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Relationship between photosynthetically active radiation and global radiation in Petrolina and Brasília, Brazil[1]

Relação entre radiação fotossinteticamente ativa e radiação global em Petrolina e Brasília, Brasil

Lady L. M. Custódio[2*], Bernardo B. da Silva[2] & Carlos A. C. dos Santos[2]

[1] Research developed at Universidade Federal de Campina Grande, Programa de Pós-Graduação em Meteorologia, Campina Grande, PB, Brazil
[2] Universidade Federal de Campina Grande, Unidade Acadêmica de Ciências Atmosféricas, Programa de Pós-Graduação em Meteorologia, Campina Grande, PB, Brazil.

HIGHLIGHTS:
Photosynthetically active radiation (PAR) estimates, used in photosynthesis, have become essential with climate change.
PAR can be related to global radiation and varies with local weather conditions.
In Petrolina and Brasília, the variation of PAR is associated, mainly with cloudiness.

ABSTRACT: Photosynthetically active radiation (PAR) comprises the spectral range of global solar radiation (Rs) that is highly related to vegetation productivity. The study aimed to evaluate the relationship between PAR and Rs in Petrolina, PE, and Brasília, DF, Brazil, with data measured in 2011 and 2013 at two stations of the Sistema Nacional de Organização de Dados Ambientais located in Petrolina, PE and Brasília, DF, Brazil, and the obtained models were evaluated using the measurements of 2014. It was verified that the PAR, in instantaneous values (μmol m^{-2} s^{-1}), can be estimated at 2.31 times the Rs (W m^{-2}) measured in Petrolina, while for daily values of PAR (MJ m^{-2}) is equal to 50% of Rs (MJ m^{-2}). In Brasília, PAR (μmol m^{-2} s^{-1}) is 2.05 times the Rs (W m^{-2}) and, in daily values, equal to 44% of Rs (MJ m^{-2}). The variability of the PAR/Rs ratio followed the local variations of clearness index (Kt) and Rs. The models presented an adequate performance based on statistical indices mean absolute error, mean relative error, and root mean square error and can be used to estimate PAR.

Key words: PAR/Rs ratio, PAR estimation, clearness index

RESUMO: A radiação fotossinteticamente ativa (PAR) compreende a faixa espectral da radiação solar global (Rs) que tem grande relação com a produtividade da vegetação. O objetivo neste estudo foi avaliar a relação entre PAR e Rs nas cidades de Petrolina, PE, e Brasília, DF, Brasil, com dados medidos no ano de 2011 e 2013 em duas estações do Sistema Nacional de Organização de Dados Ambientais localizadas em Petrolina, PE, e Brasília, DF, Brasil, e para avaliar os modelos obtidos foram utilizadas as medições de 2014. A PAR, em valores instantâneos (μmol m^{-2} s^{-1}), pode ser estimada como 2,31 vezes a Rs (W m^{-2}) medida em Petrolina, enquanto para valores diários a PAR (MJ m^{-2}) é 50% da Rs (MJ m^{-2}). Já em Brasília, a PAR (μmol m^{-2} s^{-1}) é 2,05 vezes a Rs (W m^{-2}) e, em valores diários, igual a 44% da Rs (MJ m^{-2}). A variabilidade da razão PAR/Rs seguiu as variações locais do índice de claridade (Kt) e Rs. Com base nos índices estatísticos erro absoluto médio, erro relativo médio e raiz do erro médio quadrático, os modelos apresentaram adequado desempenho, podendo ser utilizados para estimar a PAR.

Palavras-chave: razão PAR/Rs, estimativa da PAR, índice de claridade

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Introduction

Photosynthetically active radiation (PAR) comprises the ranging of the electromagnetic spectrum from 400 to 700 nm. It is a fundamental variable in the formation of gross primary productivity (GPP), an essential component of the global terrestrial carbon cycle. Although its importance is widely recognized, PAR is usually not measured in the weather station networks in Brazil and worldwide. To overcome this problem, researchers use different PAR estimation techniques, among which the most used technique to obtain PAR is through simple linear regression with global solar radiation (Rs) (Al-Shooshan, 1997; Jacovides et al., 2007; Steidle Neto et al., 2008; Escobedo et al., 2009; Galvani, 2009; Escobedo et al., 2011; Wang et al., 2014; Pashiardis et al., 2017; Chukwujindu et al., 2018).

The ratio between PAR and Rs varies from region to region (Wang et al., 2014; Chukwujindu et al., 2018), with visible dependence on local weather and climate conditions (Chukwujindu et al., 2018). According to the current literature, it is suggested that PAR/Rs be locally calibrated (Wang et al., 2014 and Yu et al., 2015). Also, it is reported that different intervals of the spectral range determined by the researcher to represent the PAR will imply the difference in the ratio between PAR and Rs. For example, Tsubo & Walker (2005), in studies that consider PAR restricted to the spectral range from 400 to 700 nm, the PAR/Rs ratio ranges from a minimum of 0.41 (Papaioannou et al., 1996) to 0.52 (Kvifte et al., 1983). However, when considering the range from 300 to 700 nm, the PAR/Rs ratio ranges from 0.43 (Papaioannou et al., 1993) to 0.57 (Kvifte et al., 1983).

Hence, there is a need to investigate the variability of the PAR/Rs ratio considering local weather and climate conditions and models to predict PAR that works well over a large area. In this context, Petrolina and Brasília have few records of PAR/Rs ratio. Simultaneously, research on GPP determinations in these cities lacks more accurate information about PAR estimates.

Therefore, this study aims to determine the PAR/Rs ratio and study its behavior in areas of two important biomes, represented by Petrolina, PE, and Brasília, DF, Brazil, both with very marked climatic differences. Local calibration is essential because the PAR fraction made available is used for photosynthesis processes, playing an important role in producing biomass and the carbon cycle.

Material and Methods

Two weather stations of the Sistema Nacional de Organização de Dados Ambientais (SONDA) (http://sonda.ccst.inpe.br/infos/index.html) were selected for the study. The first is located in Petrolina, PE (09° 04' S, 40° 19' W, 387 m) and the second one located in Brasília, DF (15° 36' S, 47° 42' W, 1023 m), Brazil. The rainy season in Petrolina is from November to April, with an average annual total precipitation (Pr, mm) of 482.6 mm, average monthly air temperature (Tair, °C) of 27 °C, and average monthly relative air humidity (RH, %) of 60.2% in June (Table 1). In Brasília, the rainy season is from October to April, with an average annual Pr of 1477.4 mm. The least rainy season is cold and dry, with monthly minimum Tair between 13 and 18 °C and RH ranging from 46.8 to 78.0% (Table 1).

For Petrolina and Brasília, the years 2011 and 2013 were selected to obtain the regression models, and 2014 was used to evaluate these models' performance.

The variables included in the study were: Rs (W m^{-2}), PAR (μmol $m^2 s^{-1}$), Pr (mm), RH (%), and Tair (°C). All these data were preprocessed and underwent a previous consistency analysis in which the Rs measurements < 5 W m^{-2} and their corresponding PAR values measured were excluded from the study. Additionally, the daily vapor pressure deficit (VPD, kPa) was calculated by obtaining the daily atmospheric water vapor saturation pressure (es, kPa) (Tetens, 1930) and the daily water vapor partial pressure (ea, kPa), obtained by multiplying es by RH. The PAR, Rs, RH, Tair, and Pr were measured every 5 s and averaged every minute.

For daily cycle was considered the conversion of 4.57 μmol J^{-1} proposed by McCree (1972) and integrating the data into daily values led to the PAR equation as a function of Rs. The simple linear regression was analyzed using instantaneous and daily data, so it will be possible to estimate PAR on both scales. Also, regressions using the different Kt will be established in this study, as in other studies, it has been reported that there is a relationship between PAR/Rs ratio and cloudiness (Escobedo et al., 2009; 2011; Wang et al., 2014; Akitsu et al., 2015; Wang et al., 2015).

Classification regarding the presence of clouds was performed considering the clearness index (Kt), given by the ratio between daily Rs (MJ m^{-2}) and daily solar radiation at the top of the atmosphere (Ro, MJ m^{-2}). Daily Ro was calculated

Table 1. Monthly climatic data of Petrolina and Brasília, Brazil, from 1981 to 2010

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Petrolina, PE, Brazil (Caatinga)												
Tair (°C)	28.0	27.8	25.7	27.2	26.3	24.9	24.4	25.1	26.7	28.4	28.6	26.9
Tn (°C)	23.3	23.3	23.4	23.0	22.1	20.6	20.0	20.1	21.1	25.5	23.0	23.5
Tx (°C)	33.3	33.0	32.6	32.2	31.4	30.0	29.7	30.7	32.7	34.1	34.2	33.9
RH (%)	54.0	57.6	59.9	60.1	58.5	60.2	58.3	53.0	47.4	43.8	47.3	51.4
Pr (mm)	91.0	90.7	114.1	44.0	12.6	5.5	4.0	1.4	2.7	10.6	52.0	54.0
Brasília, DF, Brazil (Cerrado)												
Tair (°C)	21.6	21.7	21.6	21.3	20.2	19.0	19.0	20.6	22.2	22.4	21.5	21.4
Tn (°C)	18.1	18.0	18.1	17.5	15.6	13.9	13.7	15.2	17.2	18.1	18.0	18.1
Tx (°C)	26.5	27.0	26.7	26.6	25.9	25.0	25.3	26.9	28.4	28.2	26.7	26.3
RH (%)	76.2	74.7	76.8	72.2	66.2	58.7	52.7	46.8	50.3	62.8	74.5	78.0
Pr (mm)	209.4	183.0	221.8	133.4	29.7	4.9	6.3	24.1	46.6	159.8	226.9	241.5

Source: INMET (Diniz et al., 2018); Tair - Monthly mean air temperature; Tn - Minimum air temperature; Tx Maximum air temperature; RH - Mean relative air humidity; Pr - Monthly total precipitation according to Eq. 1 (Iqbal, 1983). The sky coverage was classified according to the following intervals: Kt < 0.3, cloudy, 0.3 ≤ Kt ≤ 0.65, partially cloudy, and Kt > 0.65, clear.

$$Ro = 3.6\ dr\left[H\sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(H)\right] \quad (1)$$

where:

dr - correction of the Earth's orbit eccentricity (dimensionless);
δ - solar declination (rad);
φ - local latitude (rad); and,
H - time angle corresponding to the sunrise (rad).

The performances of the models, obtained from the linear regressions between instantaneous and daily PAR/Rs were assessed using the following statistical metrics: Mean Absolute Error (MAE), Mean Relative Error (MRE), and Root Mean Square Error (RMSE), respectively, based on the following equations:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|y_{mod} - y_{obs}\right| \quad (2)$$

$$MRE = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{y_{mod} - y_{obs}}{y_{obs}}\right| \quad (3)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(y_{mod} - y_{obs}\right)^2} \quad (4)$$

where:

y_{mod} and y_{obs} - estimated and observed values, respectively; and,
n - number of pairs in the sample.

To compare the means, the t-test ($p < 0.01$) was applied, and to verify the statistical significances of the coefficients of the linear regressions were applied F test ($p \leq 0.01$).

Results and Discussion

The minute-by-minute time series of each month for Rs and PAR in Petrolina and Brasília are shown in Figure 1. The maximum and minimum values occur in summer and winter, respectively. Irradiance values between the localities demonstrate that PAR is slightly higher in Petrolina than those in Brasília. Moreover, according to the t-test, there were no Rs differences between the localities at a significance of 0.01. The variations in irradiance result from variations in solar elevation reported by Wang et al. (2014) and seasonal variations in cloudiness, related by Peng et al. (2015). This association between cloudiness and irradiance PAR and Rs also is support in Figure 2A, which shows the variation of the clearness index.

Figure 2 shows the daily cycle of Kt, Tair, VPD, RH, PAR/Rs, and Pr for the two cities studied. Pr (Figure 2F) and Tair (Figure 2B) maximum value occur in the summer and the minimum in the winter. At the same time, the RH (Figure 2D) followed the seasonal inverse pattern, except for Brasília, where the maximum is observed in the summer, due to the incursion of cold fronts that reach the city, where it is observed cold and dry characteristics.

Figures 2A, C, and E show the daily evolution of Kt, VPD, and the PAR/Rs ratio for both cities, respectively. The Kt for

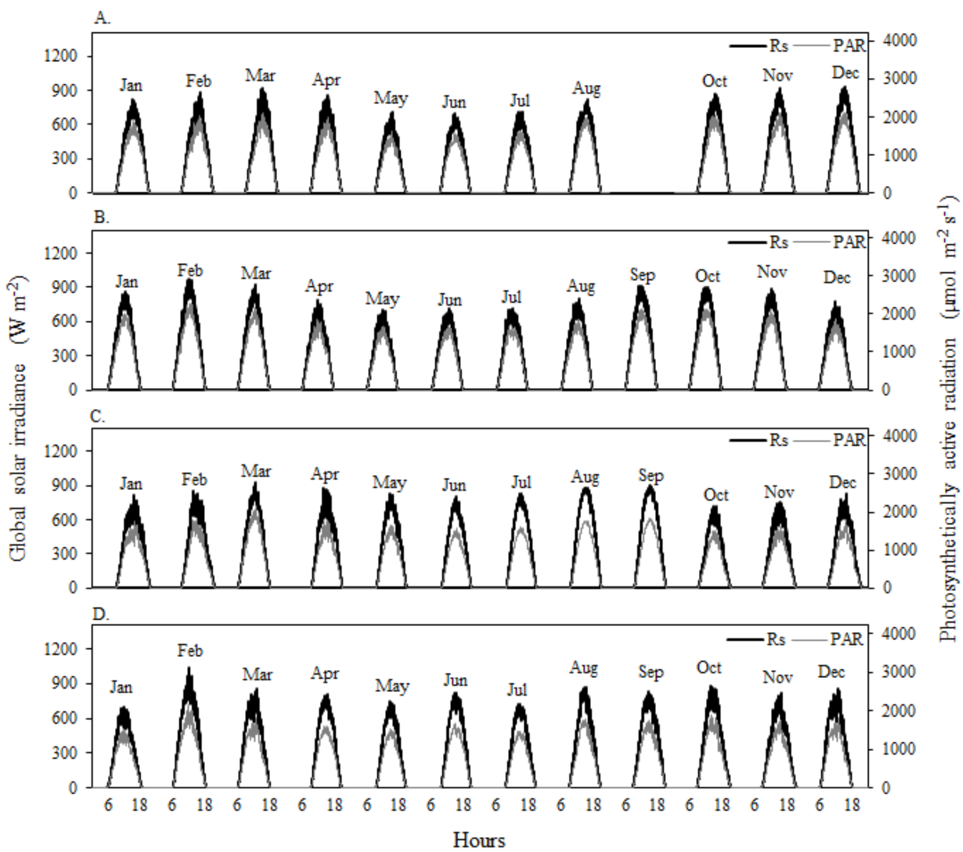


Figure 1. Mean daily temporal distribution of each month of global solar radiation (Rs) and photosynthetically active radiation (PAR) for Petrolina for 2011 (A) and 2013 (B) and Brasília for 2011 (C) and 2013 (D)

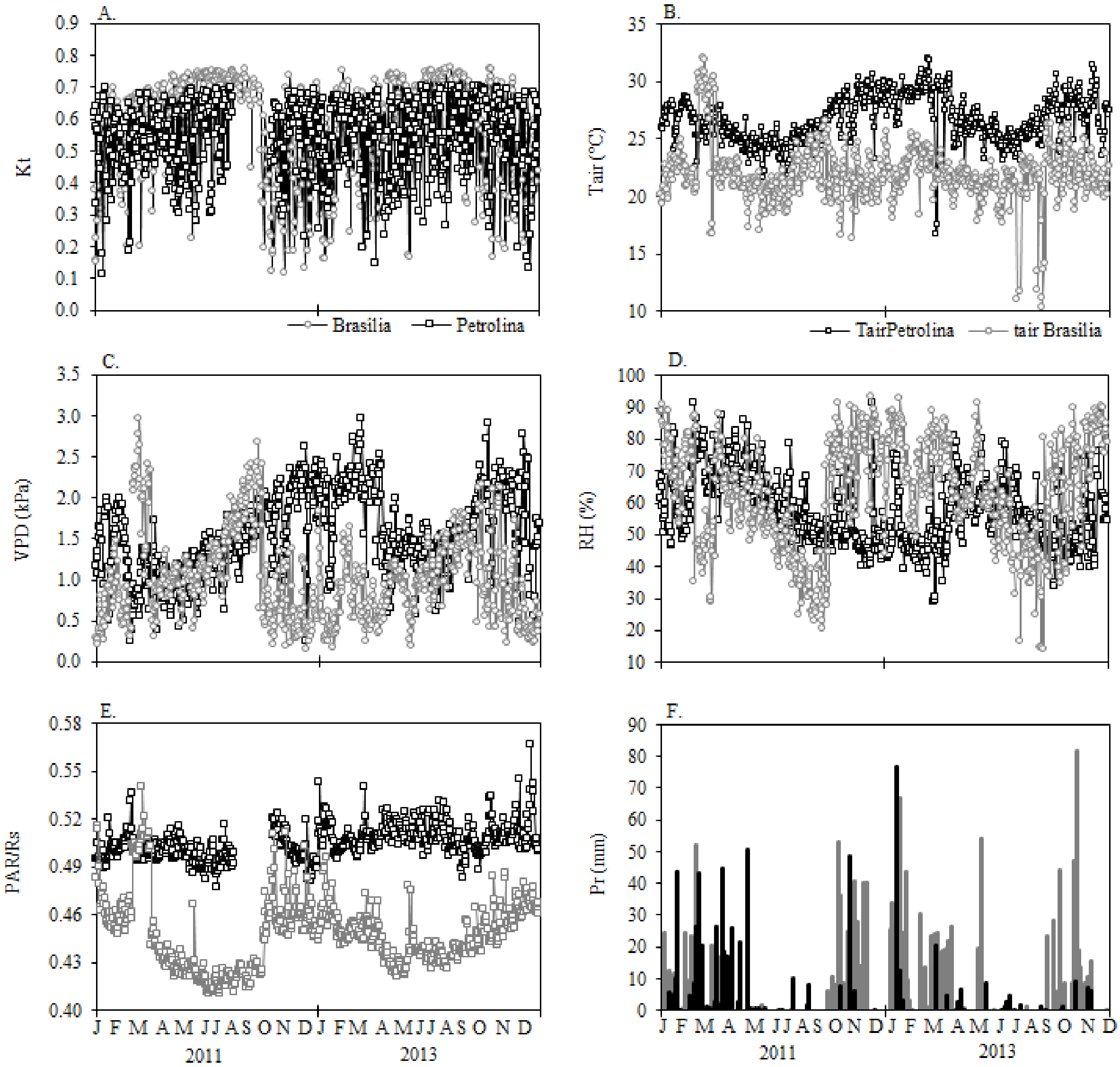


Figure 2. Daily distribution of clearness index (Kt) (unitless), vapor pressure deficit (VPD), photosynthetically active radiation/global solar radiation (PAR/Rs) (unitless) ratio (A, C, and E) and air temperature (Tair), relative air humidity (RH) and precipitation (Pr) (B, D, and F) in Petrolina and Brasília for 2011 and 2013

Petrolina showed weak, with indices ranging from 0.3 to 0.65, suggesting cloudy to the partly cloudy condition (Figure 2A). Moreover, the VPD (kPa) (Figure 2C) has the maximum and minimum values occurring in summer and winter, respectively, since the atmospheric demand for water vapor is higher in summer. For the PAR/Rs ratio (Figure 2E), a weak seasonality was observed, probably due to the low annual variation of Kt (Jacovides et al., 2007; Escobedo et al., 2009, 2011; Wang et al., 2014). The maximum, minimum, and average values were 0.57, 0.48, and 0.50, respectively.

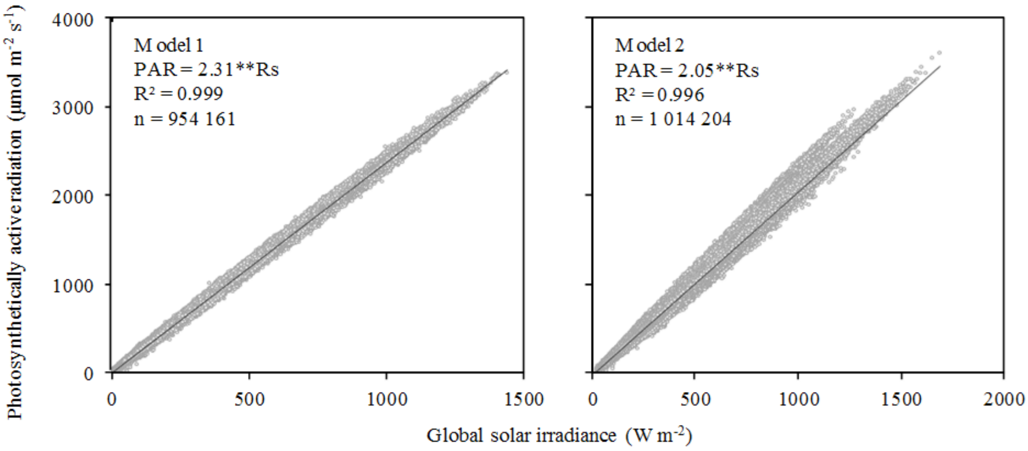
For the Brasília, the temporal distribution of PAR/Rs (Figure 2E), Kt (Figure 2A), and VPD (Figure 2C) showed a better-defined seasonality. The Kt scales were above 0.7, indicating slightly cloudy to clear conditions. The maximum and minimum VPD were 2.96 and 0.15 kPa, respectively, with an average of 1.00 kPa. The maximum, minimum, and average PAR/Rs ratio were 0.54, 0.41, and 0.45, respectively.

The seasonal variability of PAR/Rs showed similar characteristics to those of the Kt variation. Wang et al. (2014) and Akitsu et al. (2015) reported PAR/Rs increases with Kt. This inverse relationship between PAR/Rs and Kt is due to the absorption of infrared radiation (NIR) by clouds since PAR is more easily transmitted through clouds. Therefore cloudiness is a critical parameter in the estimation of the PAR/Rs ratio.

It is also noted that with the increase in VPD, the PAR/Rs ratio decreases. Akitsu et al. (2015), using water vapor partial pressure (ea), found a direct relationship between the PAR/Rs ratio and water vapor partial pressure, revealing that the PAR/Rs ratio and water vapor partial pressure increase. This is due to the increase in cloudiness, leading to an increase in the moisture content, or vice versa.

This characteristic is observed, and for Brasília, the response of the PAR/Rs ratio to the increase or decrease in VPD is more evident. While for Petrolina, PAR/Rs are very close to the average, probably due to the low variation of Kt.

Usually, to find the relationship between PAR and Rs is suggested linear regression. Therefore, instantaneous data were used to establish the equation to estimate PAR (μmol m^{-2} s^{-1}) as a function of Rs (W m^{-2}) (Figure 3). The coefficients of the regression lines were 2.31 μmol J^{-1} with R^2 = 0.99 for Petrolina (Figure 3A) and 2.05 μmol J^{-1} with R^2 = 0.99 for Brasília (Figure 3B). Similar results were found in studies



** - Significant at $p \leq 0.01$ by F test

Figure 3. Linear relationship between global solar radiation (Rs) (W m^{-2}) and photosynthetically active radiation (PAR) (μmol m^{-2} s^{-1}) for Petrolina (A) and Brasília (B), Brazil, for 2011 and 2013

conducted in Brazil by Almeida & Landsberg (2003), Galvani (2009), Escobedo et al. (2009), and Aguiar et al. (2012), with the following values: 2.12 μmol J^{-1}, 2.03 μmol J^{-1}, 2.24 μmol J^{-1} and 2.11 μmol J^{-1}, respectively. These studies have shown that the coefficients are mostly high, caused by high RH conditions and daily cloudiness. Wang et al. (2014) and Akitsu et al. (2015) explained that clouds absorb more infrared radiation than PAR, so the radiation that reaches the surface is mostly PAR and may be higher with the water vapor increase.

Table 2 shows seasonal correlations for the instantaneous mean of PAR/Rs values for Petrolina and Brasília, Brazil. The highest PAR/Rs ratios occur during the higher Pr period, i.e., from December to April in Petrolina, and from October to March in Brasília, which is consistent with the results obtained by other authors (Galvani, 2009; Aguiar et al., 2012; Wang et al., 2014; Chukwujindu et al., 2018).

Thus, it is observed that seasonal variations in the PAR fraction change as the seasonal weather conditions vary (Wang et al., 2014).

However, it is interesting to note that PAR/Rs ratio in Petrolina shows low seasonality, as the values are the same for three quarters (JFM, AMJ, and OND). Probably due to the impact of the low seasonality of Kt (Figure 2A).

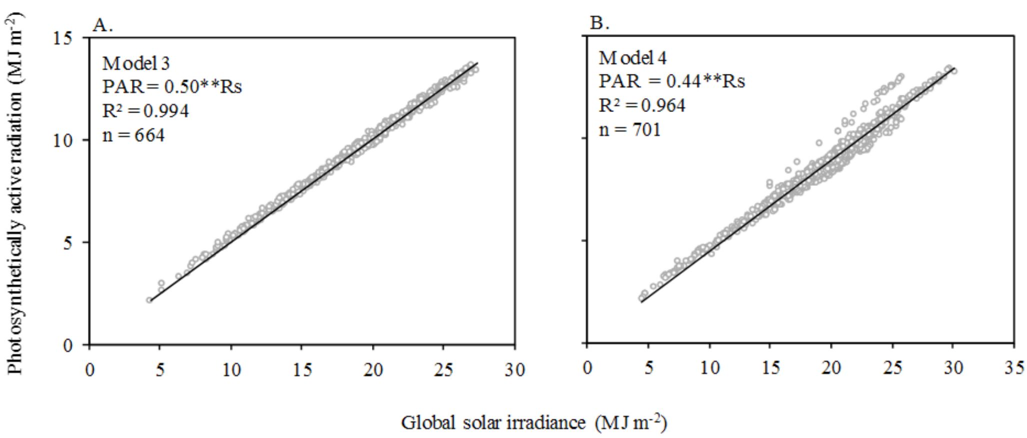
Figure 4 shows the results of the linear equation to estimate PAR in energy units (MJ m^{-2}) for Petrolina (Figure 4A) and Brasília (Figure 4B), Brazil. The daily PAR/Rs ratio for Petrolina was 0.50 (R^2 = 0.99). In the Amazon, this ratio is lower, varying between 0.44 for pasture and 0.42 for forest (Aguiar et al., 2012).

Table 2. Equations of the quarterly linear regression between photosynthetically active radiation (PAR) (μmol m^{-2} s^{-1}) and global solar radiation (Rs) (W m^{-2}) for Petrolina and Brasília, Brazil, in 2011 and 2013

Period	Regression	R^2
Petrolina, PE, Brazil (Caatinga)		
Jan-Feb-Mar	2.31**Rs	0.99
Apr-May-Jun	2.31**Rs	0.99
Jul-Aug-Sep	2.30**Rs	0.99
Oct-Nov-Dec	2.31**Rs	0.99
Brasília, DF, Brazil (Cerrado)		
Jan-Feb-Mar	2.13**Rs	0.99
Apr-May-Jun	1.99**Rs	0.99
Jul-Aug-Sep	1.98**Rs	0.99
Oct-Nov-Dec	2.09**Rs	0.99

** - Significant at $p \leq 0.01$ by F test; R^2 - Coefficient of determination

In Brasília (Figure 4B), the value of the PAR/Rs ratio in MJ m^{-2} (0.44; R^2 = 0.96) was similar to those reported by Almeida & Landsberg (2003), Galvani (2009), Jacovides et al. (2007) and Aguiar et al. (2012), but below those found by Assis & Mendez (1989) and Escobedo et al. (2011). Thus, PAR in MJ m^{-2} can be estimated at 0.44 of Rs in a daily radiometric unit (MJ m^{-2}).



** - Significant at $p \leq 0.01$ by F test

Figure 4. Linear relationship between average daily global solar radiation (Rs) and photosynthetically active radiation (PAR) for Petrolina (A) and Brasília (B) in 2011 and 2013

All the PAR/Rs ratios for Petrolina were higher than those for Brasília because PAR was slightly higher in the former city (Figures 1A and B). Therefore, Petrolina, located in the Caatinga biome, has more PAR, the energy available for photosynthetic processes, than in Brasília, located in the Cerrado biome, and other localities from Brazil (36 - 49%), observed in the works of Assis & Mendez (1989), Almeida & Landsberg (2003), Steidle Neto et al. (2008), Escobedo et al. (2011) and Aguiar et al. (2012).

To better understand the relationship between PAR/Rs ratio and Kt, the data were separated by Kt intervals for the Petrolina and Brasília, Brazil, as shown in Figures 5A and B, respectively. It was observed that, for all Kt values, the PAR fraction in Petrolina is higher than in Brasília. This may be related to the higher atmospheric transmissivity in Brasília. PAR percentages for the two cities decrease as Kt increases, also reported by Akitsu et al. (2015) and Ferrera-Cobos et al. (2020). These variations are due to differences in cloud cover and type (Escobedo et al., 2009; 2011; Aguiar et al., 2012; Wang et al., 2014; Akitsu et al., 2015; Wang et al., 2015).

The PAR/Rs ratio for the Petrolina was 52% ($R^2 = 0.98$) for $Kt < 0.35$, followed by 50% for Kt between 0.35 and 0.65 ($R^2 = 0.99$) and finally 49% for $Kt > 0.65$ ($R^2 = 0.98$) (Figure 5A). In Brasília, the ratio was 47% ($R^2 = 0.98$) for $Kt < 0.35$, 45% for partially cloudy ($0.35 \leq Kt \leq 0.65$) ($R^2 = 0.96$) and 43% for virtually cloudless condition ($Kt > 0.65$) ($R^2 = 0.92$) (Figure 5B).

Wang et al. (2014) and Akitsu et al. (2015) described that the dependence of PAR/Rs ratio on Kt is explained by the extinction of Rs, as mentioned before, because, under cloudy conditions, the infrared radiation has greater extinction, while PAR has few changes.

These results are quite impressive, as they demonstrate that PAR varies with Rs and changes in cloudiness and, to a lesser degree, with VPD. Therefore, using a single PAR ratio factor for different locations leads to inaccuracy in productivity calculation. Rodrigues et al. (2018) simplistically evaluated the impacts of the Rs proportion of 0.37 (calibrated) and the 0.48 factor suggested by Bastiaanssen & Ali (2003). The difference in the final result in the calculation of GPP was 20% with PAR = 0.48Rs, and the PAR = 0.37Rs was very close to the GPP observed.

PAR is considered 45% of Rs in the MOD17A2H product, being extrapolated to all locations. GPP data may be overestimated by 90% in some regions (Cai et al., 2014). Gilabert et al. (2015) used the proportion of 46% proposed by Iqbal (1983), which resulted in fewer errors, generally less than 30%.

The models evaluated in Figures 6A and 6C refer to Petrolina and show that the points are mostly above the continuous line (1:1 line) and, therefore, the models underestimate the observed PAR. The underestimation of the model reveals that other factors need to be considered, such as precipitable water, aerosols, and ozone absorption (Wang et al., 2014).

On the other hand, there is no apparent predominance of points above or below the 1:1 line in Figures 6B and D for Brasília. As expected, the R^2 values of the models were high due to the high relationship between Rs and PAR, which was also obtained by Escobedo et al. (2011) and Aguiar et al. (2012).

According to the statistical indices (Table 3), the models of instantaneous PAR estimation (Mod 1 and Mod 2) are efficient, justified by the low percentages of MRE for Petrolina (8.9%) and Brasília (5.4%). Also, on the instantaneous models, MAE (81.3 μmol m^{-2} s^{-1}) and RMSE (29.0 μmol m^{-2} s^{-1}) were lower in Petrolina, and R^2 showed a difference from the third decimal

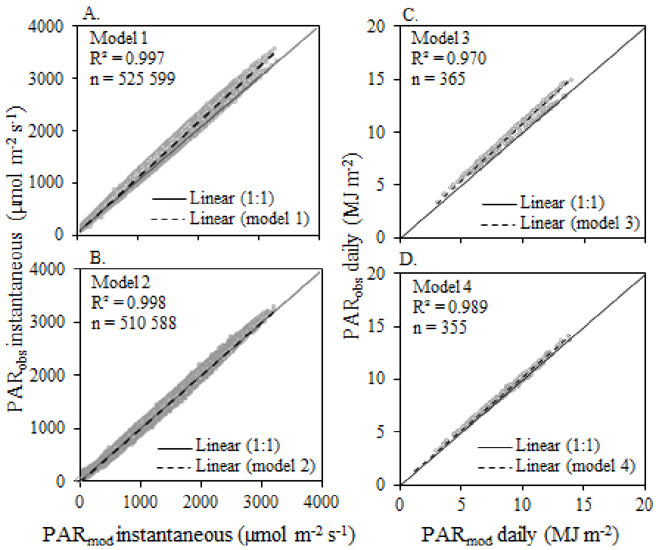
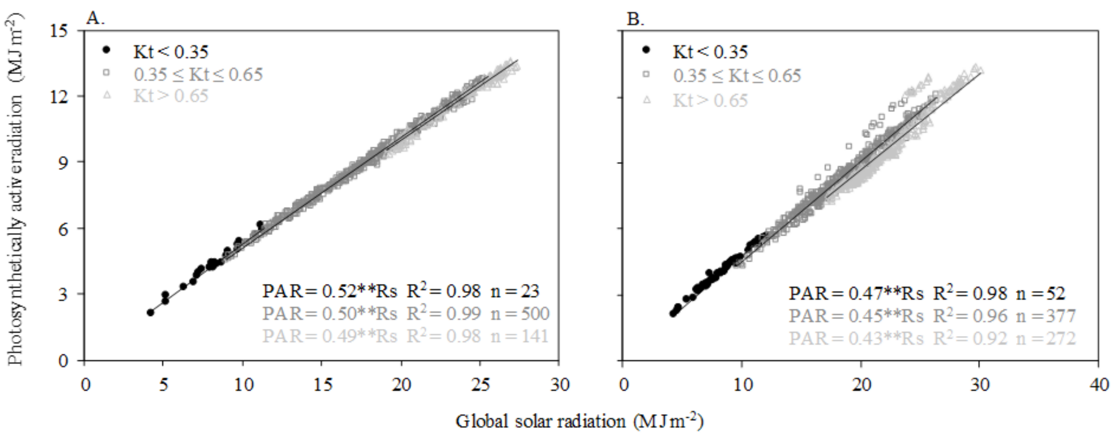


Figure 6. Dispersion of photosynthetically active radiation (PAR) data observed as a function of PAR data modeled for Petrolina (A, C) and Brasília (B, D)



** - Significant at p ≤ 0.01 by F test

Figure 5. Linear relationship between photosynthetically active radiation (PAR) and global solar radiation (Rs) for clearness index (Kt) intervals referring to Petrolina (A) and Brasília (B) for 2011 and 2013

place, i.e., R^2 = 0.998 for Petrolina and R^2 = 0.997 for Brasília, which demonstrates the high degree of relationship between the PAR and Rs variables.

For daily data, the models for Brasília were better than those for Petrolina. The errors are relatively low between the locations, and, therefore, the models can be considered well fitted. However, it is also possible to note that the estimate of PAR in MJ m^{-2} (Mod 3 and Mod 4) leads to better results (Table 3). Escobedo et al. (2011), when evaluating their results, also pointed out that the daily scale models performed better.

These results indicate that the models are very efficient and that the PAR can be accurately estimated using Rs without additional parameters. However, it can be noted in Petrolina that there are still some other variables that can be considered. Brasília's data show that PAR can, for the most part, be explained by Rs. Aguiar et al. (2012) point out that single-variable models may perform well in estimating PAR but with less accuracy.

However, it is suggested that a cluster analysis be carried out to separate regional groups with similar climatic conditions to those in Petrolina and Brasília and then use the regression models of this current research in a larger area.

Table 3. Statistical indices between observed and estimated photosynthetically active radiation (PAR) data for different linear models

Models	MAE	MRE (%)	RMSE	R^2
Petrolina, PE, Brazil (Caatinga)				
Mod 1*	81.3	8.9	104.9	0.9970
Mod 3**	0.8	7.7	0.9	0.9700
Brasília, DF, Brazil (Cerrado)				
Mod 2*	29.0	5.4	37.3	0.9980
Mod 4**	0.2	2.7	0.3	0.9890

* MAE - Mean absolute error; RMSE - Root mean square error (μmol m^{-2} s^{-1}); ** MAE and RMSE (MJ m^{-2}); MRE - Mean relative erro; R^2 - Coefficient of determination

Conclusions

1. The relationship between photosynthetically active radiation (PAR) and global solar radiation (Rs) depends on the climatic characteristics of each region, so caution should be taken when extrapolating the PAR/Rs ratio.

2. The instantaneous and daily PAR/Rs ratios were higher in Petrolina than in Brasília. In instantaneous values, PAR/Rs was 2.31 μmol J^{-1} for Petrolina and 2.05 μmol J^{-1} for Brasília. In daily values, PAR is about 50% of Rs in Petrolina and 44% in Brasília.

3. All models showed adequate performance so that PAR can be efficiently estimated for both cities without additional variables.

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