Forest Ecology and Management 377 (2016) 170–181

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Spatial distribution of forest biomass in Brazil's state of Roraima, northern Amazonia

Paulo Eduardo Barni[a], Antônio Ocimar Manzi[b,c], Tiago Monteiro Condé[a], Reinaldo Imbrozio Barbosa[d,e], Philip Martin Fearnside[b,e,*]

[a] Universidade Estadual de Roraima (UERR), Campus Rorainópolis, Av. Senador Helio Campos, s/n°, 69375-000 Rorainópolis, Roraima, Brazil
[b] Instituto Nacional de Pesquisas da Amazônia (INPA), Coordenação de Dinâmica Ambiental (CDAM), Av. André Araújo 2936, 69067-375 Manaus, Amazonas, Brazil
[c] Instituto Nacional de Pesquisas Espaciais (INPE), Rodovia Presidente Dutra, Km 39, 12630-000 Cachoeira Paulista, São Paulo, Brazil[1]
[d] Instituto Nacional de Pesquisas da Amazônia (INPA), Núcleo de Pesquisas de Roraima (NPRR), Rua Coronel Pinto 315, 69301-150 Boa Vista, Roraima, Brazil
[e] Rede Brasileira de Pesquisas sobre Mudanças Climáticas Globais (Rede Clima), São José dos Campos, São Paulo, Brazil

ARTICLE INFO

Article history:
Received 18 April 2016
Received in revised form 30 June 2016
Accepted 8 July 2016
Available online 14 July 2016

Keywords:
Carbon stock
Deforestation
Global warming
Greenhouse gas emissions
Protected areas
REDD

ABSTRACT

Forest biomass is an important variable for calculating carbon stocks and greenhouse gas emissions from deforestation and forest fires in Brazilian Amazonia. Its spatial distribution has caused controversy due to disagreements over the application of different calculation methodologies. Standardized networks of forest surveys provide an alternative to solve this problem. This study models the spatial distribution and original total stock of forest biomass (Aboveground + Belowground + Fine and coarse litter) in Brazil's state of Roraima, taking advantage of data from georeferenced forest surveys in the region. Commercial volume (bole volume) from surveys was expanded to total biomass. Kriging techniques were used to model the spatial distribution of biomass stocks and generate a benchmark map. All results were associated with phytophysiognomic groups, climatic regions and land uses (protected areas; agricultural use). We estimate forest in the state of Roraima to have an original biomass stock of 6.32×10^9 Mg. Forest biomasses in areas with shorter dry seasons were higher as compared to forests in regions with longer dry seasons. The original vegetation in protected areas, independent of phytophysiognomic group, has higher biomass compared to areas currently under agricultural use. Protected areas support 65.8% of Roraima's stock of forest biomass, indicating an important potential role in REDD projects for conservation of forest carbon. Information on spatial distribution of biomass stocks at a more refined scale is needed to reduce uncertainties about the regional character of carbon pools in Amazonia.

© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Forest biomass affects the calculation of carbon stocks and greenhouse gas (GHG) emissions, this being a major source of uncertainty regarding the climatic role of forests and their management in Brazilian Amazonia (Fearnside, 1997a, 2000; Chave et al., 2004, 2014; Houghton, 2010). Along with deforestation, biomass determines the potential for carbon emissions that can be released into the atmosphere when forests are cut (Houghton et al., 2009; Harris et al., 2012; Song et al., 2015). Cutting and burning of forest biomass in Amazonia are linked to expanding areas of agriculture and pasture. The quickest and cheapest way to "clean" the deforested area is by burning. Accurate models of forest biomass distribution can reduce the uncertainties in carbon stocks because they are based on a consistent and spatially explicit set of observational data, enabling a better understanding of the environmental and human processes that determine GHG emissions (Harris et al., 2012), in addition to providing information needed for projects for Reducing Emissions from Deforestation and Degradation (REDD) (e.g., Soares-Filho et al., 2010; Nepstad et al., 2011; Saatchi et al., 2011).

The first systematic attempt in Amazonia to obtain large-scale forest biomass estimates was derived from studies of Brown and Lugo (1992, 1994). These authors developed expansion factors and adjustments from commercial volume equations derived from forest inventories carried out by the Food and Agriculture Organization of the United Nations (UN-FAO) in the late 1950s. In the specific case of Amazonia, new adjustments were implemented

---

[*] Corresponding author at: Instituto Nacional de Pesquisas da Amazônia (INPA), Coordenação de Dinâmica Ambiental (CDAM), Av. André Araújo 2936, 69067-375 Manaus, Amazonas, Brazil.
E-mail address: pmfearn@inpa.gov.br (P.M. Fearnside).

[1] Current address.

http://dx.doi.org/10.1016/j.foreco.2016.07.010
0378-1127/© 2016 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

by Fearnside (1992) with the correction or addition of other carbon pools (e.g., dead wood, lianas, understory plants) which had been omitted by Brown and Lugo (1992). Adjustments derived from Fearnside (1992) were significantly improved by Nogueira et al. (2005, 2007, 2008) and have been applied to commercial volume (bole volume) values obtained by the RADAMBRASIL inventories (Brazil, RADAMBRASIL, 1973–1983) conducted in the entire Brazilian Amazon (Fearnside, 1994, 1996, 1997a). The bole volumes of trees from the RADAMBRASIL inventories were calculated based on diameter at breast height (DBH), or diameter 1.3 m above the ground or above any buttresses. Only individuals with circumference at breast height $\geqslant$100 cm (i.e., 31.8 cm DBH) were included in the inventory.

The values of commercial volume estimated by the RADAMBRASIL Project for the whole of Brazilian Amazonia (Brazil, IBGE, 2013) could then be expanded to total biomass (live biomass and necromass; below- and aboveground) and used in regional spatial distribution models or extrapolated in accord with physiognomies within each state (Fearnside, 2000; Sales et al., 2007; Brazil, MCT, 2010; Nogueira et al., 2015). An advantage of using the RADAMBRASIL database lies in its having been collected before the major deforestation and forest degradation events currently observed in Amazonia, thus offering a unique opportunity to assess the "original" (pre-1970) biomass distribution.

Despite advances in reducing uncertainties, the spatial distribution of Amazon forest biomass can be estimated based on land-cover maps and information on the biomasses of vegetation types and the effects of environmental factors (e.g., physiognomies, climate, soil) (Feldpausch et al., 2011; Baccini et al., 2012) and land-use history (e.g., agro-silvo-pastoral "use areas" and different types of protected areas) (Malhi et al., 2006). This auxiliary information, when supported by forest inventories and remote-sensing data, brings great advantages for the construction of reference maps (Saatchi et al., 2011; Harris et al., 2012; Baccini et al., 2012). This is due to the introduction of additional features that assist in estimating mean biomass per unit area (Mg ha^{-1}) and delimiting the spatial distribution of the biomass and carbon stocks disturbed by deforestation. Given that large areas in the Amazon lack any direct measurement of biomass, this alternative allows construction of spatially refined maps at local and regional scales arranged in a georeferenced grid that may be reproduced under varying temporal constraints (Nogueira et al., 2015; Saatchi et al., 2012). This is because the anthropogenic and environmental characteristics specific to each region (e.g., at the state level) can be analyzed separately under the same calculation basis, rather than being products of extrapolations to a less detailed scale (e.g., Saatchi et al., 2007, 2011; Baccini et al., 2012). Maps using satellite-derived data to extrapolate from a limited number of ground plots (e.g., Saatchi et al., 2011; Baccini et al., 2012) have produced inconsistent results, even though they have essentially the same data sources and methods (Mitchard et al., 2014). Progress has been made in resolving differences (Avitabile et al., 2016), but the limited ground data remain as the principal source of uncertainty. The RADAMBRASIL dataset, not used in the Saatchi et al. (2011) and Baccini et al. (2012) studies, represents a much larger source of on-the-ground data (Nogueira et al., 2015). Large-scale approaches tend to have greater uncertainties than do those on smaller scales due to the different methods of data collection used and to environmental variability among macro-regions. Local and regional approaches are less subject to the problems causing uncertainty. Use of smaller-scale procedures provides an alternate path for evaluations of the regional potential for storing carbon and for emission of greenhouse gases.

We used the state of Roraima (northern Brazilian Amazonia) as a case study to model the spatial distribution of forest biomass and to evaluate the original stock of biomass (live biomass and necromass; above- and belowground) considered here as undisturbed biomass in pre-1970 period. This region of the Amazon has phytoclimatic zones represented by savannas, seasonal forests and ombrophilous forests that are different from other Amazonian states (Barni et al., 2015a). Analysis of the distribution of forest biomass in these areas permits a more realistic estimate of the original forest biomass stocks, located in areas with different protection status and climate type, providing the basis for more robust estimates of forest carbon stocks and GHG emissions from deforestation. Our specific objectives were (i) estimate the total biomass (live biomass and necromass; below- and aboveground) based on forest volume inventories conducted in Roraima and its surroundings mainly by the RADAMBRASIL project; (ii) generate a reference map from the spatial modeling of forest biomass using geostatistical techniques; (iii) determine the biomass (Mg ha^{-1}) in each forest type by phytoclimatic zone, and (iv) determine the original biomass stock in each phytoclimatic zone in areas with protection (IL = indigenous lands and CU = conservation units) and without legal protection (UA = use areas). "Conservation units" refer to the various types of areas, both "strictly protected" and for "sustainable use," defined in Brazil's National System of Conservation Units (SNUC) (Brazil, MMA, 2000).

2. Materials and methods

2.1. Study area

Brazil's state of Roraima has an area of 224.3 × 10^3 km^2 (an area the size of the US state of Minnesota) and is located in the northernmost portion of Brazilian Amazonia, bordering Venezuela and Guyana (Fig. 1). The climate is divided into three types under the Köppen classification: "Af" (humid forest climate), which supports oligotrophic vegetation (campina and campinarana) on white-sand soil (phytophysionomies adapted to hydro-edaphic constraints; this vegetation is adapted to nutrient limitation and to periodic flooding or elevation of the water table) together with part of the ombrophilous forest in the southwestern and extreme northwestern portions of the state; "Am" (monsoon climate), which encompasses another part of the ombrophilous forest, this being a smaller section of semideciduous forest that includes the entire range of the southeastern and mid-western portions of the state, in addition to much of the northern portion, and "Aw" (savanna climate), which is characterized by "contact" forests (ecotones) and most of the seasonal forests, as well as all areas of low and high altitude grasslands occupying the northeastern portion of the state (Barbosa, 1997; Barbosa and Campos, 2011).

Annual rainfall in Roraima undergoes large variations, decreasing from the south and southwest to the northeast. In the rainforest areas in the southern and southwestern portions of the state, precipitation totals 2000–2300 mm^{-1} year. A transition zone from montane forest to ombrophilous forest to savanna has precipitation between 1700 and 2000 mm^{-1} year. The savanna formations are in the northeastern portion of the state with precipitation of 1100–1400 mm year^{-1} (Barbosa, 1997). Morphological features include dissected plateaus surrounded by intramontane pediplains and residual individual reliefs (Schaefer and Darlymple, 1995; Ab'Saber, 1997).

The state of Roraima can be divided into two major phytoclimatic zones: zone with influence of savanna (ZIS) and zone without influence of savanna (ZOS). These zones are based on geographical, climatic and geomorphological criteria (Barni et al., 2015a). The zones are associated with land-use categories (use areas, indigenous lands and conservation units). The ZIS is located

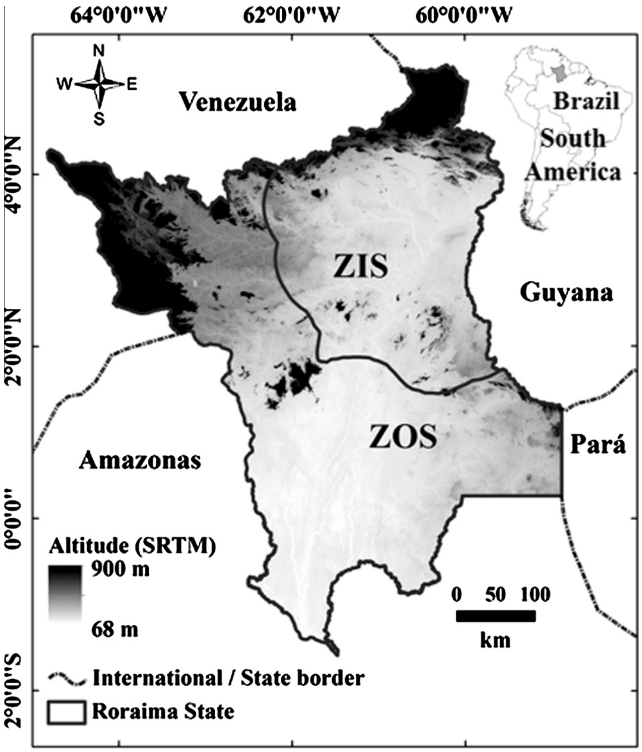

Fig. 1. Study area. The continuous solid line in the center of the figure divides the study area into two phytoclimatic zones (Barni et al., 2015a): ZIS = zone with savanna influence; ZOS = Zone without savanna influence; SRTM = Shuttle Radar Topography Mission.

in the northern and northeastern portions of Roraima (6–7 months dry), while the ZOS is located in the southern and southeastern and northwestern portions of the state where the dry period is shorter (1–5 months). Both zones are affected by deforestation, forest fires and selective logging.

2.2. Original boundaries of modeled physiognomies

The 17 forest physiognomies in Roraima were derived from a vegetation map from the Program for Conservation and Sustainable Use of Brazilian Biological Diversity (PROBio) at a scale of 1:250,000 (Brazil, PROBio, 2013). Training operations were conducted to retrieve the original coverage of forests in the state using map algebra in a geographical information system (GIS): (1) all areas occupied by humans (deforested areas, grasslands and secondary vegetation) were removed from the PROBio map and replaced by the forest or non-forest physiognomies closest to the affected area, assuming the original vegetation of Roraima without amendment; (2) the 17 physiognomies were condensed into four major forest groups (Table 1): (i) Ombrophilous forests (all classes of open and dense forest); (ii) Ecotones ("contact" physiognomies); (iii) Seasonal deciduous forests and semideciduous forest fragments, and (iv) Fragmented-physiognomies in oligotrophic ecosystems in the middle and lower Rio Branco. Savannas in the northeastern portion of the state were also added.

2.3. Estimation of the original biomass

The original total forest biomass (live + dead, aboveground and belowground) per unit area (Mg ha^{-1}) was estimated from inventories (Brazil, RADAMBRASIL, 1973–1983) conducted in Roraima and in the surrounding region (Brazil, IBGE, 2013). These inventories used commercial volume information on 296 plots (1 ha each), of which 119 were in Roraima, or within a range of 100 km from the state's borders, encompassing parts of Pará (5 plots) and Amazonas (172 plots) (Brazil, IBGE, 2013) in order to soften the edge effect (Sales et al., 2007). To this database two recently conducted forest inventories were added (Condé and Tonini, 2013; Nascimento et al., 2014), bringing the total to 298 sampling points (Supplementary Material, Fig. A.1; Table A.1). The data from these last two studies were used in the same way as the RADAMBRASIL inventories (only individuals with circumference at breast height $\geqslant$100 cm, that is, diameter at breast height $\geqslant$31.8 cm) in order to preserve the same criteria for biomass estimation throughout the spatial analysis.

The volume of each individual tree inventoried by the RADAMBRASIL Project (in a tabulation at the level of species, genus or family) was converted to dry bole biomass (biomass of the trunk from the ground to the first significant branch) by multiplying by the basic density (oven-dry weight divided by green volume; g cm^{-3}) of the wood (Fearnside, 1992, 1997b). Expansion factors were applied to all 298 sampling points to convert bole biomass to expanded aboveground biomass (Mg ha^{-1}). These factors were applied (i) to expand from bole volume to represent the total volume of each individual tree for calculating the biomass, and (ii) to add the other components of forest biomass in order to calculate the total biomass per hectare (Mg ha^{-1}) for all points in the BDG.

The volume expansion factor (VEF) adjusts for trees with DBH (diameter at breast height measured 1.3 m above the ground or above any buttresses) between 10 cm and the minimum diameter measured in the forest survey (the RADAMBRASIL database is for trees with DBH $\geqslant$ 31.8 cm). The values of VEF we used to correct for the 10–31.7 cm DBH range were 1.537 for dense forest and 1.506 for non-dense forest (Nogueira et al., 2008). These values include adjustments for hollow trees and irregularly shaped trunks. The biomass expansion factor (BEF) adjusts for the tree crowns (the portion of the tree above and including the first significant branch). The bole biomass was multiplied by the BEF, which has a value of 1.635 if bole biomass $\geqslant$190 Mg ha^{-1} (calculated by Nogueira et al. (2008) from data by Higuchi et al. (1998) normalized by diameter distribution in central Amazonia) and Exp (3.213 − (0.506 × Ln (bole biomass))) if bole biomass <190 Mg ha^{-1} (Brown and Lugo, 1992).

To convert the values for expanded biomass to total biomass, adjustments for inclusion or correction of other components of the forest (live and biomass and necromass, including the understory and roots) were applied to the database. After the 298 commercial volume points for forest were converted to total biomass (Mg ha^{-1}), additional 28 sampling points were included in the analysis to estimate savanna biomass (Mg ha^{-1}) in northern Roraima (Barbosa, 2001; Barbosa and Fearnside, 2005; Barbosa et al., 2012). Final sampling points totaled 326 (Supplementary Material, Table A.1). This dataset was called the "georeferenced database" (BDG) (Fig. 2).

2.4. Validation and the best model for interpolation

The georeferenced database was divided randomly into two subsamples: (i) a set containing 33 sampling points ($\sim$10%), and (ii) another set containing 293 sampling points ($\sim$90%). The first set ($n_1 = 33$) was reserved for validation and determination of the best interpolation model after obtaining the maps of biomass. In order to estimate each point not sampled in the execution of the three Kriging techniques, five points were used that were near neighbors to the location for which a value is to be estimated for each quadrant. This is a standard procedure in ArcGIS software.

Table 1
Forest physiognomies in the state of Roraima by phytoclimatic zone.

Group	Code[a]	Phytophysiognomy	ZIS (km^2)[b]	ZOS (km^2)[c]	Total area (km^2)
Ombrophilous forest	Ab	Open-canopy rainforest on nonflooding lowlands	–	273.8	273.8
	As	Open-canopy rainforest, submontane	1762.9	4638.1	6401.0
	Da	Dense-canopy rainforest on river floodplain	24.5	905.1	929.6
	Db	Dense-canopy rainforest on nonflooding lowlands	–	10182.9	10182.9
	Dm	Dense-canopy rainforest, montane	2877.6	22804.1	25681.7
	Ds	Dense-canopy rainforest, submontane	4811.5	52871.5	57683.0
Group total			9476.5	91675.5	101152.0
Ecotone (“Contact”)	LO	Oligotrophic vegetation/ombrophilous forest	19669.4	422.6	20092.0
	ON	Ombrophilous forest/seasonal forest	26354.1	8.9	26363.0
	SN	Savanna/seasonal forest	645.0	–	645.0
	SO	Savanna/ombrophilous forest	2174.0	–	2174.0
	TN	Steppe-like savanna/seasonal forest	2708.0	–	2708.0
Group total			51550.5	431.5	51982.0
Seasonal vegetation	Fa	Aluvial semideciduaous forest	471.2	105.8	577.0
	Fs	Sub-montane semideciduous forest	2878.0	–	2878.0
	Sa	Open woodland savanna	3937.1	1.9	3939.0
	Td	Forested steppe-like savanna	3478.0		3478.0
Group total			10764.3	107.7	10872.0
Campinarana	La	Open woody oligotrophic vegetation of swampy and sandy areas	136.2	3367.8	3504.0
	Ld	Dense woody oligotrophic vegetation of swampy and sandy areas	322.5	16666.5	16989.0
Group total			458.7	20034.3	20493.0
Forest total[d]		17 physiognomies	72250.0	112249.0	184499.0
Savanna		–	26694.0	–	26694.0
Other non-forest[e]	Lg	Grassy-woody vegetation of swampy and sandy areas (campinarana)	27.6	8689.0	8716.6
	Lb	Bushy oligotrophic oligotrophic vegetation of swampy and sandy areas (campinarana)	93.4	2390.6	2484.0
Water		–	529.6	1376.3	1905.9
Grand total		–	99594.6	124704.9	224299.5

[a] Vegetation codes (Brazil, IBGE, 2012).

[b] ZIS = zone with influence of savanna.

[c] ZOS = zone without influence of the savanna.

[d] The definition of “forest” used in this study is that of PROBio. Here Sa, Td and campinarana (La and Ld) are considered to be “forest,” as in both the PROBio vegetation map (Brazil, PROBio, 2013) and Brazil’s national inventory of greenhouse gas emissions (Brazil, MCT, 2010, p. 228), which consider all vegetation types classified as “a” (wooded) or “d” (forested) to be “forest.” This differs slightly from the definition of forest used in deforestation monitoring by PRODES (Brazil, INPE, 2016), which includes as “non-forest” treed-shrubby savannas (Sp), the part of treed savannas (Sa) with less than 10% tree cover (although, in practice, the PRODES data appear to class all Sa as forest), the wooded-grassy savannas (Sg) and some of the campinaranas (in northern Amazonia the “non-forest” campinaranas are represented only by Lg and Lb). There is some overlap of forest and non-forest under the PRODES definition (particularly in campinaranas), but we do not believe that this compromises the result because the formations listed by PRODES represent classic non-forest natural ecosystems and not their forested forms (“a” and “d”). The La and Ld campinaranas are considered to be “forest” by both PROBio and PRODES.

[e] These physiognomies (Lg and Lb) are in the campinarana group but are not considered to be “forests.” Their distribution areas (along the Rio Branco and its tributaries in the south-central portion of Roraima) are often flooded.

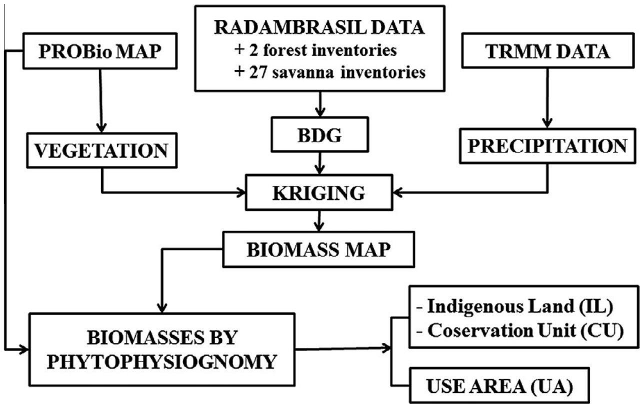

Fig. 2. Flowchart for estimation of forest biomass in Roraima. PRObio = Program for Conservation and Sustainable Use of Brazilian Biological Diversity. BDG = georeferenced database. TRMM = Tropical Rainfall Measuring Mission.

2.5. Validation criteria

The criteria for validation (accuracy) and for choosing the best model were: (i) the smallest mean-square error, (ii) the lowest efficiency percentage (%EF) and (iii) the highest coefficient of determination (adjusted R^2). The adjusted R^2 also served to assess the accuracy of the model in percentage terms, where $\text{error}_{(\varepsilon)} = (1 - R^2) \times 100$ and $\text{Accuracy} = R^2 \times 100$.

These parameters were calculated from the sub-sample of 33 points and compared with the values estimated by three methods at the same coordinates (Bello-Pineda and Hernándes-Stefanoni, 2007; Gardiman Junior et al., 2012). As an additional measure, a test of means (*t*-test) was applied between the values predicted by the three models and the sample values to compare the results and verify whether they differed from the sample mean.

2.6. Modeling and spatialization of biomass

For spatialization of forest biomass the best model was chosen among three Kriging techniques (Fig. 3): (i) ordinary Kriging (Krig-Ord), (ii) co-Kriging (Co-Krig) and (iii) Kriging with external drift

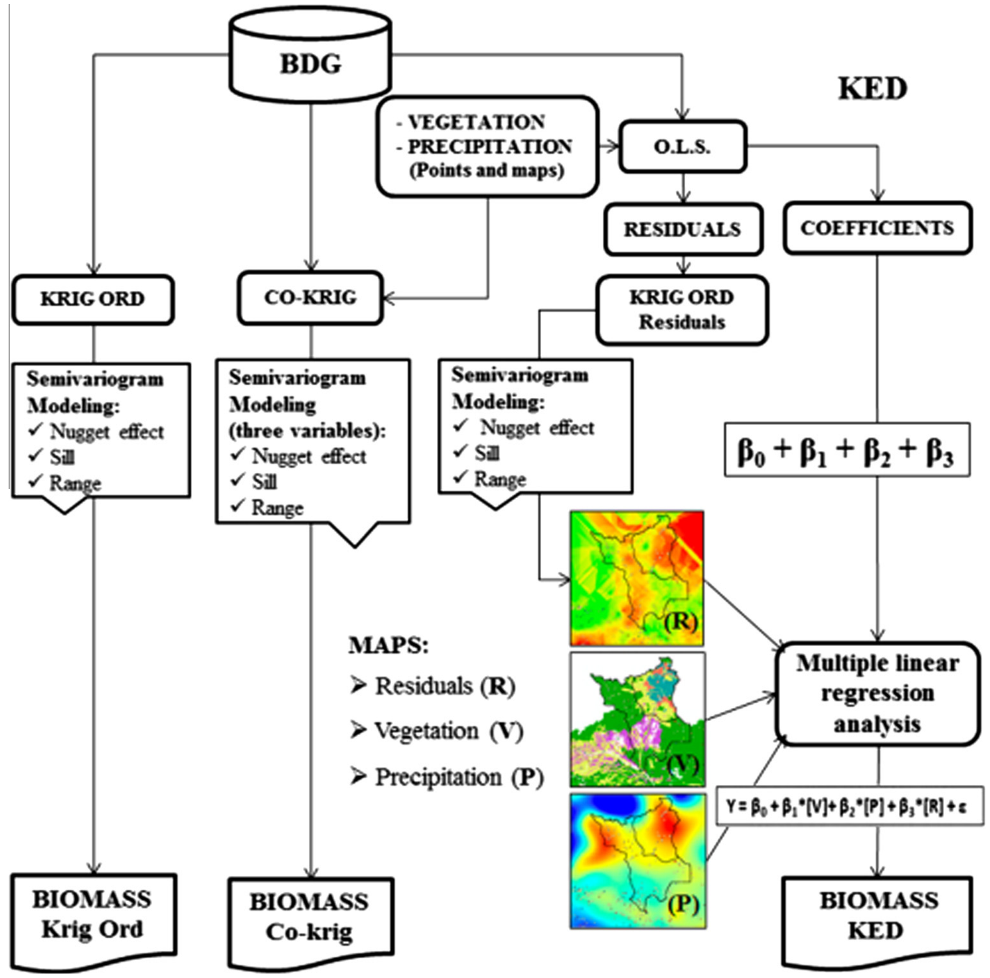

Fig. 3. Flowchart for the application of Kriging to the georeferenced database and three auxiliary variables. (V) = Vegetation map; (P) = Precipitation map; (R) = Residuals map; Krig-Ord = Ordinary Kriging; Co-Krig = Co-Kriging; KED = Kriging with external drift. In the case of co-Kriging two auxiliary variables were used (V and P) and in the KED three variables were used (V, P and R). BDG = georeferenced database.

(KED). Kriging is used to estimate the value of a variable in a location that was not sampled, with the value calculated by interpolation using moving averages of sampling points. It is assumed that the values of the spatial variable are known in the vicinity of the unsampled location that will have its value estimated. To implement Kriging one must first model the semivariogram, which associates the estimated variability between two sample points with the distance that separates them. The influence will be larger or smaller depending on how small or large the distance is between the points. The semivariogram uses the following parameters: (i) the “nugget effect,” which evaluates the stability of the data or the lack of change in their values as a function of the distance separating neighboring points; in some cases the nugget effect can be attributed to measurement error or to the fact that the data have not been collected at sufficiently close intervals; (ii) the “sill,” indicating the point of stabilization of the semivariogram curve; the sill represents the maximum variability between pairs of values (on the y-axis, starting from the sill variation in the data is not observed), and (iii) the “range,” which measures the distance (in the units of the map on the x-axis) over which such variations are observed in the data; the range indicates the distance after which the samples are no longer spatially correlated and the relationship between them becomes random (cf, Burrough and McDonell, 1998; Landim and Sturaro, 2002). A conceptual model of the semivariogram calculation is shown in Eq. (1):

$$Semivariogram\ (\gamma) = Nugget + (Sill - Nugget) * Range \tag{1}$$

Modeling of the semivariograms by the different Kriging techniques was executed in ArcGIS software.

In the case of Krig-Ord, the semivariogram was modeled from sample points of a single variable (total biomass) as the input. Kriging produces a map of total biomass (Mg ha^{-1}) with continuous values estimated from the sample data (Isaaks and Srivastava, 1989; Bohling, 2005). In Co-Krig, in addition to the main variable (total biomass), two auxiliary variables were used: (i) the vegetation map (V) from PROBio described earlier, with the four forest classes plus the savanna class (converted to raster format with spatial resolution of 1 km^2 per pixel, and (ii) the map of average annual precipitation (P) retrieved from the NASA website (NASA-TRMM, 2013). After ordinary Kriging, this map was also converted to raster format with 1-km^2 resolution. The two maps were drawn in UTM/WGS 84 Zone 20 N. During the execution, auxiliary Krig variables override the main variable in the prediction in the case of locations that were not sampled or were poorly sampled. In this case the semivariogram is modeled for the primary variable and another model is generated for each auxiliary variable. Unlike Krig-Ord and Co-Krig, in KED the final map of biomass (Mg ha^{-1}) was obtained by application of multiple linear regression to data from raster maps (grids of cells) of the auxiliary variables, with V, P and R (map) as independent variables (Eq. (2)). This map was created in three steps: (1) obtaining the residuals and the coefficients of the multiple linear regression by means of the least-squares method between the primary and the auxiliary variables (sampling points); (2) obtaining the raster map of the residuals (1 km^2, UTM/WGS 84 Zone 20 N) through ordinary Kriging, and (3) execution of the multiple linear regression (Eq. (2)).

$$\begin{aligned}\text{KED biomass }(Y) = -163.8823 &+ (2.5535 \times \text{VEGETATION})\\ &+ (0.1403 \times \text{PRECIPITATION})\\ &+ (1 \times \text{RESIDUALS})\end{aligned} \tag{2}$$

where Y = dependent variable (TOTAL BIOMASS), VEGETATION = vegetation map, PRECIPITATION = precipitation map and RESIDUALS = map of residuals.

2.7. Biomass maps by phytophysiognomy and forest group

To clarify the biomass content by forest physiognomy, binary maps (0, 1) with 1-km^2 spatial resolution were created for each phytophysiognomy in the PROBio database and for the savanna. On each map that was created, pixels representing the domain or extension of the physiognomies were assigned a value of 1 (one) and the other pixels were assigned a value of 0 (zero). All maps were created with the same number of rows (759) and columns (661). These maps were then crossed individually with the map of forest biomass (MFB) (Mg ha^{-1}) in a map-algebra operation (Eq. (3)) as follows:

$$\text{BIOM.TYPE}_{(i)} = \text{Map.Type}_{(i)} \times \text{MFB} \tag{3}$$

where BIOM.TYPE$_{(i)}$ represents the biomass map for each forest physiognomy; Map.Type$_{(i)}$ represents the map of each class generated from the PROBio dataset and, i = 1–18 (including the savanna class). Biomass maps for the forest group were created in the same way as the maps of biomass by forest type (BIOM.Type) described above (Eq. (3), with i = 1–4).

2.8. Biomass in areas with and without legal protection

To assess biomass in protected areas, the binary maps of ILs and CUs using the ISA (2012) database were crossed with the maps of biomass generated for each forest group. The original biomass of the UA (agro-silvo-pastoral use area) group was determined by the exclusion of IL, CU and savanna areas; the UA-group biomass maps were also crossed with the maps of biomass by forest group. This protocol was applied to both phytoclimatic zones in Roraima. To evaluate and compare biomass between the use types (indigenous lands, conservation units and use areas) a weighted average was applied that considered the area of each forest group in each use type.

2.9. Statistical analysis

Normality tests were applied to all datasets obtained by intersections of information between climatic zones (ZIS and ZOS), phytophysiognomic groups (ombrophilous forests, ecotones, seasonal vegetation and campinarana) and categories of land use: IL, CU and UA. In order to determine if the climatic areas explain the spatial distribution of forest biomass in Roraima nonparametric tests (Mann-Whitney; $\alpha = 0.05$) were applied between the biomass values for each forest group present in the two zones because the data are not normally distributed.

To determine if the biomass per unit area (Mg ha^{-1}) of the forest groups differed among IL, CU and UA areas located in the same phytoclimatic zone, nonparametric tests (Kruskal Wallis, Mann-Whitney; $\alpha = 0.05$) were applied to 100 pairs of biomass values chosen randomly from each forest group in the ILs, CUs and UAs present in both phytoclimatic areas. We used R software (R Development Core Team, 2015) for testing.

3. Results

The KED model was chosen as having the best performance to represent the total biomass of the state of Roraima (Table 2; Fig. 4). When Kriging was performed on the residuals the semivariogram showed no anisotropy (spatial trend in a given direction) and was therefore considered to be isotropic for the variability of biomass residuals. A variogram function composed of the nugget effect and the exponential structure (best fit to the data) was used to fit the sample of residuals and to evaluate their variability depending on the distance between sampling points. The final semivariogram fit this way had a total range of ~120 km and a nugget effect estimated at ~20% in relation to the sill (8509.1), implying a spatial correlation between sample points. However, the spatial correlation of the residuals decreased rapidly between ~73 km and 120 km, which was the maximum limit of variation.

The stock of total biomass in the state of Roraima, assuming the original vegetation (without deforestation, forest fires and selective logging), was estimated by the KED model at 6.32×10^9 Mg (184,499.0 km^2 or 82.3% of the state area), of which live aboveground biomass represented 4.52×10^9 Mg (71.6%,), dead aboveground biomass (necromass) 0.83×10^9 Mg (13.1%), and belowground biomass 0.97×10^9 Mg (15.3%) (Table 3). Considering only forest ecosystems, the weighted average per unit area, was 345 Mg ha^{-1} (range 133–434 Mg ha^{-1}). Ombrophilous forests were the group with the largest weighted average for total biomass (404 Mg ha^{-1}; range 189–488 Mg ha^{-1}), while the seasonal-forest group had the smallest weighted average (182 Mg ha^{-1}; range 116–261 Mg ha^{-1}).

Average biomass of the ZOS as a whole (357 Mg ha^{-1}) was greater than that in the ZIS (302 Mg ha^{-1}). Average total biomass in the ombrophilous group in the ZIS (385 ± 62 (±1 SD) Mg ha^{-1}) was lower (Mann-Whitney: $\alpha = 0.05$; $p < 0.0000$) than the biomass estimated for this group in the ZOS (406 ± 37 Mg ha^{-1}), considering the pixel-by-pixel values established in the modeling (Fig. 5). The other pairs of means tested for each forest group also showed significant differences between the two phytoclimatic zones.

The total biomass stock in protected areas (indigenous lands and conservation units) in Roraima was estimated at 4.16×10^9 Mg (348 Mg ha^{-1}) (Table 4). The largest stock was in indigenous lands (76%; 3.16×10^9 Mg), of which 16.3% (0.507×10^9 Mg) was in the ZIS and 83.7% (2.65×10^9 Mg) in the ZOS. The area of the Indigenous lands in Roraima is greater than the total of all conservation units. Indigenous lands also have the largest areas of dense and open ombrophilous forest in Roraima, stocking large amounts of biomass. Most of these forests are located in the area without savanna influence (ZOS). Most dense ombrophilous forest is in the ZOS, while in the ZIS there is a greater area of lower-biomass forests (e.g., ecotones). Table 4 also indicates that Indigenous lands store large amounts of biomass in dense ombrophilous forest, while conservation units stock more biomass in open forests or in less-dense forests (e.g., ecotones). In the case of use areas, the percentages of biomass are more balanced, meaning that this use type is distributed evenly among the forest types in the state.

The average original biomass of the use areas (UAs) was 332 Mg ha^{-1}, this being the largest stock in the ombrophilous group (0.96×10^9 Mg; 15.2%) in the ZOS, while the largest inventory of biomass in areas with some kind of legal protection (IL, CU) was also observed in the ombrophilous group in the ZOS (2.47×10^9 Mg; 39.1%). The mean (332 Mg ha^{-1}) was weighted for all biomass stocks covering all of the forest groups that had for-

Table 2
Results of cross-validation (accuracy) and choice of the best interpolation model for estimating mean total biomass of forest in the state of Roraima. MSE = Mean Square Error, %EF = Efficiency Percentage, R^2_{adj} = Adjusted coefficient of determination.

Interpolators	MSE	%EF	R^2_{adj}	*p*-value regression	*p*-value *t*-test	Mean biomass (Mg ha^{-1})
BDG (33 points)	–	–	–	–		388
Krig-Ord	77.2	45.9	0.75	<0.0000	0.826	380
Co-Krig	72.8	43.0	0.78	<0.0000	0.652	405
KED	65.7	37.9	0.81	<0.0000	0.672	373

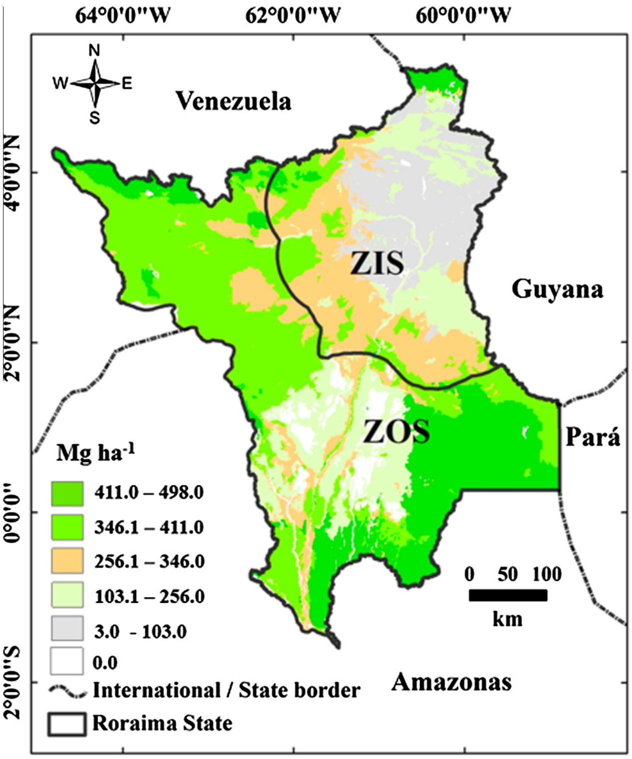

Fig. 4. Reference map of the distribution of biomass (Mg ha^{-1}) in the state of Roraima generated by Kriging for external drift (KED). (0–3): areas without data; (3–103): biomass of savanna in the northeastern portion of the state and in neighboring areas in ecotones between dense and open vegetation types; (103.1–256.0) *campinarana* areas in the south-central portion of the state surrounding areas that are seasonally flooded (for which there are no data), contact areas between *campinarana*, dense forest, open forest and savanna, in the east-central portion of the state, and ecotones between tropical forest and savanna and between ombrophilous forest and open and dense forest in the north and northeast portions of the state; (256.1–346.0) represent the distribution of biomass of ecotone forests in the southern portion of the state (along the Rio Branco) and of ecotones in the center-north portion of the state between open ombrophilous forest towards the northwest and savanna areas to the east; (346.1–411.0) represents predominantly open ombrophilous forest that is distributed over much of the state and (411.0–498.0) represents dense ombrophilous forest that predominantly occupies the southern and southeastern portions of the state and a few patches in the northernmost portion of the state.

merly covered the use areas. The largest contribution to the mean was from the ombrophilous forest group. These distinctions can best be observed by normalizing the raw data by the frequency (number of pixels) as percentages of occurrence in the biomass classes in each zone and land-use type (Fig. 6). Analyses were also conducted of biomass affected by deforestation in Roraima through the year 2014 for each climatic zone and land-use category (Table S2: Annex 1b).

4. Discussion

Use of a new geographic database (Brazil, PROBio, 2013), in addition to application of geostatistics (KED) to biomass values derived with the methodology of Nogueira et al. (2008), provided a representation of the spatial distribution of biomass stocks (Fig. 4), including information on all forest compartments (live biomass and necromass; above- and belowground) for each phytophysiognomic group and climatic zone. Using interpolation techniques associated with environmental variables proved to be appropriate in biomass prediction in Roraima. These conditions are important for evaluation of carbon stocks and greenhouse gas emissions at the regional level (Asner et al., 2010; Nogueira et al., 2015). The sequence of steps used in Roraima allowed accurate estimates of the total biomass stock, reducing the uncertainties in the calculation of carbon stocks at the landscape scale. This is needed for making baseline calculations for REDD Projects or REDD Programs.

Semivariogram analysis indicated that ~80% of the variation in total biomass residuals is spatially structured and that this showed variation up to a distance of ~120 km in our study area. This implies that methods for estimating the spatial distribution of total biomass using a simple average for each forest type are less reliable than methods using geostatistics, which consider the spatial correlation between sampling points (e.g., Sales et al., 2007).

Another important factor was the sampling density of one sampling point per 1365 km^2 in this study. Although the area per sample is still considered high, it was lower than that available for estimates for forests in the Brazilian Amazonia as a whole (1480 km^2 per sampling point) covered by the 2702 valid inventories of the RADAMBRASIL Project (Nogueira et al., 2008). However, we emphasize that in some regions the density of points increased with very short distances (<25 km) along the roads and rivers that provided access for the RADAMBRASIL teams in the early 1970s (Moreira and Barbosa, 2008). Regardless of these micro-regions with a denser coverage of sampling points, the lower ratio in Roraima as compared to Brazilian Amazonia as a whole indicates better spatial translation of the biomass values by the BDG at the scale of a phytophysiognomic group, given the uncertainty at the level of a 1-km^2 pixel (e.g., Houghton et al., 2009; Saatchi et al., 2011). The existence of a data base of inventories with spatial distribution in northern Roraima also provides a substantial improvement in the results, since the lack of representativeness in this region and in the area surrounding it was the main cause of the 19% (1 − R^2) prediction error (Ɛ) calculated in the spatial analysis. In any case, it is assumed that the current map (Fig. 4) provides a source of accurate information on the spatial distribution of biomass in Roraima.

A comparison of estimates with other studies indicates that the values calculated for this study are ~5% lower than those determined by Nogueira et al. (2015) and ~0.5% lower than those of Barbosa et al. (2010). On the other hand, biomass estimates derived by Fearnside (2010) and Fearnside et al. (2013) are ~8.8% higher than those calculated in our study. The differences in results are explained by different methods used and by differences in the area covered by modeling. For example, in the studies by Fearnside (2010) and Fearnside et al. (2013), biomass was estimated for a forest area of 176,784 km^2 (with an average total biomass of 392 Mg ha^{-1}), while our study used a base area of 184,500 km^2 (average total biomass = 345.0 Mg ha^{-1}), taking advantage of the updated data from Brazil, PROBio (2013). Our database also includes two recent local measurements (Condé and Tonini, 2013; Nascimento et al., 2014). On the other hand, Saatchi et al. (2007, 2011) and Baccini et al. (2012) used satellite data to extrapolate from a single sample in Roraima (Santos et al., 2003), using this sample as ground truth to estimate aboveground live biomass

Table 3
Original stock of total biomass (live + dead; above- and belowground) and estimated weighted average per unit area of forest in the state of Roraima, representing biomasses without recent human impacts (deforestation, selective logging and forest fires).

Group[a]	Code[b]	Live aboveground (10^6 Mg)[c]	Dead aboveground (10^6 Mg)[c]	Live belowground (10^6 Mg)[c]	Total biomass stock (10^6 Mg)	%	Mean (Mg ha^{-1})	Range (Mg ha^{-1})
Ombrophilous forest	Ab	8.3	1.5	1.8	11.6	0.2	432.1	402.4–445.1
	As	179.3	33.2	38.9	251.4	4.0	395.1	303.6–437.0
	Da	25.1	4.6	5.3	35.0	0.6	404.0	323.0–440.0
	Db	301.6	54.7	64.1	420.4	6.6	419.0	308.6–450.5
	Dm	728.2	132.1	154.9	1015.1	16.0	400.9	329.6–451.6
	Ds	1673.1	302.4	356.4	2331.8	36.8	404.2	291.5–445.0
Group total		2915.1	528.9	621.4	4065.3	64.3	404.3	304.3–446.7
Ecotone	LO	474.7	87.9	103.1	665.7	10.5	331.3	233.3–405.3
	ON	594.9	110.1	129.2	834.2	13.2	318.8	238.2–390.6
	SN	9.6	1.8	2.1	13.4	0.2	230.2	189.3–293.6
	SO	42.3	7.8	9.2	59.3	0.9	277.3	218.6–341.6
	TN	35.9	6.6	7.8	50.3	0.8	191.8	137.8–229.6
Group Total		1157.3	214.3	251.3	1622.9	25.7	314.2	229.6–384.8
Seasonal vegetation	Fa	9.8	1.8	2.1	13.7	0.2	237.3	162.3–331.7
	Fs	31.3	5.8	6.8	43.9	0.7	171.4	111.5–252.5
	Sa	68.9	3.9	0.0	72.8	1.1	185.1	142.0–264.7
	Td	56.7	3.2	0.0	59.9	0.9	179.0	122.5–252.3
Group Total		136.9	24.7	28.7	190.3	3.0	182.3	128.8–261.1
Campinarana	La	56.6	10.5	12.3	79.4	1.3	226.5	170.0–307.3
	Ld	259.6	48.1	56.4	364	5.7	214.2	182.5–343.8
Group total		316.2	58.6	68.7	443.4	7.0	216.3	180.4–337.6
Grand total		4525.4	826.4	970.1	6322.0	100	345.0	133.0–434.0

[a] The mean biomass stock of savannas was estimated at 14.7 × 10^6 Mg (5.5 Mg ha^{-1}), or approximately 0.2% of the total biomass present in the state of Roraima.
[b] Vegetation codes (Brazil, IBGE, 2012).
[c] Percentages for calculation of biomass by forest compartment as in Nogueira et al. (2008).

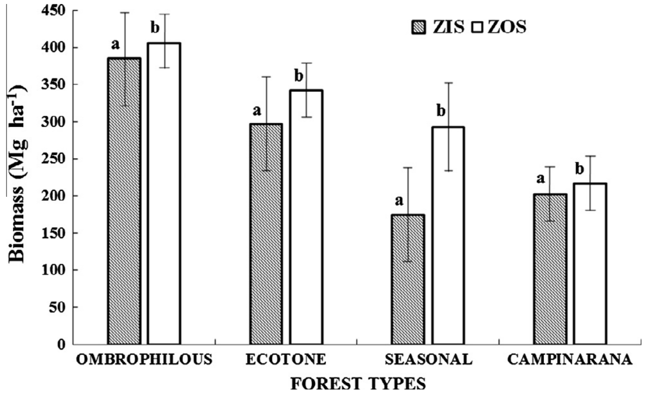

Fig. 5. Total biomass (live + dead; above- and belowground) distinguished by forest group and climatic zone in Roraima (Mg ha^{-1} ± SD): ZIS = zone with influence of savanna (with shading); ZOS = zone without savanna influence (no shading). Different lowercase letters represent significant differences between means tested in the two zones (Mann-Whitney; 95%).

and to represent the entire forest area. Although the Saatchi et al. (2011) and Baccini et al. (2012) maps can be considered valid for biomass estimates at the pan-tropical scale, much larger numbers of ground-truth plots are needed at the level of the vegetation group and/or the local forest type for more detailed regional-scale estimates.

In terms of mean forest biomass per unit area, the results indicate that the modeled values (182–404 Mg ha^{-1}) are contained in the range established by Fearnside et al. (2013) for all forest types in Roraima (392 Mg ha^{-1}; range 240–513 Mg ha^{-1}). The average value (345 Mg ha^{-1}) weighted by area suggests that the total forest biomass per unit area in Roraima is less than that in the remainder of Brazilian Amazonia. This area in Roraima is largely located in an ecotone with relatively dry climate, making it different from the humid regions of the central Amazon. This condition is best explained by the distinction between the local climatic zones because forests located close to savanna areas (ZIS) in most cases have lower biomass than forests located in regions without long dry periods (ZOS) (Table 4 and Fig. 6). This result is consistent with other studies on biomass distribution considering the length of the dry season (Saatchi et al., 2007, 2011; Hirota et al., 2011; Baccini et al., 2012), indicating that forests in Roraima also have an inverse relationship between biomass content and the length of the dry season. Given these results, policies are necessary for the conservation of carbon stocks in areas with longer dry periods in Roraima (ZIS), since the total area affected by deforestation in these regions up to 2014 is 33% higher than that observed in the zone without a severe dry period (Table A.2: Annex 1b). This would have a direct effect in the reduction of the forest fires that negatively affect carbon stocks in these regions (Barbosa and Fearnside, 1999; Xaud et al., 2013). Policy to conserve forest biomass in Roraima should include (i) regularization of land tenure; (ii) enforcement of the state's ecological-economic zoning (ZEE); (iii) creation of conservation units, and (iv) increasing the government's capacity to manage the protected areas (indigenous lands and conservation units) that are already consolidated.

The distinction among the biomass stocks in different climatic zones and land-use categories was important in determining the direct effect of these variables in the calculation of biomass and carbon stocks. For example, a rough estimate based on the rates of deforestation in Roraima up to 2014 indicated a disturbance in 4.36% (0.276 × 10^9 Mg) of the original stock of total forest biomass in Roraima; ZIS = 1.95% and ZOS = 2.41% (Table S2: Annex 1b). Of this amount, IL and CU contributed little to disturbance of the original biomass stocks (6.8%), even though these institutional areas represent >65% of the total area of all of the forest physiognomies

Table 4
Area (km^2), biomass stock (Mg) and mean biomass (%; Mg ha^{-1}) by phytoclimatic zone and forest group in Roraima. Different uppercase letters in the same row indicate significant differences (Mann-Whitney) at the 95% level between phytophysiognomic groups.

Group	ZIS				ZOS			
	Area (10^3 km^2)	Mean (Mg ha^{-1})	Biomass stock (10^6 Mg)	%	Area (10^3 km^2)	Mean (Mg ha^{-1})	Biomass stock (10^6 Mg)	%
Indigenous lands (ILs)								
Ombrophilous forest	5.26	398.5^A	209.6	56.7	62.15	397.0^A	2466.9	66.2
Ecotone	7.64	263.4^A	201.2	22.3	4.96	344.2^B	170.7	24.9
Seasonal vegetation	5.33	177.7^A	94.7	77.8	0.13	284.6^B	3.7	100
Campinarana	0.12	175.0^A	2.1	19.7	0.52	238.5^B	12.4	2.4
IL total	18.35	276.6	507.6	36.1	67.80	391.5	2653.7	49.3
Conservation units (CUs)								
Ombrophilous forest	0.96	450.0^A	43.2	11.7	7.28	403.7^B	293.9	7.9
Ecotone	2.06	346.1^A	71.3	7.9	7.92	337.5^B	267.3	39.1
Seasonal vegetation	0.16	262.5	4.2	3.4	–	–	–	–
Campinarana	0.02	220.0^A	0.44	4.1	14.77	213.4^B	315.2	61.0
CU total	3.19	373.5	119.1	8.5	29.97	292.4	876.4	21.8
Use areas (UAs)								
Ombrophilous forest	3.14	372.8^A	117.1	31.7	23.88	403.4^B	963.3	25.9
Ecotone	20.46	308.3^A	630.8	69.8	7.57	325.6^B	246.5	36.0
Seasonal vegetation	1.32	173.2	22.9	18.8	–	–	–	–
Campinarana	0.39	208.6^A	8.1	76.1	8.38	210.2^B	189.5	36.6
UA total	25.32	307.6	778.9	55.4	39.83	347.9	1385.9	28.9
Grand total	46.86	302	1405.6	100	137.63	357	4916.0	100

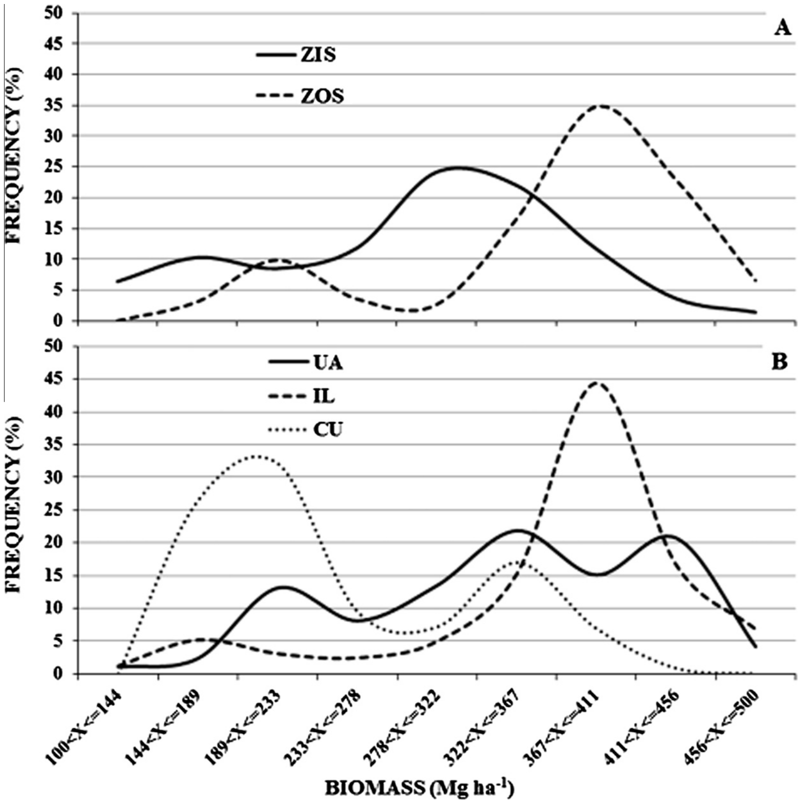

Fig. 6. Biomass (Mg ha^{-1}) by frequency (number of pixels expressed as percentages of occurrence) (A) by phytoclimatic zone and (B) by land use. ZIS = zone with savanna influence; ZOS = zone without savanna influence; IL = Indigenous land UA = use area; CU = conservation unit.

in Roraima (~119,280 km^2). In contrast, the change in forest cover in UA areas was dramatic, especially in the ecotones (ZIS) and ombrophilous forest (ZOS), which are responsible for 32.1% and 54.3%, respectively, of the total stock of forest biomass up to 2014. These values indicate that creating institutional (legal protection) areas in Roraima is an important strategy for stopping losses of carbon stocks and lowering emissions of greenhouse gases.

Although forest biomass in Roraima appears to be protected from deforestation and from degradation by selective logging and fire in Indigenous lands and conservation units, the same cannot be said of the use areas. For example, GHG emissions in Brazilian

Amazonia as a whole decreased from 2005 to 2010 due to the reduction in deforestation rates (Brazil, MCTI, 2015; Brazil, INPE, 2016), deforestation in Roraima did not obey the same logic (Supplementary Material; Fig. A.2). Deforestation stabilized around an annual average of 241.1 km^2 (2000–2015: Brazil, INPE, 2016), which is slightly less than the average of 277.0 km^2 (1978–2006) observed by Barbosa et al. (2008) at the height of uncontrolled deforestation. Although deforestation processes in Roraima are similar to those in other parts of Brazilian Amazonia (e.g., Fearnside, 2008; Carrero and Fearnside, 2011; Barni et al., 2015a, 2015b), they are also influenced by local factors. In the absence of policy changes, deforestation and consequent greenhouse gas emissions in Roraima cannot be expected to decline soon in the use area because of lax environmental surveillance and the prevalence of land grabs (*grilagem*).

For example, in the use area in the ZIS, in addition to the forest biomass having been degraded by logging as occurs throughout Brazilian Amazonia (e.g., Nepstad et al., 1999; Asner et al., 2005; Broadbent et al. 2008), degradation of forest biomass is linked to the deforestation process that is strongly related to climatic factors and to vegetation types with open canopies (seasonal forests and ecotones). These factors have influenced the occurrence of vast understory fires (Barbosa and Fearnside, 1999; Xaud et al., 2013; Barni et al., 2015a). Currently, some control over forest fires has been achieved in this phytoclimatic zone, but higher humidity in the ZOS seems to protect dense ombrophilous forest from fire. However, in January and February 2016, under the influence of a strong El Niño and due to the use of fire in land management (e.g., Alencar et al., 2004, 2006; Aragão and Shimabukuro, 2010), more than 1000 km^2 of forest was affected by understory fires (unpublished remote-sensing data); most (84.5%) of the fires were in dense ombrophilous forest that had been subject to uncontrolled logging (e.g., Barni et al., 2012).

5. Conclusions

Advances were made in quantifying stocks and in the spatialization of total original forest biomass in Roraima in relation to previous studies that have used extrapolation to spatialize biomass in the state, thereby contributing to the reduction of the uncertainties in the spatial distribution of forest biomass. This indicates the need for spatialization of biomass stocks at a more-refined scale and making use of a greater number of plots in order to reduce regional uncertainties about carbon pools in the Amazon.

The reference map made available in this study provides an easily used means of obtaining estimates at regional and local scales for studies of greenhouse-gas emissions. This map is also needed for REDD projects and for public policies requiring a baseline for assessment of additionality and/or the impact of reductions in deforestation and for assessing conservation of carbon stocks in areas under some kind of legal protection (IL and CU). The use area covers the central portion of the state and accompanies the main access highways (BR-174 and BR-210) that favor deforestation, selective logging and the invasion of public lands with consequent degradation of forest biomass and carbon stocks. The original vegetation in protected areas, independent of phytophysiognomic group, has higher biomass compared to the original vegetation in areas currently under agricultural use. Protected areas (119,310.0 km^2 or 53.2% of the state) support 65.8% of Roraima's stock of forest biomass, indicating an important potential role in REDD projects for conservation of forest carbon.

Our map of forest biomass provides an alternative reference for studies on degradation of biomass and the emission of greenhouse gas within the local and regional contexts and contributes information needed for the Brazilian inventory of greenhouse gas emissions.

Finally, the spatial analysis shows that, as compared to estimates in other studies, areas under some type of agro-silvopastoral use in Roraima had lower average biomass prior to deforestation, indicating that greenhouse gas emissions from deforestation and land-use change in Roraima may be lower than previously calculated.

Acknowledgements

This study was supported by the Universidade Estadual de Roraima (UERR), Instituto Nacional de Pesquisas da Amazônia (INPA-Roraima) and National Institute of Science & Technology for the Environmental Services of Amazonia (CNPq-INCT/SERVAMB). The Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) provided P.E.B with a scholarship for the postgraduate program in climate and environment (CLIAMB). We thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq 303081/2011-2; 304020/2010-9/2008; 573810-7; 304020/2010-9) and the Brazilian Research Network on Climate Change (Rede Clima). P.M.L.A. Graça, L. Nagy and two reviewers provided useful suggestions.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2016.07.010.

References

Ab'Saber, A.N., 1997. A Formação Boa Vista: O significado geomorfológico e geoecológico no contexto do relevo de Roraima. In: Barbosa, R.I., Ferreira, E.J.G., Castellon, E.G. (Eds.), Homem, Ambiente e Ecologia no Estado de Roraima. INPA, Manaus, Amazonas, Brazil, pp. 267–293.

Alencar, A., Nepstad, D., Diaz, M.C.V., 2006. Forest understory fire in the Brazilian Amazon in ENSO and non-ENSO years: area burned and committed carbon emissions. Earth Interact. 10, S139–S149.

Alencar, A.A., Solórzano, L.A., Nepstad, D.C., 2004. Modeling forest understory fires in an Eastern Amazonian landscape. Ecol. Appl. 14, 139–149.

Aragão, L.E.O.C., Shimabukuro, Y.E., 2010. The incidence of fire in Amazonian forests with implications for REDD. Science 328, 1275–1278.

Asner, G.P., Powell, G.V.N., Mascaro, J., Knapp, D.E., Clark, J.K., Jacobson, J., Kennedy-Bowdoin, T., Balaji, A., Paez-Acosta, G., Victoria, E., Secada, L., Valqui, M., Hughes, R.F., 2010. High resolution forest carbon stock and emissions in the Amazon. Proc. Nat. Acad. Sci. USA 107, 16738–16742.

Asner, G.P., Knapp, D.E., Broadbent, E.N., Oliveira, P.J.C., Keller, M., Silva, J.N.M., 2005. Selective logging in the Amazon. Science 310, 480–482.

Avitabile, V., Herold, M., Heuvelink, G.B.M., Lewis, S.L., Phillips, O.L., Asner, G.P., Armston, J., Ashton, P.S., Banin, L., Bayol, N., et al., 2016. An integrated pan-tropical biomass map using multiple reference datasets. Glob. Change Biol. 22 (4), 1406–1420. http://dx.doi.org/10.1111/gcb.13139.

Baccini, A., Goetz, S.J., Walker, W.S., Laporte, N.T., Sun, M., Sulla-Menashe, D., Hackler, J., Beck, P.S.A., Dubayah, R., Friedl, M.A., Samanta, S., Houghton, R.A., 2012. Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. Nat. Clim. Change 2, 182–185.

Barbosa, R.I., 1997. Distribuição das chuvas em Roraima. In: Barbosa, R.I., Ferreira, E.J.G., Castellon, E.G. (Eds.), Homem, Ambiente e Ecologia no Estado de Roraima. Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, Amazonas, Brazil, pp. 325–335.

Barbosa, R.I., 2001. Estoque de Carbono e Emissão de CO_2 e Gases-Traço pela Queima e Decomposição da Biomassa Vegetal em Ecossistemas de Savana (Cerrado) de Roraima, Amazônia Brasileira Ph.D. thesis in ecology. Instituto Nacional de Pesquisas da Amazônia (INPA) and Universidade Federal do Amazonas (UFAM), Manaus, Amazonas, Brazil, 212 pp.

Barbosa, R.I., Campos, C., 2011. Detection and geographical distribution of clearing areas in the savannas ('lavrado') of Roraima using Google Earth web tool. J. Geogr. Reg. Plan. 4, 122–136.

Barbosa, R.I., Fearnside, P.M., 1999. Incêndios na Amazônia: estimativa da emissão de gases de efeito estufa pela queima de diferentes ecossistemas de Roraima na passagem do evento "El-Niño" (1997/1998). Acta Amazon. 29, 513–534.

Barbosa, R.I., Fearnside, P.M., 2005. Aboveground biomass and the fate of carbon after burning in the savannas of Roraima, Brazilian Amazonia. For. Ecol. Manage. 216, 295–316.

Barbosa, R.I., Pinto, F., Keizer, E., 2010. Ecossistemas terrestres de Roraima: Área e modelagem espacial da biomassa. In: Barbosa, R.I., Melo, V.F. (Eds.), Roraima: Homem, Ambiente e Ecologia. FEMACT, Boa Vista, Roraima, Brazil, pp. 347–368.

Barbosa, R.I., Santos, J.R.S., Cunha, M.S., Pimentel, T.P., Fearnside, P.M., 2012. Root biomass, root: shoot ratio and belowground carbon stocks in the open savannahs of Roraima, Brazilian Amazonia. Aust. J. Bot. 60, 405–416.

Barbosa, R.I., Pinto, F.S., Souza, C.C., 2008. Desmatamento em Roraima: Dados históricos e distribuição espaço-temporal Relatório Técnico. Ministério da Ciência e Tecnologia, Instituto Nacional de Pesquisas da Amazônia – INPA, Núcleo de Pesquisas de Roraima, 10 pp.

Barni, P.E., Fearnside, P.M., Graça, P.M.L.A., 2012. Desmatamento no Sul do Estado de Roraima: padrões de distribuição em função de Projetos de Assentamento do INCRA e da distância das principais rodovias (BR-174 e BR-210). Acta Amazon. 42, 195–204.

Barni, P.E., Pereira, V.B., Manzi, A.O., Barbosa, R.I., 2015a. Deforestation and forest fires in Roraima and their relationship with phytoclimatic regions in the Northern Brazilian Amazon. Environ. Manage. 55, 1124–1138.

Barni, P.E., Fearnside, P.M., Graça, P.M.L.A., 2015b. Simulating deforestation and carbon loss in Amazonia: impacts in Brazil's Roraima state from reconstructing Highway BR-319 (Manaus-Porto Velho). Environ. Manage. 55, 259–278.

Bello-Pineda, J., Hernándes-Stefanoni, J.L., 2007. Comparing the performance of two spatial interpolation methods for creating a digital bathymetric model of the Yucatan submerged platform. Pan-Am. J. Aquat. Sci. 2, 247–254.

Bohling, G., 2005. Introduction to Geostatistics and Variograms Analysis. Kansas Geological Survey. Available at: <http://people.ku.edu/~gbohling/cpe940/> (accessed 29/07/2013).

Brazil, IBGE (Instituto Brasileiro de Geografia e Estatística), 2012. Manual Técnico da Vegetação Brasileira – Manuais Técnicos em Geociências No 1. 2ª Edição Revista e Ampliada. IBGE, Rio de Janeiro, RJ, Brazil, 271 pp <ftp://geoftp.ibge.gov.br/documentos/recursos_naturais/manuais tecnicos/manual_tecnico_vegetacao_brasileira.pdf> (accessed 20/08/2013).

Brazil, IBGE (Instituto Brasileiro de Geografia e Estatística), 2013. Banco de Dados Georreferenciado da Amazonia Legal Recursos Naturais, Vegetação. IBGE, Rio de Janeiro, RJ, Brazil <http://dados.gov.br/dataset/banco-de-dados-georreferenciado-da-amazonia-legal-recursos-naturais-vegetacao> (accessed 12/05/2013).

Brazil, INPE (Instituto Nacional de Pesquisas Espaciais), 2016. Projeto PRODES – Monitoramento da Floresta Amazônica por Satélite. INPE, São José dos Campos, SP, Brazil <http://www.obt.inpe.br/prodes/index.html> (accessed 13/04/2016).

Brazil, MCT (Ministério da Ciência e Tecnologia), 2010. Segunda Comunicação Nacional do Brasil à Convenção-Quadro das Nações Unidas sobre Mudança do Clima. MCT, Brasília, DF, Brazil, 280 pp.

Brazil, MCTI (Ministério da Ciência, Tecnologia e Inovação), 2015. Terceira Comunicação Nacional do Brasil à Convenção-Quadro das Nações Unidas sobre Mudança do Clima. Setor Uso da Terra, Mudança do Uso da Terra e Florestas. MCT, Brasília, DF, Brazil, 343 pp.

Brazil, MMA (Ministério do Meio Ambiente), 2000. Sistema Nacional de Unidades de Conservação (SNUC), Lei No. 9985 de 18 de Julho de 2000. MMA, Brasília, DF, Brazil, 32 pp.

Brazil, PROBio, 2013. Mapas de Cobertura Vegetal dos Biomas Brasileiros <http://mapas.mma.gov.br/mapas/aplic/probio/datadownload.htm> (accessed 21/07/2013).

Brazil, RADAMBRASIL, 1973–1983. Levantamento dos Recursos Naturais (Folhas SA.20 Manaus; SA.21 Santarém; SB.19 Juruá; SB.20 Purus; SC.19 Rio Branco; SC.20 Porto Velho). Ministério das Minas e Energia, Rio de Janeiro, RJ, Brazil.

Broadbent, E.N., Asner, G.P., Keller, M., Knapp, D.E., Oliveira, P.J.C., Silva, J.N., 2008. Forest fragmentation and edge effects from deforestation and selective logging in the Brazilian Amazon. Biol. Conserv. 141, 1745–1757.

Brown, S., Lugo, A.E., 1992. Biomass estimates for tropical moist forests of the Brazilian Amazon. Interciencia 17 (1), 8–18.

Brown, S., Lugo, A.E., 1994. Biomass of tropical forests: a new estimate based on forest volumes. Science 223, 1290–1293.

Burrough, P., McDonell, R., 1998. Principles of Geographical Information Systems. Oxford University Press, Oxford, UK. Available at: <http://www.rc.unesp.br/igce/ geologia/GAA01048/papers/Burrough_McDonnell-Two.pdf> (accessed 29/05/2013).

Carrero, G.C., Fearnside, P.M., 2011. Forest clearing dynamics and the expansion of land holdings in Apuí, a deforestation hotspot on Brazil's Transamazon Highway. Ecol. Soc. 16 (2), 26 <http://www.ecologyandsociety.org/vol16/iss2/art26/>.

Chave, J., Condit, R., Aguilar, S., Hernandez, A., Lao, S., Perez, R., 2004. Error propagation and scaling for tropical forest biomass estimates. Philos. Trans. R. Soc. B 359, 409–420.

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B.C., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C., Henry, M., Martínez-Yrízar, A., Mugasha, W.A., Muller-Landau, H.C., Mencuccini, M., Nelson, B.W., Ngomanda, A., Nogueira, E.M., Ortiz-Malavassi, E., Pélissier, R., Ploton, P., Ryan, C.M., Saldarriaga, J.G., Vieilledent, G., 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. Glob. Change Biol. 20 (10), 3177–3190. http://dx.doi.org/10.1111/gcb.12629.

Condé, T.M., Tonini, H., 2013. Fitossociologia de uma Floresta Ombrófila Densa na Amazônia Setentrional, Roraima, Brasil. Acta Amazon. 43, 247–260.

Fearnside, P.M., 1992. Forest biomass in Brazilian Amazônia: comments on the estimate by Brown and Lugo. Interciencia 17 (1), 19–27.

Fearnside, P.M., 1994. Biomassa das florestas Amazônicas brasileiras. In: Bandeira, R.L., Reis, M., Borgonovi, M.N., Cedrola, S. (Eds.), Emissão × Seqüestro de CO_2: Uma Nova Oportunidade de Negócios para o Brasil. Companhia Vale do Rio Doce (CVRD), Rio de Janeiro, RJ, Brazil, pp. 95–124.

Fearnside, P.M., 1996. Amazonia and global warming: annual balance of greenhouse gas emissions from land-use change in Brazil's Amazon region. In: Levine, J. (Ed.), Biomass Burning and Global Change, Biomass Burning in South America, Southeast Asia and Temperate and Boreal Ecosystems and the Oil Fires of Kuwait, vol. 2. MIT Press, Cambridge, Massachusetts, USA, pp. 606–617.

Fearnside, P.M., 1997a. Greenhouse gases from deforestation in Brazilian Amazonia: net committed emissions. Clim. Change 35 (3), 321–360.

Fearnside, P.M., 1997b. Wood density for estimating forest biomass in Brazilian Amazonia. For. Ecol. Manage. 90, 59–87.

Fearnside, P.M., 2000. Global warming and tropical land-use change: greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. Clim. Change 46 (1–2), 115–158.

Fearnside, P.M., 2008. The roles and movements of actors in the deforestation of Brazilian Amazonia. Ecol. Soc. 13, 23 [Online] URL: <http://www.ecologyandsociety.org/vol13/iss1/art23/>.

Fearnside, P.M., 2010. Roraima e o aquecimento global: estimativa atualizada do balanço anual das emissões de gases do efeito estufa provenientes da mudança de uso da terra. In: Barbosa, R.I., Melo, V.F. (Eds.), Roraima: Homem, Ambiente e Ecologia. FEMACT, Boa Vista, Roraima, Brazil, pp. 369–389.

Fearnside, P.M., Barbosa, R.I., Pereira, V.B., 2013. Emissões de gases do efeito estufa por desmatamento e incêndios florestais em Roraima: Fontes e sumidouros. Revista Agroambiente 7, 95–111.

Feldpausch, T.R., Banin, L., Phillips, O.L., Lewis, S.L., Quesada, C.A., et al., 2011. Height-diameter allometry of tropical forest trees. Biogeosciences 8, 1081–1106.

Gardiman Junior, B.S., Magalhães, I.A.L., Freitas, C.A.A., Cecílio, R.A., 2012. Análise de técnicas de interpolação para espacialização da precipitação pluvial na bacia do rio Itapemirim (ES). Ambiência 8, 61–71.

Harris, N.L., Brown, S., Hagen, S.C., Saatchi, S.S., Petrova, S., Salas, W., Hansen, M.C., Potapov, P.V., Lotsch, A., 2012. Baseline map of carbon emissions from deforestation in tropical regions. Science 336, 1573–1576.

Higuchi, N., dos Santos, J., Ribeiro, R.J., Minette, Y.B., 1998. Biomassa da parte aérea da vegetação da floresta tropical úmida de terra-firme da Amazônia brasileira. Acta Amazon. 28 (2), 153–166.

Hirota, M., Holmgren, M., Nes, E.H.V., Scheffer, M., 2011. Global resilience of tropical forest and savanna to critical transitions. Science 234, 232–235.

Houghton, R.A., 2010. How well do we know the flux of CO_2 from land-use change? Tellus 62B, 337–351.

Houghton, R.A., Hall, F., Goetz, S.J., 2009. Importance of biomass in the global carbon cycle. J. Geophys. Res. 114, G00E03.

ISA (Instituto Socioambiental), 2012. Terras Indígenas do Brasil. ISA Roraima, Boa Vista – RR (Compact Disc).

Isaaks, E., Srivastava, R., 1989. Applied Geostatistics. Oxford University Press, New York, USA.

Landim, P.M.B., Sturaro, J.R., 2002. Krigagem indicativa aplicada à elaboração de mapas probabilísticos de riscos. Geomatematica, Texto didático, 6. DGA, IGCE, Universidade Estadual de São Paulo (UNESP), Rio Claro, São Paulo, Brazil. Available at: <http://www.rc.unesp.br/igce/aplicada/textodi.html>. Accessed 25/05/13.

Malhi, Y., Wood, D., Baker, T.R., Wright, J., Phillips, O.L., Cochrane, T., Meir, P., Chave, J., Almeida, S., Arroyo, L., Higuchi, N., Killeen, T.J., Laurance, S.G., Laurance, W.F., Lewis, S.L., Monteagudo, A., Neill, D.A., Vargas, P.N., Pitman, N.C.A., Quesada, C.A., Salomão, R., Silva, J.N.M., Lezama, A.T., Terborgh, J., Martinez, R.V., Vinceti, B., 2006. The regional variation of aboveground live biomass in old-growth Amazonian forests. Glob. Change Biol. 12, 1107–1138.

Moreira, J., Barbosa, R.I., 2008. Composição, riqueza e diversidade de árvores comerciais inventariadas pelo Projeto RADAMBRASIL para Roraima e áreas adjacências. Mens Agitat 3 (2), 115–124.

Mitchard, E.T.A., Feldpausch, T.R., Brienen, R.J.W., Lopez-Gonzalez, G., et al., 2014. Markedly divergent estimates of Amazon forest carbon density from ground plots and satellites. Glob. Ecol. Biogeogr. 23, 935–946.

NASA-TRMM, 2013. TRMM level-3 monthly products <http://gdata1.sci.gsfc.nasa.gov/daac-binG3/gui.cgi?instance_id=TRMM_Monthly> (accessed 23/05/2013).

Nascimento, M.T., Carvalho, L.C.S., Barbosa, R.I., Villela, D.M., 2014. Variation in floristic composition, demography and above-ground biomass over a 20-year period in an Amazonian monodominant forest. Plant Ecol. Divers. 7 (1–2), 293–303.

Nepstad, D.C., McGrath, D.G., Soares-Filho, B., 2011. Systemic conservation, REDD, and the future of the Amazon Basin. Conserv. Biol. 25, 1113–1116.

Nepstad, D.C., Veríssimo, A., Alencar, A., Nobre, C., Lima, E., Lefebvre, P., Schlesinger, P., Potter, C., Moutinho, P., Mendoza, E., Cochrane, M., Brooks, V., 1999. Large-scale impoverishment of Amazonian forests by logging and fire. Nature 398, 505–508.

Nogueira, E.M., Nelson, B.W., Fearnside, P.M., 2005. Wood density in dense forest in central Amazonia, Brazil. For. Ecol. Manage. 208, 261–286.

Nogueira, E.M., Fearnside, P.M., Nelson, B.W., Barbosa, R.I., Keizer, E.W.H., 2008. Estimates of forest biomass in the Brazilian Amazon: new allometric equations and adjustments to biomass from wood-volume inventories. For. Ecol. Manage. 256, 1853–1867.

Nogueira, E.M., Fearnside, P.M., Nelson, B.W., França, M.B., 2007. Wood density in forests of Brazil's 'arc of deforestation': implications for biomass and flux of carbon from land-use change in Amazonia. For. Ecol. Manage. 248, 119–135.

Nogueira, E.M., Yanai, A.M., Fonseca, F.O.R., Fearnside, P.M., 2015. Carbon stock loss from deforestation through 2013 in Brazilian Amazonia. Glob. Change Biol. 21, 1271–1292.

R Development Core Team, 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria <http://www.R-project.org>.

Saatchi, S.S., Houghton, R.A., Dos Santos Alvalá, R.C., Soares, J.V., Yu, Y., 2007. Distribution of aboveground live biomass in the Amazon basin. Glob. Change Biol. 13, 816–837.

Saatchi, S.S., Harris, N.L., Brown, S., Lefsky, M., Mitchard, E.T.A., Salas, W., et al., 2011. Benchmark map of forest carbon stocks in tropical regions across three continents. Proc. Nat. Acad. Sci. USA 108, 9899–9904.

Saatchi, S., Ulander, L., Williams, M., Quegan, S., LeToan, T., Shugart, H., Chave, J., 2012. Forest biomass and the science of inventory from space. Nat. Clim. Change 2 (12), 826–827.

Sales, M.H., Souza Jr., C.M., Kyriakidis, P.C., Roberts, D.A., Vidal, E., 2007. Improving spatial distribution estimation of forest biomass with geostatistics: a case study for Rondônia, Brazil. Ecol. Model. 205, 221–230.

Santos, J.R., Freitas, C.C., Araujo, L.S., 2003. Airborne P-band SAR applied to the above ground biomass studies in the Brazilian tropical rainforest. Remote Sens. Environ. 87, 482–493.

Schaefer, C., Darlymple, J., 1995. Landscape evolution in Roraima, North Amazonia: planation, paleosols and palioclimates. Zeitschrift für Geomorphologie 39, 1–28.

Soares-Filho, B., Moutinho, P., Nepstad, D., Anderson, A., Rodrigues, H., Garcia, R., et al., 2010. Role of Brazilian Amazon protected areas in climate change mitigation. Proc. Nat. Acad. Sci. USA 107, 10821–10826.

Song, X.P., Huang, C., Saatchi, S.S., Hansen, M.C., Townshend, J.R., 2015. Annual carbon emissions from deforestation in the Amazon Basin between 2000 and 2010. PLoS ONE 10 (5), e0126754. http://dx.doi.org/10.1371/journal.pone.0126754.

Xaud, H.A.M., Martins, F.S.R.V., dos Santos, J.R., 2013. Tropical forest degradation by mega-fires in the northern Brazilian Amazon. For. Ecol. Manage. 294, 97–106.