Gross Primary Production Variability in the Amazon River Basin based on 2009-2011 MOD17A2 MODIS data

Diógenes Salas Alves, Mariane Souza Reis, David Guimarães Monteiro França, Laura Barbosa Vedovato, João Arthur Pompeu Pavanelli [1]

[1] Instituto Nacional de Pesquisas Espaciais - INPE
Caixa Postal 515 - 12227-010 - São José dos Campos - SP, Brasil
{dalves, reis}@dpi.inpe.br, {jpompeu, laurabv, davidgmf}@dsr.inpe.br

Abstract. This paper presents a preliminary analysis of Gross Primary Production (GPP) for the Amazon River basin based on the MODIS MOD17A2 product for a 24-month period including an El Niño-La Niña transition. Monthly 0.05-degree resolution MOD17A2 data from June 2009 thru May 2011 were used to produce GPP estimates for the globe, for the Amazonian basin, and, within the basin, for Brazilian Amazon forests. Annual GPP was estimated to be 111.8×10^9 MgC year^{-1} for global terrestrial ecosystems, 14.8×10^9 MgC year^{-1} (13.2% of the global GPP) for the Amazon River basin, and 7.6×10^9 MgC year^{-1} (6.7% of the global value) for the basin's forests in Brazil. Average monthly GPP was estimated to be $1{,}23 \times 10^9$ MgC month^{-1} for the basin, and 0.63×10^9 MgC month^{-1} for the basin's forests in Brazil. Analysis of GPP spatial variability indicated that GPP declined with increasing elevation, with areas below 1,250 m accounting for nearly 95% of the basin's annualized GPP; also, forest variance at the monthly scale showed that GPP was more homogeneously distributed in forests than in the entire basin, where GPP variability would be affected by different factors like elevation, land cover, land use, and landscape patterns. Principal components analysis of the 24-month time series suggested a more important decline in forest GPP in the southern forests in comparison with the northern ones at the onset of the La Niña in mid-2010. Though preliminary, these results may help investigate how MODIS data might improve our understanding of primary production variability due to large scale events like the Southern Oscillations.

Keywords: Gross Primary Production, Earth Observing System, MODIS, Carbon Cycle, ENSO, principal componentes analysis
Palavras-chave: Produtividade Primária Bruta, Earth Observing System, MODIS, Ciclo do Carbono, ENSO, Análise de Componentes Principais

1. Introduction

Remote sensing from orbital platforms has evolved from an initial focus on the survey of Earth resources in the 1960-1970s (e.g. Mack 1990) to a broad area of technological innovation and interdisciplinary scientific research, where earth sciences, climate and environmental change represents one of the most significant fields of investigation, and of which NASA's Mission to Planet Earth (MTPE) and Earth Observing System (EOS) constitute major elements (e.g. Wilson and Huntress 1991, Tilford et al 1994, Lambright 1997). In this last field, the carbon cycle and the role of terrestrial and ocean ecosystems in this cycle is a crucial area of inquiry, because of the relationships between ecosystems production, succession and mortality and global climate change, and the many unknowns in these processes (e.g. Schimel et al 1994, Schimel 2001, Running et al 2004, Friend et al 2007, Yuan et al 2010, Zhao et al 2005).

EOS Moderate Resolution Imaging Spectroradiometer (MODIS) has played a significant part in the investigation of ecosystems functioning, most particularly in estimating and modeling Gross and Net Primary Production (e.g. Running et al 2004, Yuan et al 2010, Zhao et al 2005). MODIS data have been systematically processed and combined with meteorological to generate MODIS products that can be obtained at different spatial and temporal resolutions (MODIS Data Products Table, MODIS GPP/NPP Project (MOD17)).

In this paper, monthly 0.05-degree resolution MOD17 GPP imagery was used to assess Gross Primary Production for the Amazon River Basin for the 24-month period from June

2009 thru May 2011, which included an El Niño-La Niña transition. Our goals were, first, to understand the region's contribution to global GPP, and, second, to make a preliminary assessement of GPP variability within a period where El Niño and La Niña events succeeded each other.

2. Data and Methods

MODIS products were obtained from the Numerical Terradynamic Simulation Group at the University of Montana (MODIS NTSG Products a, b). The GPP product MOD17A2 (MODIS NTSG Products a) consisted of monthly 0.05-degree global images for the June-2009-May-2011 period, which were the basis to evaluate both Amazonian GPP in comparison to global production, and intraannual GPP variability in the Amazon. The MODIS land cover product MOD12Q1 (MODIS NTSG Products b) was also used as a reference of vegetation types.

MOD17A2 GPP estimation takes as its input Photosynthetically Active Radiation (FPAR), Leaf Area Index (LAI), and land cover MODIS products, as well as temperature, incoming solar radiation, and water vapor deficit obtained from different NASA and NCAR datasets, and incorporates improved interpolation of meteorological data input and with temporal filling of cloud-contaminated data (MODIS NTSG Products a, Zhao e al 2005).

LBA-ECO datasets provided data on the limits for the Amazon river basin (Costa et al 2011), and elevation data (Saatchi 2013). The area of the Amazon River basin represented 5.98×10^6 km^2, including 2.96×10^6 km^2 of forests in Brazil (Figure 1). Elevation data presented a mean elevation of 406 m (maximum value 5656 m, standard deviation 750 m) in the basin, and 161 m (maximum value 2271 m, standard deviation 123 m) in the basin's forests in Brazil.

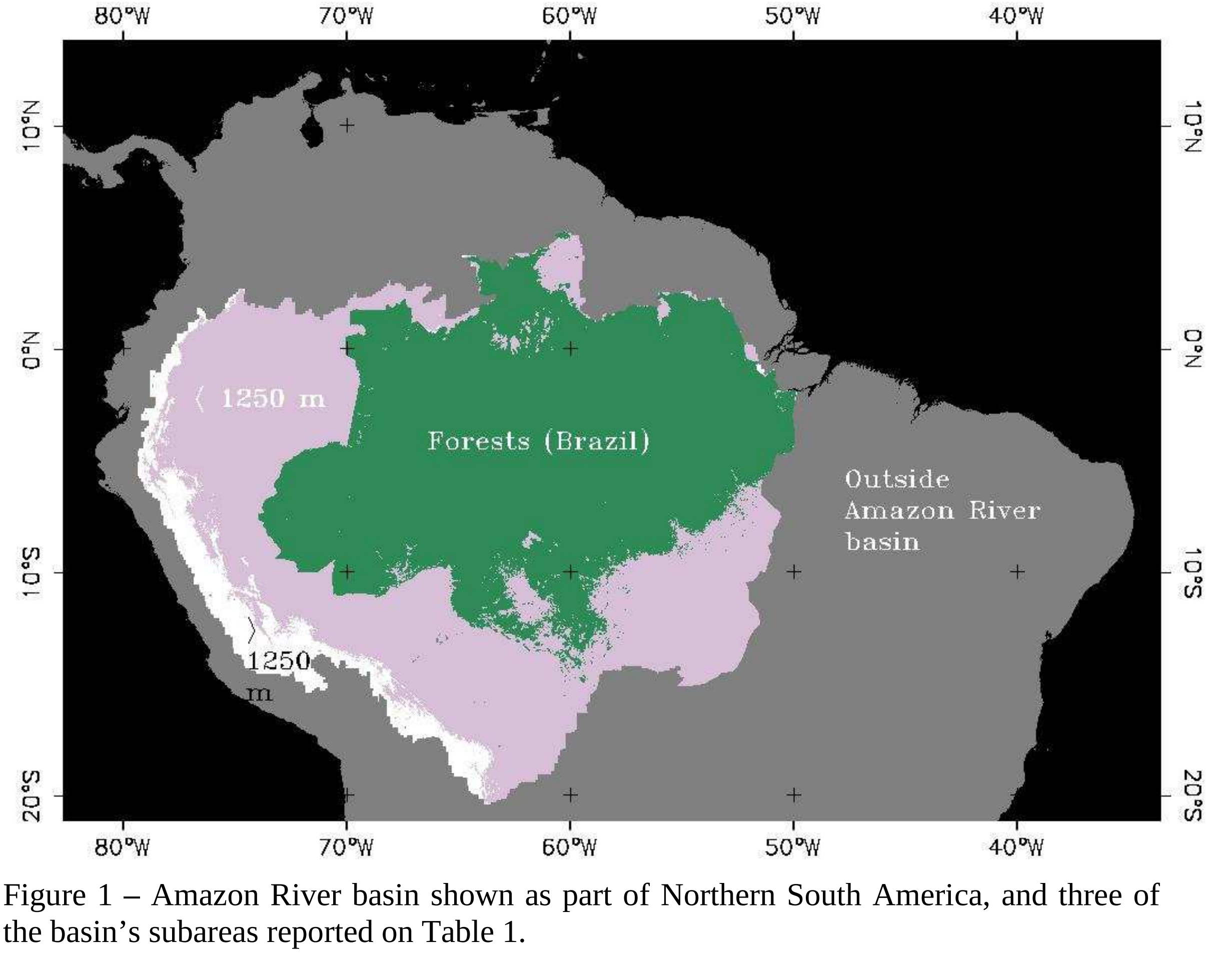


Figure 1 – Amazon River basin shown as part of Northern South America, and three of the basin's subareas reported on Table 1.

An estimate of the area of different vegetation types within the Amazon river basin was obtained by overlaying the MOD12Q1 land cover map (MODIS NTSG Products b) and Amazon river basin limits from Costa et al (2011), showing 86.6% of evergreen broadleaf forests, 6.23% of savannas, 2,7% of grasslands, 2% of open shrublands, 1.5% of woody savannas, 0.7% of deciduous broadleaf forest, and 0.3% of croplands. These statistics were used only as a reference for land cover class distribution in what concerns the MOD17A2 production (MODIS NTSG Products a); more detailed analysis would need to consider that a preliminary evaluation suggested that MOD12A2 may underestimate areas of deciduous/semi-decidous forests, pastures and agriculture.

The 24-month GPP image time-series were organized as a simple database, which provided basic functionalities to organize the time-series of global, basin, and Brazilian forest GPP data, estimate the summary GPP statistics reported in the next section, calculate GPP principal components, and run a number of classification algorithms.

Principal components were calculated mainly to reduce data dimensionality to make an exploratory analysis of possible patterns in GPP variability. This analysis was performed by calculating the principal components of the 24-month GPP time-series for both the basin and the forest area, and then running unsupervised and supervised classifications algorithms on the 3 components amassing the largest fractions of total variance (i.e. for the 3 components corresponding to the 3 largest eigenvalues). After classification, GPP monthly variation was analyzed for individual clusters, and those clusters showing most notable differences were retained to be reported.

3. Results and Discussion

Average MOD17A2 gross primary production during the period of study was estimated to be of $1.23x10^9$ MgC $month^{-1}$ or $14.8x10^9$ MgC $year^{-1}$ for the Amazon River basin, while the basin's forests in Brazilian Amazon accounted for $0.63x10^9$ MgC $month^{-1}$ or $7.6x10^9$ MgC $year^{-1}$. Forest areas in Brazil (Figure 1) represented nearly half of the basin's area, and contributed to nearly half of the basin's GPP during the entire period of study (Figure 2.a, Table 1). At the same time, average monthly forest GPP per unit area was within 93-112% of that of the entire basin, while its standard deviation was always smaller –within 27-76%, median value 56% - than that of the entire basin (Figure 2.b), indicating that GPP spatial variability was more important in the basin as a whole than within the basin's forests in Brazil.

Our GPP estimates also showed that the Amazon River basin and the Brazilian forests have responded, respectively, for 13.2% and 6.7% of the annual global GPP estimated from the MOD17A2 product during the period of study, which amounted to some $111.8x10^9$ MgC $year^{-1}$. This global GPP estimate was comparable to the 110 $x10^9$ MgC $year^{-1}$ reported by Yuan et al (2010) for the 2000-2003 period, although the $2x10^3$ gC m^{-2} $year^{-1}$ reported by these authors for the humid forests is considerably smaller than the $2.45x10^3$ gC m^{-2} $year^{-1}$ and $2.54x10^3$ gC m^{-2} $year^{-1}$ that we found, respectively, for the basin and the basin's forests in Brazil. Our GPP estimates were also higher than those reported by Souza et al (2014) for a forest-cerrado transition in Mato Grosso ($1.74\text{-}1.93x10^3$ gC m^{-2} $year^{-1}$).

Although a detailed comparison between these estimates would be beyond the scope of this work, it could be noted that these differences may reflect some shortcomings in vegetation, FPAR, GPP, and other MODIS-derived estimates that have been addressed in the literature (e.g. Xu et al 2010, Yuan et al 2010, Cheng et al 2014, Maeda et al 2014, Zhang et al 2014). At the same time, it could be suggested that MOD17A2 estimates might be sufficiently consistent for comparisons among certain biomes, as in the case of the forest-cerrado transition (Souza et al 2014) and the Brazilian forests reported here, provided that other factors like land use, elevation, landscape patterns, or atmospheric conditions would not affect GPP estimation.

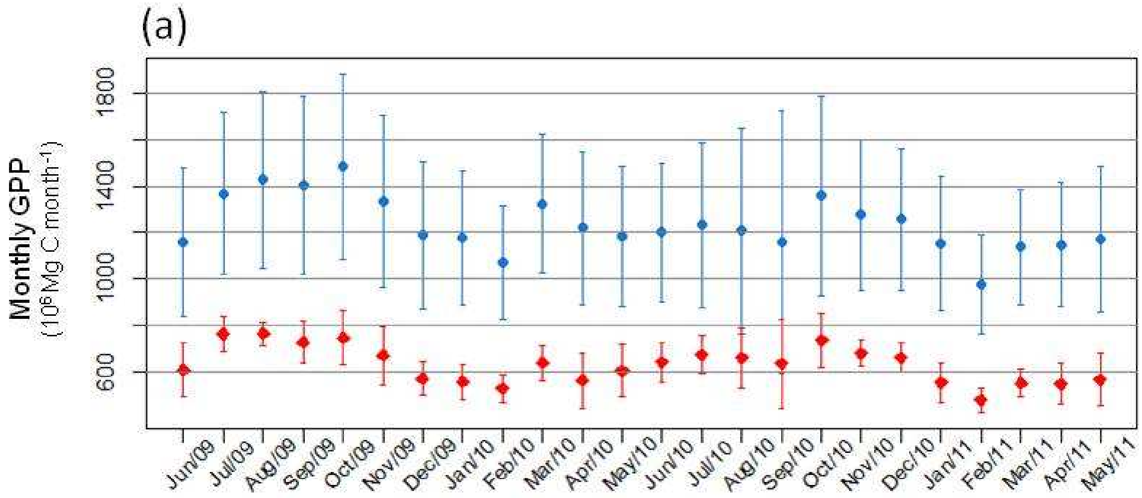
Inasmuch as the MOD17A2 product is a given for this work, and since detailed, reliable data on land cover and use are not available for the entire basin, the further analysis is restricted to using the LBA-ECO elevation dataset (Saatchi 2013) and the MOD12Q2 land cover product for an initial, preliminary stratification of GPP for some areas.

By stratifying our GPP estimates by elevation (Table 1), we found that more than 95% of the basin's gross primary production occurred below 1,250 m (Figure 1, Table1), where 90% of the area are classified as forests on the MOD12Q1 land cover product (MODIS NTSG Products b). Conversely, areas above 1,250 m accounted for nearly 5% of the basin's GPP, with most of it probably occurring outside the 60% of shrublands and grasslands that cover the area according to the MOD12Q2 land cover product. It is important to consider that a more refined land cover and land use classification – unavailable at this time - would certainly allow to further refine GPP distribution among different ecosystems and land use systems.

Table 1. Contribution of the basin's forests in Brazil and of areas of varied elevation to total basin area (Area) and basin GPP (GPP), monthly GPP standard deviation median (MED) and the fraction of the total variance accumulated by the first 3 principal components calculated for the 24-month time-series.

Analysed Area	**Area** (%)	**GPP** (%)	**MED** (gC m^{-2} $month^{-1}$)	**Fraction of total variance**		
				1st PC (%)	1st+2snd PC (%)	1st+2nd+3rd PC (%)
Brazilian Forests	49.5	50.9	28.7	46.0	72.9	81.4
< 1250 m (excl. forests)	42.3	43.3	54.7	72.8	87.4	93.1
< 1250 m	93.0	95.1	47.3	56.8	78.2	88.5
< 1150 m	92.6	94.6	47.1	56.8	78.3	88.6
< 1050 m	92.2	94.2	47.0	56.7	78.4	88.6
< 950 m	91.8	93.7	46.9	56.6	78.4	88.6
< 750 m	90.8	92.5	46.5	56.3	78.5	88.7
< 500 m	87.7	89.5	45.1	54.7	77.9	88.4
< 400 m	83.7	85.7	44.5	53.1	77.1	87.9
> 1250m	7.0	4.9	86.7	91.7	96.2	97.5
All basin	100	100	53.3	65.4	82.1	90.6

Taking the median of the standard deviation of each monthly GPP estimate (Table 1, column MED) as a rough indication of spatial variability, we suggest that GPP from the basin's forests in Brazil was more homogeneously distributed in comparison with GPP from the entire basin; moreover, GPP would tend to be more heterogeneous with increasing elevation and in more varied mosaics of land covers and land uses, as is the case of the areas outside the Brazilian forests (Table 1). Although these suggestions might seem relatively obvious, it should be useful to consider them when exploring GPP variability in future studies.



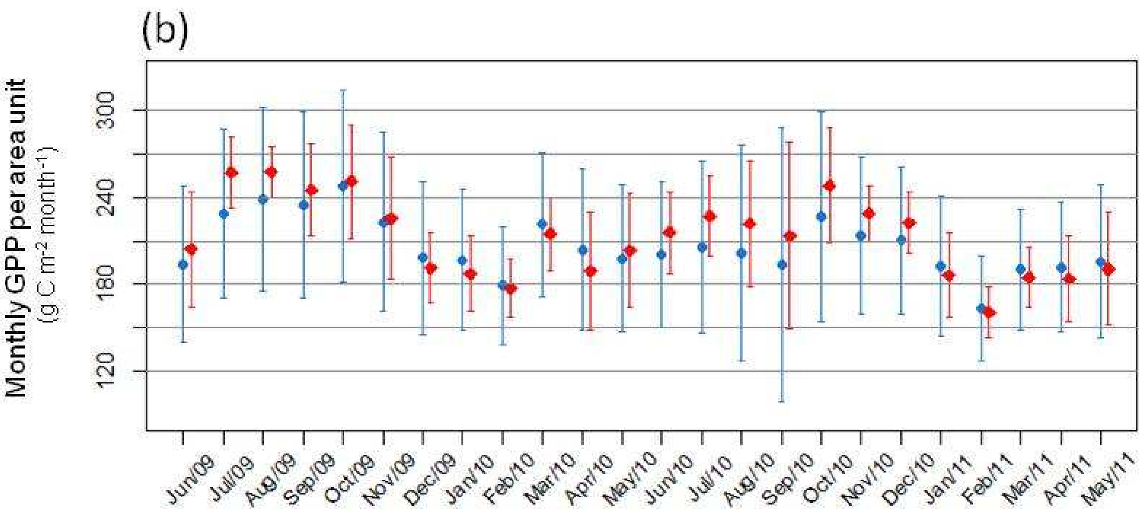


Figure 2 – Monthly Gross Primary Production (GPP) (a) and monthly GPP per area unit (b) for the Amazon River basin (blue) and the basin's forests in Brazil (red). Line segments show one standard deviation around the GPP means by the markers.

Introducing the temporal dimension into the analysis makes it more difficult as it becomes more complex to identify regions in which production varies over time. An exploratory analysis based on the calculation for the principal components (PC) for the time series showed, iniatially, that the basin's forests in Brazil accumulated relatively smaller fractions of the total variation in the first 3 components in comparison with the basin (Table 1). Still, the spatially more homogeneous forests seemed to produce more easily interpretable PC color composites (Figure 3.a) than the more heterogeneous areas outside the Brazilian forests (Figure 3.b), suggesting that the forest's first 3 principal components might allow to identify areas of different intraannual variability more easily than for the more heterogeneous basin areas. In fact, by testing different supervised and unsupervised algorithms, we found a relatively persistent pattern of classes differentiating the northern parts of the Brazilian forests from the southern parts (Figure 3.c, 3.d). After analyzing different classification results and

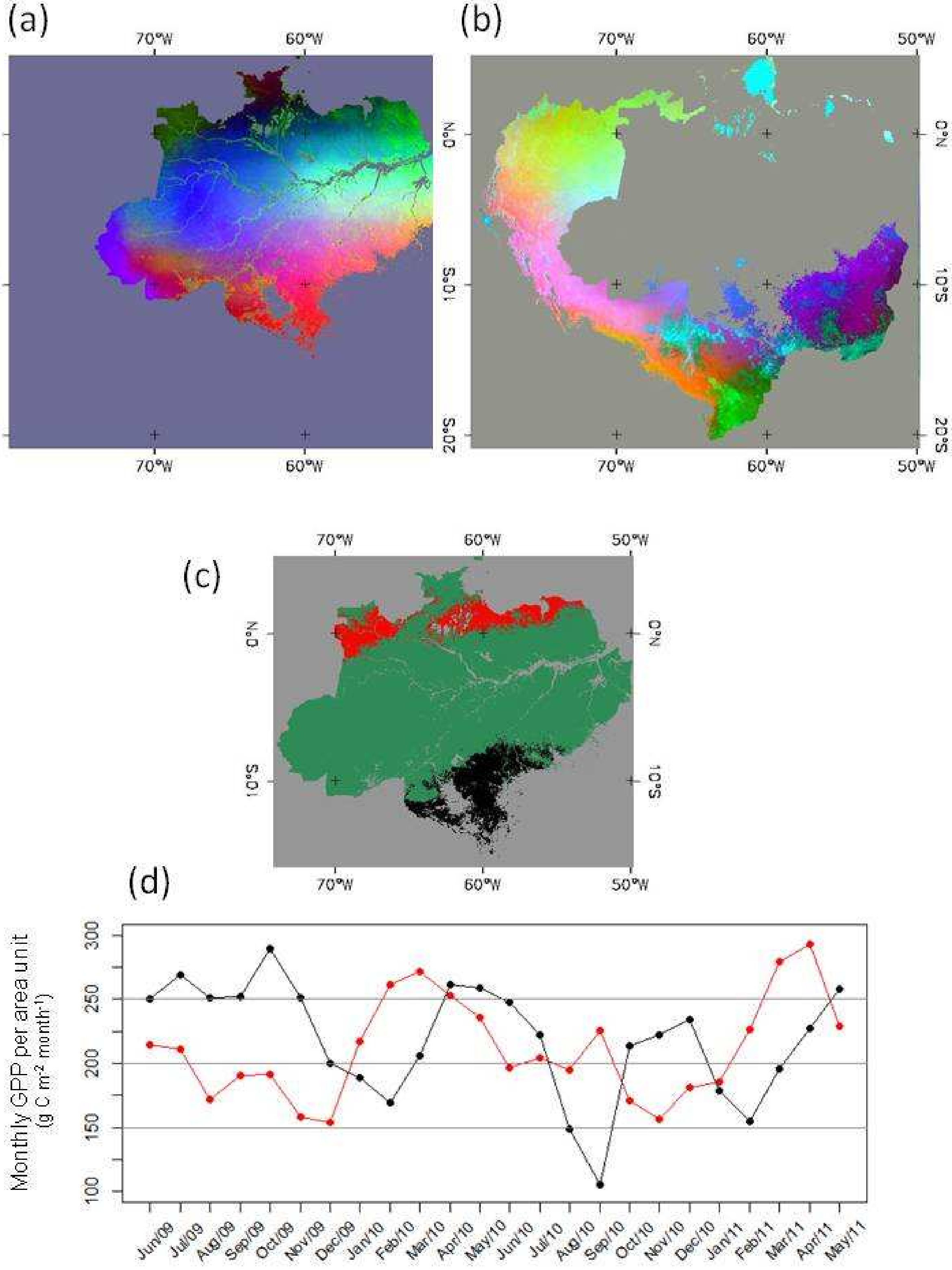


Figure 3 – First 3 principal components (PC) for Amazon River forests in Brazil (a) and for areas below 1,250 m outside Brazilian forests (b) (color composites: PC1 (R), PC2 (G), PC3 (B)). Red and black areas on (c) were obtained by classification of (a) and their corresponding monthly GPP are shown on (d).

calculating GPP estimates for the classes, we suggest that GPP in the southern parts of the Brazilian forests might have suffered a more significant impact from the transition into La Niña in mid 2010 or from the manifestation of the severe 2010 drought reported for the same period (Xu et al 2011). Although these results are preliminary, we suggest that they are worth of further investigation; also, we would argue that investigating the effects of GPP temporal variability in areas which are more homogeneous in space, might be a valid abductive strategy.

4. Conclusion

GPP estimates for the Amazon River basin and for the basin's forests in Brazil indicated that these regions account for a considerable fraction of the global GPP, and that a large part of GPP corresponds to areas of less important elevation, possibly by those covered by forests. An exploratory analysis of principal components data also suggested that the onsetting of La Niña in mid-2010 may have been associated with a more important decline in GPP in the southern forests than in the northern ones.

It seems relevant to recognize that the spatial and the temporal variability of GPP may be influenced by several factors related to the basin's large area, its latitudinal and longitudinal width, and elevation gradient, its different ecosystems, agricultural systems and land management practices. Also, it is important to notice that analyses of GPP variability for different ecosystems, land use systems, and, in general, for varied physical conditions, are particularly difficult for the Amazon basin due to the scarcity of reliable, spatially explicit data.

The results presented here should be considered as preliminary, in particular, because the analysis was restricted to using the MOD17A2 GPP product, which were analyzed in combination with the LBA-ECO elevation dataset (Saatchi 2013) and the MOD12Q2 land cover product for an initial, preliminary stratification of GPP for some areas. To conclude, we might consider that improving the understanding of both GPP spatial and temporal variability and of the characteristics of MODIS products might considerably benefit from including more detailed and reliable data allowing for the characterization of different biomes, land use systems, and land management practices occurring in the Amazon.

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