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Biomass and Greenhouse-Gas Emissions from Land-Use Change in Brazil's Amazonian "Arc of Deforestation": The States of Mato Grosso and Rondônia

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Abstract

We calculate greenhouse-gas emissions from land-use change in Mato Grosso and Rondônia, two states that are responsible for more than half of the deforestation in Brazilian Amazonia. In addition to deforestation (clearing of forest), we also estimate clearing rates and emissions for savannas (especially the *cerrado*, or central Brazilian savanna), which have not been included in Brazil's monitoring of deforestation. The rate of clearing of savannas was much more rapid in the 1980s and 1990s than in recent years. Over the 2006-2007 period (one year) 204 × 10^3 ha of forest and 30 × 10^3 ha of savanna were cleared in Mato Grosso, representing a gross loss of biomass carbon (above + belowground) of 66.0 and 1.8 × 10^6 MgC, respectively. In the same year in Rondônia, 130 × 10^3 ha of forest was cleared, representing gross losses of biomass of 40.4 × 10^6 MgC. Data on clearing of savanna in Rondônia are unavailable, but the rate is believed to be small in the year in question. Net losses of carbon stock for Mato Grosso forest, Mato Grosso savanna and Rondônia forest were 29.0, 0.5 and 18.5 × 10^6 MgC, respectively. Including soil carbon loss and the effects of trace-gas emissions (using global warming potentials for CH_4 and N_2O from the IPCC's 2007 Fourth Assessment Report) , the impact of these emission sources totaled 30.9, 0.6 and 25.4 × 10^6 Mg CO_2-equivalent C, respectively. These impacts approximate the combined effect of logging and clearing because the forest biomasses used are based on surveys conducted before many forests were exposed to logging. The total emission from Mato Grosso and Rondônia of 56.9 × 10^6 Mg CO_2-equivalent C can be compared with Brazil's annual emission of approximately 80 × 10^6 MgC from fossil-fuel combustion.

Keywords: Amazon; Burning; Carbon; *Cerrado*; Deforestation; Global Warming; Rainforest; Savanna; Tropical Forest

1. Introduction

Forests and savannas in Brazilian Amazonia are rapidly being cleared for cattle pastures and agriculture with serious impacts on biodiversity and greenhouse-gas emissions. Brazil is one of the most important countries both from the standpoint of carbon emission associated with land-use change today and because the country's vast areas of remaining tropical forest represent tremendous potential future emissions (e.g., Fearnside, 2000a, b). Mato Grosso alone represents about half of the annual deforestation in Brazil's 500-million hectare Legal Amazon region (Brazil, INPE, 2008). Mato Grosso and Rondônia (Figure 1) together constitute almost half of the "arc of deforestation" that extends around the southern edge of Amazonia from Pará and Maranhão in the east to Acre in the west. Mato Grosso and Rondônia cover 114 million hectares, an area larger than the US states of Texas and California combined or about one-third the area of Western Europe.

[Figure 1 here]

Burning releases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Decay releases CO_2 and CH_4, while soils in native forest are sources and sinks of CH_4 and N_2O that are eliminated by clearing. Deforestation also creates sources of CH_4 from cattle and of N_2O from pasture soil.

Greenhouse-gas emission estimates are generally obtained by multiplying the deforested area by the biomass per unit area. The result can then be transformed by using the burning efficiency (burn factor) and the emission coefficient (emission factor) for each gas per unit of carbon or biomass burned (Fearnside et al., 1999). This simple calculation (area × biomass loading × burning efficiency) can lead to great uncertainties, which tend to explode when the coefficients of variation of the individual terms exceed 0.3 (Robinson, 1989).

Estimates of global carbon emissions due to land-use change vary enormously, with estimates for emissions in the 1990s ranging from +0.5 to +3.0 GtC yr^{-1} (Houghton, 2003a). About half of the variation in global estimates results from uncertainty concerning emissions in tropical regions (Houghton, 2003b).

For the tropics, uncertainties in biomass estimates may contribute as much to the disparate estimates of carbon emissions as do uncertainties in deforestation rates (Houghton, 2005). Three recent estimates of carbon emissions from tropical deforestation (Achard et al., 2002; DeFries et al., 2002; Houghton, 2003a) used nearly identical data for carbon stocks and varied only in their rates of deforestation. Uncertainty in estimates of carbon stocks in tropical forests (Houghton et al., 2001; Eva et al., 2003; Fearnside and Laurance, 2003, 2004) make the range of possible emissions of carbon from tropical deforestation and degradation very broad. However, recent estimates of biomass and additional data make it possible to improve emissions estimates for tropical forests, in this case for two key states in Brazil's "arc of deforestation": Mato Grosso and Rondônia.

The Amazon forest is composed of a mosaic of vegetation types. These have been mapped by RADAMBRASIL, a large-scale Brazilian government project for identifying the natural resources in Amazonia and other regions of Brazil. We used 2702 of the approximately 3000 1-ha plots that were sampled in this forest inventory in Brazilian Amazonia as a whole. The trees in each plot were measured by RADAMBRASIL technicians. The locations of the plots were chosen to sample all areas that appeared to differ on the project's side-looking airborne radar imagery.

Where plots were far from river or road access, chainsaw operators were first lowered into the forest by rope from helicopters in order to clear a helicopter landing pad for the technical team. All live trees were measured that were greater than one meter in circumference at breast height (1.3 m above the ground), which is equivalent to 31.8 cm diameter at breast height (DBH), Commercial height (to the first large branch) was estimated by visual comparison with a tall pole held next to the tree. Most identifications relied on matching scientific names with common names provided by parabotanists, a practice that introduces considerable uncertainty at the species level (see Fearnside, 1997a). Palms and non-tree components such as strangler figs were not included.

The unparalleled coverage of the RADAMBRASIL dataset makes this the most reliable basis for indirect estimates of biomass in the diverse vegetation types of Brazilian Amazonia (see review in Fearnside, 2008). Care is necessary in interpreting the RADAMBRASIL data and a series of adjustments must be applied (Fearnside, 1994, 2000b; Nogueira et al., 2008).

The *cerrado* biome occupies an area of about 2.0×10^6 km^2 and is the second largest biome in Brazil (Sano et al., 2008). Only 0.85% of the *cerrado* is protected in conservation areas (*e.g*., Parque Nacional da Chapada dos Veadeiros and Parque Nacional das Emas) (PROBIO, 2007). Clearing data for the Brazilian *cerrado* are scarce because *cerrado* clearing is not monitored by the government agency responsible for evaluating deforestation in Brazil: Instituto Nacional de Pesquisas Espaciais (INPE). Determination of the area cleared in *cerrado* only occurs when specific projects are undertaken. No *cerrado* clearing data are available for Rondônia, where the original vegetation included of 2.3×10^6 ha of *cerrado*, or about 10% of the state.

Rondônia and Mato Grosso are prominent contributors to Amazonian deforestation and greenhouse-gas emissions. The objective of the present study was to estimate greenhouse-gas emissions due to land-use change (including both deforestation and *cerrado* clearing) in these two states based on forest inventory data, forest and savanna biomass and spatial deforestation maps in a geographical information system (GIS).

2. Materials and methods

Three kinds of maps were developed: 1. Vegetation cover before most of the deforestation took place (pre-1976) and reconstruction of "original" (pre-1500) vegetation; 2. Biomass of the "original" vegetation, including both forest and non-forest (*cerrado*) vegetation types, and 3. Cleared areas covering the 1976-2007 period. Maps for 2006 and 2007 allow a one-year estimate to be made of biomass loss and emissions. By superposing biomass and clearing maps it was possible to calculate greenhouse-gas emissions from land-use change. In creating these maps the following aspects were taken into consideration:

2.1. Original Vegetation Cover

Mapping the original vegetation cover requires reconstruction of the vegetation types that existed before the beginning of large-scale deforestation. Past alterations of the vegetation by indigenous peoples who have inhabited these areas for millennia were not considered. The pre-existing vegetation was characterized starting from mapping carried out by the RADAMBRASIL Project (Brazil, Projeto RADAMBRASIL, 1973-1983). The phyto-ecological classes for the whole of Brazilian Amazonia were digitized and made available to us by SIPAM (System of Protection of Amazonia), and a map was generated at a scale of 1:250,000. The RADAMBRASIL vegetation classification system follows the nomenclature of Veloso et al. (1991). Structural aspects of the vegetation in the classification include the dominant life form and the degree of canopy closure. The system also considers abiotic factors such as soil texture, seasonality of rainfall, altitude and the length of time under annual flooding. The boundaries of each phyto-ecological unit were drawn on radar images (band X) at a scale of 1:250,000.

In reconstructing the original vegetation cover, secondary information was used from the RADAMBRASIL/SIPAM database for the class denominated as "*antropizado*" (altered by human action), with and without past information. For the areas altered by human action with past information, the original vegetation cover was derived from attribute information in the database. For areas classed as "*antropizado*" without past information, recovery of the original vegetation class was based on: (i) the IBGE-RADAMBRASIL vegetation map at a scale of 1: 2,500,000 and (ii) the Mato Grosso Secretariat of Planning vegetation maps at a scale of 1:250,000 (which are derived from the RADAMBRASIL maps) (Mello, 2007; SEPLAN-MT, 2009). We used the SIPAM-digitized version of the IBGE -RADAMBRASIL map as updated version 2006. An earlier (2004) version had coarser resolution (1:1,000,000 scale rather than 1:250,000) and lacked attribute data on the original vegetation types before alterations by human action.

Spatial data processing to produce the vegetation maps was performed using ARCGIS version 9 software. Political boundaries are from Brazil, IBGE (2009). All calculations on the vegetation and deforestation maps were done in raster format at 250-m resolution using the Lambert conical equal-area projection with datum SAD 1969.

2.2. Vegetation classes in the areas altered by human action

At the time of the RADAMBRASIL vegetation survey (considered to be 1976), 26% of the total area of the two states had already been altered. The altered areas were either clear (primarily under cattle pasture) or under secondary regeneration. Only 5.4% of the cases were not covered by information on the original vegetation type. Areas that remained unclassified after integrating the three maps were classified manually using information on the classes of neighboring polygons. The vegetation class of each unclassified polygon was considered to be the most frequently occurring class around the edges of the polygon. In most cases of areas altered by human action the information on the sub-classes of savanna (forested, woodland, parkland or grassland) and of forest (pioneer formations, open ombrophilous, dense ombrophilous, seasonal deciduous or seasonal semideciduous) was derived from the description of the vegetation unit in the database.

Abiotic attributes (elevation and soil type) in the RADAMBRASIL classification were discarded. For ombrophilous dense submontane forest the "submontane" descriptor was discarded; we believe that these attributes have little additional effect on mean biomass. The resulting information from integration of the maps discussed above, which resulted in the map of original vegetation cover, is based on the legend of the IBGE vegetation map (Brazil, IBGE, 2007) with the exception of the information on abiotic attributes.

2.3. Original forest biomass

2.3.1. Forest vegetation types

We estimated mean biomass for each vegetation type based on wood-volume data by species and diameter class in 2702 1-ha plots distributed throughout Brazilian Amazonia (Brazil, Projeto RADAMBRASIL, 1973-1983). RADAMBRASIL volumes from Volume 8 onwards (including all volumes for Mato Grosso and Rondônia) contain a green-covered report of approximately 600 pages describing the vegetation, soils and other characteristics and a white-covered supplement of approximately 700 pages containing tables of wood volumes for each plot, and a packet of six 1:1,000,000-scale thematic maps. Each volume covers 4º of latitude by 6º of longitude (approximately 440 ×660 km, or 29 million ha). The inventory for each plot includes the names of the species, the number of trees, the wood volume by species and diameter class, and a description of the ecosystem. We calculated the average biomass of the plots in each type to produce a map of biomass classes in Rondônia and Mato Grosso. Variance in inventory plots was ignored and spatial homogeneity was assumed for the forest-type distribution map obtained from RADAMBRASIL data.

The bole volume published in the RADAMBRASIL reports must be corrected for differences in form factor. This is the ratio of the volume of a bole (commercial volume, meaning volume to the first large branch) to the volume of a cylinder with the diameter of the DBH (diameter at breast height = diameter at 1.3 m above the ground) and the length of the commercial bole. The RADAMBRASIL values were calculated using a value of 0.70 as the form factor for all forest types; these are corrected using the values measured by Nogueira et al. (2008): 0.660 for open forest and 0.709 for dense forest.

The bole volume estimate is adjusted to include the volumes of trees with diameters between 10 cm and the 31.8-cm minimum limit in the RADAMBRASIL dataset by multiplying by the Volume Expansion Factor (VEF) (e.g., Brown, 1997). The VEF values used were those measured by Nogueira et al. (2008): 1.506 for open forest and 1.537 for dense forest. The resulting bole volume must then be adjusted for the crown biomass by multiplying by the Biomass Expansion Factor (BEF) (e.g., Brown, 1997). The BEF values used were those measured by Nogueira et al. (2008): 1.580 for open forest and 1.635 for dense forest.

Biomass of trees < 10 cm DBH was considered to be 6.5% in dense forest (de Castilho et al., 2006), while a value of 4% was used for non-dense forest for all trees 1-10 cm DBH since the number of young or sub-canopy trees (102.5 ± 24.5 trees/ha 5-10 cm DBH: Pereira et al., 2005) is lower than in dense forest (715 trees/ha: de Castilho et al., 2006). In order to include palms, 1.9% was added to biomass in dense forests and 8.6% in non-dense forests; an additional 3.1% was added to biomass for vines for both dense and non-dense (open) forests, while 13.7% was included for dead aboveground biomass in both groups of forests (Nogueira et al., 2008). A correction of 0.21% was added for non-tree forest components (see Fearnside, 1997b, 2000a,b).

The bole volume data calculated as described above were converted to bole biomass based on a large dataset on wood density that includes data published by Fearnside (1997a) with some sources corrected for radial variation based on linear equations (Nogueira et al., 2005), other sources by Chave et al. (2006) and recent data by Nogueira et al. (2007). Belowground biomasses in forest vegetation types are from Nogueira et al. (2008).

2.3.2. Non-forest vegetation types

Above- and belowground biomass for savannas in Mato Grosso and Rondônia was calculated from a georeferenced database of the nine studies that measured this parameter using both direct (destructive) and indirect methods in both the Amazonian biome and the *cerrado* biome. This was necessary because only a very few studies of savanna biomass have been done in Mato Grosso, and none have been done in Rondônia.

Indirect measurements for calculating aboveground biomass have only been done by Ottmar et al. (2001), who used a methodology based on stereo-photographs to estimate biomass at a series of locations in the *cerrado* biome in Goiás, Mato Grosso, Distrito Federal and Minas Gerais. Only the studies of Abdala et al. (1998) and Castro and Kauffman (1998), both done in the Distrito Federal near Brasília, quantified belowground biomass (coarse roots), relating this measure to the corresponding aboveground biomass. Other studies quantified aboveground biomass in the *cerrado* biome, such as the studies by Kauffman et al. (1994) and Miranda et al. (1996) near Brasília; and in savanna in the Amazonian biome, such as Barbosa (2001) and Barbosa and Fearnside (2005) in Roraima, in addition to Araújo et al. (2001) and Santos et al. (2002), in Roraima and Mato Grosso. The nine studies totaled 117 sample plots in 84 locations.

In order to standardize the procedure throughout the calculation, all of the vegetation types defined by each of the authors were translated into the vegetation classification system adopted by Brazil, IBGE (1992). For example, vegetation defined as "clean field" (*campo limpo*) and "dirty field” (*campo sujo*) were lumped as "grassland savanna” (Sg), while "tall woodland" (*cerradão*) was redefined as the "forested savanna" (Sd) of Brazil, IBGE (1992). All results were assigned to IBGE categories and mean values for aboveground and belowground biomass were calculated (Table 1).

[Table 1 here]

The studies of Abdala et al (1998) and Castro and Kauffman (1998) were used for determining of the mean root:shoot ratio for application in all savanna vegetation types that did not have sampling of underground biomass. An overall mean of 2.81, was used, disregarding discrepancies between the vegetation types and the depths sampled in the two studies mentioned above. This ratio was applied to each of the studies that only had data for aboveground biomass in order to obtain the total biomass in each of the vegetation types. The mean of each vegetation type was then calculated individually, containing all of the values obtained for each state and type of measurement; this result was considered to be an overall mean for the *cerrado* vegetation types in Mato Grosso and Rondônia (Table 2).

[Table 2 here]

2.4. Cleared Areas

2.4.1. Clearing of forest vegetation types

The vegetation types are divided into two great groups: (a) forests, or all vegetation types with over 90% canopy cover (ombrophilous forest, deciduous and semideciduous forests, forested savanna, etc.) and (b) non-forest, considered to be all forms of open vegetation with canopy cover less than 50% (grassland, parkland and open woodland savannas). The "*cerradões*" (forested savannas) have canopy cover in the 50-90% range and are counted as forest by the PRODES (Monitoring of the Brazilian Amazon Forest by Satellite) program of the National Institute of Space Research (INPE) in quantifying deforestation throughout Brazilian Amazonia.

Areas of deforestation in the forest vegetation types were obtained from data recently made publicly available through the PRODES internet system (http://www.obt.inpe.br/prodes/index.html). This database has been updated regularly since 1988, producing annual estimates of the rates of deforestation in Brazil's Legal Amazon region. Automatic digital classification of images began in 2002, which increased the precision of geo-referencing the deforested polygons, producing a multi-temporal geographical database. The annual deforestation estimates were obtained starting from the increments in areas identified in each image for the first of August of the reference year (Brazil, INPE, 2008).

2.4.2. Clearing of non-forest vegetation types

Cerrado clearing data up to 2002 were provided by EMBRAPA-Cerrados, the PROBIO Project (PROBIO, 2007) and Laboratory for Image Processing and Geoprocessing (LAPIG) at the Federal University of Goiás (UFG), which updated the data through 2007 (LAPIG, 2008). Maps of cumulative clearing were generated and the 2006-2007 clearing rate was calculated for the *cerrado* biome in Mato Grosso.

2.5. Greenhouse-gas emission calculation procedure

Calculation of greenhouse-gas emissions converts wood biomass (dry weight) to carbon considering a wood carbon content of 48% (da Silva, 2007). Burning efficiency for the initial burn in forest is 39.4% and charcoal formation is 2.2% (Fearnside, 2003, p. 51 based on: Fearnside et al., 1993, 1999, 2001; Carvalho et al., 1995; Kauffman et al., 1995; Araújo et al., 1999; Graça et al., 1999).

Studies of the fate of carbon in Amazonian forests subsequent to the initial burn (Barbosa and Fearnside, 1996, updated with burning efficiencies from Fearnside et al., 2007) indicate that 80.5% of the remains of the initial burn is oxidized through decay and 18.6% through burning; remains burned over the course of a decade in a typical three-burn sequence have an efficiency per burn of 21.6% with 1% charcoal formation per burn. These values imply an overall burning release 50.8% for forest. For *cerrado* (open woodland and forested savanna), based on results from a semi-deciduous forest burn in Mato Grosso (Righi et al., in prep.), burning efficiency of the initial burn is 65.0% and the overall burning efficiency is 70.7%. Overall charcoal formation is 2.9% for forest and 6.7% for *cerrado*. Overall decay release is 47.0% for forest and 23.3% for *cerrado*. Overall graphitic particulate release is 0.17% of preburn C for both forest and *cerrado* (Fearnside, 2003, p. 50 based on Kuhlbusch and Crutzen, 1995). Emission factors per Mg C burned are 0.0136 Mg CH_4, 0.0004 Mg N_2O, and 3.53 Mg CO_2 (from Andreae and Merlet, 2001). Emission factors for decay are from Martius et al. (1996): each Mg C decayed releases 0.00012 Mg CH_4 and 3.67 Mg CO_2.

The calculation uses the replacement landscape derived by Fearnside (1996), which has an equilibrium carbon stock in biomass of 12.8 MgC ha^{-1}. Soil carbon loss to 8-m depth causes emissions of 14.85 Mg CO_2/ha of landscape/100 years (Fearnside and Barbosa, 1998). Emissions from cattle (0.723 Mg CH_4/ha of landscape/100 years), recurrent pasture burning (0.051 Mg CH_4 and 0.0032 Mg N_2O/ha of landscape/100 years), and loss of forest sinks and sources (0.0001 Mg CH_4/ha of landscape/100 years) are from Fearnside (2000a,b). Loss of forest termites represents -0.0208 Mg CH_4/ha of landscape/100 years (Martius et al., 1996). Emissions from recurrent secondary forest burning were not included. Belowground biomass decay is conservatively assumed only to release CO_2. Soil N_2O release is 0.0018 Mg/ha of landscape/100 years, based on Verchot *et al*. (1999, p. 37).

Trace-gas emissions are converted to CO_2 equivalents using the 100-year global warming potentials of CH_4 and N_2O from the IPCC's Fourth Assessment Report: one Mg of CH_4 gas has an impact on global warming equivalent to 25 Mg of CO_2, while one Mg of N_2O is equivalent to 298 Mg of CO_2 (Forster et al., 2007, p. 212). Emissions in CO_2 equivalents are converted to CO_2 carbon equivalents by multiplying by 12 (the atomic weight of carbon) and dividing by 44 (the molecular weight of CO_2).

3. Results cumulative

3.1. Original stocks and cumulative loss of biomass through 2007

The areas originally covered by forests and *cerrados* in Mato Grosso and Rondônia are shown in Figure 2. The original areas and the areas remaining in 2007 of each vegetation type are given in Table 3. Cumulative forest loss in Rondônia totaled 7.8×10^6 ha or about 33% of the state by 2007. The biomass map is given in Figure 3.

[Figures 2 and 3 and Table 3 here]

Forests contained most of the biomass in both states, representing 97.5% (6.6×10^9 Mg) of the original biomass in Rondônia and 89% (17.5×10^9 Mg) in Mato Grosso. Clearing of forest was responsible for most biomass losses. In Mato Grosso, forest loss was responsible for 90% of the cumulative total biomass loss. We do not have *cerrado* clearing data for Rondônia, but the percentage contribution of forest clearing would be even higher in Rondônia than in Mato Grosso because the original vegetation of Rondônia was almost completely dominated by high forests.

Mato Grosso has lost 32.2% of its original biomass. Seasonal semi-deciduous forest (Fa+Fb+Fs) , which is both the most common and the most deforested vegetation type in Mato Grosso, had the largest total biomass (6.7×10^9 Mg) and a loss of 1.8×10^9 Mg. The representation of these forests in the state's loss of biomass is slightly lower than the corresponding percentage in area cleared because a small part of the biomass loss is offset by higher-biomass forest types such as open and dense ombrophilous forests (Aa+Ab+As+Da+Db). The percentages calculated for area were roughly similar to those calculated for biomass for all forest types due to their relatively small variation in biomass.

Open and dense ombrophilous forests were well represented, with original biomass stocks totaling 4.6 and 2.2×10^9 Mg, respectively. Open ombrophilous forest (Aa+Ab+As) lost 1.5×10^9 Mg, or almost 27% of its original biomass stock, while dense ombrophilous forest (Da+Db) lost 0.35×10^9 Mg. The ombrophilous forest -- seasonal forest contact (ON) is in third position for biomass loss, with 1.0×10^9 Mg lost and only 0.1×10^9 Mg remaining in 2007. This vegetation type originally represented only 5.7% of the original biomass in Mato Grosso but it represented 16% of the total biomass loss in 2006-2007. The seasonal forest -- *cerrado* contact (SN) area has lost 0.8×10^9 Mg of its original 1.9×10^9 Mg (41% of its original biomass) and was responsible for 14% of the total forest biomass loss. The other forest losses were less significant.

In Rondônia, open ombrophilous forest (Aa+Ab+As) represented 76% of the original biomass (5.2×10^9 Mg) and accounted for the largest biomass loss: 1.7×10^9

Mg, or 73% of the total. The seasonal semi-deciduous forest (Fa+Fb+Fs) has lost 0.18 × 10^9 Mg (from its original biomass of 0.44 × 10^9 Mg) while dense ombrophilous forests (Da+Db) has lost 0.19 × 10^9 Mg and ombrophilous forest -- *cerrado* contact (SO) has lost 1.75 × 10^9 Mg. These vegetation types originally accounted for 6.4, 8.0 and 5% of Rondônia's biomass stock. In total, Rondônia has lost 35% of its original biomass.

3.2. Annual emissions for 2006-2007

Figure 4 maps clearing of forests based on data from PRODES and clearing of *cerrado* based on data from LAPIG. Losses of area and biomass of vegetation are summarized in Table 4. Net losses of carbon and emissions of greenhouse gases are summarized in Table 5.

[Figure 4 and Tables 4 & 5 here]

Net emissions for 2006-2007 total 56.9 × 10^6 Mg CO_2-equivalent C/year. Of this, 3.9 × 10^6 Mg CO_2-equivalent C represents trace-gas impacts. The remaining 53.1 × 10^6 Mg CO_2-equivalent C of net emission that is in the form of CO_2 is the gross emission of 57.8 × 10^6 Mg C (55.5 × 10^6 Mg C from forest biomass + 0.8 × 10^6 Mg C from *cerrado* biomass + 1.5 × 10^6 Mg C from soil carbon) minus 4.7 × 10^6 Mg C from the annual increase in carbon stock from expansion of the replacement landscape.

4. Discussion

Estimation of biomass directly from remote sensing data has long been a goal of research in Amazonia, but has so far proved illusive as a tool for large-scale estimates. Progress has been made at the level of experimental plots (e.g., Santos et al., 2003). Another approach is to use remote-sensing information to estimate biomass by associating a variety of parameters detected from space with the biomass measured at a series of reference points on the ground. This has been done by Saatchi et al. (2007) using 1-km resolution satellite-borne radar data, from which a number of characters were extracted and associated with published or otherwise available data from plots surveyed since 1990. The characters in the satellite data (such as measures of crown humidity and surface roughness) are indicators of forest appearance, rather than measures directly linked to biomass (such as tree height or basal area). The estimate was based on 280 plots in primary forests (approximately half of which were in Brazil) The older, but much larger, data sets from the RADAMBRASIL were not used for calibrating the satellite-borne radar results, nor were the vegetation maps that the RADAMBRASIL project derived from high-resolution airborne radar coupled with extensive field observations.

A number of estimates of Amazonian biomass dispense entirely with spatial information from either satellite imagery or vegetation maps and derive values either as simple averages of point measurements or by interpolating between the locations of sampled plots. This throws out the tremendous amount of labor that the RADAMBRASIL teams invested in classifying and mapping the vegetation. One estimate (Achard et al., 2002) was based on a mean of two values, one of which Brown (1997, p. 24) was for a single plot located in the Tapajós National Forest in Pará (FAO, 1978) and made no claim to represent the whole of Amazonia (see Fearnside and Laurance, 2004). Malhi et al. (2006) interpolated (followed by adjustments for the effects of various environmental variables) based on 226 plots of which 81 were in

Brazil, these being heavily clustered in the Manaus, Belém and Santarém areas. Houghton et al. (2000) derived an estimate interpolated from 56 plots, while Houghton et al. (2001) produced an estimate interpolated from 44 plots, of which only 25 were in Brazilian terra firme (upland) forests; these authors then averaged the resulting 192 MgC/ha value with six other regional estimates to produce the 177 MgC/ha average biomass carbon stock used by Ramankutty et al. (2007, p. 64) in calculating emissions. The large uncertainty inherent in these measures also applies to studies that have based calculations on the average value derived by Houghton et al. (2000), such as Soares-Filho et al. (2004, 2006) and DeFries et al. (2002). An additional factor adding uncertainty to interpolation from the small number of samples used in the estimates by Houghton and coworkers is the effect of a pronounced clustering of sample locations, with the samples heavily concentrated along rivers and roads. The concentration of samples near rivers means that riparian vegetation is proportionately more heavily sampled than the upland interfluves between the rivers. Simply converting the RADAMBRASIL volume estimates to biomass and interpolating between the locations will therefore over-emphasize the lower biomass riparian vegetation types and will tend to underestimate average biomass in the region (i.e., the "RADAMBRASIL" estimates in Houghton et al., 2001).

The 250×250-m picture element (pixel) dimension of the MODIS satellite imagery on which the PROBIO (2007) and LAPIG (2008) data we used for *cerrado* clearing are based limits the resolution of the study. The forest clearing data from PRODES, which are gathered by satellites with 30-m resolution (ETM+ and Landsat) and reported at 60-m resolution, were degraded to the same resolution (250 m). Future analyses with higher-resolution data could achieve greater accuracy. In Rondônia, *cerrado* vegetation types contained only 0.16×10^9 Mg or 2.44% of the total original biomass. Absence of data on *cerrado* clearing in Rondônia will therefore cause only a small bias in biomass loss for this state.

The forest volume data from RADAMBRASIL used in this study are the published values of bole volume by species and size class in 2702 1-ha plots, not the unpublished measurements of approximately 145,000 individual trees. The dataset of individual tree measurements contains numerous errors and inconsistencies (see Fearnside, 2008). This dataset is being culled and corrected by a task force from IBGE, which estimates that correcting the dataset will take six years (2009-2015). Once usable tree-level data are available, greater accuracy in the forest biomass estimates can be achieved by direct application of the allometric equations and corrections developed by Nogueira et al. (2006, 2007, 2008).

The values for forest biomasses used here are based on forest volume surveys carried out in the 1970s, before many of the forest areas were exposed to biomass depletion through logging. Care must be taken to neither omit nor double count the logging emission in estimates of the global-warming impact of land-use change. If biomass estimates are adjusted downward to reflect the effect of logging, then the logging emission must be calculated and reported separately, while if logging emissions are reported then the "original" or "undisturbed" forest biomass cannot be used for computing deforestation emission because it would represent double counting (see Fearnside, 1997b, 2000b). The land-use change emissions reported here approximate the combined effect of logging and subsequent clearing in the area that was cleared in 2006-2007. As a point of comparison, forests cleared in 1990 throughout the Legal Amazon had had their average total biomasses reduced by an estimated 12.3% as a result of logging, based on logging parameters in Fearnside (1995). The forests cleared in Mato Grosso and Rondônia in 2006-2007 would have had their average biomasses reduced by more than this percentage, with a correspondingly greater proportion of the emission occurring through the logging rather than the clearing pathway.

Deforestation rates have varied substantially over the past three decades, and differences in the year or years to which different estimates of emissions refer often explains the widely differing results that have been put forward for Brazil's Amazonian emissions. In Mato Grosso the rate of *cerrado* clearing was much higher in the past and is believed to have been approximately 13 × 10^3 km^2/year in the late 1980s (Fearnside, 1990). Rapid clearing in the 1990s and early 2000s was driven by soy expansion (Fearnside, 2001), while the lower rate in the 2006-2007 period of the present study was affected by price drops of both soy and beef (McAlpine et al., 2009).

5. Conclusions

Clearing of forests and savannas (*cerrado*) in Brazilian Amazonia releases large amounts of greenhouse gases. Uncertainty regarding the magnitude of emissions stems both from poor quantification of the areas cleared in each vegetation type and from the paucity of data on the biomass of different vegetation types, especially in the "arc of deforestation" that includes the states of Rondônia and Mato Grosso. Overlaying vegetation maps with satellite data for clearing of savanna and forest in these two states shows that over the 2006-2007 period (one year) 204 × 10^3 ha of forest and 30 × 10^3 ha of savanna were cleared in Mato Grosso, representing gross losses of biomass carbon (above + belowground) of 66.0 × 10^6 MgC for forest and 1.8 × 10^6 MgC for *cerrado*. In the same year in Rondônia, 130 × 10^3 ha of forest were cleared, representing a gross loss of biomass of 40.4 × 10^6 MgC. Net losses of carbon stocks for Mato Grosso forest, Mato Grosso *cerrado* and Rondônia forest were 29.0, 0.5 and 18.5 × 10^6 MgC, respectively. Including the effects of trace-gas emissions (using global warming potentials for CH_4 and N_2O from the IPCC's 2007 Fourth Assessment Report) and loss of soil carbon, the impact of clearing in these vegetation groups totaled 30.9, 0.6 and 25.4 × 10^6 Mg CO_2-equivalent C, respectively. These emissions represent the approximate combined effect of clearing and logging in the area that was cleared in 2006-2007, since the biomass estimates represent the vegetation before significant depletion from logging. The total emission from Mato Grosso and Rondônia in the year of the estimate (2006-2007) was 56.9 × 10^6 Mg CO_2-equivalent C. Clearing of forests in Mato Grosso and Rondônia in 2006-2007 was only about half the rate in 2004, and the decrease in the rate of *cerrado* clearing (for which no 2004 data exist) was probably proportionately even greater. The large amounts of emissions indicate a substantial potential for mitigating global warming by avoiding further loss of natural vegetation here and throughout Amazonia.

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Figure Legends

Figure 1. Map with the boundaries Mato Grosso and Rondônia, Brazil

Figure 2. Original vegetation of Mato Grosso and Rondônia.

Figure 3. Total biomass (above- and belowground) of original vegetation in Mato Grosso and Rondônia. Forest vegetation types are shown in the green scale and non-forest types in the red scale.

Figure 4. Vegetation cleared by 2007 in the states of Mato Grosso and Rondônia.

Table 1 - Studies for quantification of biomass (above- and belowground) in savannas obtained by direct and indirect measures in the *cerrado* and Amazonian biomes

Type of Measure-ment	State (*)	IBGE classification (**)	Grassy-Woody biomass	Biomass in trees and bushes	Belowground biomass	Abovegound biomass	Total biomass	Source
Direct	DF	Sa	10.77	26.31	41.10	37.08	78.18	Abdala et al. 1998 (to 6.2 m depth)
		Sa	10.30	14.50	46.60	24.80	71.40	Castro and Kauffman, 1998 (to 2 m depth)
		Sd	7.00	18.00	52.90	25.00	77.90	
		Sg	6.55	0.85	23.20	7.40	30.60	
		Sa	9.33	1.58				Kauffman et al., 1994
		Sg	7.23					
		Sa	9.43					Miranda et al., 1996; H. Miranda, unpublished report; Brazil, MCT, 2002)
		Sd	7.64					
		Sg	7.18					
	MT	Sa				14.11		Araujo et al., 2001; Santos et al., 2002
		Sd				72.30		
		Sp				7.65		
	RR	Sa	2.13	9.60		11.73		Barbosa, 2001; Barbosa and Fearnside, 2005
		Sg	2.99	0.27		3.26		
		Sp	4.18	4.07		8.25		
		Ta	2.13	8.90		11.04		
		Tg	1.90	0.53		2.43		
		Tp	3.72	2.67		6.39		
		Sg				4.77		Santos et al., 2002
		Sp				7.07		
Indirect	DF	Sa	7.58	29.85		37.43		Ottmar et al., 2001
		Sd	5.23	45.98		51.21		
		Sg	6.72	2.64		9.36		
		Sp	7.47	10.83		18.29		
	GO	Sg	8.94	2.19		11.13		Ottmar et al., 2001
		Sp	7.00	10.48		17.47		
	MG	Sa	3.40	21.82		25.22		Ottmar et al., 2001
		Sg	8.45	1.95		10.40		
		Sp	5.03	20.58		25.61		
	MT	Sa	6.79	40.99		47.78		Ottmar et al., 2001

(*) States: DF=Federal District (Brasília), MT=Mato Grosso; RR=Roraima; GO=Goiás; MG=Minas Gerais.

(**) See Table 2 for IBGE codes. Td (Forested [or dense woodland] steppe-like savanna) was not measured in any of the studies.

Table 2. Mean total biomass used for vegetation types in Mato Grosso and Rondônia

IBGE code	English description	Portuguese description	Aboveground biomass (Mg ha^{-1})	Belowground biomass (Mg ha^{-1})	Total biomass (Mg ha^{-1})	Source
FOREST VEGETATION TYPES						
Aa	Open alluvial rain forest	Ombrófila aberta aluvial	298.4	59.4	357.8	Nogueira (2008)
Ab	Open lowland rain forest	Ombrófila aberta de terras baixas	303.1	60.3	363.4	Nogueira et al. (2008)
As	Open submontane rain forest	Ombrófila aberta submontana	280.2	55.8	336.0	Nogueira et al. (2008)
Cs	Seasonal deciduous submontane	Sazonal decídua submontana	241.9	48.2	290.1	Nogueira (2008)
Da	Dense alluvial rain forest	Ombrófila densa aluvial	299.3	61.5	360.8	Nogueira et al. (2008)
Db	Dense lowland rain forest	Ombrófila densa de terras baixas	318.9	65.6	384.5	Nogueira et al. (2008)
Dm	Dense montane rain forest	Ombrófila densa montana	299.7	61.6	361.3	Nogueira et al. (2008)
Ds	Dense submontane rain forest	Ombrófila densa sub-montana	319.6	65.7	385.3	Nogueira et al. (2008)
Fa	Seasonal semideciduous alluvial	Aluvial sazonal semidecídua	236.4	47.0	283.4	Nogueira (2008)
Fb	Seasonal semideciduous in	Sazonal semidecídua em terras	258.0	51.3	309.3	Nogueira et al. (2008)

	lowland areas	baixas				
Fs	Seasonal semideciduous submontane	Sazonal semidecídua submontana	263.3	52.4	315.7	Nogueira et al. (2008)
LO	Contact woody oligotrophic vegetation of swampy & sandy areas /rain forest	Contato campina / floresta ombrófila	320.8	63.8	384.6	Nogueira et al. (2008)
ON	Contact rain forest/seasonal forest	Contato floresta ombrófila/floresta sazonal	259.1	51.5	310.6	Nogueira et al. (2008)
SN	Contact savanna / seasonal forest	Contato savanna/floresta sazonal	252.4	50.3	302.7	Nogueira et al. (2008)
SO	Contact savanna / rain forest	Contato savana/floresta ombrófila	262.1	52.2	314.3	Nogueira et al. (2008)
NON-FOREST VEGETATION TYPES						
Sd	Forested (or dense woodland) savanna	Savana florestada	51.21	92.61	143.82	This study
Sa	Open woodland savanna	Savana arborizada	28.20	40.21	68.42	This study
Sp	Parkland savanna	Savana parque	14.67	26.53	41.20	This study

Sg	Grassland savanna	Savana gramineo-lenhosa	7.96	18.76	26.71	This study
Td	Forested (or dense woodland) steppe-like savanna	Savana estépica florestada	19.87	40.33	60.20	Derived from Graça (1997)
Ta	Open woodland steppe-like savanna	Savana estépica arborizada	11.04	19.96	30.99	This study
Tp	Parkland steppe-like savanna	Savana estépica parque	6.39	11.55	17.94	This study
Tg	Grassland steppe-like savanna	Savana estépica gramineo-lenhosa	2.84	5.13	7.97	This study

Table 3. Original areas and clearing by vegetation type

Category	IBGE code	Description	Mato Grosso Original area (10^6 ha)	% of state	Area cleared by 2007 (10^6 ha)	% of original area lost	Rondônia Original area (10^6 ha)	% of state	Area cleared by 2007(10^6 ha)	% of original area lost
Forest										
	F (Fa+Fb+Fs)	Seasonal semi-deciduous forest	22.1	24.5	5.9	26.6	1.4	6.0	0.6	42.3
	A (Aa+Ab+As)	Open ombrophilious forest	13.2	14.7	4.2	31.5	16.7	70.4	5.7	33.9
	D (Da+Db)	Dense ombrophilous forest	5.9	6.5	0.9	1.7	1.8	7.5	0.6	35.1
	SN	Seasonal forest-cerrado contact	6.4	7.1	2.6	41.1	0.12	0.05	0.05	44.0
	SO	Ombrophilous forest-cerrado contact	1.6	1.8	0.6	39.1	1.1	4.6	0.6	51.6
	ON	Ombrophilous forest-seasonal forest contact	3.6	4.0	3.3	90.4	0.31	1.3	0.28	91.7
	C (Cs)	Seasonal deciduous forest	1.3	1.4	0.6	42.4	0.01	0.04	0.005	58.1
	LO	Contact ombrophilous forest-*campinarana*	0.001	0.001	0.00004	6.0	--	--	--	--
	TN	Contact seasonal forest – steppe-like savanna	0.057	0.06	0.004	0.07	--	--	--	--
Non-forest										
	Sd	Forested (or dense woodland) savanna	1.7	1.9	0.2	12.0	0.46	1.93	No data	No data
	Sa	Open woodland savanna	20.9	23.2	6.4	30.6	0.55	2.31	0.0002*	0.0349*
	Sp	Parkland savanna	10.3	11.4	3.0	29.1	0.35	1.49	No data	No data
	Sg	Grassland savanna	0.5	0.6	0.01	2.0	0.03	0.12	No data	No data
	Td	Forested (or dense woodland) steppe-like savanna	0.24	0.27	0	0	--	--	--	--
	Ta	Open woodland steppe-like savanna	0.17	0.19	0	0	--	--	--	--
	Tp	Parkland steppe-like savanna	0.02	0.02	0	0	--	--	--	--

Table 3. Original areas and clearing by vegetation type

Tg	Grassland steppe-like savanna	0.39	0.43	0	0	--	--	--	--
Pa	Alluvial pioneer formations	1.2	1.4	0.001	0.08	0.69	2.91	No data	No data
	Others	0.11	0.11	0.0001	0.1	0.02	0.079	No data	No data

* Clearing data for Sa in Rondônia for 2002 only (from PROBIO, 2007). Savanna clearing data for Rondônia are not available from LAPIG (2008) because IBGE defines the state as outside of the *cerrado* biome.

Table 4. Original stocks and subsequent losses of vegetation and biomass

Category	Number of vegetation types	Original area (10^3 km^2)	Area in 2006	Area in 2007	Loss rate 2006-2007 (10^3 km^2 $year^{-1}$)	Aboveground biomass (Mg ha^{-1})	Belowground biomass (Mg ha^{-1})	Total biomass (Mg ha^{-1})	Aboveground biomass Stock (10^6 Mg)	Total biomass stock (10^6 Mg)	Gross loss of biomass (10^6 Mg $year^{-1}$)
Forest – Mato Grosso	9	541.5	363.0	361.0	2.04	269.3	53.8	323.1	14,580.0	17,494.3	66.0
Cerrado – Mato Grosso	15	360.5	275.8	275.5	0.30	23.0	36.0	59.0	829.2	2,127.0	1.8
Forest - Rondônia	7	214.2	137.6	136.3	1.30	259.0	51.6	310.6	5,549.2	6,654.0	40.4
Cerrado- Rondônia	6	22.9									

Table 5. Net losses of carbon and estimates of greenhouse-gas emissions

Category	Gross loss of carbon (10^6 MgC $year^{-1}$)	Carbon stock in replacement landscape (MgC ha^{-1})	Annual increase in C from expansion of the replacement landscape (10^6 MgC $year^{-1}$)	Net loss of carbon (10^6 MgC $year^{-1}$)	Net emission CO_2 (10^6 Mg gas $year^{-1}$)	Net emission CH_4 (10^6 Mg gas $year^{-1}$)	Net emission N_2O (10^6 Mg gas $year^{-1}$)	Trace-gas emission (10^6 Mg CO_2-C eq $year^{-1}$)	Total net emissions 10^6 Mg CO_2-C eq $year^{-1}$)
Forest – Mato Grosso	31.7	12.8	2.62	29.0	114.7	0.32	0.0010	2.3	30.9
Cerrado – Mato Grosso	0.8	12.8	0.38	0.5	3.4	0.003	0.0001	0.03	0.6
Forest - Rondônia	20.2	12.8	1.67	18.5	94.0	0.21	0.0006	1.5	25.4
Total	52.7		4.67	48.0	212.0	0.53	0.0018	3.8	56.9

Figure-1

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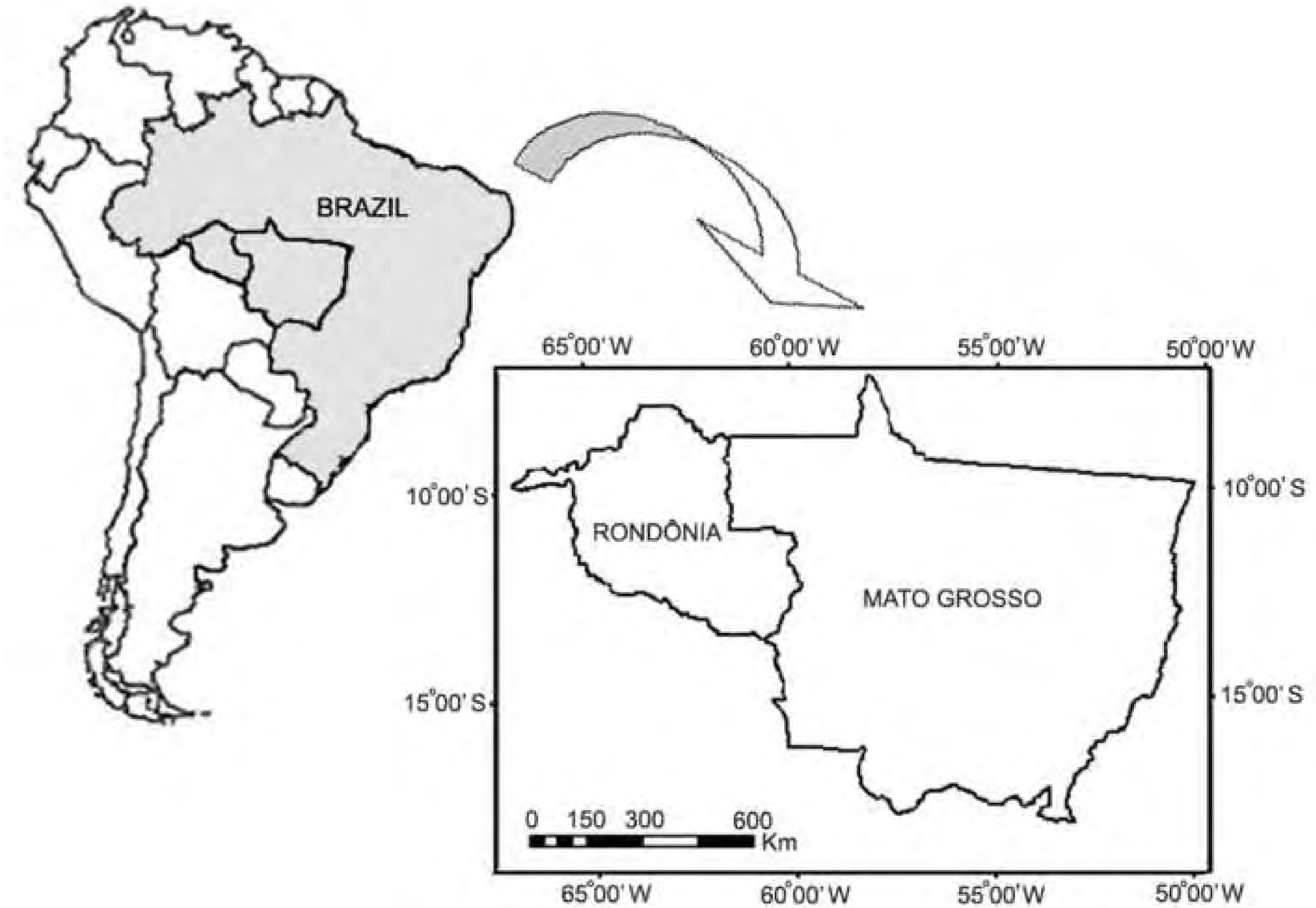

Figure-2

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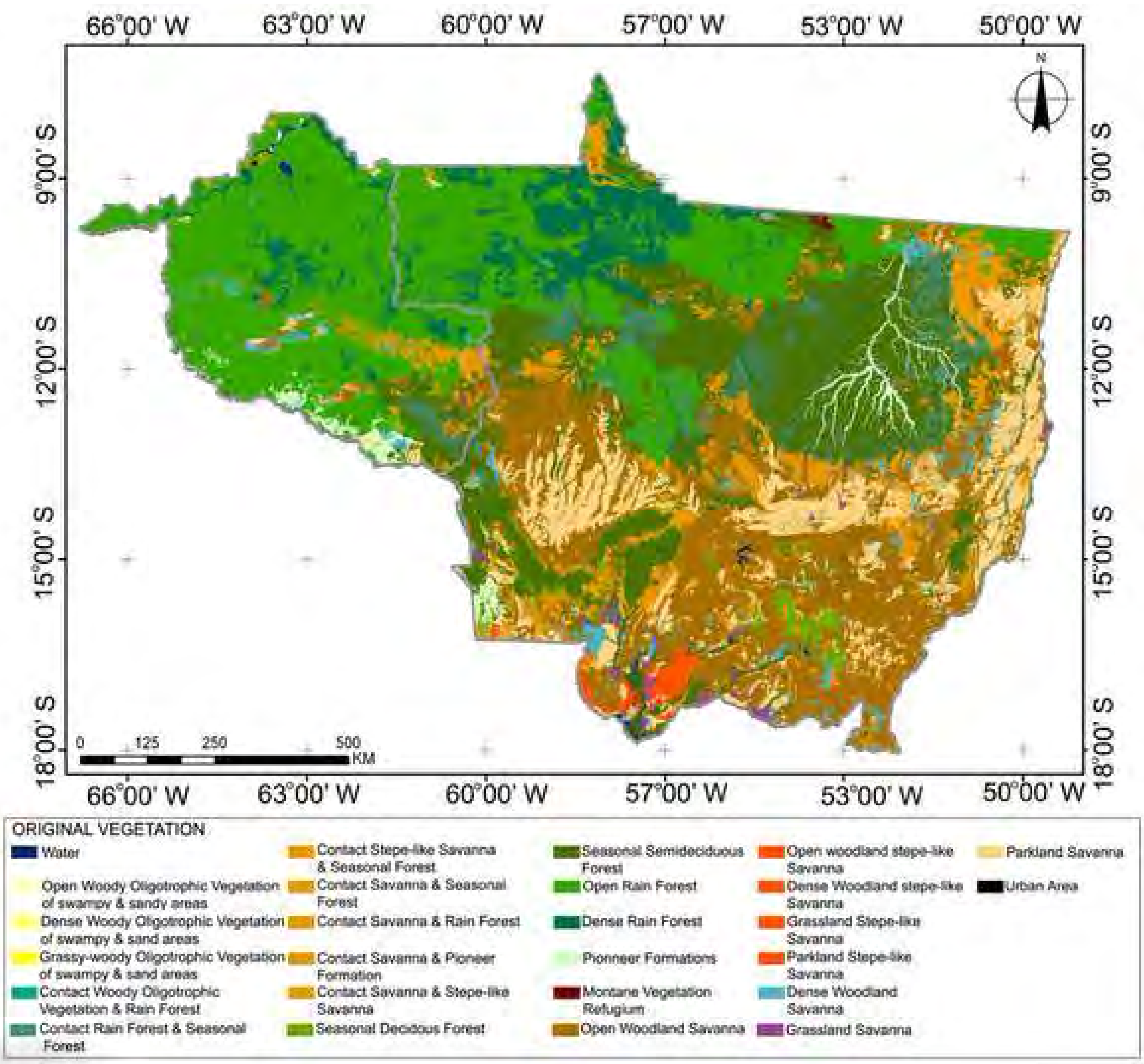

Figure-3
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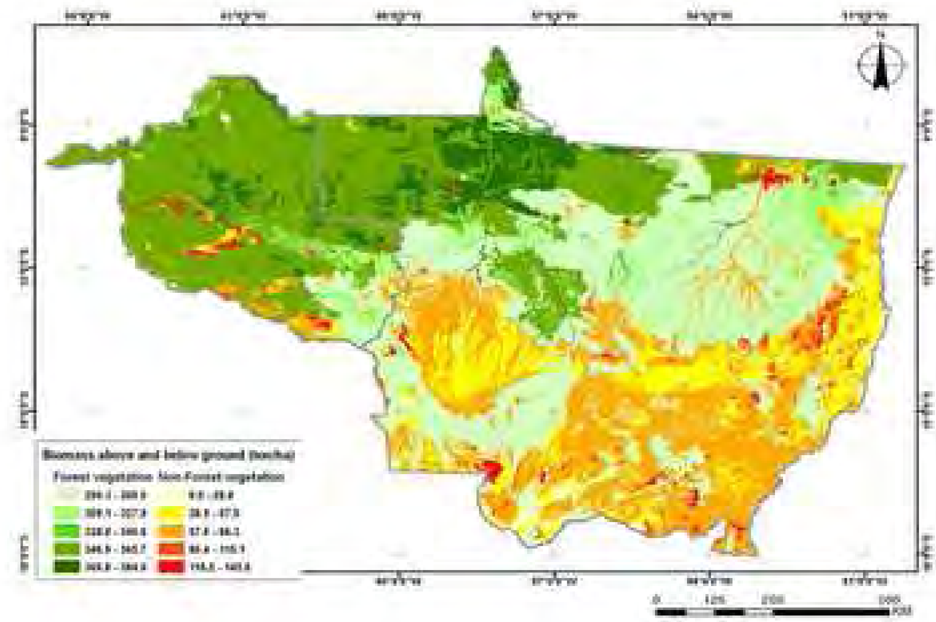

Figure-4

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