon | 1 km (landscape level) | 1973-1983[a] | 1710[c]/ RadamBrasil and literature | 1682/ 1682 | No/ Vegetation (MCT, 2010), Soils (BERNOUX; VOLKOFF; CERRI, 2002) | None |
| Saatchi et al. (2011) | Pantropical | 1 km | 2000 | 4079[b] (493 for calibration)/ Many sources | ~707/ ~1770[d] | MODIS (NDVI, LAI, % tree cover), LiDAR from GLAS/ Forest height map | MaxEnt |
| Baccini et al. (2012) | Pantropical | 500 m | 2007-2008 | 283[b]/ Measured | No Data | MODIS, LiDAR from GLAS, SRTM | RandomForest |
| Mitchard et al. (2014) | Amazon Basin | 500 m | 1960-2013[a] | 413/ RAINFOR and TEAM | 105/ 404.6 | No/ Regions map based on geography and substrate origin | Kriging, inverse distance kernel |
| Nogueira et al. (2015) | Brazilian Amazon | 1 km (landscape level) | 1970[a] | 2317[c]/ RadamBrasil and literature | 2373/ 2317 | No/ Vegetation map (IBGE, 2012) | None |
| MCT (2016) | Brazilian Amazon | 1 km (landscape level) | 1973-1983[a] | 1682 plots/ RadamBrasil | 1682/ 1682 | No/ Vegetation (MCT, 2010), Soils (BERNOUX; VOLKOFF; CERRI, 2002) | Inverse Distance Weighting |
| Avitabile et al. (2016) | Pantropical | 1 km | 2000-2013[a] | 648/ RAINFOR, TEAM and Sustainable Landscapes | ~500/ No data | No/ High-resolution AGB maps | Fusion model |

a) Considering the date of the AGB field measurements; b) we did not have access to the location of the plots; c) in the case of RadamBrasil plots, we only have the location on 1682 plots; and d) this is an estimated number due to we do not have the area of each plot, only ranges.
RAINFOR: Amazon Forest Inventory Network; TEAM: Tropical Ecology, Assessment and Monitoring; MODIS: Moderate Resolution Imaging Spectroradiometer; NDVI: Normalized Difference Vegetation; LAI: Leaf area index; GLAS: Geoscience Laser Altimeter System; LiDAR: Light Detection and Ranging; SRTM: Shuttle Radar Topography Mission; and JERS-1: Japanese Earth Resources Satellite 1.
Source: by the author

### 4.1.2 Networks of AGB stakeholders

The results of the social network analysis are an attempt to understand the interrelationship between the different stakeholders working with AGB data. We found strong relationships between universities, research institutions, projects and sites, represented by the size of each box (more connections between the stakeholders, bigger the box size) as shown in Figure 4.4. The LBA, is one of the projects with more connections, which is well-known for its flux towers and AGB plots in ZF2 in Manaus, Tapajós in Santarem, Humaita in Acre and Caxiuanã in Belem, with highly studied sites shown in green in Figure 4.4. The INPA which coordinated the LBA, is now in charge of the Amazonas State CFI (in yellow of Fig. 4.4), gathering forest data from many projects (shown in the right corner of Fig. 4.4). Some plots of INPA and other projects are shared with RAINFOR, which has the largest number of connections (Fig. 4.4). RAINFOR has AGB plots throughout the Amazon Basin and many connections with other projects such as Sustainable Landscapes (also with many connections), TREES and EBA, and networks as TEAM. The National Forest Service, also visible in Figure 4.4 for its connections, is in charge of the NFI that started in the Amazon in 2014 field data collection through systematic sampling, in partnership with the EBA project and the Redeflor network, among others. Figure 4.4 is a first attempt to show the connections of the AGB networks that can be improved and modified with the participation of the stakeholders.

Figure 4.4 - Connections between stakeholders assessing forest AGB: networks, projects, institutions, universities and sites.




The relationships between the stakeholders are represented by the size of each box, more connections between the stakeholders, bigger the box size. A1 contains all the acronyms.
Source: by the author.

### 4.1.3 Coverage of AGB field data

Taking into account the current plots of the NFI and others reported in the various networks, there are at least 4224 plots in the Brazilian forest biome (Table 4.3). Among the total plots, 33% belong to INPA and 29% to RadamBrasil, followed by the current plots of the NFI (17%) and Sustainable Landscapes (11%), while the remaining networks are responsible for less than 5%.

Table 4.3 - AGB plots per network in the Brazilian Amazon forest biome (using the 2014 forest mask).

| | Field plots | | | | | | | | LiDAR transects | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Radam Brasil** | **RAIN-FOR** | **SL** | **INPA** | **TREES** | **NFI** | **TEAM** | **Total** | **SL** | **EBA** | **Total** |
| **Plots per network** | 1,362 | 105 | 473 | 1,374 | 49 | 725 | 136 | 4,224 | - | - | |
| **LiDAR Transects** | - | - | - | - | - | - | - | | a | 612 | - |
| **% of plots from the total** | 32 | 2 | 11 | 33 | 1 | 17 | 3 | 100 | - | - | |
| **Area of plots (ha)** | 1,362 | 405 | 115 | 1,374* | 17 | 145* | 136 | 3,553 | 44,761 | 229,500 | 274,261 |
| **Forest area** | | | | | | | | | | | 313,917,200 |
| **% of area from the total** | 0.00043 | 0.00013 | 0.00004 | 0.00044 | 0.00001 | 0.00005 | 0.00004 | 0.00113 | 0.01426 | 0.07311 | 0.08737 |
| **% of area of plots and LiDAR** | 0.088 | | | | | | | | | | |

RAINFOR: Amazon Forest Inventory Network; Sustainable Landscapes Brazil; TEAM: Tropical Ecology, Assessment and Monitoring; INPA: National Institute of Amazon Research; Tropical Ecosystems and Environmental Sciences Laboratory (TREES); and IFN: National Forest Inventory.

Note: In the case of INPA and RadamBrasil is not the total plots, only those with spatial location. In the case of the NFI, are those measured or in process of measurement and 192 plots of forest concessions.

* We assume 1 ha area of INPA plots. In the case the NFI we assume that the plot size of the NFI (0.2 ha) are the same for the plots of the forest concessions

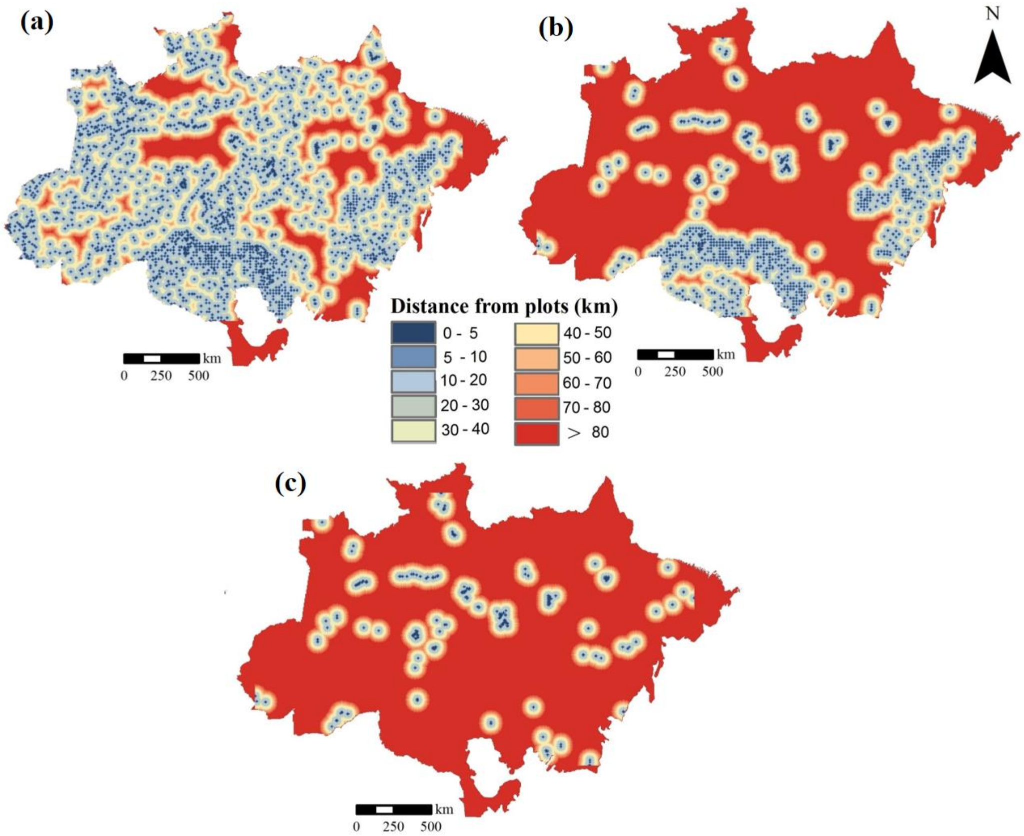
a. In the case of SL LiDAR data, they work with sites, not transects. They have 66 sites along the Brazilian Amazon.

Source: by the author.

It is difficult to determine the area covered by the AGB plots because different sampling protocols result in different plot sizes, and this information is not available for all networks. Assuming 1 ha plot area for those networks without plot area information (see Table 4.3) we observed that the AGB field plots cover only around 0.00113% of the total forest area of the Brazilian Amazon biome. Even though the airborne LiDAR transects have much more sampled area, they only cover 0.087% in total (0.014% SL and 0.08737% EBA) (Table 4.3). Considering both, AGB field plots and LiDAR data, only 0.088% of the Brazilian Amazon Biome is sampled, meaning less than 0.1% of the whole area.

The coverage of the current plots is shown in Figure 4.5 Areas in red indicate plots distance higher than 100 km, light blue areas indicate a distance of more than 10 km and blue dots show the distribution of AGB plots separated by a distance of 5 km or less, related to RadamBrasil and the systematic distribution of the NFI. In Figure 4.5b, we show the updated distribution of the AGB dataset (without RadamBrasil), indicating a large increase in the places with no plots data. The data sharing policy for the NFI is not yet well defined. However, Figure 4.5c represents the situation without the RadamBrasil and NFI plots and shows a considerable increase in the areas with no plots representativeness.

Figure 4.5 - Distance from forest AGB plot networks.




(a) with RadamBrasil plots; (b) without RadamBrasil plots; and (c) without RadamBrasil and National Forest Inventory plots.
Source: by the author.

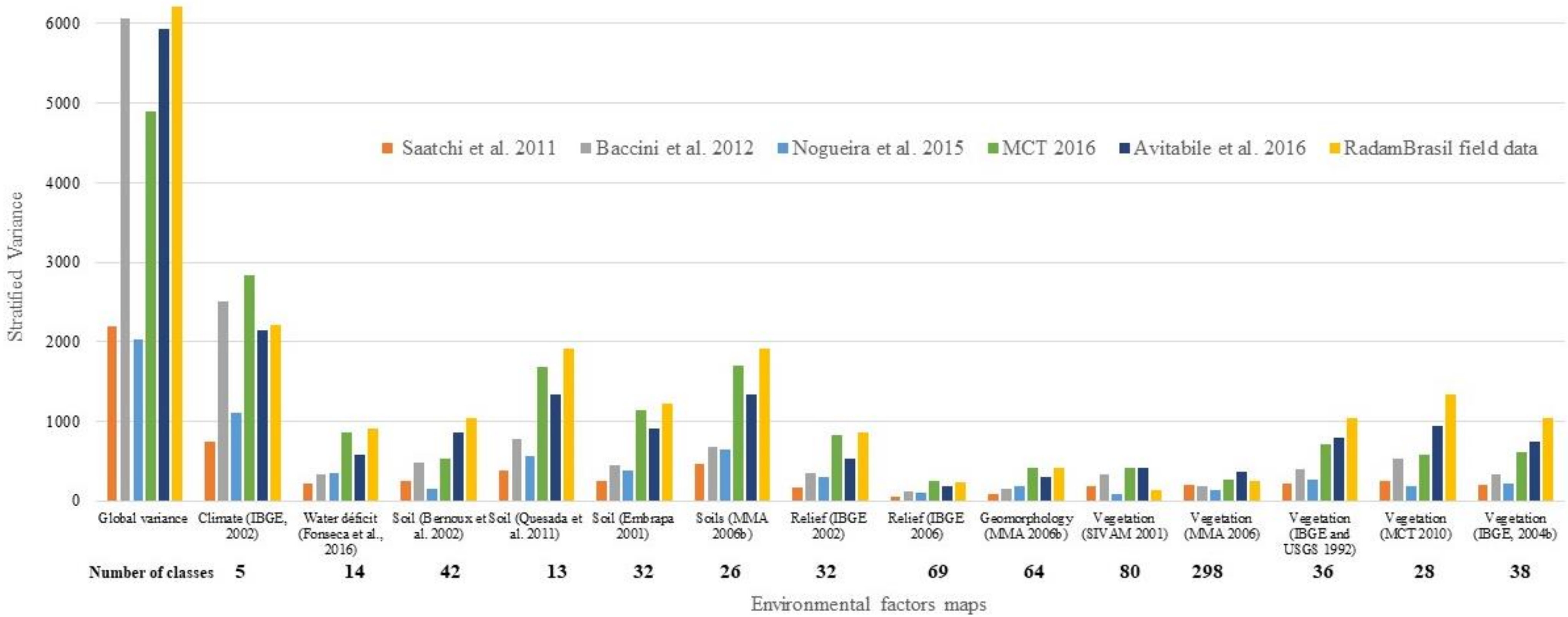
## 4.2 Forest AGB maps and environmental factors

This section shows the variance analysis between the AGB maps and the different environmental factor maps. Also, as a way to compare AGB field data with AGB maps, we included, in each analysis, the stratified variance of the RadamBrasil plots per environmental factor (we did not have the AGB data of the rest of the plots networks, only the location). A variance closer to zero, means that the AGB variability in that class is more homogenous and higher variance means more heterogeneity in the AGB distribution.

The global variance (normal population variance) is higher than the stratified variance (SV) of each AGB map and the RadamBrasil field data within each environmental factor maps analyses (Fig. 4.6 and 4.7). Results of the variance analyses show that environmental factor maps with few classes (e.g. climate and water) deficit has more SV than those with more classes. Taking into consideration environmental factors variance analyses, there are some tendencies in general, such as soils have more SV than relief maps (or geomorphology), and vegetation maps are similar to relief maps. What draws attention, is that the IBGE, (2006) relief map has the lowest SV among all the environmental factors maps, being even lower than inclusive the vegetation map of MMA, (2006a) that has 298 classes.

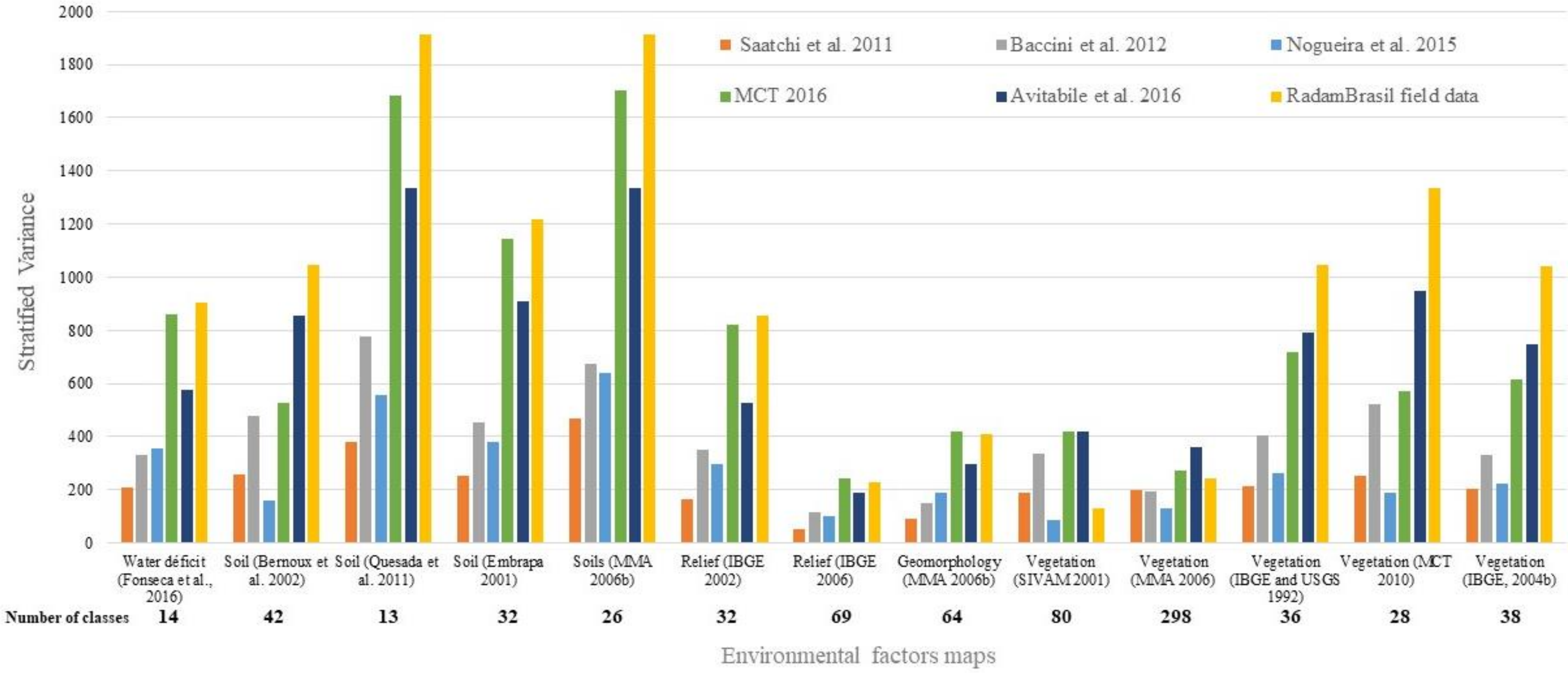
Looking at general SV tendencies of the AGB maps, Saatchi et al., (2011) has the lowest SV, the AGB maps of Baccini et al., (2012) and Nogueira et al., (2015) have an intermediate SV, and the higher SV is from MCT (2016), Avitabile et al., (2016) and the field data of Radambrasil, (1983).

Figure 4.6 - Stratified variance of the AGB maps, RadamBrasil AGB field data, and the environmental factors maps.




Source: by the author.

Figure 4.7 - Stratified variance of the AGB map, RadamBrasil AGB field data and the environmental factors map, excluding the global variance and the climate map to have a better visualization scale.




Source: by the author.

Figure 4.7, only shows the SV of each environmental factor map. It does not show the SV per class of environmental factor. For this reason, we will present the results of the SV per environmental factor, with the AGB variability within each class in Figures 4.8 to 4.15.

Many AGB maps can have a direct relationship with one or many environmental factors maps, since an specific environmental factor map was used to produce the AGB map. For example, the AGB map of Nogueira et al. (2015) used SIVAM et al., (2002) vegetation map, so there is a direct relationship between them and the expected stratified variance should be low (Table 4.4). Other AGB maps have an indirect relationship with the environmental factor maps, since both used similar remote sensing products such as SRTM or Landsat images. This is the case of the IBGE, (2006) relief map, the MMA, (2006b) geomorphology map and the Saatchi et al., (2011) and Baccini et al., (2012) AGB maps, which used SRTM and other remote sensing products. These direct and indirect relationships are summarized in Table 4.4. Although direct and indirect relationships exist, we chose to perform the variance analysis with all the AGB maps and environmental factors, to see how these relationships influence the stratified variance.

Table 4.4 - Relationships between the environmental factors and AGB maps.

| Environmental factor | Maps | Saatchi et al. (2011) | Baccini et al. (2012) | Nogueira et al. (2015) | MCT (2016) | Avitabile et al. (2016) |
|---|---|---|---|---|---|---|
| **Vegetation** | Vegetation map of Brazil (IBGE; USGS, 1992) | I: Both used satellite images | I: Both used SRTM, and satellite images | | | D: Avitabile et al. (2016) combine Saatchi et al. (2011) and Baccini et al. (2012), having relation with the maps that they used. |
| | Vegetation map (SIVAM, 2002) | I: Both used satellite images | I: Both used SRTM, and satellite images | D: Nogueira et al. (2015) used this map | | |
| | Vegetation map of Brazil (IBGE, 2004b) | I: Both used SRTM, and satellite images | I: Both used SRTM, and satellite images | | I: the MCT 2010 vegetation map, used this map | |
| | Brazilian biomes vegetation cover (MMA, 2006b) | I: Both used SRTM, and satellite images | I: Both used SRTM, and satellite images | | I: the MCT 2010 vegetation map, used this map | |
| | Vegetation physiognomies of Brazil (MCT, 2010) | | | | D: MCT (2016) used this map | |
| **Soils** | Soil map of Brazil (IBGE, 2001) | | | | | |
| | Soils of Legal Amazon (MMA, 2006a) | | | | | |
| | Soil carbon stocks (BERNOUX; VOLKOFF; CERRI, 2002) | | | | | |
| | Soil map (QUESADA et al., 2011) | | | | | |
| **Climate** | Water deficit (FONSECA et al., 2016) | | | | | |
| | Climate map of Brazil (IBGE, 2002) | | | | | |
| **Topography** | Relief map 2002 (MMA, 2002) | | | | | |
| | Relief units map of Brazil (IBGE, 2006) | I: Both used SRTM, and satellite images | I: Both used SRTM, and satellite images | | | |
| | Geomorphology of the Legal Amazon (MMA, 2006a) | I: Both used SRTM, and satellite images | I: Both used SRTM, and satellite images | | | |

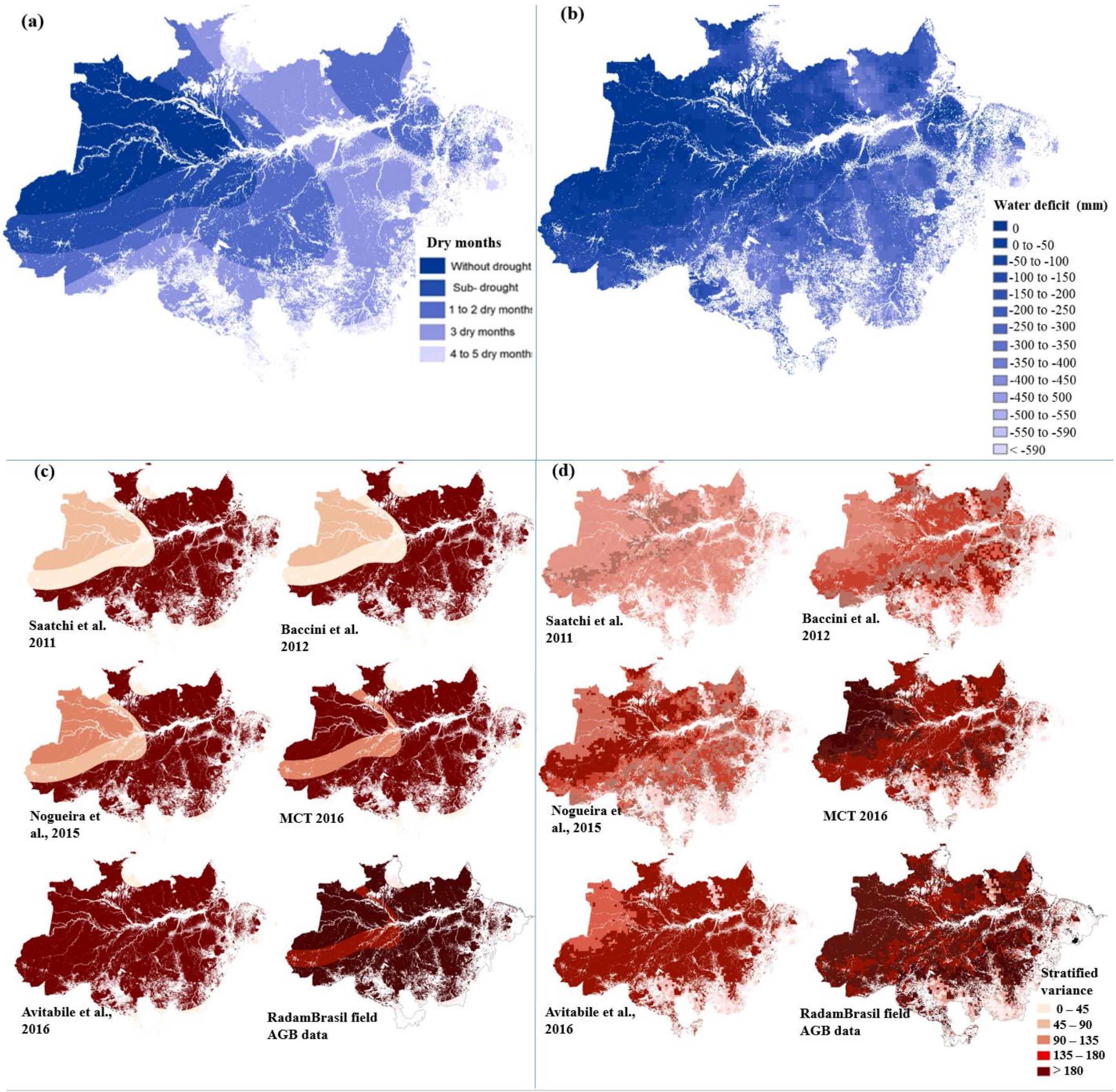
D: Direct relationship (orange); I: Indirect relationship (light blue).
Source: by the author.

### 4.2.3 Climate

The classes with more precipitation and less water deficit are the ones with lower SV. Therefore, the class “4 to 5 dry moths” with higher water deficit, has the lower SV (Fig. 4.8). The Saatchi et al., (2011) AGB map has the lower variance and, MCT, (2016) and the RadamBrasil field data the highest.

The reason why they have high SV could be the large class size of both maps (dry months and water deficit).

Figure 4.8 - Stratified variance of dry months and water deficit maps.




(a) Climate map (dry months) and the % of the class area; (b) Water deficit and the % of the class area; (c) Dry months map stratified variance (d) Water deficit map stratified variance.
Source: (a) IBGE, (2002a); (b) FONSECA et al., (2016).

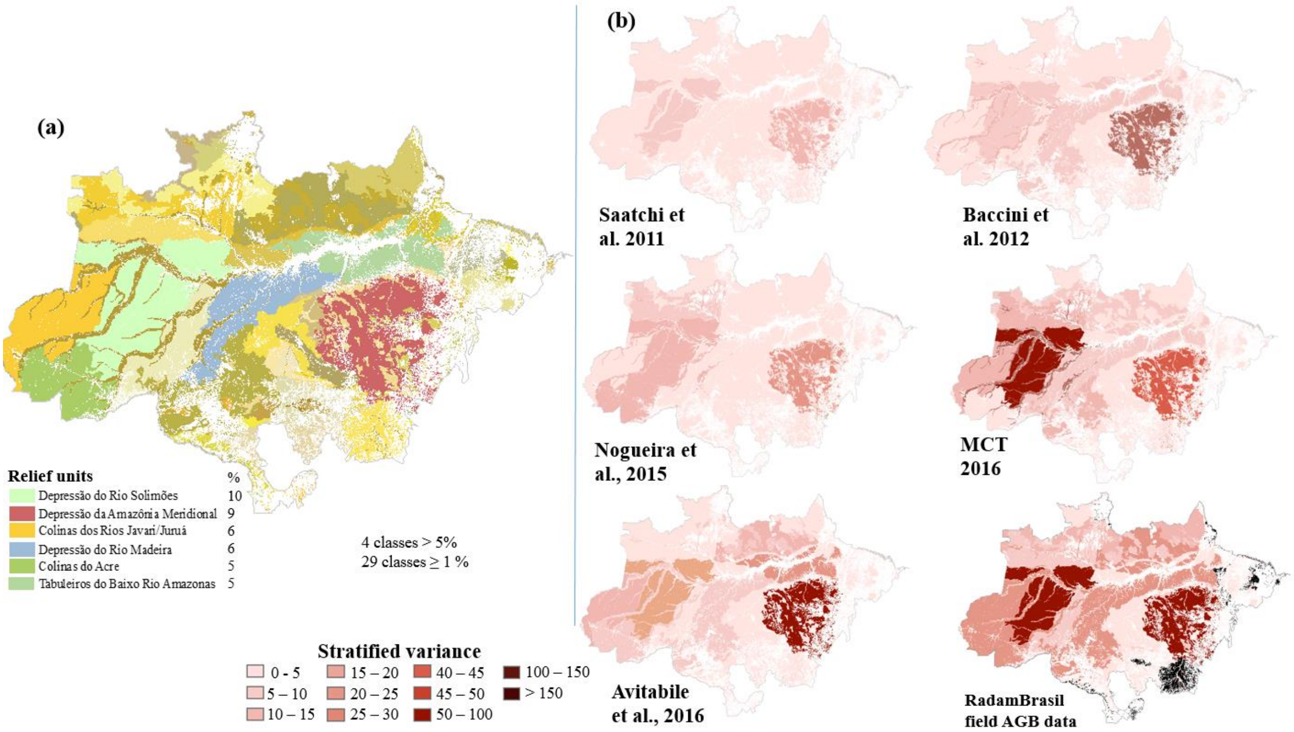
### 4.2.4 Geomorphology

Of all the environmental factors maps, the IBGE (2006) relief units (or geomorphology) map has the lowest SV with 69 classes (Fig 4.9a and 4.9b), followed by MMA (2006b) geomorphology map with 64 classes (Fig. 4.9c and 4.9d). The IBGE, (2002b) relief map with only half of classes (32) has higher SV (Fig. 4.10b and 4.10c) comparing with the other geomorphology maps, the reason could be the larger class sizes.

The IBGE, (2006) map (Fig. 4.9) shows that in all the AGB maps, only two classes have high SV, Solimões River and meridional Amazon depression. The rest of the classes present low SV, including the RadamBrasil data map. The AGB maps with indirect relationship with the IBGE, (2006) map are Saatchi et al., (2011) and Baccini et al. (2012).

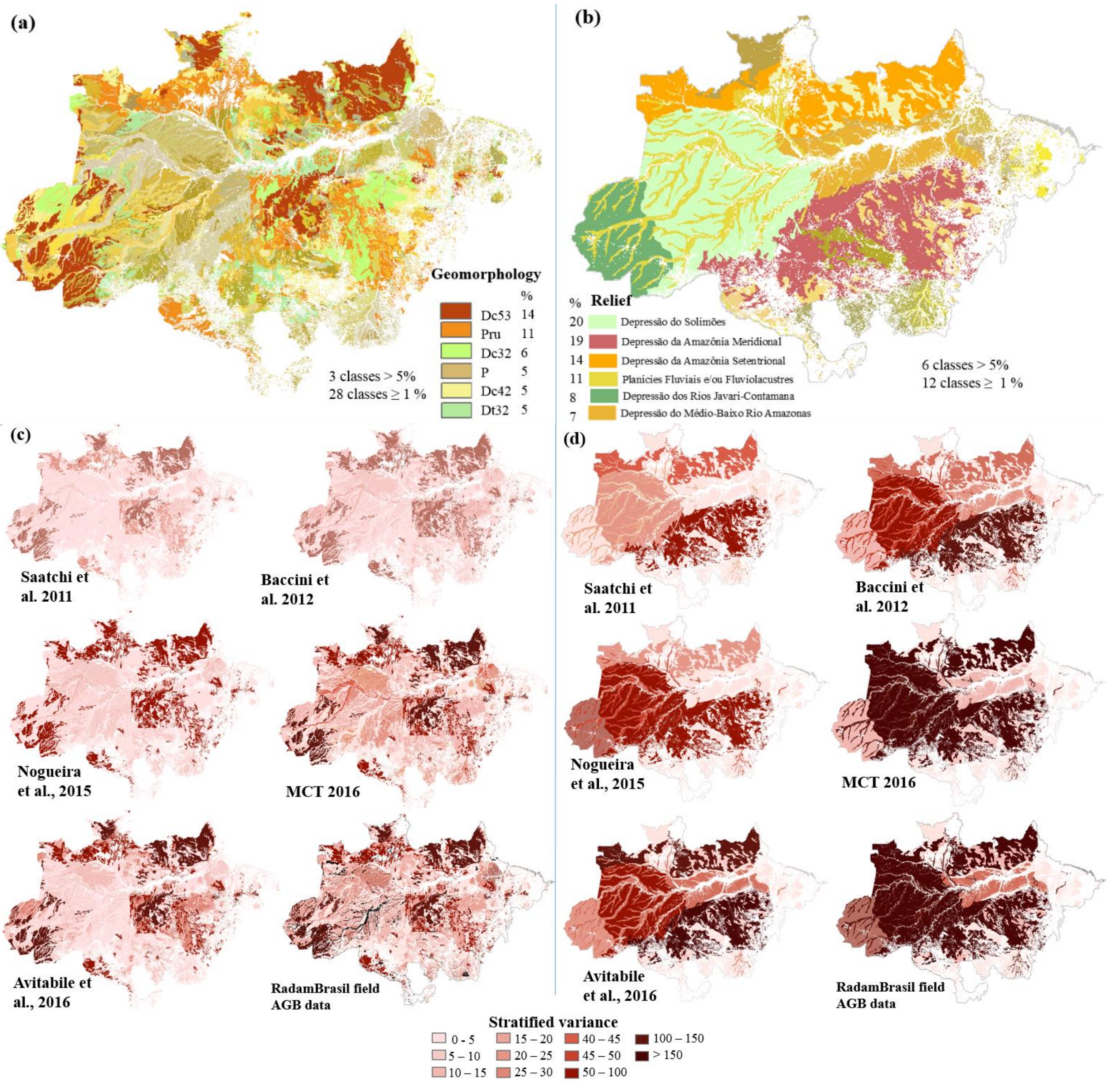
In the MMA, (2006b), the AGB maps present low SV, with the exception of class Dc 53 and Pru (Fig. 4.10). Saatchi et al., (2011) and Baccini et al., (2012) have a lower SV, because of the indirect relationship with this map, using SRTM and other remote sensing products (see Table 5.1).

Figure 4.9 - Stratified variance of the relief units map.




(a) Relief units map of Brazil and the % of the class area; and (b) Relief map stratified variance. Detailed legend is in A2.
Source: (a) IBGE, (2006).

Figure 4.10 - Stratified variance of the geomorphology and relief maps.



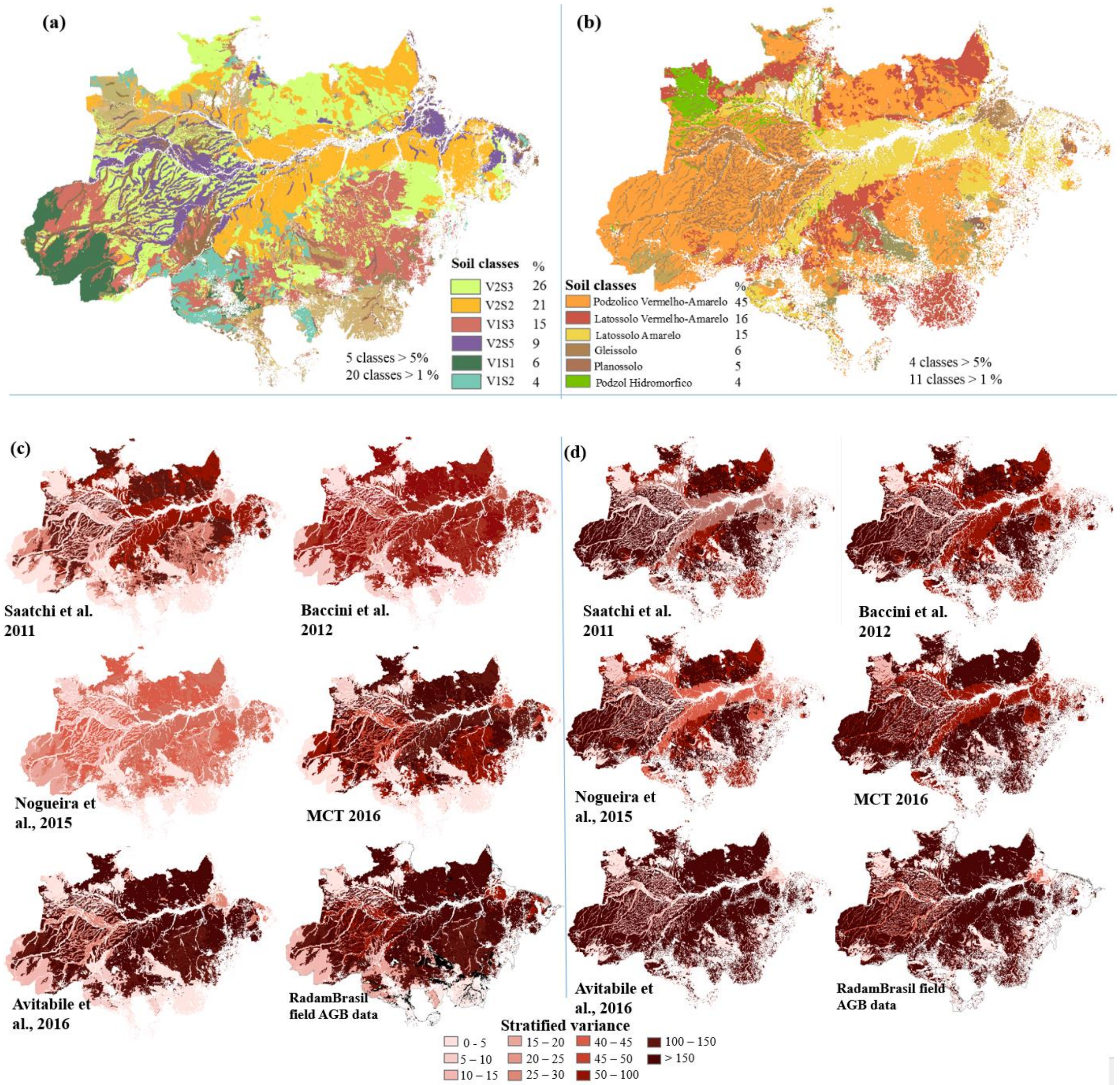

(a) Geomorphology of the Legal Amazon map and the % of the class area; (b) Relief map and the % of the class area; (c) Geomorphology map stratified variance; and (d) Relief map stratified variance. Detailed legend is in A2.
Source: (a) MMA, (2006a); (b) IBGE, (2002b).

### 4.2.5 Soil

The soil maps have many classes (except for the Figure 4.12a map which has 13 classes) reason why we show only the first 6 larger classes (detailed legend is in A2). Almost all the soil maps have less than 5 classes with more than 5% of the total area.

In all maps, soil is the environmental factor that had the highest SV. The V1S1 class, the south west classes (Fig. 4.11), the Podzol Hydromorphic class (Fig. 4.12) have low SV, the reason could be the small size of these classes. Looking at the soil map of Bernoux et al., (1997), we find that Nogueira et al., (2015) AGB map has a lower SV that the rest of the maps maybe because it takes into consideration vegetation, while the rest of the AGB have high SV.

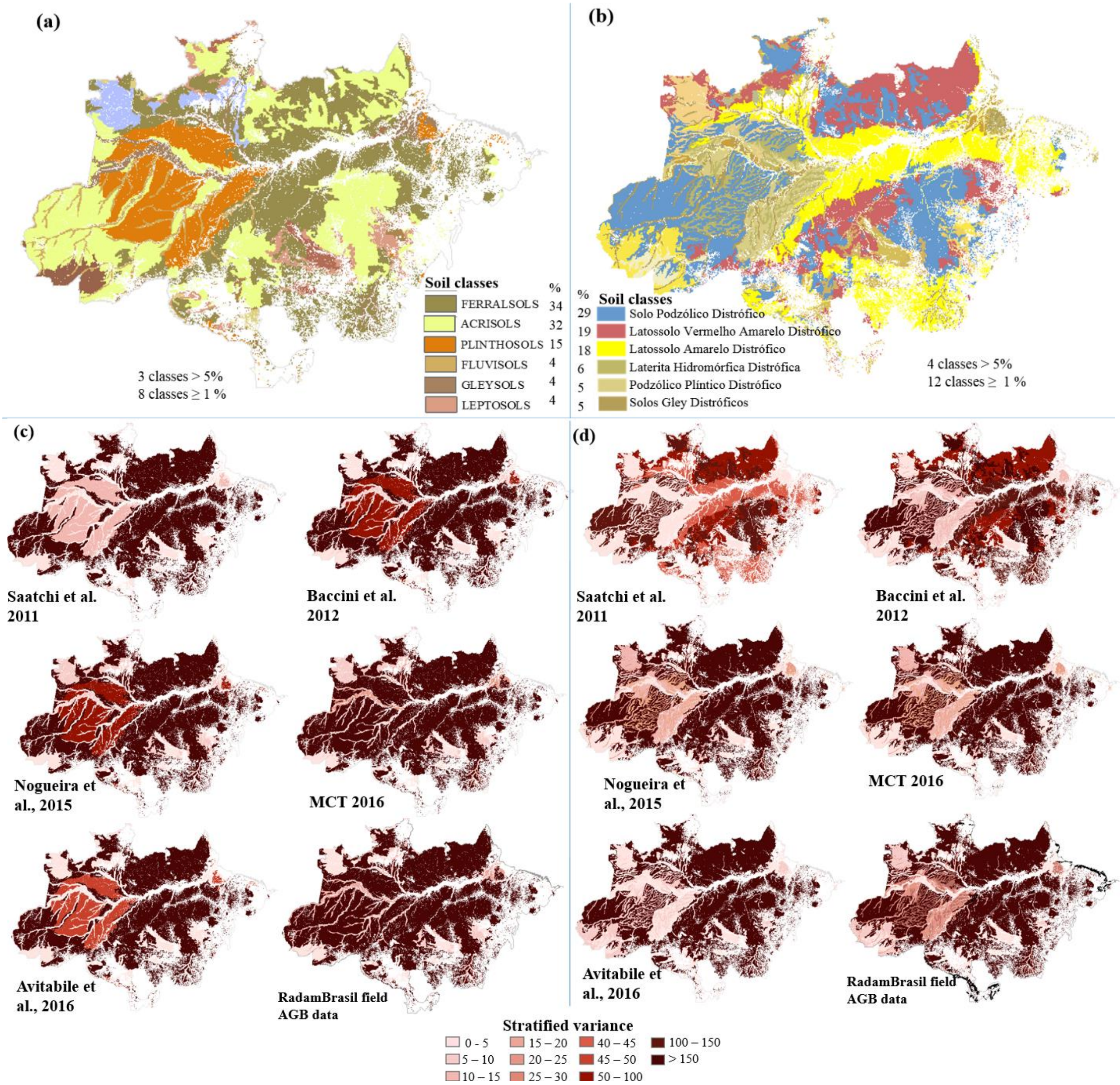
Figure 4.11 - Stratified variance of soil carbon stocks and soils of Legal Amazon maps.




(a) Soil carbon stocks and the % of the class area; (b) Soils of Legal Amazon and the % of the class area; (c) stratified variance of (a); and (d) stratified variance of (b). Detailed legend is in A2.

Source: (a) Bernoux; Volkoff; Cerri, (1997); (b) MMA, (2006a).

Figure 4.12 - Stratified variance of soil maps.




(a) Soil map and the % of the class area; (b) Soil map of Brazil and the % of the class area; (c) stratified variance of (a); and (d) stratified variance of (b). Detailed legend is in A2.

Source: (a) Quesada et al., (2011); (b) IBGE, (2001).

### 4.2.6 Vegetation

Each vegetation map has different forms of designating the vegetation class, but when carrying out a visual analysis of the five vegetation maps, we realized that the legend is the same (IBGE, 2012) but they use different forms (names and codes) to group classes (different levels of detail). Also, we notice that there are few large classes in all the vegetation maps, only are 5 classes with more than 5 % of the total area. Since some maps have large legends, we chose, in all cases, to show the first 8 large classes in the maps (detailed legend is in A2).

The general tendency of the 5 vegetation maps, is higher SV in central Amazon (Lowland Dense Humid Forests or Db) close to main rivers and in the northeast (Submontane Dense Humid Forest or Ds).

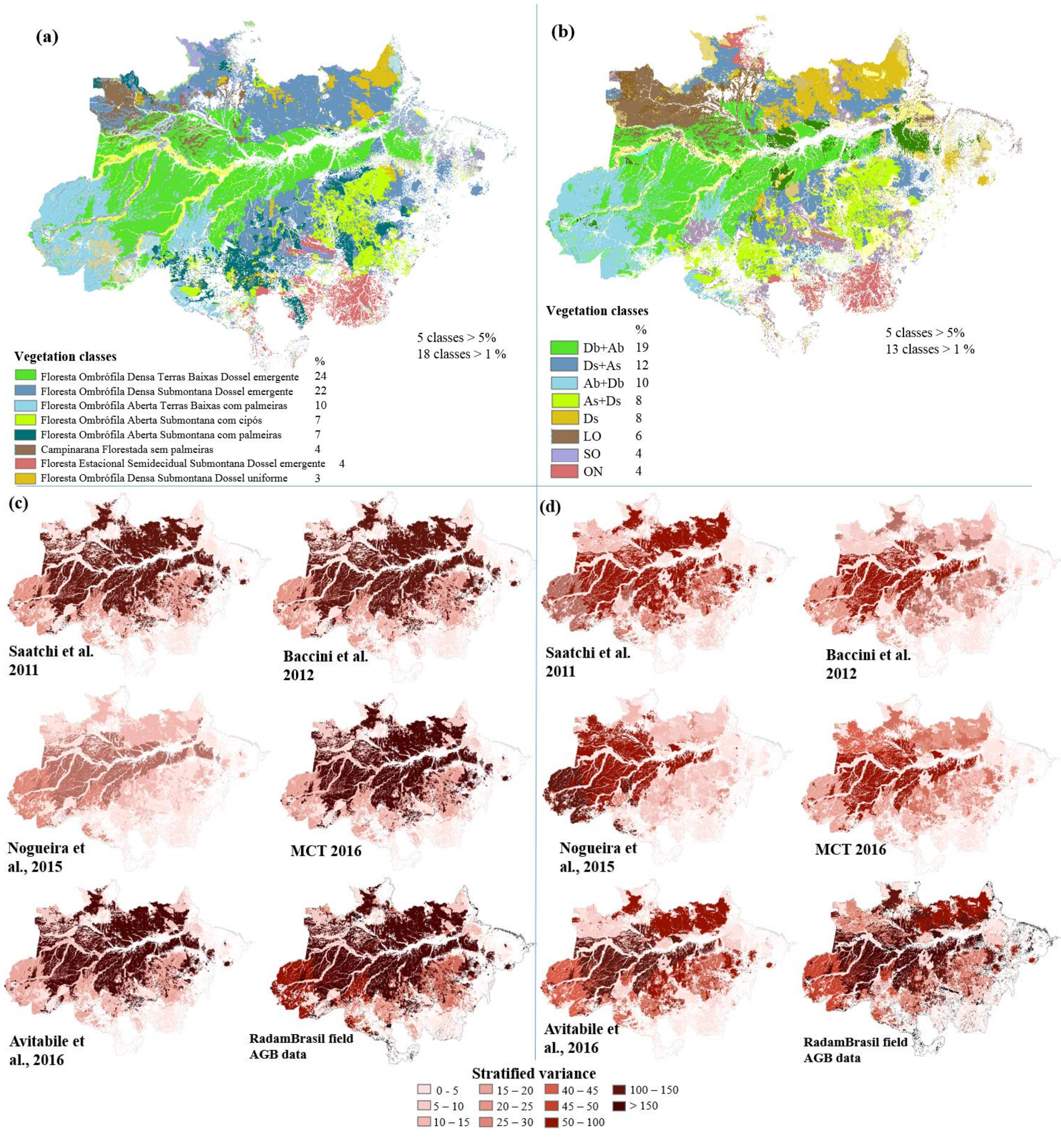
The PROBIO map (Fig. 4.13b) with more classes that the rest of the maps (298 classes), has the lowest SV, followed by SIVAM, (2002) with 80 classes in Figure 4.13a. On the other hand, the low SV of Nogueira et al., (2015) map in the SIVAM, (2002) vegetation map, is due to a direct relationship between them (these vegetation map was used to extrapolate AGB) (Table 4.4). Saatchi et al., (2011) and Baccini et al., (2012) AGB maps show another indirect relationship with the PROBIO map, also using SRTM digital elevation model. In addition, MCT, (2016) has also an indirect relationship with the PROBIO map, since the MCT (2010) vegetation map (used by MCT 2016 AGB map) was based on this map.

The higher SV of all vegetation maps is found in IBGE & USGS, (1992) map and the MCT, (2010) have the higher SV of all vegetation maps (Fig. 4.14). We expected, that the MCT (2016) AGB map that used the MCT (2010) vegetation map (direct relationship) has a low SV in this map, but has lower variance in the PROBIO map (MMA, 2006b) with which has an indirect relationship, as we explain above.

Avitabile et al. (2016) has also a higher SV, even though is a fused map of Saatchi et al., (2011) and Baccini et al., (2012) that have lower SV in almost all the environmental factors.

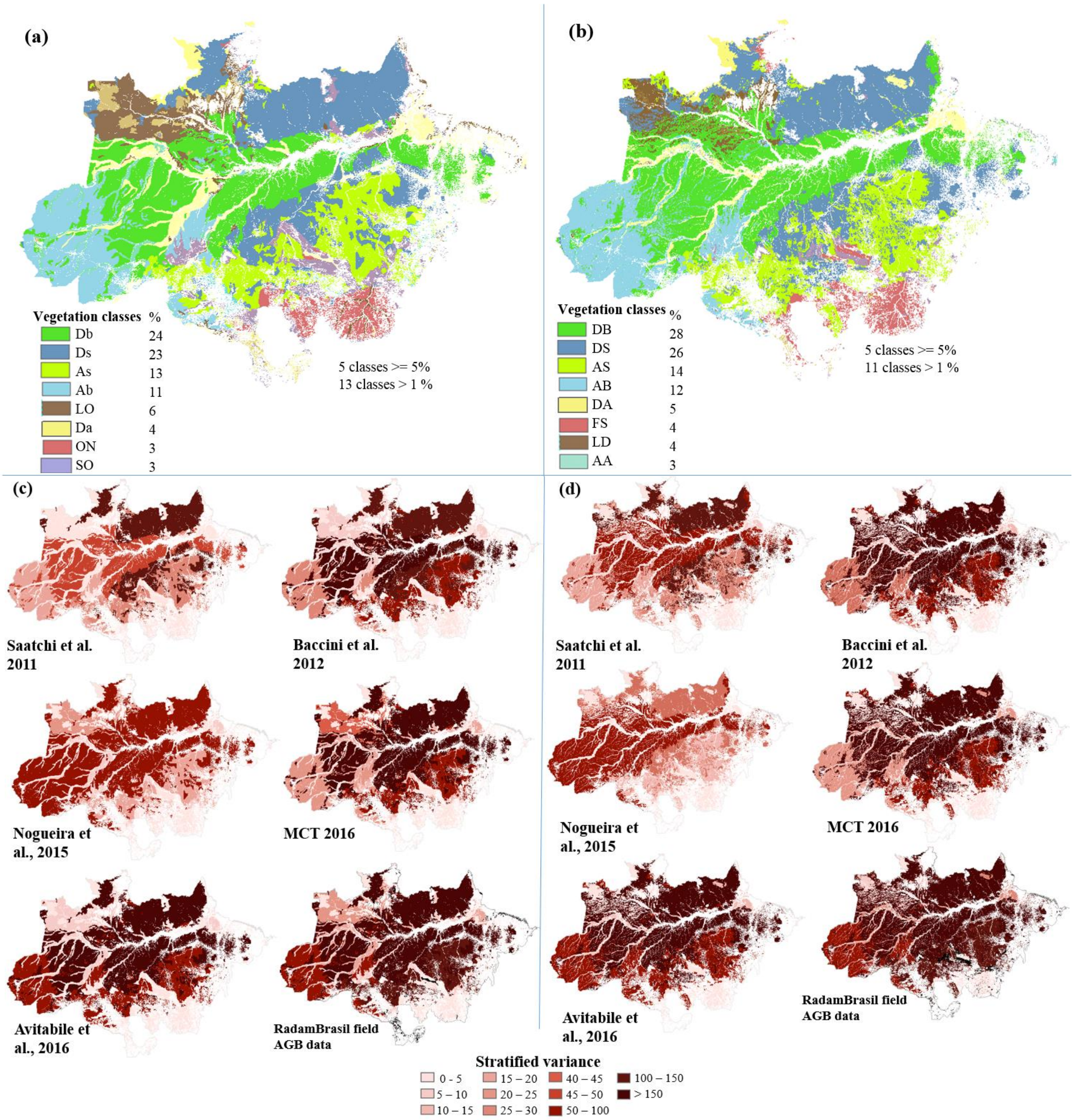
The IBGE, (2004b) is very similar, low SV in some classes in Campirana/Floresta Ombrofila and Floresta Ombrofila Estacional (Fig. 4.15).

Figure 4.13 - Stratified variance of the vegetation and Brazilian biomes vegetation cover maps.



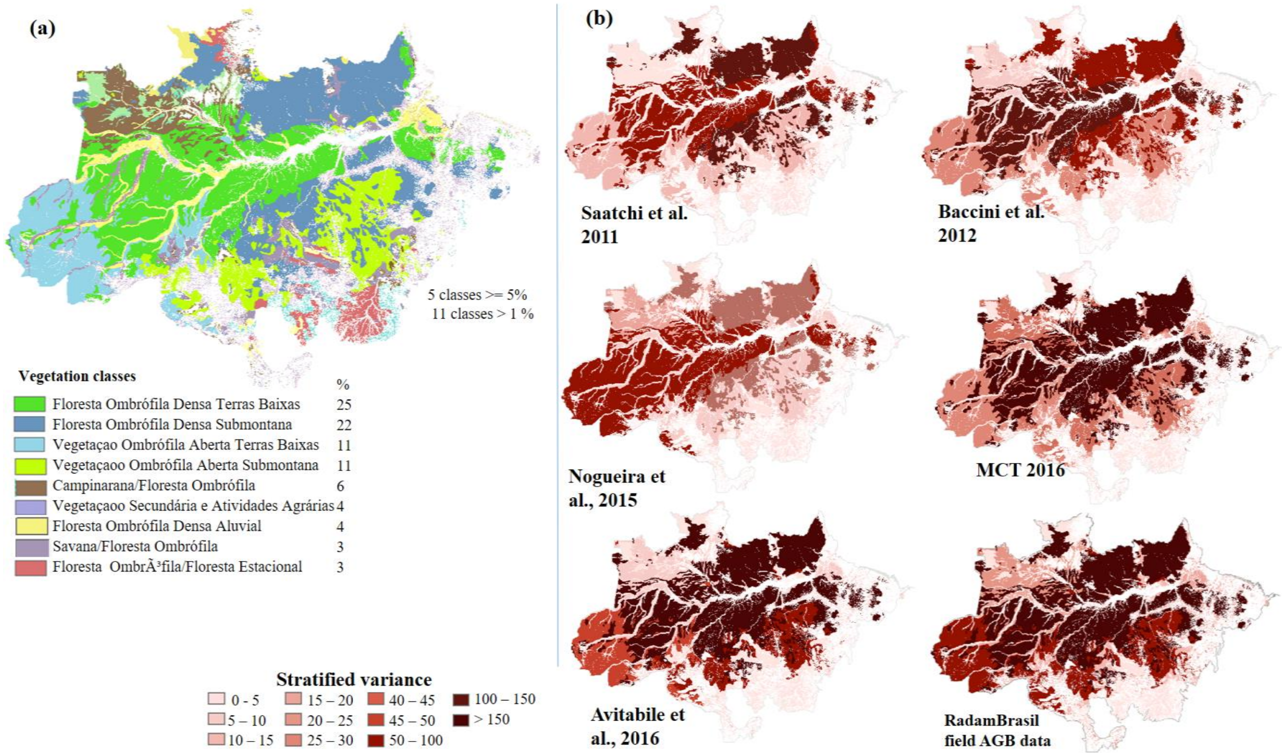

(a) Vegetation map and the % of the class area; (b) Brazilian biomes vegetation cover and the % of the class area; (c) stratified variance of (a); and (d) stratified variance of (b). Detailed legend is in A2.
Source: (a) SIVAM, (2002); (b) MMA, (2006b).

Figure 4.14 - Stratified variance of the vegetation of Brazil and Vegetation Physiognomies of Brazil maps.




(a) Vegetation map of Brazil and the % of the class area; (b) Vegetation physiognomies of Brazil and the % of the class area; (c) stratified variance of (a); and (d) stratified variance of (b). Detailed legend is in A2.
Source: (a) IBGE; USGS, (1992); (b) MCT, (2010).

Figure 4.15 - Stratified variance of the vegetation map of Brazil.




(a) Vegetation map of Brazil and the % of the class area; (b) stratified variance of (a). Detailed legend is in A2.
Source: (a) IBGE, (2004b).

## 4.3 Analysis of differences between forest AGB maps

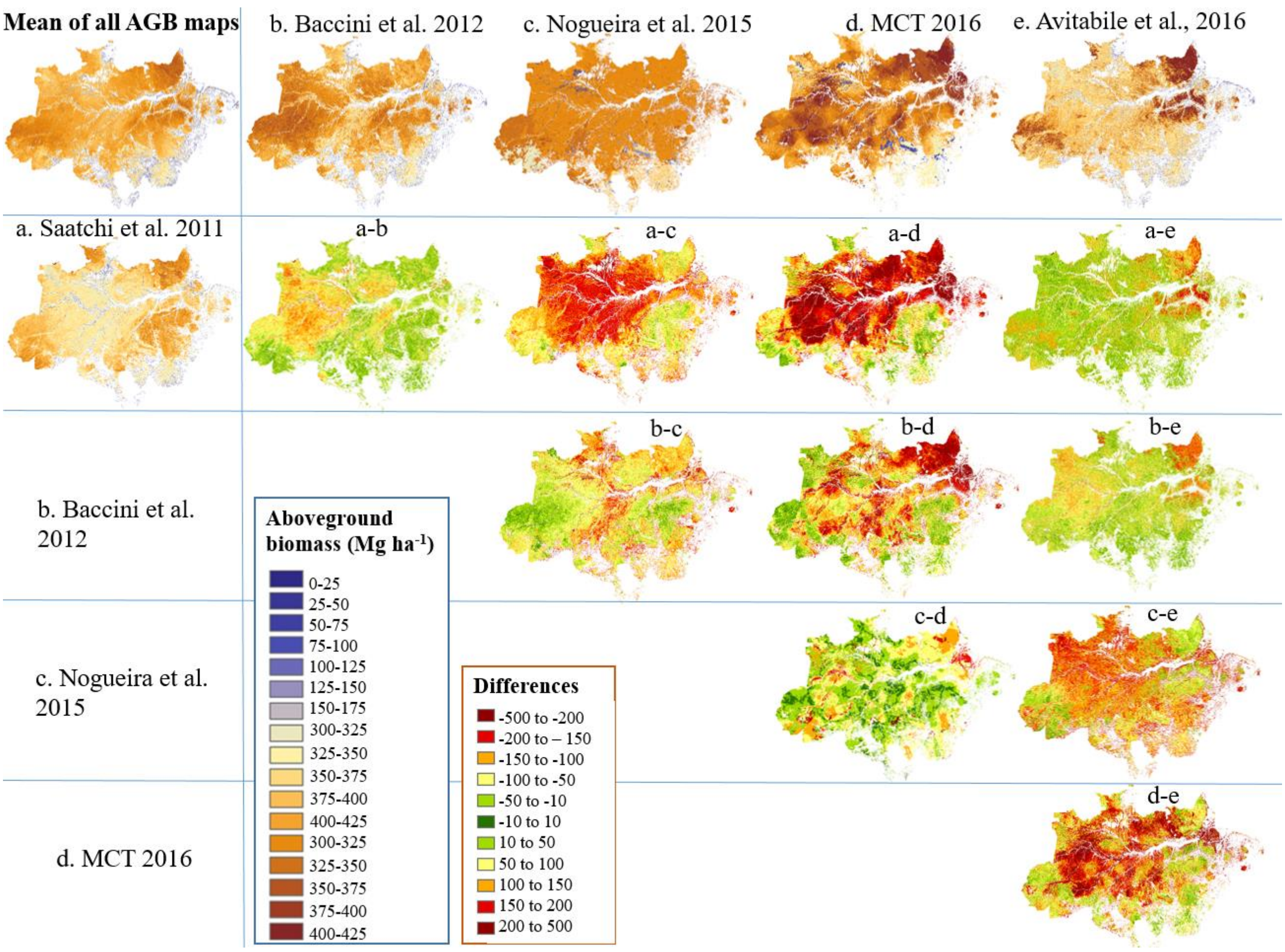
As AGB maps are a result of several AGB datasets, is interesting to find out where the main differences and similarities in AGB estimates occur, assuming that the places which have the most similarities in AGB are places whit better biomass estimates. You can find the results in a matrix that show the differences in pairs of AGB maps and the mean AGB map of all maps (Fig. 4.16).

The main difference between Saatchi et al., (2011) and Baccini et al., (2012) is in the west central Amazon (Amazonas State). This difference is much more pronounced if you compare it with Nogueira et al., (2015) and MCT, (2016) that has higher AGB differences in all this region. Avitabile et al., (2016) is more similar to Saatchi et al., (2011) with differences mainly in Amapá, Northeast of Pará and in the Amazonas State close to the limit with Acre (Fig. 4.16). Baccini et al., (2012) has specific differences with Nogueira et al., (2015) in Roraima and south of Amazonas State, also with MCT, (2016) in central Amazon and with Avitabile et al., (2016) in Amapá and Northeast of Pará. Avitabile et al., (2016) differs a lot from Nogueira et al., 2015 and MCT, (2016). Even though they used the same field data and a similar extrapolation method, MCT, (2016) and Nogueira et al., (2015) have punctual differences. The AGB maps average has less extremes, in other words, the places with high biomass (limit between Acre and Amazonas State and in Amapá and north east of Pará) are not that high if you compare them to MCT, (2016) or Avitabile et al., (2016).

By calculating the cell statistics of the whole AGB maps, is possible to see that the main differences above mentioned remain (Fig. 4.17). The range shows that the extreme differences are next to the rivers, mainly the Amazon River and, in Amapá and northeast of Pará States.

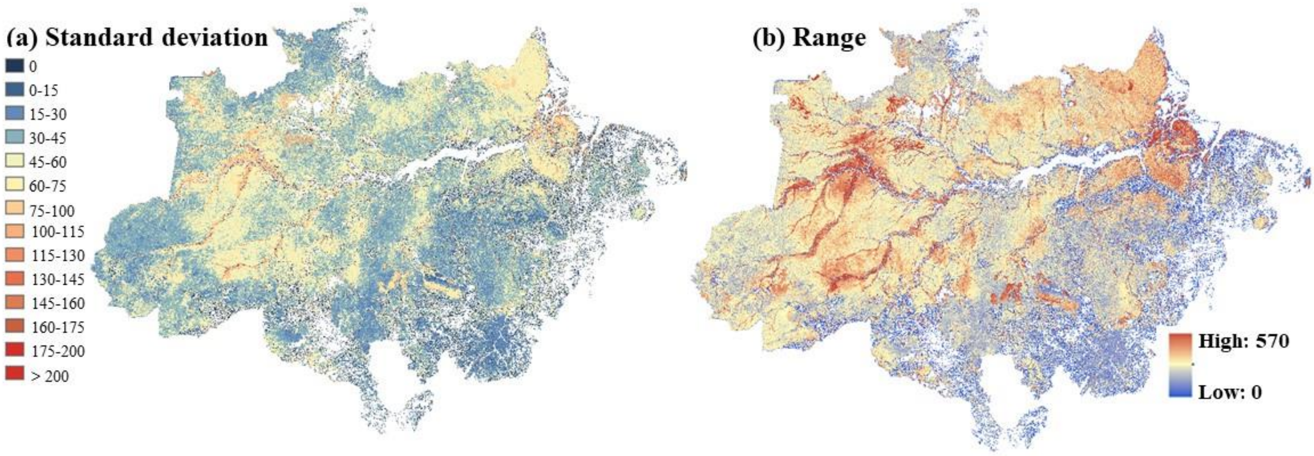
The standard deviation (Fig. 4.17) calculated from these set of AGB maps, explains objectively the magnitude of these differences. Also, the range, which is the difference between the maximum and minimum AGB values, represents the discrepancies of the set of AGB maps. Most of the differences in the standard deviation map, are found in west central and west north amazon. The extremes (more than 130) are in the bank of the rivers, Amapá and northeast of Pará.

Figure 4.16 - Differences analysis in pair of AGB maps.




Source: by the author.

Figure 4.17 - Statistics between the AGB maps.



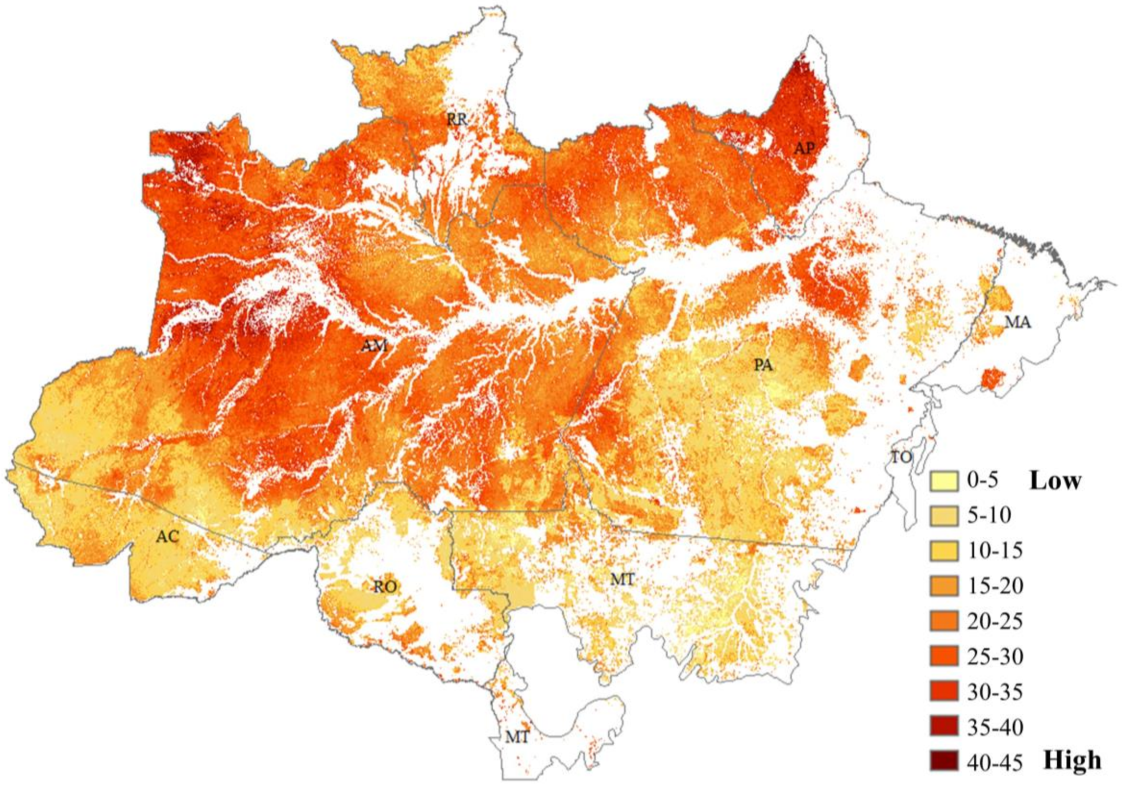

Source: by the author.

## 4.4 Forest AGB spatial data gaps map

Our final product is a forest AGB spatial data gaps map that combines the AGB data coverage analysis and the difference and statistical analysis of AGB maps (Fig. 4.18). For this purpose, gaps are places with no LiDAR or field plots, and areas where high differences exist between the AGB maps (high standard deviation).

The data gaps map was obtained with the inputs of the multicriteria analysis, distance from plots map, distance from LiDAR data map, and standard deviation together. The final AGB spatial data gaps map (Fig. 4.18) shows in red the areas with high gaps and in orange the areas that have middle coverage of field and LiDAR data, where the differences of AGB are intermediate. Following the same criteria, yellow areas are the places that have good coverage of AGB plots and LiDAR transects and where AGB maps have more similarities. Consequently, the main gaps or priority areas where further biomass assessments should be focus are the northeast of Amazon State, Amapá, northeast of Pará and along the rivers.

Figure 4.18 - Spatial AGB data gaps map, using spatial multicriteria analysis.




Source: by the author.

# 5 DISCUSSION

## 5.1 Current status of AGB data

As shown in section 4.1, different networks have been gathering AGB data for the Brazilian Amazon (Fig. 4.1 and Table 4.1). However, each network exhibits different protocol for data collection and treatment, collection dates and different plot sizes. Moreover, most of the datasets are not publicly available. These aspects make it difficult to determine the uncertainty associated to AGB estimates from plots (CHAVE et al., 2004), which is a requirement for the transparency of Monitoring and Measurement, Reporting and Verification (MRV) in the context of the REDD+ national program under the UNFCCC requirements (ROMIJN et al., 2012). That is why, a consolidated and open-access AGB database is urgently needed to improve NC and biomass mapping. Funders play an important role in the AGB data availability, and it should be a requirement that the results of the projects they finance be public and fully available.

The analysis of AGB data coverage, section 4.1.3-Fig. 4.5, shows that there is a lack of *in situ* information in extensive from large regions of the Amazon. Furthermore, if we exclude the RadamBrasil plots, because of the age of the measurements (1973-1983), the areas without plots data representativeness increase greatly.

Highly divergent estimates of forest carbon rely on data collection and treatment (MCT, 2016, 2010; Nogueira et al., 2015). The problem regarding the AGB data coverage will not be completely solved by implementing more plots if the information remains unavailable. In this context, the NFI is a particularly important initiative and depending whether this, data becomes available, the number of AGB plots will be improved significantly, reaching 7000 systematically distributed plots in the Amazon biome, which will be re-measured regularly for long term biomass monitoring. The NFI has been questioned because of the small plot size (0.2 ha). Actually, local and regional efforts such as INPA and networks such as RAINFOR and TEAM are essential to monitor AGB changes over time and the impacts of anthropogenic and climate change on carbon storage in the Amazon forest. It is also important to improve collaborations and develop a consistent data sharing policy.

A great deal of interaction between the AGB stakeholders, exist but it does not mean that there is synergy between them. Availability, data protocols and standardization of current AGB data is still a pending task. The social network analysis, section 4.1.2- Fig. 4.4, can be considered as an initial experience. The relevance of this topic deserves further efforts, since the analysis could be improved with an active stakeholders participation. It is fundamental to improve collaboration techniques and provide financial aid for an open policy of data distribution. Public universities and research institutes are fundamental players in the current network framework for generating AGB data over the Brazilian Amazon and so, are public funds.

At the scale of the Brazilian Amazon, airborne LiDAR data will soon improve the AGB data coverage, section 4.1.2.-Fig. 4.2, mainly through datasets collected by the Sustainable Landscapes and EBA projects (EBA, 2016; SUSTAINABLE-LANDSCAPES, 2016), expecting to reach 950 LiDAR transects until the end of 2017. The goal of the EBA project with all the LiDAR data and many field datasets (i.e., Sustainable Landscapes, FNI, TREES and INPA), is to create a newer and more accurate AGB map for the Brazilian Amazon (EBA, 2016). At global scale, the BIOMASS and GEDI missions promise to achieve great advances in the next 5 years (SAATCHI, 2015), therefore our work results and analyzes could serve for the articulation of these initiatives.

## 5.2 Environmental factors and AGB map

In the Brazilian Amazon, there are many environmental factors maps available online as showed in section 4.2- Table 3.2. The challenge is to ascertain environmental factor or which combinations represent AGB distribution in the Brazilian Amazon, to obtain the stratification adherent to the IPCC (2006) guidelines and the Voluntary Carbon Standards (standard for many projects in voluntary carbon market) (VCS, 2015). It is difficult to define an AGB stratum derived from a combination of factors, such as climate, precipitation and topography, because the interrelationships between these factors are not completely understood at the regional scale (SAATCHI et al., 2007, 2011; PAN et al., 2013).

The concept behind having classes or stratums that represent AGB in the Brazilian Amazon is that if we have similar stratums, spatial units where the AGB quantity is similar, we can calculate the number of plots or the number of LiDAR transects with a pre-test. The pre-test consists in establishing a number of AGB plots or LiDAR transects per stratum, and according to the variance in each stratum, the final number of representative plots and transects are calculated. In the case of the Brazilian Amazon, where the establishment of plots demands logistics and budget, an alternative might be the use of existing data, as RadamBrasil data for the pre-test. Following this stratification logic, the stratified variance of RadamBrasil plots data can point to areas with greater variance, where more plots are needed. But, again, the challenge here is to use a proper environmental factor map or combination of maps according to the study scale.

Our results show a great variation, in SV of AGB maps and AGB field data, even in the same environmental factors maps (Fig. 4.6 to 4.15). The three soil maps have the highest SV, and two geomorphology maps the lowest (IBGE, 2006; MMA, 2006a) were similar to two vegetation maps with low SV (SIVAM, 2002; MMA, 2006b). What draws attention is that the vegetation maps (five in total) have the same vegetation classification (IBGE, 2012), but vary in the level of detail (vegetation aggrupation levels) and number of classes. Therefore, it may be concluded that SV is very sensitive to stratum size and number of classes. For example, the MMA (2006b), with 298 classes has the lowest SV of vegetation maps followed by SIVAM (2002) with 80 classes. On the other hand, in the vegetation maps, only 5 classes represent more than 5% of the total Brazilian Amazon Biome area, and in these classes you find the higher SV. With this in mind, we can state that the number of classes is not as important as the stratum size.

The low SV found in some AGB maps, within some environmental factors, could be a consequence of the use of the same remote sensing inputs for obtaining AGB maps, as the case of Saatchi et al. (2011), Baccini et al. (2012) and the relief map IBGE (2006) that used the SRTM DEM. In the case of the vegetation maps, most of them used satellite images, but the SV variance is high in three of the five vegetation maps, also the AGB map of MCT (2016), used the MCT (2010) vegetation map, and has a high SV (Fig. 4.14). Nogueira et al. (2015) used the SIVAM (2002) vegetation map having a low SV and because is a stratified map (one value per class) with less variability. For all these reasons, it is hard to see a clear relationship between AGB maps and the environmental factors. Addressing this issue, the EBA (2016) project for the LiDAR transects location, opted to make a random sampling design rather than a stratified sampling.

Looking at the statistical analysis between all AGB maps (Fig. 4.17), areas with higher standard deviation coincide with areas of higher SV of the vegetation maps, while no such matches were found in the rest of the environmental factors. This could mean that there is high uncertainty in the central Amazon (Lowland Dense Humid Forests or Db) close to main rivers and in the northeast (Submontane Dense Humid Forest or Ds).

## 5.3 Similarities and differences between AGB maps

Many AGB maps are available, although significant differences exist between the approaches used to generate these maps (Table 5.1). The reason for the observed differences, in the quantity and distribution of AGB (Fig. 4.16), is that each AGB carbon map relies on different field data and different techniques for upscaling the AGB punctual information to a map level (MITCHARD et al., 2013; OMETTO et al., 2014; SAATCHI et al., 2015).

Table 5.1 - Carbon density maps and their approach.

| **Carbon density maps** | **Approaches to map carbon stocks (Goetz et al. 2009)** | **Description Approaches to map carbon stocks (Goetz et al. 2009)** |
|---|---|---|
| Nogueira et al. (2015)<br>MCT (2010)<br>Mitchard et al. (2014)<br>MCT (2016) | Stratify & Multiply (SM) Approach | Assign an average AGB value to land cover/vegetation type map |
| Saatchi et al. (2011)<br>Baccini et al. (2012)<br>Avitabile et al. (2016) | Direct Remote Sensing (DR) Approach | Empirical Models where RS data is calibrated to field estimates |

Source: by the author.

According to our analysis, AGB maps that are derived from the direct remote sensing (DR) approach (SAATCHI et al., 2011; BACCINI et al., 2012; AVITABILE et al., 2016) have lower AGB than the maps derived from stratify and multiply (SM) approach (NOGUEIRA et al., 2015; MCT, 2016) (Table 5.1). The reason for this difference is that the DR approach maps are for actual biomass which considers forest degradation (deforestation was taken out with the forest mask), and the SM maps are for potential biomass per vegetation class. The differences between the DR maps are located in specific places (west Amazon, Amapá, northeast of Pará), while there are larger areas of high differences in the SM maps due to larger areas with higher values of biomass (whole Amazon State, west Pará and the same places of DR) (Fig. 4.16). On the other hand, differences in scale between SR and SM maps, are worth mentioning. The DR maps represent a pantropical scale, this implies general assumptions to extrapolate the AGB, while the SM maps, conceived specifically for the Brazilian Amazon, adopt local assumptions.

As mentioned above, the standard deviation of all AGB maps is higher in places where SV is higher in the vegetation maps (SIVAM, 2002; IBGE, 2004a; MMA, 2006b). For this reason, there should be further analysis of these areas that correspond mainly to three vegetation classes (lowland dense humid forests, submontane dense humid forest and open submontane humid forest) should be further analyzed.

The results found in this study provide useful elements for analyzing the current AGB maps, AGB datasets, environmental factors and the relation between the stakeholders working with AGB. Moreover, it will help to prioritize areas and efforts on future AGB assessments.

## 5.4 Priority areas for future AGB assessments

The forest AGB spatial data gaps map (Fig. 4.18) shows the places with few or no AGB field plots or LiDAR transects, and where AGB maps differ most. In other words, the AGB data gaps map represents the priority areas for further AGB assessments. Considering the large extension, accessibility difficulties and costs in the Brazilian Amazon, this information is of high relevance for designing further studies and AGB assessments.

The differences in AGB variance analysis within the environmental factors showed that choosing an environmental factor map (or a combination of maps) with stratums or classes that represents accurately the AGB is very relative. For that reason, no of the environmental factor maps were used in the multicriteria analysis to obtain the forest AGB spatial data gaps map. Nevertheless, having a stratified map with similar AGB quantities in each class or stratum, would have permitted to calculate the number of missing AGB plots and LiDAR transects in each stratum.

# 6 CONCLUSIONS

Our analysis of existing AGB data provides a comprehensive review of the current status of AGB estimates in Brazil. Initially, we found that it was very difficult to gather AGB data due to low access and availability of these datasets. Although there are long-term relationships between the stakeholders working with AGB data, there is no standard protocol for collection, monitoring and sharing of forest AGB data. To overcome this constraint, what is needed is some initiatives to make these data open and freely available (Sustainable Landscapes) to have positive implications for NC, carbon mapping and MRV REED + activities. Linking research funds to open data distribution policies could also be helpful for improving collaboration and standardization.

With regard to the distribution of the existing AGB data in Brazilian Amazon forests, the existing plots in the Amazon are not sufficient to represent the entire AGB distribution. Governmental initiatives such as the NFI play an important role in filling the existing data gaps and complementing current datasets. Additionally, the LiDAR remote sensing data currently in development through airborne campaigns, together with available long-term AGB data, and communication between stakeholders, with a clear data distribution policy, are fundamental in this process, for generating quality data to monitor forest carbon and understanding the resilience of tropical forests facing deforestation, degradation, and climate change.

The results of the variance analysis between the environmental factors maps and the AGB maps including also the RadamBrasil field data, showed that is hard to find an environmental class (or a combination) that represent the AGB as guidelines (IPCC, 2006; VCS, 2015) to assess biomass of NC and REDD+ recommend. The reason is that the SV of the AGB maps and AGB field data, even in the same environmental factors maps vary a lot, meaning that the SV could be very sensitive to the stratum size or that the delimitation of the classes do not represent AGB. The lowest stratified variance is in two geomorphology maps (IBGE, 2006; MMA, 2006a) and two vegetation maps (SIVAM, 2002; MMA, 2006b). The vegetation maps areas (5 classes with more than 5% of the total area) with higher SV, coincide with high standard deviation areas between all AGB maps, showing a relationship to prioritize this high variation areas, that was not found in the other environmental factors.

Our SV analysis should serve as reference of AGB products and their relationship with the environmental factors, not only in Brazil but in the rest of the countries that will try to obtain AGB maps using IPCC (2006) guidelines recommended under REDD+ projects especially now REDD + is now under the UNFCCC.

We found two tendencies in the quantity of AGB in the maps. The maps derived with DR approach (SAATCHI et al., 2011; BACCINI et al., 2012; AVITABILE et al., 2016) have lower AGB than the ones derived from SM approach (NOGUEIRA et al., 2015; MCT, 2016). Areas with higher differences in DR maps are found in specific places (west Amazon, Amapá, Northeast of Pará), while high differences in the SM maps are larger, since they extrapolate AGB from RadamBrasil plots in classes (whole Amazon State, west Pará and the same places of DR). On the other hand, extreme differences between all maps are found next to the rivers (mainly the Amazon River), in Amapá, northeast of Pará and central and north Amazon. These areas coincide with areas of higher AGB (Lowland Dense Humid Forests or Db, Submontane Dense Humid Forest or Ds).

The AGB maps differences and statistical cell analyses, will help decision makers, scientists and consultants to choose AGB products according to their needs and the scale of the study.

The forest AGB spatial data gaps map was obtained gathering all previous analysis and products. This map represents zones with AGB data gaps, places with no field or LiDAR data where AGB maps differs the most; in other words, priority places to implement further AGB assessments.

We hope that this study and the AGB data gaps map become useful tools for policy makers and different stakeholders working on AGB, on which to base their decisionsto choose AGB data or products for NC, REDD+, or carbon emissions modeling. We also expect that the knowledge generated in this study will be a contribution to the difficult task of conserving forests and the ecosystem services they provide.

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## Appendix A

### A1. Acronyms of Table 3.1 and Figure 4.4.

**Projects**

| | |
|---|---|
| Amazon FACE | Amazon Free-air CO2 enrichment (FACE) Project |
| AMAZONICA | Amazon Integrated Carbon Analysis Project |
| ATTO | University of Leeds |
| Bionte | Biomassa e Nutrientes |
| CADAF | Carbon Dynamics of Amazonian Forests Project |
| Chichuá | - |
| EBA | Estimativa de Biomassa na Amazônia, subproject 7 of Remote Sensing Environmental Monitoring of the Amazon Project |
| ESECAFLOR | Estudo Da Seca Na Floresta |
| FATE-Amazonia | Fire-Associated Transient Emissions |
| Geoma | - |
| Go Amazon | Green Ocean Amazon |
| INCT-Madeiras | Instituto Nacional de Ciência e Tecnologia de Madeiras da Amazônia |
| Jacaranda | Pesquisas da Floresta Amazônica Brasileira |
| LBA | Large Scale Biosphere-Atmosphere Experiment in Amazonia |
| Piculus | - |
| PPBio | The Research Program for Biodiversity |
| PPOPE | - |
| Pronex | Programa de Apoio a Núcleos de Excelência |
| RadamBrasil | Projeto Radar da Amazônia |
| Silva Carbon Project | - |
| Sustainable Landscapes | - |
| Tacape | - |

**Networks**

| | |
|---|---|
| Amazon State Forest Inventory | Inventario Florestal Continuo |
| National Forest Inventory (NFI) | Inventario Florestal Nacional |
| RAINFOR | Amazon Forest Inventory Network |
| Redeflor | Rede de Monitoramento da Dinâmica de Florestas na Amazônia Brasileira |
| TEAM | Tropical Ecology, Assessment, and Monitoring Network |
| TMFO | Tropical Managed Forests Observatory |

**Institutions**

| | |
|---|---|
| FAO FRA | Global Forest Resources Assessments |
| Conservation International | - |
| Embrapa | Empresa Brasileira de Pesquisa Agropecuária |
| Emilio Goeldi Museum | Museu Paraense Emílio Goeldi |
| IBAMA | Instituto Brasileiro de Meio Ambiente e Recursos Naturais Renováveis |
| IBGE | Instituto Brasileiro de Geografia e Estatística |
| ICMBio | Instituto Chico Mendes de Conservação da Biodiversidade |
| IDEFLOR | Instituto de Desenvolvimento Florestal do Pará |
| IMAZON | Instituto do Homem e Meio Ambiente da Amazônia |

| | |
|---|---|
| INPA | National Institute of Amazon Researches (Instituto Nacional de Pesquisas da Amazônia) |
| INPE | National Institute for Space Research of Brazil (Instituto Nacional de Pesquisas Espaciais) |
| IPAM | Instituto de Pesquisa Ambiental da Amazônia |
| NASA | National Aeronautics and Space Administration |
| National Forest Service | Serviço Florestal Brasileiro (SFB) |
| SDS | Secretária de Estado do Meio Ambiente e Desenvolvimento Sustentável |
| TNC | The Nature Conservancy |

**Sites**

| | |
|---|---|
| Caxiuanã national | Flona de Caxiuanã, Floresta Nacional de Caxiuanã |
| EEST-INPA/ZF2 | Estação Experimental de Silvicultura Tropical (INPA) |
| Floresta Nacional Tapajós | - |
| Humaita Forest Reserve | - |

**National Universities**

| | |
|---|---|
| ESALQ | Escola Superior de Agricultura Luiz de Queiroz |
| UFAC | Universidade Federal do Acre |
| UFAL | Universidade Federal do Alagoas |
| UFAM | Universidade Federal do Amazonas |
| UFCG | Universidade Federal de Campina Grande |
| UFMT | Universidade Federal do Mato Grosso |
| UFOPA | Universidade Federal do Oeste do Pará |
| UFPR | Universidade Federal do Paraná |
| UFRA | Universidade Federal Rural da Amazônia |
| UFRN | Universidade Federal do Rio Grande do Norte |
| UNEMAT | Universidade do Estado de Mato Grosso |
| UNICAMP | Universidade Estadual de Campinas |
| UNIR | Universidade Federal de Rondônia |
| USP | USP - Universidade de São Paulo |

**International Universities**

| | |
|---|---|
| Exeter | University of Exeter, |
| Landcaster | Lancaster University |
| Leeds | University of Leeds |
| New Hampshire | University of New Hampshire |
| Oxford | University of Oxford |

## A2. Detailed legend of Figures 4.9 to 4.15.

Figure 4.9. (a) Relief units map of Brazil (IBGE, 2006).

**Relief units**

Baixada Maranhense
Chapada dos Parecis
Colinas do Acre
Colinas do Amapá
Colinas dos Rios Javari/Juruá
Cristas e Colinas do Rio Gurupi
Depresssão do Médio Rio Tocantins
Depressão Interplanáltica dos Caiabis
Depressão Interplanáltica dos Rios Juruena/Teles Pires
Depressão da Amazônia Meridional
Depressão da Amazônia Setentrional
Depressão de Boa Vista
Depressão do Alto Paraguai
Depressão do Baixo Rio Araguaia
Depressão do Médio Rio Araguaia
Depressão do Norte de Mato Grosso
Depressão do Rio Guaporé
Depressão do Rio Ji-Paraná
Depressão do Rio Madeira
Depressão do Rio Purus
Depressão do Rio Solimões
Depressão dos Rios Branco/Negro
Depressão dos Rios Negro/Japurá
Leque Aluvial do Rio Tocantins
Massa Dagua Continental
Massa Dagua Costeira - Mar Territorial, 12 milhas
Patamar de Marabá
Patamar do Rio Itapecuru
Patamares Meridionais da Borda da Bacia do Amazonas
Patamares Setentrionais da Borda da Bacia do Amazonas
Patamares de Roraima
Pediplano do Médio Rio Araguaia
Pediplano dos Rios Branco/Negro
Planalto Rebaixado dos Rios Negro/Uatumã
Planalto do Cachimbo
Planalto do Divisor dos Rios Amazonas/Orinoco
Planalto do Médio Rio Sucunduri
Planalto do Rio Tapajós
Planalto do Rio Tiquié
Planalto dos Dardanelos
Planalto dos Parecis
Planalto dos Rios Roosevelt/Aripuanã
Planaltos Residuais do Guaporé/Sa. dos Pacaás Novos
Planaltos Residuais do Norte da Amazônia
Planaltos Residuais do Sul da Amazônia
Planaltos do Norte de Roraima
Planaltos dos Rios Apiacás/Sucunduri/Crepori
Planície Amazônica
Planície do Rio Araguaia/Ilha do Bananal
Planície dos Rios Paraguai/Paraná/Uruguai
Planícies Fluviais
Planícies Fluviolacustres
Planícies Fluviomarinhas
Planícies e Pantanais do Rio Guaporé
Província Serrana
Serra do Roncador
Serras do Cachimbo
Serras do Divisor-Moa
Serras do Espinhaço Setentrional
Serras do Sul do Pará
Serras dos Caiabis
Serras e Patamares dos Rios Tocantins/Araguaia
Superfície de Bacabal
Superfície do Alto Rio Xingu
Superfície do Rio Gurupi
Tabuleiros Costeiros
Tabuleiros de Barreirinhas
Tabuleiros do Baixo Rio Amazonas
Tabuleiros dos Rios Gurupi/Grajaú

Figure 4.10. (a) Geomorphology of the Legal Amazon map (MMA, 2006a).

**Geomorphology classes**

Aed
Af
Afl
Afm
Ai
Am
Aptf
Atf
Atfm
Atm
Da32
Da33
Da34
Da41
Da42
Da43
Da44
Da51
Da52
Da53
Da54
Da55
Dc12
Dc21
Dc22
Dc23
Dc25
Dc31
Dc32
Dc33
Dc34
Dc41
Dc42
Dc43
Dc44
Dc45
Dc51
Dc52
Dc53
Dc54
De
Dr
Dt11
Dt12
Dt21
Dt22
Dt23
Dt31
Dt32
Dt33
Dt34
Dt41
Dt42
Dt43
Dt44
Dt51
Dt52
Dt53
Massa de agua
P
Pgi
Pgu
Pri
Pru

(b) Relief map 2002 (IBGE, 2002b).

**Relief classes**

- Chapada do Meio-Norte
- Chapada dos Parecis
- Cristas e Colinas do Rio Gurupi
- Depressão da Amazônia Meridional
- Depressão da Amazônia Setentrional
- Depressão de Boa Vista
- Depressão do Baixo Rio Araguaia
- Depressão do Meio-Norte
- Depressão do Médio-Baixo Rio Amazonas
- Depressão do Médios Rios Tocantins/Araguaia
- Depressão do Rio Araguaia/Pantanal
- Depressão do Rio Xingu
- Depressão do Solimões
- Depressão dos Altos Rios Paraguai/Guaporé
- Depressão dos Altos Rios Tocantins/Araguaia
- Depressão dos Rios Javari-Contamana
- Depressão dos Rios Negro/Branco
- Escarpas e Reversos do Planalto de Roraima
- Lençóis Maranhenses
- Pantanais Matogrossenses
- Pantanal do Rio Guaporé
- Planalto dos Parecis
- Planaltos Marginais ao Rio Amazonas
- Planaltos Residuais da Amazônia Meridional
- Planaltos Residuais da Amazônia Setentrional
- Planaltos e Serras dos Altos Rios Paraguai/Guaporé
- Planaltos residuais dos Rios Tocantins/Araguaia
- Planícies Fluviais e/ou Fluviolacustres
- Planícies Marinhas, Fluviomarinhas e/ou Fluviolacustres
- Serras do Cachimbo/Sucunduri
- Tabuleiros Costeiros

Figure 4.11 (a) Soil carbon stocks (BERNOUX; VOLKOFF; CERRI, 1997). Is the intersection of a soil class (V) and vegetation class (S)

**(V) Vegetation category**
V1 Open Amazon forest
V2 Dense Amazon forest
V3 Atlantic forest
V4 Seasonal deciduous forest
V5 Seasonal semi-deciduous forest
V6 Mixed ombrophyllous forest
V7 South savanna
V8 Amazon savanna
V9 Savanna (Brazilian Cerrado)
V10 South Steppe
V11 Northeast steppe
V12 Western Steppe (Pantanal)
V13 Highland fields
V14 Areas of pioneer formations
V15 Woody oligotrophic vegetation

**(S) Soil Category**
S1 HAC soils
S2 LAC Latossolos
S3 LAC non-Latossolos
S4 Sandy soils
S5 Wet soils
S6 Other soils

**Soil class**

| | | | | | |
|---|---|---|---|---|---|
| V13S2 | V15S4 | V2S1 | V4S2 | V5S4 | V8S4 |
| V13S3 | V15S5 | V2S2 | V4S3 | V5S5 | V8S5 |
| V14S1 | V1S1 | V2S3 | V4S4 | V5S6 | V8S6 |
| V14S3 | V1S2 | V2S4 | V4S5 | V6S5 | V9S2 |
| V14S4 | V1S3 | V2S5 | V5S1 | V8S1 | Water |
| V14S5 | V1S4 | V2S6 | V5S2 | V8S2 | |
| V15S2 | V1S5 | V4S1 | V5S3 | V8S3 | |

b) Soils of Legal Amazon (MMA, 2006a).

**Soil classes**

| | |
|---|---|
| | Planossolo |
| Afloramento de Rochas | Plintossolo |
| Areias Quartzosas | Podzol Hidromorfico |
| Areias Quartzosas Hidromorficas | Podzolico Vermelho-Amarelo |
| Areias Quartzosas Marinhas | Podzolico Vermelho-Amarelo Latossolico |
| Brunizem Avermelhado | Podzolico Vermelho-Escuro |
| Cambissolo | Solonchak |
| Gleissolo | Solos Aluviais |
| Hidromorfico Cinzento | Solos Hidromorficos Indiscriminados |
| Latossolo Amarelo | Solos Indiscriminados de Mangue |
| Latossolo Roxo | Solos Litolicos |
| Latossolo Vermelho-Amarelo | Solos Petroplinticos |
| Latossolo Vermelho-Escuro | Terra Roxa Estruturada |

Figure 4.12 (a) Soil map (QUESADA et al., 2011).

**Soil classes**

| | |
|---|---|
| ACRISOLS | LEPTOSOLS |
| ARENOSOLS | LIXISOLS |
| CAMBISOLS | NITISOLS |
| FERRALSOLS | PLINTHOSOLS |
| FLUVISOLS | PODZOLS |
| GLEYSOLS | REGOSOLS |
| HISTOSOLS | |

(b) Soil map of Brazil (IBGE, 2001)

Figure 4.13 (a) Vegetation map (SIVAM, 2002).

Campinarana Arborizada com palmeiras
Campinarana Arborizada sem palmeiras
Campinarana Arbustiva com palmeiras
Campinarana Arbustiva sem palmeiras
Campinarana Florestada com palmeiras
Campinarana Florestada sem palmeiras
Campinarana Gramíneo - lenhosa sem palmeiras
Campinarana Gramíneo-Lenhosa
Contato Campinarana / Floresta Ombrófila - ecotono
Contato Floresta Ombrófila / Floresta Estacional - ecotono
Contato Savana / Floresta Estacional - ecotono
Contato Savana / Floresta Ombrófila - ecotono
Contato Savana / Formações Pioneiras - ecotono
Contato Savana / Savana-Estépica - encotono
Floresta Estacional Decidual Submontana
Floresta Estacional Decidual Submontana Dossel emergente
Floresta Estacional Decidual Terras Baixas Dossel emergente
Floresta Estacional Semidecidual Aluvial
Floresta Estacional Semidecidual Aluvial Dossel emergente
Floresta Estacional Semidecidual Aluvial Dossel uniforme
Floresta Estacional Semidecidual Montana Dossel emergente
Floresta Estacional Semidecidual Submontana
Floresta Estacional Semidecidual Submontana Dossel emergente
Floresta Estacional Semidecidual Submontana Dossel uniforme
Floresta Estacional Semidecidual Terras Baixas
Floresta Estacional Semidecidual Terras Baixas Dossel emergente
Floresta Ombrófila Aberta Aluvial
Floresta Ombrófila Aberta Aluvial com bambus
Floresta Ombrófila Aberta Aluvial com cipós
Floresta Ombrófila Aberta Aluvial com palmeiras
Floresta Ombrófila Aberta Submontana
Floresta Ombrófila Aberta Submontana com bambus
Floresta Ombrófila Aberta Submontana com cipós
Floresta Ombrófila Aberta Submontana com palmeiras
Floresta Ombrófila Aberta Submontana com sororocas
Floresta Ombrófila Aberta Terras Baixas
Floresta Ombrófila Aberta Terras Baixas com bambus
Floresta Ombrófila Aberta Terras Baixas com cipós
Floresta Ombrófila Aberta Terras Baixas com palmeiras
Floresta Ombrófila Densa Aluvial
Floresta Ombrófila Densa Aluvial Dossel emergente
Floresta Ombrófila Densa Aluvial Dossel uniforme
Floresta Ombrófila Densa Montana Dossel emergente
Floresta Ombrófila Densa Montana Dossel uniforme
Floresta Ombrófila Densa Submontana
Floresta Ombrófila Densa Submontana Dossel emergente
Floresta Ombrófila Densa Submontana Dossel uniforme
Floresta Ombrófila Densa Terras Baixas
Floresta Ombrófila Densa Terras Baixas Dossel emergente
Floresta Ombrófila Densa Terras Baixas Dossel uniforme
Formações Pioneiras com influência fluvial e / ou lacustre - arbustiva
Formações Pioneiras com influência fluvial e / ou lacustre - arbustiva com palmeiras
Formações Pioneiras com influência fluvial e / ou lacustre - arbustiva sem palmeiras
Formações Pioneiras com influência fluvial e / ou lacustre - buritizal
Formações Pioneiras com influência fluvial e / ou lacustre - herbácea
Formações Pioneiras com influência fluvial e / ou lacustre - herbácea com palmeiras
Formações Pioneiras com influência fluvial e / ou lacustre - herbácea sem palmeiras
Formações Pioneiras com influência fluviomarinha - arbórea
Formações Pioneiras com influência fluviomarinha - herbácea
Formações Pioneiras com influência marinha - arbustiva
Refúgio Vegetacional Altomontano herbáceo
Refúgio Vegetacional Montano arbustivo
Refúgio Vegetacional Montano herbácea
Refúgio Vegetacional Submontano arbustivo
Savana Arborizada
Savana Arborizada com floresta-de-galeria
Savana Arborizada sem floresta-de-galeria
Savana Estépica Arborizada sem palmeiras e sem floresta-de-galeria
Savana Estépica Florestada sem palmeiras
Savana Estépica Gramíneo-Lenhosa com floresta-de-galeria
Savana Estépica Parque sem palmeiras e sem floresta-de-galeria
Savana Florestada
Savana Gramíneo-Lenhosa
Savana Gramíneo-Lenhosa com floresta-de-galeria
Savana Gramíneo-Lenhosa sem floresta-de-galeria
Savana Parque
Savana Parque com floresta-de-galeria
Savana Parque sem floresta-de-galeria

(b) Brazilian Biomes Vegetation Cover (MMA, 2006b)

**Legend**

**veg3_s**

**SPRCLASSE**

- 
- Aa
- Aa+Ab
- Aa+Ap
- Aa+As
- Aa+As+Vs
- Aa+Da
- Aa+Da+Ap
- Aa+Da+Pa
- Aa+Db
- Aa+Pa
- Aa+Pf
- Aa+Vs
- Aa+Vs+Ac
- Ab
- Ab+Aa
- Ab+Da
- Ab+Db
- Ab+Ds
- Ab+Pa
- Ab+Vs
- Ac
- Ac+Fs+Vs
- Ac+Vs
- Ac+Vs+As
- Ac+Vs+Fs
- Afr
- Ag
- Ag+As
- Ag+Ds
- Ag+ON
- Ag+Sp
- Ag+Vs
- Ag+Vs+As
- Ai
- Ai+Vs
- Ap
- Ap+Ac
- Ap+As
- Ap+Da
- Ap+Db
- Ap+Ds
- Ap+Fs
- Ap+Pa+Da
- Ap+Sa
- Ap+Sa+Sd
- Ap+Sd
- Ap+SN

- Ap+Sp
- Ap+Sp+Sa
- Ap+Vs
- Ap+Vs+As
- Ap+Vs+Db
- Ap+Vs+Ds+As
- Ap+Vs+Fs
- Ap.A
- As
- As+Ac
- As+Ag
- As+Ap
- As+Ap+Vs
- As+Ds
- As+Ds+Ac
- As+Ds+Ag
- As+Ds+As
- As+Ds+Vs
- As+rm
- As+Vs
- As+Vs+Ac
- As+Vs+Ap
- As+Vs+Ds
- Cs
- Cs+rm
- Cs+Vs
- Da
- Da+Aa
- Da+Aa+Ac
- Da+Aa+Pa
- Da+Ab
- Da+Ac
- Da+Ap
- Da+Ap+Vs
- Da+Db
- Da+Ds
- Da+Pa
- Da+Pa+Aa
- Da+Pa+Ac
- Da+Pa+Ap
- Da+Pa+Vs
- Da+Vs
- Da+Vs+Ac
- Da+Vs+Ap
- Da+Vs+Pa
- Db
- Db+Aa
- Db+Ab
- Db+Ab+Ap
- Db+Ab+Vs

- Db+Ac+Vs
- Db+Ap
- Db+As
- Db+As+Ds
- Db+Da
- Db+Da+Pa
- Db+Ds
- Db+Ld+La
- Db+Pa
- Db+Pa+Ap
- Db+Vs
- Db+Vs+Ap
- Dm
- Dm+Am
- Dm+Ds
- Dm+rm
- Ds
- Ds+Ab
- Ds+Ac+Vs
- Ds+Ap
- Ds+As
- Ds+As+Ac
- Ds+As+Ac+Vs
- Ds+As+Ap
- Ds+As+Ap+Vs
- Ds+As+Da
- Ds+As+Db
- Ds+As+Ld
- Ds+As+rm
- Ds+As+Vs
- Ds+Da
- Ds+Db
- Ds+Dm
- Ds+rm
- Ds+Vs
- Ds+Vs+Ap
- Fa
- Fa+Ap+Pa
- Fa+Pa
- Fb
- Fb+Ap
- Fb+Pa
- Fb+Vs
- Fs
- Fs+Ap+Vs
- Fs+Cs
- Fs+Cs+Vs
- Fs+rm
- Fs+Vs
- Fs+Vs+Ac

- Fs+Vs+Ap
- Im
- Iu
- La
- La+Lb
- La+Ld
- La+Ld+Lb
- La+Ld+Lg
- La+Lg
- La+Lg+Lb
- La+Lg+Ld
- Lb
- Lb+La
- Lb+La+Ld
- Lb+La+Lg
- Lb+Ld
- Lb+Lg
- Lb+Lg+La
- Lb+Lg+Ld
- Ld
- Ld+La
- Ld+La+Lb
- Ld+La+Lg
- Ld+La+Vs
- Ld+Lb
- Ld+Lb+La
- Ld+Lb+Lg
- Ld+Lg
- Ld+Lp
- Lg
- Lg+La
- Lg+La+Ld
- Lg+Lb
- Lg+Lb+La
- Lg+Lb+La+Ld
- Lg+Ld
- LO
- Massa_agua
- ON
- Pa
- Pa+Aa
- Pa+Aa+Ap
- Pa+Ab
- Pa+Ac+Da
- Pa+Ap
- Pa+Da
- Pa+Da+Vs
- Pa+Fa
- Pa+Sa
- Pa+Sd

- Pa+Sp
- Pa+Vs
- Pa+Vs+Da
- Pf
- Pf+Aa
- Pf+Pm
- Pf+Vs
- Pm
- Pm+Pf
- R
- Re+Rp+Sp
- Re+Sp+Sd
- rm
- rm+As
- rm+Cs
- rm+Dm
- rm+Fs
- rm_Cs
- Sa
- Sa+Ap
- Sa+Ap+Sd
- Sa+Ap+Sp
- Sa+Pa
- Sa+Sd
- Sa+Sd+Sp
- Sa+Sg
- Sa+Sp
- Sa+Sp+Ap
- Sa+Sp+Sd
- Sd
- Sd+Ap
- Sd+Sa
- Sd+Sa+Ap
- Sd+Sa+Vs
- Sd+Sg
- Sd+Sp
- Sd+Sp+Pa
- Sg
- Sg+Ap
- Sg+Sa
- Sg+Sa+Sd
- Sg+Sd
- Sg+Sp
- Sg+Sp+Ap
- Sg+Sp+Sa
- SN
- SN+Vs
- SO
- Sp
- Sp+Ap

- Sp+Pa
- Sp+Sa
- Sp+Sa+Ac
- Sp+Sa+Ap
- Sp+Sa+Sg
- Sp+Sd
- Sp+Sd+Vs
- Sp+Sg
- Sp+Sg+Ap
- Sp+Sg+Sd
- ST
- ST+Pa
- Td
- Td+Tp
- Tg+Tp
- TN
- Tp
- Tp+Ta+Td
- Tp+Td
- Tp+Tg
- Tp+Tg+Td
- Vs
- Vs+Ab
- Vs+Ac
- Vs+Ac+Aa
- Vs+Ac+Ap
- Vs+Ac+Db
- Vs+Ag
- Vs+Ag+Db
- Vs+Ap
- Vs+Ap+Ab
- Vs+Ap+As
- Vs+Ap+Da
- Vs+Ap+Db
- Vs+Ap+Db+Sp
- Vs+Ap+Ds
- Vs+Ap+Pa
- Vs+Cs
- Vs+Da
- Vs+Da+Ap
- Vs+Db
- Vs+Db+Ac
- Vs+Db+Ap
- Vs+Db+Pa
- Vs+Ds
- Vs+Ds+As
- Vs+Fb
- Vs+Pa
- Vs+Pa+Da
- Ds+As+Ld

Figure 4.14 (a) Vegetation map of Brazil (IBGE; USGS, 1992).

**Legend**

| **veg5_s** | F | S |
|---|---|---|
| **SIGLA4** | Fa | Sa |
| A | Fs | Sd |
| Aa | La | Sg |
| Ab | Ld | SM |
| As | Lg | SN |
| C | LO | SO |
| Cs | NOLAB | Sp |
| D | ON | ST |
| Da | P | Td |
| Db | Pa | Tp |
| Dm | Pf | WATER |
| Ds | rm | |

(b) Vegetation physiognomies of Brazil (MCT, 2010).

| **Phytophysiognomies** | **Abbreviation** |
|---|---|
| Alluvial Open Humid Forest | Aa |
| Lowland Open Humid Forests | Ab |
| Open Submontane Humid Forest | As |
| Lowland Deciduous Seasonal Forest | Cb |
| Submontane Deciduous Seasonal Forest | Cs |
| Alluvial Dense Humid Forest | Da |
| Lowland Dense Humid Forests | Db |
| Montane Dense Humid Forest | Dm |
| Submontane Dense Humid Forest | Ds |
| Alluvial Semi deciduous Seasonal Forest | Fa |
| Lowland Semi deciduous Seasonal Forest | Fb |
| Montane Semi deciduous Seasonal Forest | Fm |
| Submontane Semi deciduous Seasonal Forest | Fs |
| Wooded Campinarana | La |
| Shrub Campinarana | Lb |
| Forested Campinarana | Ld |
| Wooded grassy Campinarana | Lg |
| Fluvial and/or lacustre influenced Vegetation | Pa |
| Pioneering formation of Fluviomarine influence (mangroves) | Pf |
| Pioneering formation of marine influence (sand banks) | Pm |
| Mountain refuge | Rm |
| Wooded Savanna | Sa |
| Forested Savanna | Sd |
| Wooded grassy Savanna | Sg |
| Park Savanna | Sp |
| Wooded Steppe Savanna | Ta |
| Forested Steppe Savanna | Td |
| Esthetic Park Savanna | Tp |

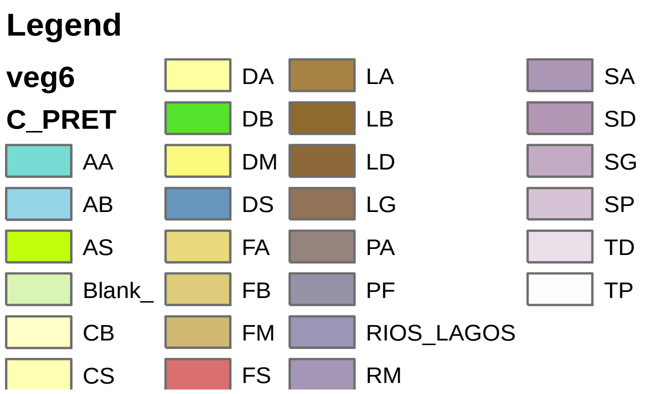
Legend
veg6
C_PRET
AA
AB
AS
Blank_
CB
CS
DA
DB
DM
DS
FA
FB
FM
FS
LA
LB
LD
LG
PA
PF
RIOS_LAGOS
RM
SA
SD
SG
SP
TD
TP

Figure 4.15 (a) Vegetation Map of Brazil (IBGE, 2004b).

**Legend**

**veg7**

**DSC_CLASS_**

- Atividades AgrÃ¡rias
- Campinarana Arborizada
- Campinarana Arbustiva
- Campinarana Florestada
- Campinarana Gramineo-Lenhosa
- Campinarana/Floresta OmbrÃ³fila
- Floresta  OmbrÃ³fila/Floresta Estacional
- Floresta Estacional Decidual Submontana
- Floresta Estacional Semidecidual Aluvial
- Floresta Estacional Semidecidual Submontana
- Floresta Estacional Semidecidual Terras Baixas
- Floresta OmbrÃ³fila Densa Aluvial
- Floresta OmbrÃ³fila Densa Montana
- Floresta OmbrÃ³fila Densa Submontana
- Floresta OmbrÃ³fila Densa Terras Baixas
- Massa Dagua Continental
- Massa Dagua Costeira - Mar Territorial, 12 milhas
- RefÃºgios Vegetacionais Alto-Montano
- RefÃºgios Vegetacionais Montano
- Savana Arborizada
- Savana EstÃ©pica/Floresta Estacional
- Savana Florestada
- Savana Gramineo-Lenhosa
- Savana Parque
- Savana-EstÃ©pica Arborizada
- Savana-EstÃ©pica Florestada
- Savana-EstÃ©pica Gramineo-Lenhosa
- Savana-EstÃ©pica Parque
- Savana/ Floresta Estacional
- Savana/Floresta OmbrÃ³fila
- Savana/Savana EstÃ©pica
- VegetaÃ§Ã£o OmbrÃ³fila Aberta Aluvial
- VegetaÃ§Ã£o OmbrÃ³fila Aberta Submontana
- VegetaÃ§Ã£o OmbrÃ³fila Aberta Terras Baixas
- VegetaÃ§Ã£o SecundÃ¡ria e Atividades AgrÃ¡rias
- Ã• reas das FormaÃ§Ãµes Pioneiras VegetaÃ§Ã£o com InfluÃªncia Fluvial e/ou Lacust
- Ã• reas das FormaÃ§Ãµes Pioneiras VegetaÃ§Ã£o com InfluÃªncia Fluvio- marinha
- Ã• reas das FormaÃ§Ãµes Pioneiras VegetaÃ§Ã£o com InfluÃªncia Marinha