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ESTIMATION OF GROSS PRIMARY PRODUCTION OF THE AMAZON-CERRADO TRANSITIONAL FOREST BY REMOTE SENSING TECHNIQUES

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ABSTRACT

The gross primary production (GPP) of ecosystems is an important variable in the study of global climate change. Generally, the GPP has been estimated by micrometeorological techniques. However, these techniques have a high cost of implantation and maintenance, making the use of orbital sensor data an option to be evaluated. Thus, the objective of this study was to evaluate the potential of the MODIS (*Moderate Resolution Imaging Spectroradiometer*) MOD17A2 product and the vegetation photosynthesis model (VPM) to predict the GPP of the Amazon-Cerrado transitional forest. The GPP predicted by MOD17A2 (GPP_{MODIS}) and VPM (GPP_{VPM}) were validated with the GPP estimated by eddy covariance (GPP_{EC}). The GPP_{MODIS}, GPP_{VPM} and GPP_{EC} have similar seasonality, with higher values in the wet season and lower in the dry season. However, the VPM performed was better than the MOD17A2 to estimate the GPP, due to use local climatic data for predict the light use efficiency, while the MOD17A2 use a global circulation model and the lookup table of each vegetation type to estimate the light use efficiency.
Keywords: semi-deciduous forest, VPM model, remote sensing and net CO_2 exchange.

RESUMO: ESTIMATIVA DA PRODUTIVIDADE PRIMÁRIA LÍQUIDA BRUTA DA FLORESTA DE TRANSIÇÃO AMAZÔNIA-CERRADO POR TÉCNICAS DE SENSORIAMENTO REMOTO
A produtividade primária bruta (GPP) de ecossistemas é uma importante variável no estudo de mudanças climáticas globais. A GPP, geralmente, tem sido estimada por técnicas micrometeorológicas. No entanto, essas técnicas possuem elevado custo de implantação e manutenção, fazendo com que o uso de dados de sensores orbitais seja uma opção a ser avaliada. Sendo assim, o objetivo deste estudo foi avaliar a potencialidade do produto MODIS (*Moderate Resolution Imaging Spectroradiometer*) MOD17A2 e o modelo de fotossíntese da vegetação (VPM) para estimar a GPP de uma floresta de transição Amazônia-Cerrado. A GPP estimada pelo MOD17A2 (GPP_{MODIS}) e pelo VPM (GPP_{VPM}) foram validadas com a GPP estimada pelo método de correlação de vórtices turbulentos (GPP_{EC}). A GPP_{MODIS}, GPP_{VPM} e GPP_{EC} apresentaram sazonalidade similar, com maiores valores na estação chuvosa e menores na estação seca. No entanto, o VPM apresentou melhor desempenho do que o MOD17A2 em estimar a GPP, por utilizar dados climáticos locais para estimar a eficiência do uso da luz, enquanto que o produto MODIS utiliza um modelo de circulação global e uma tabela baseada no tipo de vegetação para estimar a eficiência do uso da luz.
Palavras-chave: floresta semidecídua, modelo VPM, sensoriamento remoto e troca líquida de CO_2.

1. INTRODUCTION

Tropical forests are important in the control of regional and global climate (Keller *et al*., 2004; Dalmagro *et al*., 2011). Brazil has one of the largest expanses of the Amazon forest in the world. According to Bernoux *et al*. (2002), only the Amazon forest is responsible for 20-25% of all global carbon storage. Conversion of forests to pasture and crops has altered the carbon cycle in the region, thus it is necessary to understand the impact of anthropogenic activity and climate changes on ecosystem functioning (Vourlitis *et al*., 2011).

Located 50 km far from Sinop city, northwest of Mato Grosso State, we feature an Amazon-Cerrado transitional forest. This forest is 423 m above sea level and is located in a region known as the "arc of deforestation". The forest transition or ecotone, as it is also known, is described as two distinct vegetation that interpenetrate, but each one keeps its own characteristics. Transition forests have a CO_2 exchange close to zero due to carbon sink during the wet season and release carbon during the dry season (Vourlitis *et al.*, 2002, 2004). However, this balance can be altered with climate change (Dalmagro *et al.*, 2011).

The study of net ecosystem exchange (NEE) and gross primary production (GPP) provide important information about the environment, as the critical component of the global carbon cycle is the vegetation, mainly due to photosynthesis, which regulates this flux of carbon between the biosphere and atmosphere. The study of carbon flux variation over a time series is very useful to provide the knowledge of possible factors that influence the carbon cycle or even make future estimates (Stagakis *et al*., 2007). Several methods to measure the carbon flux of a vegetated surface are used. The eddy covariance technique is a key atmospheric measurement technique to measure and calculate the carbon flux within atmospheric boundary layers (Albinet *et al*., 2012). This technique has been exhaustive used to monitoring the forest carbon exchange (Santos e Costa, 2003; Baldocchi, 2003; Aguiar *et al*., 2006). However, in some cases, this technique can be impractical because its operating costs and its little representation for heterogeneous locals.

The use of field data integrated with satellite data has become a powerful tool for obtaining information which allow studies of the carbon ecosystem exchange. Studies relying on satellite-based remote sensing indicate that canopy greenness in the Amazon forest is negatively correlated with precipitation patterns with increased greenness and higher productivity occurring during the dry season (Huerte *et al.*, 2006; Myneni *et al*., 2007). In addition, flux tower measurements indicate that the canopy greening that occurs during the dry season is associated with the net primary production (NPP) and evapotranspiration (ET) increase during the dry season (Hutyra *et al*., 2007). This variability pattern is the opposite of observed in several studies and ecosystem model predictions, that overall, seasonal drought causes a decline in productivity (Saleska *et al*., 2003; Samanta *et al*., 2010; Zhao and Running, 2010). Such opposite's results highlight the complex interaction between drought, phenology and ecosystem productivity (Saleska *et al*., 2009).

In this study we combined analyses of satellite images with field data from a CO_2 flux tower site of semi-deciduous forest in the Amazon Basin. In general, many current models of ecosystem carbon exchange based on remote sensing require considerable input from ground-based meteorological measurements and lookup tables based on vegetation types (Wu *et al*., 2010), such as the Moderate Resolution Imaging Spectroradiometer (MODIS) product termed MOD17A2 (Turner *et al*., 2006; Silva *et al*., 2013). Recently, the vegetation photosynthesis model (VPM) was developed (Xiao *et al*., 2004a,b) to predict light absorption by chlorophyll and GPP of terrestrial ecosystems, based on the concept that vegetation canopy is composed of chlorophyll and non-photosynthetically active vegetation. The potential of the VPM for predict GPP has been evaluated by estimates of GPP in flux towers sites in temperate deciduous broadleaf forest (Xiao *et al*., 2004a,b; Wu *et al*., 2010), seasonally moist tropical forest (Xiao *et al*., 2005), and croplands (Li *et al*., 2007; Wang *et al*., 2010). However, the VPM has not been evaluated and applied in semi-deciduous forest in the Amazon Basin. Furthermore, these studies have used a fixed light use efficiency to predict GPP. Here, we evaluate the potential of MOD17A2 and VPM to estimate the GPP of the Amazon-Cerrado transitional forest.

2. MATERIAL AND METHODS

2.1 Description of experimental area

This study was conducted between July 2005 and May 2008, 50 km from Sinop, Mato Grosso State, Brazil, in the Maracaí Farm. On site, there was a micrometeorological tower of 42 m height, coordinates 11° 24' 43.4'' S and 55° 19' 25.7'' W, altitude of 435 m above sea level (Figure 1). The climate is classified as Aw, according to Köppen (Kottek *et al*., 2006), with a dry season from May to September and a wet season from October to April (Vourlitis *et al*., 2011). The average annual temperature is 24ºC and the average annual rainfall is 2037 mm (Vourlitis *et al*., 2002). The region is an Amazon-Cerrado transitional forest, defined as tropical semideciduous forest, with trees around 25-28 m height. The leaf area index (LAI) varies from 5-6 m^2m^{-2} in the wet season and 2-2.5 m^2m^{-2} in the dry season (Vourlitis *et al*., 2002; Sanches *et al*., 2008) and the soil was classified as a sandy soil.

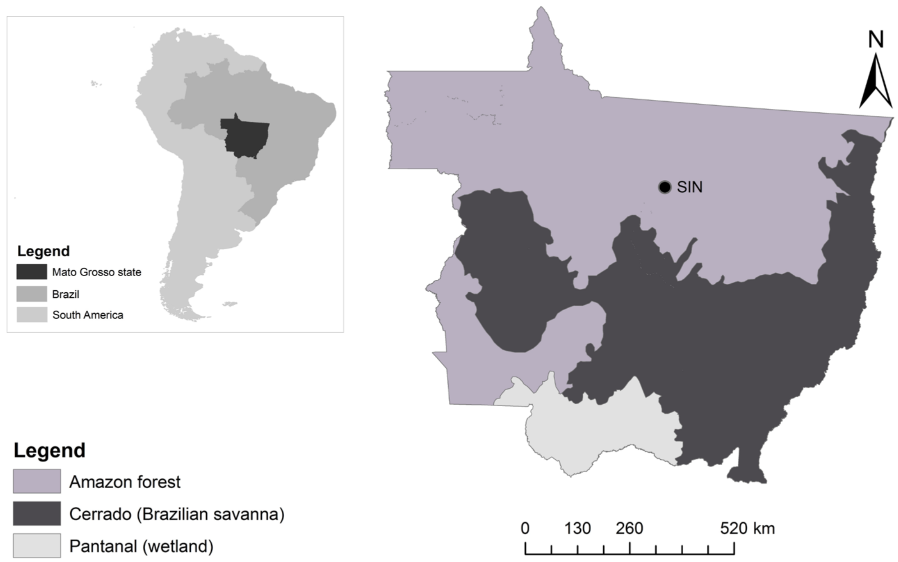

Figure 1 - Location of micrometeorological tower in the Amazon-Cerrado transitional forest.

2.2 Instrumentation used

The photosynthetically active radiation was measured using a quantum sensor (LI-190SB, LI-COR, Lincoln, NE, USA) at 40 m height. The air temperature and relative humidity were measured by a thermohygrometer (HMP-45 C, Vaisala, Inc., Helsinki, Finland) also at 40 m height. The fluctuation of the three-dimensional wind speed was measured by a sonic anemometer (CSAT-3, Campbell Scientific, Inc., Logan, UT, USA) and the carbon dioxide concentration fluctuating was measured by an infrared gas analyzer (LI-7500 , LI-COR, Inc., Lincoln, NE, USA), both installed at 42 m height. The data signals produced by the transducers were processed at a frequency of 10 Hz and stored every 30 minutes by a datalogger (CR5000, Campbell Scientific, Inc., Logan, UT, USA). The rainfall was obtained daily in Farm Maracaí by a pluviometer located 5 km southwest of micrometeorological tower.

2.3 Eddy covariance method

The data series used in this study was collected from July 2005 to June 2008. The GPP was measured by the eddy covariance method. This method is most appropriate for studying of physical phenomena in forests because the carbon exchange occurs turbulently (Aguiar, 2006). The infrared gas analyzer was installed at the wind direction approximately 5 cm of sonic anemometer to minimizing the effect of separation of sensors, and with an inclination of 20° to prevent water accumulation. The sensors were oriented at the predominant wind direction to minimize estimating distortions. The predominant wind direction was SSW-SW.

The raw data and CO_2 flux were stored and processed by a datalogger (CR5000, Campbell Scientific, Inc., Logan, UT, USA). The average CO_2 flux was calculated by the covariance between the vertical wind speed fluctuations and CO_2 concentration fluctuations. The estimated CO_2 flux was corrected by simultaneous heat fluctuation (Webb *et al*., 1980). The GPP was calculated hourly as the sum of the estimated CO_2 flux and the canopy CO_2 storage (Grace *et al*., 1996). The canopy CO_2 storage was determined by quantifying the CO_2 rate in the air column between the ground and sensors (Vourlitis *et al*., 2011). The CO_2 concentrations were measured using a closed-path infra-red gas analyzer (LI -820, LI-COR, Inc., Lincoln, NE, USA) at 1, 4, 12, 20 and 28 m above ground level and a diaphragm pump and a solenoid switching system. The estimated GPP (gC m^{-2} day^{-1}) by the eddy covariance method was calculated using the equation:

$$GPP = NEE + R \quad (1)$$

where *NEE* is the net ecosystem exchange (gC m^{-2} day^{-1}) and R is the ecosystem respiration (gC m^{-2} day^{-1}) (Wohlfarhrt *et al*., 2005). The *GPP* and *R* were calculated half-hourly and integrated for each day. The *R* of each half-hour was calculated as the average of first four hours of the day of the *NEE*, assuming zero CO_2 assimilation during this period (Vourlitis *et al*., 2011).

2.4 MODIS 8-day surface reflectance product

The MODIS is a sensor aboard the Terra and Aqua satellites, acquiring data in 36 spectral bands ranging from 450 nm to 2100 nm. Of these 36 spectral bands, seven bands of them were designed for the study of vegetation and land surface:

blue (459-479 nm) – band 3, green (545-565 nm) – band 4, red (620-670 nm) – band 1, near-infrared NIR (841-875 nm, 1230-1250 nm) – band 2 and 5, and short wave infrared SWIR (1628-1652 nm, 2105-2155 nm) – band 6 and 7. The MODIS Land Science Team provides several data products derived from MODIS data, including the 8-day compose Land Surface Reflectance (MOD09A1). The MOD09A1 datasets include seven spectral bands mentioned above, at a spatial resolution of 500 m, corrected for the effects of atmospheric gases, aerosols, and thin cirrus clouds.

We obtained the land surface reflectance data (MOD09A1) based on the geo-location information (latitude and longitude) of eddy covariance flux tower in the Amazon-Cerrado transitional forest from July 2005 to February 2008. The data are published by the EROS Data Center Active Archive Center (EDC Daac). As noise in vegetation index should be low and the distance between the tower and the edge of the forest is greater than 5 km, we used a 3x3 pixel group as a guarantee of high quality metric (QA). Land surface reflectance values were average for the nine pixels partially covering the eddy flux tower, and only the pixel with highest quality assurance metrics were used. However, varying sensor viewing geometry, cloud presence, aerosols and bidirectional reflectance can limit the efficacy of reflectance data for assessing spatial-temporal dynamics in biophysical processes (Hird and McDermid, 2009), and signal extraction techniques are often needed to improve the signal-noise ratio (Hermance *et al*., 2007). Thus, we applied Singular Spectrum Analysis (Zeilhofer *et al*., 2011), using the CatMV software (Golyandina and Osipova, 2007), which is particularly effective for the filtered reconstruction of short, irregularly spaced, and noisy time series (Ghil *et al*., 2002; Golyandina and Osipova, 2007) to improve the signal-noise ratio of the MODIS land surface reflectance.

2.5 MODIS 8-day gross primary production product

The Gross Primary Production product (MOD17A2) is designed to provide regular measure of the growth of terrestrial vegetation based on the light-use efficiency (LUE) concept using daily MODIS land cover, FPAR/LAI and surface meteorology at 1 km for the global vegetated land surface (Turner *et al*., 2006). The product is calculated using the equation:

$$GPP = \varepsilon_{max}.m(T_{min}).m(VPD).FPAR.SWrad.0.45 \quad (2)$$

where ε_{max} is the maximum LUE obtained from lookup table on the basis of vegetation type, $m(T_{mim})$ and $m(VPD)$ are the scalers to reduce ε_{max} under unfavorable conditions of low temperature and high vapor pressure deficit (*VPD*), *FPAR* is the Fraction of Photosynthetically Active Radiation absorbed by the vegetation and SW_{rad} is shortwave radiation. As the MOD09A1, we used a 3x3 pixel group of MOD17A2 as a guarantee of high quality metric (QA).

2.6 Vegetation index

Land surface reflectance values from blue (ρ_{blue}), red (ρ_{red}), near-infrared (ρ_{nir}) and short wave infrared (ρ_{swir}) were used to calculate the Enhanced Vegetation Index (EVI, Huete *et al*., 1997) and the Land Surface Water Index (LSWI) (Xiao *et al*., 2004a). The LSWI was proposed by Xiao *et al*. (2002). EVI has been used for characterizing the seasonal variation of temperate forest (Xiao *et al*., 2004a,b) and tropical forest (Xiao *et al*., 2005; Vourlitis *et al*., 2011). EVI (Equation 3) includes the blue band for atmospheric correction, and it works well in accounting for residual atmospheric contamination (e.g. aerosols), variable soil, and canopy background reflectance (Huete *et al*., 1997). EVI directly normalizes the reflectance in red band as a function of the reflectance in blue band.

$$EVI = 2.5\frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + 6\rho_{blue} - 7.5\rho_{red} + 1} \quad (3)$$

As the short infrared (SWIR) spectral band is sensitive to vegetation water content and soil moisture, a combination of NIR (band 2) and SWIR (band 6) have been used to derive water sensitive vegetation indices (Equation 4). The SWIR absorption increases and SWIR reflectance decreases as the leaf liquid water content increases or soil moisture increases, resulting in an increase of LSWI.

$$LSWI = \frac{\rho_{nir} - \rho_{swir}}{\rho_{nir} + \rho_{swir}} \quad (4)$$

2.7 Vegetation photosynthesis model (VPM)

The GPP_{VPM} estimated by the VPM model (Equation 5) is a function of incident photosynthetically active radiation (PAR) (mol m^{-2} s^{-1}), light use efficiency ε_g (Equation 7; gC $molPAR^{-1}$) and fraction of absorbed PAR by chlorophyll (FPAR) in the vegetation canopy (Vetrita *et al*., 2011):

$$GPP = \varepsilon_g.FPAR.PAR \quad (5)$$

In this study FPAR (Equation 6) was assumed to be a linear function of EVI (Equation 3), and the coefficient α was simply set to be 1.0 (Xiao *et al*., 2004a,b; Xiao *et al*., 2005; Wang *et al*., 2010).

$$FPAR = \alpha.EVI \quad (6)$$

The ε_g (Equation 6) is a challenging variable to be determined at a global scale (Wu *et al*., 2010) because it is often measurable meteorological variables representing canopy stresses, such as temperature and water content (Running *et al*., 2004).

$$\varepsilon_g = \varepsilon_o . T_{esc} . W_{esc} . P_{esc} \quad (7)$$

where ε_0 is the maximum light use efficiency (gC molPAR^{-1}) and T_{esc} , W_{esc} and P_{esc} are down-regulation scalars, ranging between 0 and 1, for the effects of temperature (Equation 8), water (Equation 9), and leaf phenology (Equation 10) on light use efficiency of vegetation, respectively:

$$T_{esc} = \frac{(T - T_{min})(T - T_{max})}{[(T - T_{min})(T - T_{max})] - \left(T - T_{opt}\right)^2} \quad (8)$$

$$W_{esc} = \frac{1 + LSWI}{1 + LSWI_{max}} \quad (9)$$

$$P_{esc} = \frac{1 + LSWI}{2} \quad (10)$$

where T is the air temperature at 40 m at each time step (ºC), and T_{min}, T_{max} and T_{opt} are the minimum, maximum and optimal air temperature for photosynthetic activities (ºC), respectively. If air temperature falls below T_{min}, T_{scalar} is set to zero. $LSWI_{max}$ is the maximum $LSWI$ within the plant growing season for individual pixels.

Semi-deciduous trees in the tropical zone have a green canopy throughout the year because foliage is retained for several growing seasons. Canopies of semi-deciduous forests are thus composed of green leaves of various ages. In this study, a simple assumption of P_{scalar} set to 1, similar to the assumption used for evergreen broadleaf forest (Xiao *et al*., 2005).

2.8 Analysis of the model parameters

Some of the factors that control vegetation productivity are the amount of green biomass, chlorophyll concentration and some environmental parameters that may affect photosynthesis, e.g., light, air temperature and water availability in the system. To estimate the GPP by VPM model according to the MODIS data and local climate data, we estimated the ε_o , T_{min} , T_{max} ,T_{opt} and $LSWI_{max}$.

2.8.1 Estimation of maximum light use efficiency

According to Pinheiro (1994), 55% of solar energy is not used for photosynthesis due to light loss by reflection and transmission to the ground. The concept of light use efficiency (LUE) was proposed by Monteith (1972) and its application brought contributions to the concepts of the carbon sink processes by vegetation.

The value of light use efficiency need to be strictly calibrated, because it has great impact on the model, beyond it is a factor that varies according to each specific vegetation (Yang *et al*., 2007; Sims *et al*., 2008). The estimation of ε_0 is determined by the choice of the model, which can be linear or nonlinear (e.g., hyperbolic) (Xiao *et al*., 2004b). As proposed by the VPM model (Xiao *et al*., 2004a), we estimated the light use efficiency according to the Michaelis-Menten function:

$$NEE = \frac{\varepsilon_o . PAR . GPP_{max}}{\varepsilon_o . PAR + GPP_{max}} - R \quad (11)$$

where GPP_{max} is the maximum gross primary production (gC m^{-2} day^{-1}).

The VPM model proposes a fixed value for ε_0 (Xiao *et al*., 2004a). However, we consider the GPP dynamics and monthly estimate of ε_0 due to the amount of data.

2.8.2 Estimation of down-regulation scalars

The photosynthetic activity of plants is most effective within a certain air temperature range, and above or below this range the chemical reactions necessary for photosynthesis are inhibited (Xiao *et al*., 2004b). This range is large and varies from vegetation to vegetation. We estimated the T_{min}, as 2.0ºC, T_{max} as 48.0ºC and T_{opt}, as 28.0ºC, which is similar to the values found by Xiao *et al*. (2005) and Vetrita *et al*. (2011) for tropical forests.

To calculate W_{esc}, it was necessary to estimate $LSWI$ during the study period (Equation 3). The estimated value $LSWI_{max}$ was 0.38, which is consistent with the value found by Vetrita *et al*. (2011) in tropical forests.

3. RESULTS AND DISCUSSION

3.1 Seasonal and interannual analyses of estimated GPP by eddy covariance and meteorological data

The GPP estimate by eddy covariance (GPP_{EC}) did not differentiate one year following the other (Table 1), but the GPP_{EC} during 2007-2008 was 16% higher than during 2005-2006, showing an increasing trend during the three years. The GPP_{EC} had a seasonal cycle, and it was on average 28% higher in the wet season (Table 1). In the three years analyzed, the GPP_{EC} had similar dynamic, increasing gradually from July to November, whose peak was in November during 2005-2006, in January during 2006-2007, and 2007-2008 (Figure 2a).

The difference in annual and monthly GPP_{EC} mean can be explained by the dynamics of precipitation (Figure 2b), temperature and photosynthetically active radiation (PAR) (Figure 3). The GPP_{EC} had strongly correlated with rainfall (r = 0.64), and well-defined peaks in the wet season. The total annual rainfall during 2005-2006 and 2007-2008 was lower (60-100 mm) than the 30 years historical average of the study area

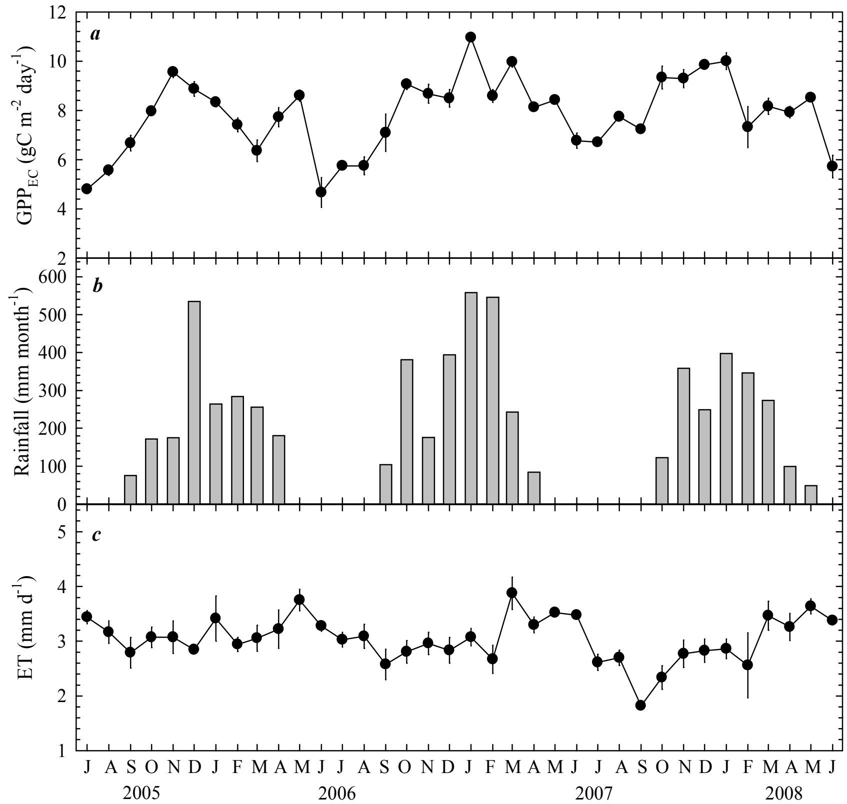

Figure 2 - (a) Average (±sd) monthly gross primary production estimated by eddy covariance (GPPEC), (b) total monthly precipitation and (c) Average (±sd) monthly evapotranspiration between July 2005 and June 2008.

Table 1 - Average (± Standard Deviation) air temperature (Air Temp. – °C), photosynthetically active radiation (PAR – µmol m^{-2} day^{-1}), fraction of absorbed PAR (FPAR), Land Surface Water Index (LSWI), Enhanced Vegetation Index (EVI), down-regulation scalars for the effects of temperature (Tesc) and water (Wesc), maximum light use efficiency (εo – gC µmolPAR^{-1}), light use efficiency (εg – gC µmolPAR^{-1}), Gross Primary Production estimated by eddy covariance method (GPP – gC m^{-2} day^{-1}), Gross Primary Production predicted by VPM model (GPPVPM – gC m^{-2} day^{-1}), Gross Primary Production predicted by MODIS product (GPPMODIS – gC m^{-2} day^{-1}) and precipitation (mm), calculated for annual, dry season, and wet season periods from 2005 to 2008.

	Annual			**Dry**			**Wet**		
	2005-06	**2006-07**	**2007-08**	**2005-06**	**2006-07**	**2007-08**	**2005-06**	**2006-07**	**2007-08**
Air Temp.	25.18±1.33	24.62±0.80	24.34±0.68	25.01±1.52	24.31±0.83	24.24±0.69	25.32±1.22	24.84±0.73	24.39±0.70
PAR	432.30±94.82	418.77±84.51	379.84±84.27	478.96±51.04	477.02±64.61	445.15±80.30	394.96±107.11	377.16±72.62	340.66±60.86
FPAR	0.894±0.008	0.886±0.020	0.883±0.023	0.893±0.007	0.892±0.009	0.889±0.011	0.894±0.009	0.881±0.025	0.880±0.028
LSWI	0.335±0.019	0.335±0.019	0.333±0.018	0.350±0.010	0.351±0.011	0.350±0.013	0.323±0.016	0.324±0.016	0.324±0.014
EVI	0.59±0,01	0.58±0,01	0.59±0,01	0.58±0,02	0.56±0,02	0.57±0,02	0.60±0,01	0.60±0,01	0.60±0,01
T_{esc}	0.987±0.016	0.994±0.007	0.995±0.003	0.988±0.016	0.995±0.004	0.996±0.003	0.986±0.017	0.993±0.009	0.995±0.002
W_{esc}	0.967±0.013	0.967±0.014	0.966±0.013	0.978±0.007	0.979±0.008	0.978±0.009	0.959±0.011	0.959±0.012	0.959±0.010
ε_o	0.028±0.014	0.0322±0.013	0.043±0.018	0.018±0.007	0.022±0.007	0.033±0.024	0.036±0.013	0.039±0.011	0.049±0.012
ε_g	0.017±0.008	0.020±0.008	0.027±0.011	0.012±0.004	0.014±0.0047	0.022±0.015	0.022±0.008	0.025±0.006	0.031±0.008
GPP_{EC}	7.32±1.49	7.97±1.45	8.87±1.46	6.18±1.29	6.93±1.18	7.98±1.62	8.24±0.92	8.72±1.16	9.40±1.12
GPP_{VPM}	6.30±1.74	7.13±1.86	8.37±2.14	5.05±1.45	5.94±1.36	7.36±2.44	7.30±1.27	7.97±1.72	8.97±1.79
GPP_{MODIS}	4.76±1.47	5.30±1.40	5.65±1.30	4.15±1.87	4.74±1.82	5.19±1.53	5.26±0.86	5.67±0.96	5.86±1.21
Ppt	1498.5	2100.6	1663.1	89.5	104	49	1409	2048.6	1638.6

Table 2 - Matrix of Pearson correlation of air temperature, photosynthetically active radiation (PAR), fraction of absorbed PAR (FPAR), Land Surface Water Index (LSWI), Enhanced Vegetation Index (EVI), maximum light use efficiency (εo), Gross Primary Production estimated by eddy covariance method (GPPEC), Gross Primary Production estimated by VPM model (GPPVPM), Gross Primary Production estimated by MODIS product (GPPMODIS) and precipitation.

	Air Temp.	PAR	FPAR	LSWI	EVI	ε_o	GPP	GPP_{VPM}	GPP_{MODIS}
PAR	0.025	1							
FPAR	0.016	0.105	1						
LSWI	0.004	0.667**	-0.103	1					
EVI	0.471*	-0.128	-0.164	0.054	1				
ε_o	-0.091	-0.785**	-0.159	-0.499**	0.112	1			
GPP_{EC}	-0.052	-0.468**	-0.235	-0.389*	0.253	0.828**	1		
GPP_{VPM}	-0.129	-0.420*	-0.176	-0.323	0.203	0.831**	0.984**	1	
GPP_{MODIS}	-0.455**	-0.376*	0.075	-0.636**	-0.407*	0.430*	0.439*	0.429*	1
Ppt	0.062	-0.626**	-0.108	-0.524**	0.472*	0.575**	0.498**	0.446**	0.190

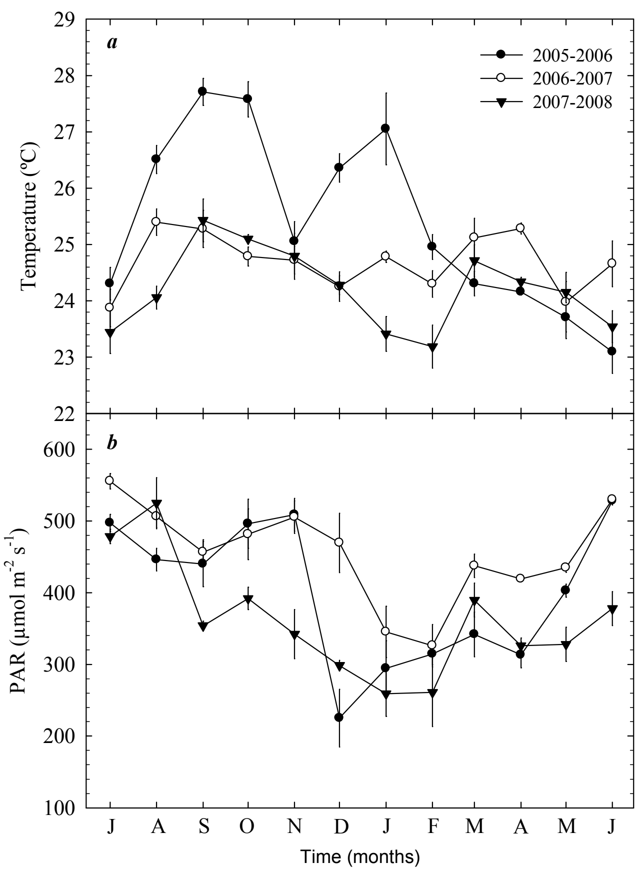

Figure 3 - (a) Average (±sd) monthly air temperature and (b) photosyntheticaly active radiation for 2005-2006 (solid circles), 2006-2007 (open circles) and 2007-2008 (solid triangles).

(Vourlitis *et al*., 2002), while during 2006-2007 the precipitation was approximately 500 mm higher than the historical average (Figure 2b). The greatest total annual rainfall during 2006-2007 was due to peaks occurred during October, January and February, during the wet season occurred on average 96% of the total rainfall (Table 1), and between June and August there was no precipitation. The air temperature was higher during 2005-2006, no difference during 2006-2007, and during 2005-2006 was lower than 2007-2008 (Table 1 and Figure 3a). The air temperature had not seasonality, so there was no correlation between air temperature and GPP_{EC}. However, we observed the highest average air temperature in the wet season of 2005-2006 (Figure 3a). The photosynthetically active radiation (PAR) was negatively correlated with GPP (r = -0.39) (Table 2), because the greater number of days of clear skies, which increased PAR values during June and July of the dry season (Table 1 and Figure 3b).

Evapotranspiration (ET) was consistent over the three years of study, no seasonal variation and interannual, which influenced the lack of correlation between ET and GPP (Table 1 and Figure 2c). The temporal consistency of ET can be explained by root access to deep water reserves. Vourlitis *et al*. (2008) reported that ET and sap flow of the Amazon-Cerrado transitional forest are supplied by groundwater during the dry season. Due to access to water by plants, high values of vapor pressure deficit and solar radiation during the dry season leading to high rates of ET.

Thus, the lowest values of GPP_{EC} during 2005-2006, intermediate during 2006-2007 and higher during 2007-2008 were not due to soil water stress caused by water scarcity. Probably, the annual variation of GPP_{EC} occurred by the dynamic of meteorological conditions during the study period in the Amazon-Cerrado transitional forest: dry and hot during 2005-2006, humid and hot during 2006-2007, and dry and cold during 2007-2008 (Vourlitis *et al*., 2011). The dry season of 2005 has particular interest due to a severe drought reported in the south of the Amazon basin (Marengo *et al*., 2008). The occurrences of seasonal and interannual droughts are potentially important in controlling the productivity of tropical ecosystems (Vourlitis *et al*., 2005; Vourlitis and da Rocha, 2010).

Since the GPP_{EC} was not limited by soil water, probably the canopy phenology, represented by the maximum light use efficiency (ε_0) has influenced the dynamics of GPP_{EC}. The ε_0 increased over the three years analyzed and ε_0 was 2-fold higher in the wet season than in dry season (Table 1; Figure 4). The ε_0 showed the same causes of variation in the estimated GPP_{EC}, however, with higher values of correlation coefficients (Table

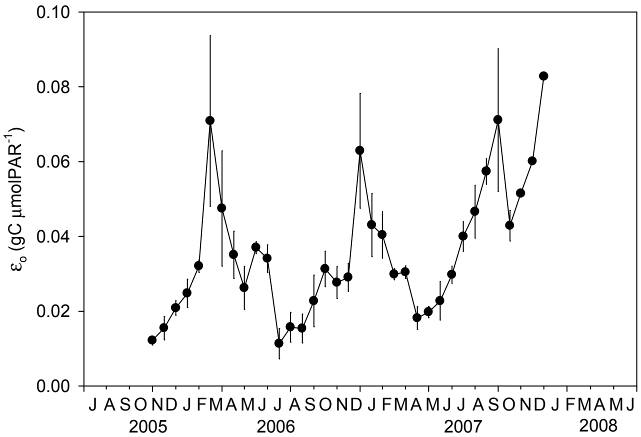

Figure 4 - Average (±sd) monthly maximum light use efficiency (ε0) of the Amazon-Cerrado transitional forest from July 2005 to June 2008.

2). The ε_0 was positively correlated with precipitation (r = 0.77), not correlated with air temperature and was negatively correlated with PAR (r = -0.77). In tropical forests, rates of photosynthesis and respiration of the ecosystem are strongly correlated with rainfall due to its high seasonal variability (Vourlitis *et al*., 2011; Samanta *et al*., 2010). The importance of precipitation for the light use efficiency has been well documented and observed by Sendall *et al*. (2009) and Vourlitis *et al*. (2011) to study the photosynthesis rates and CO_2 net ecosystem exchange (NEE) in the same area of this study. The negative relationship between PAR and ε_0 is not conclusive, because there is little evidence that the light use efficiency is affected by the amount of radiation (Boardman, 1977).

3.2 Variation of orbital data

The mean EVI and LSWI were not different between years (Table 1), but there were seasonal dynamics of them. The EVI was on average 5% higher in the wet season, increasing from June to November, with maximum in December (Figure 5a). The LSWI had a distinct seasonal dynamics, with on average 8% higher during the dry season, increasing from April to August, with maximum in August (Figure 5b). The differences in the EVI and LSWI dynamics were due to a time lag of two months between these indices, which influenced the weak correlation between EVI and GPP_{EC} (r = 0.44) and between LSWI and GPP_{EC} (r = -0.30).

The positive relationship of GPP_{EC} and EVI of tropical forests is well documented and expected, since the EVI dynamic is related to the forest canopy cover dynamics (Xiao *et al*., 2005). Thus, the spectral reflectance is positively correlated with LAI, concentration of photosynthetic pigments and nutrients in the leaf (Asner and Martin, 2008). The EVI was positively correlated with precipitation (r = 0.47) (Table 2). There is an increase in leaf area index (LAI) and consequently photosynthesis in the wet season (Vourlitis *et al*., 2005, 2011).

The LSWI has been used to characterize water conditions of the vegetation in this study, its highest values occur when the ecosystem water availability increases (Xiao *et al*., 2004a; Xiao *et al*., 2005). However, the LSWI was negatively correlated with precipitation (r = -0.48) (Table 2). During the study period, the highest value of LSWI occurred in the month prior to the occurrence of precipitation (in August) and the lowest value LSWI occurred in the last month of occurrence of precipitation (April). The soil water content is lower during the dry season than in wet season (Saleska *et al*., 2003; Vourlitis *et al*., 2011). However, ET is slightly higher during the dry season than during wet season (Figure 2c). Due to the Amazon-Cerrado transitional forest canopy be closed, the values of reflectance measured by orbital sensors are not directly influenced by soil water content, but by leaves water content. The high values of LSWI during the dry season can be attributed to: (1) high proportion of young leaves (higher leaf water content) as indicated by the seasonal dynamics of

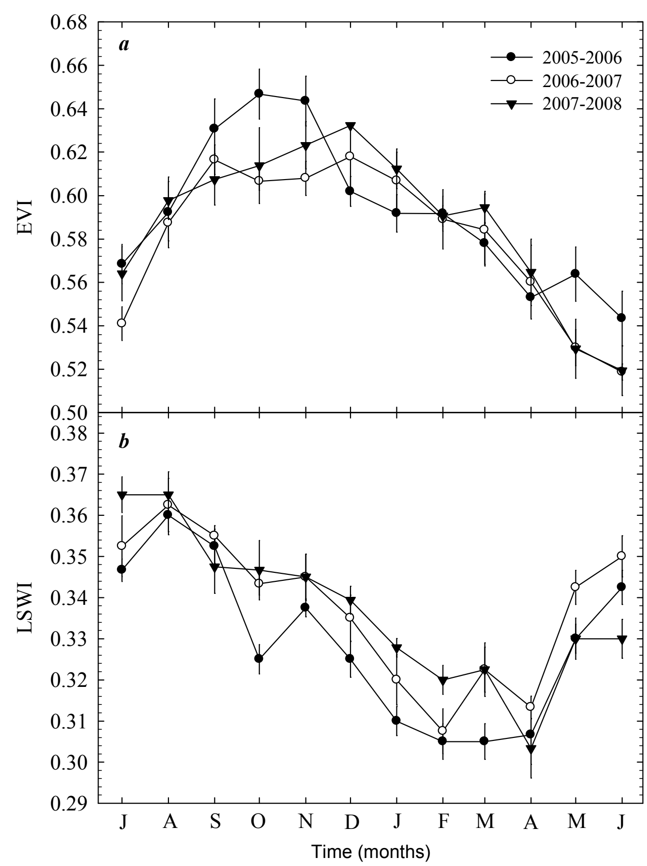

Figure 5 - (a) Average (±sd) monthly enhanced vegetation index (EVI) and (b) land surface water index (LSWI) for 2005-2006 (solid circles), 2006-2007 (open circles) and 2007-2008 (solid triangles).

EVI, and (2) high water-equivalent thickness the upper canopy supplied by the deep root system. Young leaves have higher water content than the older leaves (Roberts *et al*., 1998). Thus, the seasonal dynamic of LSWI indicates no water stress along the dry season in the evaluated years.

3.3 GPP Estimated by VPM and MODIS product

The seasonal dynamics of predicted GPP of Amazon-Cerrado transitional forest by VPM using MODIS data and microclimate data (GPP_{VPM}) and GPP by GPP MODIS product (GPP_{MODIS}) agreed with GPP estimated by eddy covariance (GPP_{EC}) on both, phase and magnitude, according MANOVA test (Figure 6). The annual GPP_{EC} was 26.9 ton ha^{-1}, 30.3 ton ha^{-1} and 31.2 ton ha^{-1}, the annual GPP_{VPM} was 24.2 ton ha^{-1}, 28.8 ton ha^{-1} and 31.0 ton ha^{-1} and the annual GPP_{MODIS} was 17.4 ton ha^{-1}, 19.3 ton ha^{-1} and 20.6 ton ha^{-}1 during 2005-2006, 2006-2007 and 2007-2008, respectively. In general, the GPP_{VPM} was underestimated 8.0% on average, due 21.4% of underestimation in the dry season and 3.5% of overestimation in the wet season; and the GPP_{MODIS} was underestimated 38.0% on average, due the underestimation of 33.2% and 36.3% in the dry and wet seasons, respectively (Table 1). Linear regression showed high correlation between the GPP_{EC} and GPP_{VPM} (r = 0.93), with a MAE of 0.43 gC m^{-2} day^{-1}, RMSE of 0.87 gC m^{-2} day^{-1}. However, the GPP_{MODIS} had low correlation with GPP_{EC} (r = 0.43), with a MAE of 1.95 gC m^{-2} day^{-1}, RMSE of 4.35 gC m^{-2} day^{-1} (Figure 7).

Since the T_{scalar} and W_{scalar} presented practically no variation between the years and seasons (Table 1), the underestimation of GPP_{VPM} in the dry season may be due to lower EVI values between May and July. As the dynamics of EVI reflects the phenology of plants, this enhances that the phenology of plants has an important influence on GPP. Some found errors could be attributed to climate input data and vegetation indices. This result corroborates the estimated GPP in Amazon forests (Xiao *et al*., 2005).

The low capacity of MODIS product to predict GPP is due to the improper of characterizing of LUE of the Amazon-Cerrado transitional forest of this study. The MOD17A2 uses lookup tables of maximum LUE determination for a given vegetation type and the adjustment of LUE values can be downward on the basis of environmental stress factor (Sims *et al*., 2006). The typical difference between VPM and GPP MODIS product is the calculation of LUE, although both models use climate variables to reduce the maximum LUE under unfavorable condition (Wu *et al*., 2010). The VPM use local climate variables whereas MOD17A2 uses produced data derived by a global circulation model (GCM), with incorporates both ground and satellite-based observation (Schubert *et al*., 1993).

4. CONCLUSIONS

GPP_{VPM} and GPP_{MODIS} showed similar dynamics with higher values in wet season and lower in dry season. Both methods have advantage and limitation to predict GPP. The GPP_{VPM} showed better adjustment with GPP_{EC}, however VPM is limited by the local climate data input. The GPP_{MODIS} had no good adjustment with GPP_{EC}, but the MOD17A2 can be used to predict GPP of a wide scale.

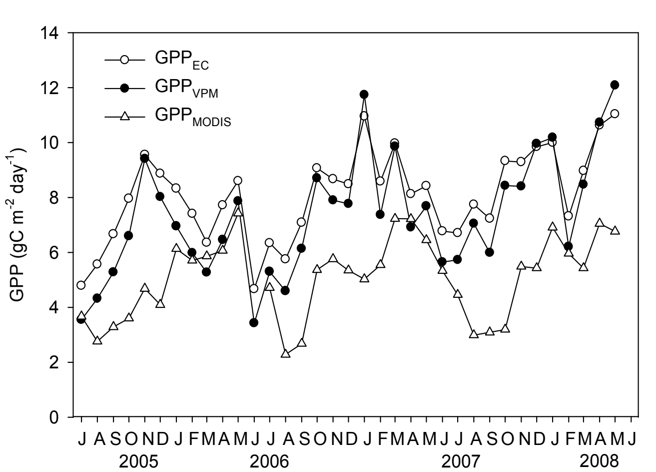

Figure 6 - Average monthly GPP estimated by eddy covariance method (GPPEC) and predicted by vegetation photosynthesis model (GPPVPM) and MODIS product (GPPMODIS) in the Amazon-Cerrado transitional forest from July 2005 to June 2008.

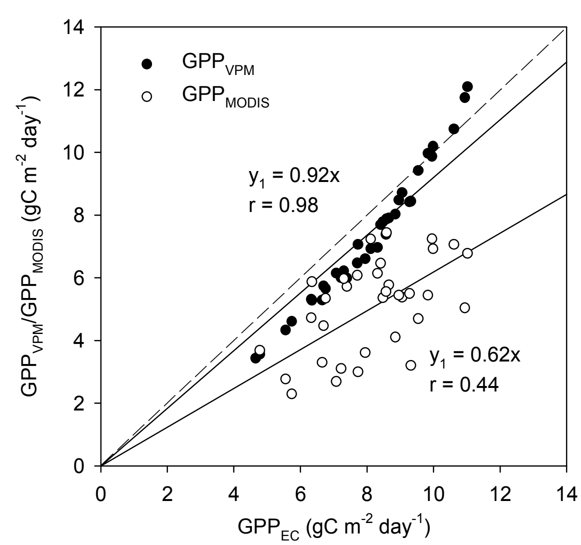

Figure 7 - Relationship of GPP predicted by vegetation photosynthesis model (GPPVPM) and MODIS product (GPPMODIS) with GPP estimated by eddy covariance (GPPEC) in the Amazon-Cerrado transitional forest.

These results indicate the potential of VPM, which uses vegetation indices (EVI and LSWI) with meteorological data, and the MOD17A2 MODIS product to characterize the interannual and seasonal variation of GPP from an Amazon-Cerrado transitional forest. Moreover, it indicates the requirement of more study that uses the MOD17A2 in different tropical type of vegetation.

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