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Balance of photosynthetically active radiation by remote sensing in a seasonally dry tropical forest in Northeastern Brazil

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ABSTRACT

The objective of this work was to characterize the fractionation of Photosynthetically Active Radiation (PAR) and its interaction with the vegetation cover of a portion of Seasonally Dry Tropical Forest at the end of the rainy season in Northeast Brazil. The leaf area index was correlated with each component of the PAR radiation balance to find the best fit models. Second-order polynomial models were used to identify the relationship between the PAR components and the LAI. It was observed that the fractionation of the PAR radiation reflected, absorbed, transmitted, and reflected by the soil and absorbed by the canopy varied according to the class of use and vegetation cover. Besides, as the density of vegetation increased, there was a decrease in the PAR transmitted and reflected, and an increase in the PAR absorbed and, in the PAR, reflected by the soil and absorbed by the canopy, on all the analyzed dates. It was also found that vegetated areas showed greater use of PAR radiation compared to other areas such as urban infrastructure. The vegetation of the São Francisco Valley has great heterogeneity and, consequently, there is a complex relationship with the distribution of photosynthetically active radiation on the surface.

Palavras-chave: Landsat-8, Caatinga, WVBI, MapBiomass.

Balanço de radiação fotossinteticamente ativa por sensoriamento remoto em floresta tropical sazonalmente seca no Nordeste brasileiro

RESUMO

O objetivo deste trabalho foi caracterizar o fracionamento da Radiação Fotossinteticamente Ativa (PAR) e sua interação com a cobertura vegetal de uma porção da Floresta Tropical Sazonalmente Seca no final da estação chuvosa no Nordeste do Brasil. O índice de área foliar foi correlacionado com cada componente do balanço de radiação PAR para encontrar os modelos de melhor ajuste. Modelos polinomiais de segunda ordem foram usados para identificar a relação entre os componentes PAR e o IAF. Observou-se que o fracionamento da radiação PAR refletida, absorvida, transmitida e refletida pelo solo e absorvida pelo dossel variou de acordo com a classe de uso e cobertura vegetal. Além disso, com o aumento da densidade da vegetação, houve uma diminuição na PAR transmitida e refletida, e um aumento na PAR absorvida e, na PAR refletida pelo solo e absorvida pelo dossel, em todas as datas analisadas. Verificou-se também que áreas com vegetação apresentaram maior uso de radiação PAR em comparação com outras áreas, como infraestrutura urbana. A vegetação do Vale do São Francisco apresenta grande heterogeneidade e, conseqüentemente, existe uma relação complexa com a distribuição da radiação fotossinteticamente ativa na superfície.

Keywords: Landsat-8, Caatinga, WVBI, MapBiomass.

Introduction

Solar radiation with wavelengths between 400 to 700 nm is called Photosynthetically Active

Radiation, precisely because of its photosynthetic power, it is essential to plant growth and development, being one of the input variables in

models that simulate the accumulation of dry matter during the crop cycle (Liu et al., 2021). Upon reaching a vegetated surface (canopy), this radiation can be absorbed, reflected, and transmitted in different proportions depending on the variation of the sun's zenith angle and factors inherent to vegetation such as phenological stage, size, and leaf architecture (Pereira et al., 2002).

Knowledge of the spatial and temporal distribution of PAR in a vegetative canopy is fundamental for understanding the processes of capture and fixation of solar radiation by green biomass, in addition to being an important basis for understanding the local and regional effects of changes in vegetation cover in ecosystem processes (Edreira et al., 2020). This radiation balance is due to the characterization of its components, the fraction reflected by the canopy (RPAR), reflected by the soil (RPARs), absorbed by the canopy (APAR), and transmitted through the canopy (TPAR) (Gallo and Daughtry, 1986).

The determination of this radiative regime in areas of dry tropical forest, represented in the Northeast of Brazil by the Caatinga, is extremely complex, mainly because this biome has high heterogeneity in its phytophysiology due to its high diversity of species (Pereira et al., 2021, Machado et al., 2014; Silva et al., 2013), which causes a high variation in the density and distribution of vegetation and carbon sequestration Morais et al., (2017).

The dry tropical forest is found in 60% of the Brazilian Northeast and constitutes typical vegetation of the Semi-Arid, which is configured as a hot, dry, and high evapotranspiration region (MDR, 2018). This biome aggregates 5,344 plant species, 318 of which are endemic and, in most cases, are characteristic of tree and shrub forests, with deciduous or xerophytic behavior (Loiola et al., 2012).

One of the limitations in studies involving the radiation balance at the surface is the need for meteorological instrumentation. This methodology encompasses a costly implementation, especially in situations of regional scale. In this sense, the estimation of these components via remote sensing

emerges as an effective and economical alternative (Fernandes et al., 2021).

Knowledge of the interaction of vegetation with the PAR provides support for understanding variations in the carbon balance at the surface, characterizing the growth of species, the productivity of an ecosystem, accumulation of biomass, among others (Edreira et al., 2020; Junior et al., 2020; Thun e Mundia, 2020).

Besides, the relevance of carrying out works of this nature is emphasized, because of its scarcity in the literature, especially with the use of remote sensing and in the area under study. Therefore, there are essential contributions in these studies concerning scientific knowledge of the soil-plant-atmosphere interaction, the importance of the presence of natural vegetation in the radiative processes of the surface, and in the formulation of environmental and climatic policies aimed at the preservation of the biome.

In this sense, the objective was to characterize the fractionation of photosynthetically active radiation and its interaction with the vegetation cover of a seasonally dry tropical forest at the end of the rainy season in Northeast Brazil. It is assumed that the PAR has different fragmentation in each type of vegetation and that the presence of vegetation contributes to a better use of radiation by the Caatinga ecosystem.

Material and methods

The study area includes the municipalities of Petrolina, located at 9°23'39" S and 40°30'35" W, with an average altitude of 380 m; Lagoa Grande located at 8°59'49" S, 40°16'19" W and 345 m, both belonging to the state of Pernambuco; Juazeiro which is at 9°24'50" S and 40°30'10" W and 368 m and; Curaçá located at 8°59'31" S, 39°54'28" W and 366 m. They are located in the Senador Nilo Coelho irrigated perimeter, known as the Vale do Submédio do São Francisco. The land cover in the region is predominantly composed of forest formations of native forests, pastures, and agricultural areas (Figure 1).

Figure 1. Map of vegetation cover and land use in the study area, region of the Vale do Submédio do São Francisco. Source: MapBiomass, Collection 5 (2019). * Rectangular area in purple was used to determine the distribution of PAR specifically in areas of native forest.

The Region is part of the northeastern semiarid with a BSwH' climate, according to the Köppen classification (Alvares et al., 2013), is characterized as hot and dry, with an average precipitation of 571.5 mm.year⁻¹, an average annual temperature of 26.4 °C, with a minimum average of 20.6 °C, a maximum of 31.7 °C (Lopes et al., 2018) and sunshine of 3,000 hours.year⁻¹ (Ortega and Sobel, 2010).

The predominant natural vegetation is the Hyperxerophilous Caatinga, typical of a hot and dry environment, well adapted to stony soils, with *Mimosa tenuiflora* (Willd.) Poir., *Caesalpinia*

mycophylla Mart. ex G. Don (A) and *Cnidosculus phyllanthus* Pax & Hoffm as predominant species and Fabaceae and Euphorbiaceae as more representative families (Calisto Júnior and Drumond, 2014).

The region has smooth-wavy relief (Figure 2), but containing residual elevations, crystals, and/or peaks that are testimonies of the erosion cycles that occurred in past times in this region (Castro and Santos, 2015). The soils are deep and developed, highlighting Red-Yellow and Yellow Argisols (Silva et al., 2006).

Figure 2. The slope of the terrain in the Vale do Submédio São Francisco is derived from the digital elevation model of the ASTER/Terra sensor with a spatial resolution of 30 m. Source: Fernandes, (2020).

The meteorological radiation data were obtained from the Automatic Meteorological Station (EMA) of the National Institute for Space Research (INPE), located at the geographical coordinates: 09°04'08" S; 40°19'11" W and 387 m, in the municipality Petrolina - PE, in the area belonging to Embrapa Semiárido.

The variables correspond to the meteorological elements: global solar radiation ($W \cdot m^{-2}$); photosynthetically active radiation ($W \cdot m^{-2}$); air temperature ($^{\circ}C$); relative humidity (%); atmospheric pressure (hPa); precipitation (mm) and; wind speed ($m \cdot s^{-1}$) and wind direction (degrees) (Table 1).

Table 1. Available meteorological data for the dates of the Landsat-5 and Landsat-8 images.

Date	DJ	UTC	T _a	RH	P	Rg	Ws	Par	Wd	Rainfall
06/04/09	155	12:36	27.74	55.15	974.49	672.5	4.381	341.3	123.8	0
06/10/11	161	12:37	26.00	59.89	974.68	667.6	2.576	328.7	152.4	0
05/30/13	150	12:50	28.46	54.15	972.08	713.0	4.218	361.1	123.5	0
06/10/17	161	12:47	27.08	60.79	973.71	767.0	3.08	331.9	82.9	0

DJ - Julian Day; UTC - Central Time Unit; T_a - air temperature ($^{\circ}C$); RH - relative humidity (%); P - atmospheric pressure (hPa); Rg - global solar radiation ($W \cdot m^{-2}$); Ws - wind speed (m/s); Par - photosynthetically active radiation ($W \cdot m^{-2}$); Wd - wind direction ($^{\circ}$).

The rainfall data were obtained from the EMA of the National Institute of Meteorology (INMET), located at the coordinates 09°23'18" S; 40°31'23" W and 372.54 m, in the same Municipality. Monthly data were obtained for the months corresponding to the dates of obtaining the images for the years 2009, 2011, 2013, 2016, 2017, and 2019.

The remote sensing data comes from the images obtained from the Landsat 5 TM (Thematic Mapper) sensor, for the years 2009 and 2011, and from the OLI (Operational Land Imager) and TIRS (Thermal Infrared Sensor) sensors, which are onboard Landsat 8, in the years 2013, 2016, 2017 and 2019 (Table 2). Besides, we used the Global Digital Elevation Model Version 3 (ASTER GDEM V003) acquired by the Advanced

Spaceborne Thermal Emission and Reflection Radiometer sensor, both with a 30 m spatial resolution (NASA, 2019), used to obtain the slope and transmittance atmospheric.

The Landsat 5, 8 (Table 2) and ASTER GDEM V003 images of the region were obtained from the United States Geological Survey (USGS, 2019) for the municipality of Petrolina - PE, which corresponds to the 217/line 66 orbit scene. The Landsat images 5 and 8 were selected considering the absence or little cloud cover (less than 10%) and, because of the purpose of observing the vegetation cover, coming from the end of the region's rainy season, which according to the climatological normal, is set between the months of April to May (INMET, 2019).

Table 2. Images obtained from Landsat 5 and 8 satellites. UTC = Central Time Unit.

Satellite	Date	UTC	z ($^{\circ}$)	Dsun	a ($^{\circ}$)
Landsat 5	06/04/2009	12:36	43.33	1.01453	43.49
	06/10/2011	12:37	43.65	1.01523	42.86
Landsat 8	05/30/2013	12:50	40.44	1.01376	40.62
	05/22/2016	12:47	39.76	1.01241	42.44
	06/10/2017	12:47	41.99	1.01525	40.41
	04/29/2019	12:47	35.89	1.00703	50.06

UTC - Central Time Unit; z - Zenith angle; Dsun - distance between land and sun; a - Azimuth angle.
Source: USGS (2019).

After clipping the study area, the radiometric calibration of the spectral bands was performed, converting the digital number of each

pixel and band into spectral reflectance. The images were cropped and processed using the

QGIS 3.6.2 software (QGIS Development Team, 2019).

The procedure started with the calculation of the spectral reflectance. This refers to the solar energy reflected by each pixel per unit area, solid angle, time, and wavelength. To obtain reflectance, it is necessary to convert the quantized and calibrated gray level values of each band, however, using the additive and multiplicative factors related to monochrome reflectance, available in the metadata of the images (USGS, 2019).

The planetary albedo (α_{toa}) is related to the amount of radiation reflected by each pixel without atmospheric correction, being determined through a linear combination of the spectral reflectance's in each of the bands and their respective weights (P_b), according to Silva et al., (2016) given by:

$$\alpha_{atm} = 0.300 \cdot r_2 + 0.277 \cdot r_3 + 0.233 \cdot r_4 + 0.143 \cdot r_5 + 0.035 \cdot r_6 + 0.012 \cdot r_7 \quad (1)$$

where, r_2 , r_3 , r_4 , r_5 , r_6 , and r_7 are the reflectance's of each of the bands used, respectively.

Due to the atmospheric interference in solar radiation, mainly due to the absorption and scattering processes, it is essential to correct the planetary albedo, which can be done using the equation of Allen et al. (2002):

$$\alpha_{sup} = \frac{\alpha_{toa} - \alpha_{atm}}{\tau_{sw}^2} \quad (2)$$

where, α_{sup} is the corrected surface albedo; α_{atm} consists of the reflectance of the atmosphere itself,

where, S is the solar constant (1367 W. m^{-2}), Z is the zenith angle of the sun, dr is the inverse of the square of the Earth-Sun relative distance and τ_{sw} is the atmospheric transmissivity.

The radiation portion related to photosynthetically active (PAR, W. m^{-2}) was estimated from R_g , using Equation 13 (Tsubo and Walker, 2005).

$$PAR = (0.12 kt^2 - 0.334 \times kt + 0.613) \times R_g \quad (8)$$

where, kt is the lightness index (ratio between global radiation and extraterrestrial solar radiation).

with a value of 0.03 being recommended (Bastiaanssen, 2000) and τ_{sw} is the transmissivity of the atmosphere that under clear sky conditions is calculated using Equation 3.

$$\tau_{sw} = 0.75 + 2 \times 10^{-5} \times \text{SRTM} \quad (3)$$

where, SRTM consists of the digital elevation model of the region (ASTER GDEM V003).

The normalized difference vegetation indices (NDVI), soil adjusted vegetation index (SAVI), and the leaf area index (LAI) were calculated according to Rouse et al. (1973), Huete et al. (1988), and Allen et al. (2002), respectively, expressed by:

$$\text{NDVI} = \frac{\rho_{IV} - \rho_V}{\rho_{IV} + \rho_V} \quad (4)$$

$$\text{SAVI} = \frac{(1+L)(\rho_{IV} - \rho_V)}{(L + \rho_{IV} + \rho_V)} \quad (5)$$

$$\text{LAI} = - \frac{\ln\left(\frac{0.69 - \text{SAVI}}{0.59}\right)}{0.91} \quad (6)$$

where, ρ_{IV} = Reflection of the near-infrared band; ρ_V = Reflection of the red band; L = Soil adjustment factor (0.5).

The flux of incident short wave solar radiation or global radiation (R_g , W. m^{-2}) was calculated using the following equation (Allen et al., 2002):

$$R_g = S_0 \times \cos Z \times dr \times \tau_{sw} \quad (7)$$

The PAR component reflected (PAR_R , W. m^{-2}) by the surface is defined by the reflectance of the vegetation plus that of the soil, considering an area with no water bodies. Thus, this variable was quantified with the following equation:

$$PAR_R = PAR \times \alpha_{sup} \quad (9)$$

The intercepted photosynthetically active radiation (PAR_i , W. m^{-2}) is characterized as the portion of the incident PAR that is intercepted by the vegetation canopy. This variable was determined through the empirical expression suggested by Daughtry et al. (1992):

$$PAR_i = -0.161 + 1.257 \times \text{NDVI} \quad (10)$$

Once the PAR and PAR_I are estimated, the absorbed fraction (PAR_A) can then be determined in W. m⁻² using the equation (Souza et al., 2015):

$$PAR_A = PAR_I \times 0.9368 \quad (11)$$

Considering that the incident PAR can undergo absorption, reflection, and transmission processes, it is clear that the PAR portion transmitted (PAR_T, W. m⁻²) can be obtained from the following equation (Daughtry et al., 1992):

$$PAR_T = PAR - PAR_I - PAR_R \quad (12)$$

A fraction of the PAR transmitted by the canopy reaches the ground, part of which is reflected by it and absorbed by the lower surface of the canopy. Its determination was made with Equation 18, according to (Daughtry et al., 1992).

$$PAR_{RD} = PAR - PAR_A - PAR_T - PAR_R \quad (13)$$

where, PAR_{RD} is the photosynthetically active radiation reflected by the soil and absorbed by the canopy (W. m⁻²).

The interception efficiency (ε) was estimated as follows:

$$\varepsilon = \frac{PAR_i}{PAR} \quad (14)$$

PAR_i was calculated from the equation:

$$PAR_i = PAR - PAR_t \quad (15)$$

PAR_i being the photosynthetically intercepted radiation (W. m⁻²), PAR the photosynthetically incident radiation (W. m⁻²) and PAR_t the radiation photosynthetically transmitted through the canopy (W. m⁻²).

Table 3. Pearson's correlation coefficient.

R	Definition
0.00 a 0.19	Very Weak Correlation (VWC)
0.20 a 0.39	Weak Correlation (WC)
0.40 a 0.69	Moderate Correlation (MC)
0.70 a 0.89	Strong Correlation (SC)
0.90 a 1.00	Very Strong Correlation (VSC)

Source: Adapted from Devore (2006).

Because of the different radioactive interactions between vegetation and the atmosphere according to the type of vegetation, as previously emphasized, the vegetation cover was

For each year, the ε was related to LAI data to estimate the plant population extinction coefficient. This estimate was made by adjusting the slope of the linear function, based on Beer's law adapted by Monsi and Saeki (1953):

$$\ln(\varepsilon - 1) = -b \text{ LAI} \quad (16)$$

PAR component data obtained from the area of native vegetation (area highlighted in purple in Figure 6) were related to the LAI to find spatial distribution patterns and test which is the best fit model. Besides, the determination coefficients (R²), Pearson's correlation coefficients (r) were determined, checking the significance of the coefficients with the t-student test at the 95 or 99% confidence level using Software R version 3.6.1 (R CORE TEAM, 2019). The correlation coefficient was classified according to Devore (2006) according to Table 3.

With the identification of vegetation classes, it was possible to quantify the components of the photosynthetically active radiation balance in each type of class, observing their behavior concerning the variation of plant density. This quantification was performed after disregarding the areas of non-forest formations (pasture, agriculture, water bodies, and urban areas) aiming at their non-interference in the radioactive components (area highlighted in purple in Figure 1)

The same methodology was used to identify the distribution of photosynthetic radiation in the classes of land use and cover characterized by the MapBiomass project (MAPBIOMAS, 2019), as shown in Figure 1.

classified in the classes of the Woody Vegetation Biomass Index (WVBI) according to the NDVI (Table 4).

Table 4. Classification of vegetation according to the Woody Vegetation Biomass Index and the NDVI.

WVBI classes	NDVI
11 - Very dense tree	>0.350
10 - Dense tree	0.32 to 0.35
9 - Dense subarboreal	0.30 to 0.32
8 - Subarboreal dense shrub	0.285 to 0.30
7 - Dense Subarboreal Shrub	0.265 to 0.285
6 - Subarboreal shrub open	0.25 to 0.265
5 - Open Subshrub Shrub	0.225 to 0.25
4 - Sub-shrub Thin shrub	0.20 to 0.225
3 - Sub-shrub Very thin shrub	0.15 to 0.20
2 - Exposed soil	0.0 to 0.15
1 - Bodies of water	1 to 0.0

Source: Francisco et al. (2014).

Results and discussion

As it comprises an area of the Caatinga Biome, the vegetation cover of the region has an evident annual variation in the vegetation indices. About the NDVI (Figure 3), it is observed that in 2009, vegetation was predominant with higher NDVI (above 0.391) in areas of natural vegetation and agriculture.

In the years 2011, 2013, and 2017, it is noted that there is a decrease in this index, causing

the manifestation of thinner vegetation and the presence of exposed soil areas (yellow color). In 2016 and 2019 it is possible to verify a predominance of denser vegetation, with NDVI ranging from 0.391 to 0.854. It is worth noting that the areas of agricultural production have their NDVI values unchanged concerning time, as these regions are constantly under irrigation, thus preventing the action of environmental factors in their density.

Figure 3. Spatial distribution of the Vegetation Index for Normalized Difference (NDVI) in the Vale do Submédio do São Francisco in the years 2009, 2011, 2013, 2016, 2017, and 2019

The variation in NDVI is mainly related to the variation in total rainfall in the region and, according to Liu et al. (1991), the greatest correlation between these variables occurs when comparing the NDVI with the precipitation of the previous month. Thus, years in which there are more precipitation and greater accumulation of rain in the previous month, such as 2009 and 2019

(Figure 4), tend to present vegetation with higher values of this index. In contrast, years that obtained lower average NDVI values, such as 2011, 2013, and 2017, are related to the lower number of precipitations and less rain accumulation in the month before the passage of the satellite (Figure 4).

Figure 4. Monthly daily precipitation (a) and accumulated in the month before the date of passage of the satellite (b) in the municipality of Petrolina, Pernambuco.

In June 2009, there was a greater number of rainfall compared to the others, one of which was above the climatological average (Figure 9), however, it is noted that the date of the satellite's passage is at the beginning of the month, thus the highest NDVI values are conditioned mainly by the precipitation of the previous month (57.8 mm). In the other years, there was a record of below-average rainfall, except for April 2019, which obtained two records above the climatological average of 2 mm. The month of April 2019 is the one with the highest rainfall totals with the accumulation of 7 mm of rain, with the 15th being the rainiest. June 2009 had an accumulation of 5.2 mm, while the other years had accumulations below 3 mm of rain.

The months of May to October constitute the dry period of the region, which justifies the low total rainfall observed in April, on the other hand, it integrates the end of the rainy period that underlies the greatest accumulation of precipitation in that month. According to Silva et al. (2017), in this region, most annual precipitation is concentrated in the first and fourth quarters, with 57 and 24%, respectively. In the second (season evaluated in this study) and third quarters, the percentage is lower, with 16 and 3%, respectively.

Like the NDVI, the Leaf Area Index (LAI) is also related to water availability. Thus, the years 2009 and 2019 showed a higher LAI, as they have more vegetation cover and, consequently, a higher density of vegetation (Figure 5). In those years,

values are predominant between 1.3647 m. m⁻² in the areas of forest formation and LAI ranging from 1.3647 to 7.0111 m. m⁻² in agricultural areas.

Figure 5. Spatial distribution of the Leaf Area Index (LAI) in Vale do Submédio São Francisco in the years 2009, 2011, 2013, 2016, 2017, and 2019.

In 2011, 2013, 2016, and 2017 it can be seen that the LAI is mostly located at around 0.2084 m. m⁻², characterizing low rates about the other years, indicating the presence of thinner vegetation, except for areas focused on agriculture.

The variation in vegetation density can be seen more clearly in Figure 6, where through NDVI, the classification of vegetation cover was obtained according to the Woody Vegetation Biomass Index (WVBI). Following the same pattern of the indices already discussed, the years 2009 and 2019 show a higher plant density showing the dense and very dense tree classes in

most of the analyzed territorial extension, which explains the higher values of NDVI, SAVI, and LAI for those years.

It is noted that in the years 2011, 2013, 2016, and 2017, there is a characterization of more heterogeneous vegetation, revealing a more diverse distribution of vegetation cover in the region, in which there is the existence of very thin shrubby to very dense tree vegetation. Areas of non-forest formation (agriculture and pastures) are included in the classification, although they do not represent native vegetation in the Caatinga, to have a broader view of the region's plant distribution.

Figure 6. Classification of vegetation in the Vale do Submédio São Francisco in the years 2009, 2011, 2013, 2016, 2017, and 2019.

PAR distribution in the São Francisco Valley region follows the same pattern over the years (Figure 7) with values ranging from approximately 311 to 357 $W. m^{-2}$. As the slope directly influences the radiation that reaches the surface (Vianello and Alves, 2012) it is observed that in all situations, regions with lower slopes presented lower values of PAR available at the

surface, while locations of higher altitudes had higher values of radiation. Studies by Lopes et al. (2013), in the Serra da Mantiqueira, southeastern Brazil, observed that the increase in solar radiation incident with altitude is related to the increase in direct solar radiation and the decrease in diffuse solar radiation.

Figure 7. Distribution of Photosynthetically Active Radiation (W. m^{-2}) in the Vale do Submédio São Francisco in the years 2009, 2011, 2013, 2016, 2017, and 2019.

As shown in Figure 7, the years 2009 and 2011 presented the lowest PAR values, with very close spatial variation (311.47 to 316.13 W. m^{-2}), with the predominant incidence from 311 to 314 W. m^{-2} in the analyzed extent. In contrast, 2019 had the highest amounts of incident radiation, ranging from 354.41 to 357.38 W. m^{-2} , with major values from 354 to 355 W. m^{-2} spatially distributed. Souza et al. (2015) found PAR values ranging from 92 to 370 W. m^{-2} , between the years 2011 and 2013, for the same region.

Although the difference in the ranges of variation of the PAR between the images (Figure 7) is small, this inequality can occur due to solar declination and some factors that act on the transmissivity of the atmosphere at the time of the satellite's passage, such as the presence of cloudiness and the amount of atmospheric

humidity, which showed close values between the dates, as can be seen in Table 1.

Days when the solar declination is closer to the latitude of the region cause greater availability of radiation on the surface, thus, images collected in months closer to the day when the Sun reaches the region's vertical location (end of February) have higher values of PAR (image obtained in April, in the fall), showing a decrease as the distance from this event (images obtained in June, in winter).

The PAR data obtained at the meteorological station of the National Institute for Space Research (INPE), are close to those obtained in the satellite estimate, which has an underestimation in the values, as can be seen in Table 5.

Table 5. Photosynthetically Active Radiation (PAR) obtained from the automatic meteorological station at INPE, Petrolina, Pernambuco (PARobs) and estimated via satellite Landsat 5 and 8 (PARest).

Date	Time	PARobs	PAR est	Standard deviation	Error (%)
06/04/2009	12:36	341.30	313.80	13.75	8.06
06/10/2011	12:37	328.70	311.73	8.48	5.16
05/30/2013	12:50	361.09	328.83	16.13	8.93
06/10/2017	12:47	331.96	320.19	5.88	3.54

With the incidence of photosynthetically active radiation, radiative processes begin. These processes are related to the fractionation of the

PAR through its interaction with the surface, being predisposed to be reflected, absorbed, and transmitted, which depend on the surface

conditions. Vegetated regions tend to absorb and transmit more radiation than regions of exposed soil (Monteiro et al., 2014). It is worth mentioning that factors such as the physiology of the plant species, size, and geometry of the plants; color, size, architecture, and age of the leaves; spatial distribution of vegetation and angle of incidence of sunlight (Pereira et al., 2002) directly affect the PAR fragmentation proportions.

Upon contact with the surface, the first process by which the PAR is submitted is

reflection, which is directly related to the albedo. The region of Vale do Submédio São Francisco had the lowest albedos in the years 2009 and 2011 (Figure 9), exposing the prevalence of values ranging from 0.026 to 0.14 in most of the region, indicating a lower reflectance of solar radiation in these areas. There is a manifestation of areas with an albedo of 0.251, and ranging from 0.363 to 0.475, being related to areas of exposed soil and urban infrastructure.

Figure 9. Spatial distribution of the surface albedo in the Vale do Submédio São Francisco in the years 2009, 2011, 2013, 2016, 2017, and 2019.

In the other years, the spatial distribution of albedo was similar (Figure 9), with 0.140 to 0.251 as the predominant variation range, where the highest values of this variable are located in areas of thinner vegetation, exposed soil, and urban infrastructure. Areas focused on agriculture, located close to the São Francisco River (Figure 1), showed an albedo of around 0.251 (Figure 9), an albedo characteristic of agricultural areas in this region (Silva et al., 2016; Silva et al., 2019).

Places with higher albedos (0.363 to 0.475) are more expressive and regular in the years 2013, 2016, 2017, and 2019 than in 2009 and 2011, suggesting the existence of more areas with no vegetation. Conti (2011) reports that those areas that show high reflectance due to deforestation, when in large extensions, result in the reduction of available thermal energy, and when aggravated by

the absence of cloudiness (favoring the escape of infrared radiation), they can cause a change in the dynamics convective of the region, causing the non-formation of upward convective currents, an unfavorable condition for the formation of rains.

In general, regions of Caatinga (forest and countryside formation) obtained albedo ranging from 0.026 to 0.251, a result that is within the reflectance patterns of natural vegetation in the Caatinga (Silva et al., 2019). Areas with this type of coverage have lower albedo values, as the presence of vegetation on the surface alters the dynamics of reflection, since plants, especially large ones, have a high capacity for absorbing solar radiation as a result of reflections multiple inside the canopy (Monteiro et al., 2014).

The areas of water bodies, especially the São Francisco River, showed albedo values

ranging from 2.5 to 14% (Figure 9) corroborating these results, Silva et al. (2016) and Silva et al. (2019) found values below 9% of albedo for water bodies in that region.

In this sense, the distribution and density of vegetation directly influence this variable, consequently affecting the quantity of reflected

PAR. Figure 10 shows the variation of the average albedo in favor of the vegetation classes (Table 3), it is noted that there is an inversely proportional association between the plant density and the reflectance of the surface, as already reported by Pavão et al. (2015) and Pavão et al. (2017).

Figure 10. Variation of the average surface albedo from 2009 to 2019 according to the classification of the vegetation cover in the Vale do Submédio São Francisco.

The reflected fraction of photosynthetically active radiation (PAR_r) follows the same albedo distribution pattern, as shown in Figure 11, where the highest amounts of PAR were reflected in regions that had lower vegetation densities, exposed soil, and urban areas.

The years 2009 and 2011 obtained in the areas of native vegetation (forest and countryside formation) reflected amounts of 15.03 to 49.01 $W \cdot m^{-2}$ of radiation (Figure 11), corresponding to 2.6 and 14% of PAR, respectively. In the other years, these regions exhibited PAR_r values around 49.01 $W \cdot m^{-2}$. Andrade et al. (2014) found the reflected

PAR ranging from 0 to 16 $W \cdot m^{-2}$, in areas of the Atlantic Forest, values relatively lower than the Caatinga because the Atlantic Forest has denser biomass (Lopes et al., 2013)

In agricultural areas, PAR_r showed a variation from 49.01 to 83.54 $W \cdot m^{-2}$ (14 to 25.1% of the incident PAR) in the years 2009 and 2011 and a value of 83.54 $W \cdot m^{-2}$ in 2013, 2016, 2017, and 2019. In urban areas and exposed soil, these values were between 116.33 and 150.75 $W \cdot m^{-2}$, representing 36.3 and 47.5%, respectively, of the incident photosynthetically active radiation.

Figure 11. Distribution of the reflected fraction (PAR_r) of Photosynthetically Active Radiation in the Vale do Submédio São Francisco in the years 2009, 2011, 2013, 2016, 2017, and 2019, in two units of measurement ($W. m^{-2}$ and percentage - %).

The irregularity in the distribution of this fraction of radiation is a direct consequence of the action of the surface reflectance. Therefore, vegetated areas, especially those with large vegetation, tend to have less albedo due to the multiple processes of reflection inside the canopy, as previously emphasized and thus have a lower amount of reflected PAR. Parker et al. (2005) found lower canopy reflectance values in deciduous forest regions in the rainy season, when compared to the same region in the dry season, showing the effect of the presence of leaves on the albedo. Lopes et al. (2013) observed that, in areas of Atlantic Forest, the albedo of the surface varied from 8 to 17% between the rainy and dry seasons.

In contrast, regions, which have the most exposed surface, have a greater capacity for reflection due to the absence of vegetation, so that the “naked” surface, with no component that can trap this radiation, tends to reflect it. Consequences of this type of surface-atmosphere interaction

include the reduction of the thermo-hydro regulatory effect of biomass, leading to the priority conversion of the balance of available radiation to the sensitive heat flow, responsible for heating the air (Santos et al. 2014; Fausto et al., 2016; Pavão et al. 2017).

The amount of PAR absorbed (PAR_a) by the vegetation varied from 0 to $267.73 W. m^{-2}$, reaching absorption values of up to 74.05% of the incident PAR (Figure 12). The year 2009 presented the highest values of PAR_a spatially distributed in most of the territory, where there were amounts of radiation absorbed between 133.86 and $267.73 W. m^{-2}$ in the areas of forest formation, countryside, pasture, and agriculture.

The other years exhibited a similar spatial distribution, in which the highest values of absorbed radiation were recorded in the agricultural areas, characterizing the fraction of 37.03 to 74.05% (133.86 to $267.73 W. m^{-2}$) of the Incident PAR.

Figure 12. Distribution of the absorbed fraction (PAR_a) of Photosynthetically Active Radiation in Vale do Submédio São Francisco in the years 2009, 2011, 2013, 2016, 2017, and 2019, in two units of measurement ($W. m^{-2}$ and percentage - %).

The areas of forest and countryside formation in the years 2011, 2013, 2016, 2017, and 2019 had a variation in PAR_a from 0 to 133.86 $W. m^{-2}$, corresponding to 0 and 37.03% of PAR, respectively, being visibly lower to the year 2009 (Figure 12). Souza et al. (2015) found a variation of 24 to 61% in the fraction absorbed from PAR by the Caatinga vegetation, in the city of Petrolina between the months of January 2012 and January 2013.

It is noted that agricultural areas have a higher amount of absorbed PAR, this situation is probably due to the higher LAI of these areas when compared to natural vegetation. The efficiency in

absorbing the intercepted radiation is directly related to the leaf area index, therefore higher densities of biomass absorb a greater amount of incident radiation.

The fraction transmitted from PAR (PAR_t) showed a very close distribution pattern between years (Figure 13), in which the largest proportions of PAR (128.78 to 255.23 $W. m^{-2}$) were transmitted in native forest regions, except for 2009, in which these areas had lower values of radiation transmitted through the canopy (0 to 128.78 $W. m^{-2}$), probably due to the higher vegetation rates recorded on this date.

Figure 13. Distribution of the transmitted fraction (PAR_t) of Photosynthetically Active Radiation in Vale do Submédio São Francisco in the years 2009, 2011, 2013, 2016, 2017, and 2019, in two measurements units ($W. m^{-2}$ and percentage - %).

The agricultural regions showed to have a smaller amount of transmitted radiation concerning the other vegetated areas (Figure 13), varying from 10.75 to 103.48 $W. m^{-2}$, representing from 2.23 to 26.67% of the PAR. Because they have smaller vegetation, the radioactive processes that act in these areas in greater quantity are absorption and reflection, as can be seen in Figures 11 and 12.

The areas that contain vegetation in lower density have a greater amount of radiation transmitted because they have a lesser capacity to intercept radiation, so more voluminous canopies allow less solar radiation to pass through (Andrade et al., 2014). Studying tropical deciduous forests in Mexico, in different seasons (rainy and dry), Parker et al. (2005) showed that in the rainy season the PAR transmittance fraction was lower than in the dry season, precisely due to the greater presence of

leaves, since it is a deciduous forest. In an area of the Atlantic Forest, in Alagoas, Andrade et al. (2014) found a variation in the PAR transmitted from 0 to 40 $W. m^{-2}$.

Among the PAR subdivisions on the surface, the transmitted portion that is reflected by the soil and absorbed by the lower portion of the plant canopy (PAR_{ra}) is the one that represents the lowest proportion. It can be seen in Figure 14 that the variation of PAR_{ra} reaches up to 5% of the incident PAR. The year 2009 stands out for presenting higher values of PAR_{ra} spatially distributed (Figure 14) with a variation of 3.75 to 5% of the PAR (12.7 to 16.93 $W. m^{-2}$), possibly because it has a greater quantity of vegetation, the reflective processes that take place inside the vegetation favor the reflection of radiation by the soil and absorption by the abaxial leaf region.

Figure 14. Distribution of the fraction reflected by the soil and absorbed by the lower part of the vegetation (PAR_{ra}) of the Photosynthetically Active Radiation in the Vale do Submédio São Francisco in the years 2009, 2011, 2013, 2016, 2017, and 2019, in two units of measurement ($W. m^{-2}$ and percentage - %).

A slight increase in the distribution of PAR_{ra} can be observed in the years 2011 and 2019 when compared to 2013, 2016, and 2017, especially in the Caatinga areas, where majority values were obtained between 4.24 and 12.70 $W. m^{-2}$ (1.25 and 3.75%). In 2013, 2016, and 2017, there is a similar provision of PAR_{ra} , with a variation from 0 to 4.24 $W. m^{-2}$ (0 to 1.25%) in native forest areas. Andrade et al. (2014) found a

variation from 0 to 1.5 $W. m^{-2}$ of this PAR component, in Atlantic Forest, showing the absorption of most of the radiation that is transmitted by the leaves and branches inside the canopy.

The extinction coefficients found ranged from 0.73 to 0.86 (Table 6). These coefficients indicate that the Caatinga vegetation has predominantly horizontally arranged leaves, capable of intercepting a greater amount of photosynthetically active radiation, being more efficient in harnessing this energy. According to Lambers et al. (1998), the extinction coefficient tends to be low for predominantly erect leaves, but it is high for horizontally arranged leaves, especially for larger leaves or leaflets.

Table 6. Leaf area index and extinction coefficient according to the Lambert-Beer Law for the natural vegetation of the Vale do Submédio São Francisco.

Year	LAI	ϵ	Equation	k
2009	0.87915	0.61	$\ln(1 - 0.61) = -0.86 \text{ LAI}$	0.86
2011	0.30362	0.38	$\ln(1 - 0.38) = -0.83 \text{ LAI}$	0.83
2013	0.43239	0.44	$\ln(1 - 0.44) = -0.82 \text{ LAI}$	0.82
2016	0.44235	0.45	$\ln(1 - 0.45) = -0.79 \text{ LAI}$	0.79
2017	0.32272	0.39	$\ln(1 - 0.39) = -0.73 \text{ LAI}$	0.73
2019	0.61565	0.52	$\ln(1 - 0.52) = -0.73 \text{ LAI}$	0.73

LAI – Leaf Area Index; ϵ – Interception efficiency; k – light extinction coefficient.

Statistically, clear relationships between the PAR components and the leaf area index can be seen in Figure 15. With little distinction between

the dates studied, there are directly proportional relationships between the absorbed fractions (PAR_a and PAR_{ra}) and the area index leaf with the

coefficient of determination (R^2) varying from 0.89 to 0.98 (Table 5), indicating that when there is a higher leaf area index, there is a greater absorption of solar radiation, obviously due to the greater number of leaves exposed to this radiation. The LAI explains the variation of the PAR absorbed by

the canopy from 89 to 98%, is significant at the 99% confidence level and probability $p < 0.01$. Pearson's coefficient (r) ranged from 0.94 to 0.99, indicating a very strong correlation between the two variables.

Figure 15. The second-order polynomial model between the Leaf Area Index (LAI) and the PAR balance components, photosynthetically active radiation absorbed (PAR_a), reflected (PAR_r), reflected by the soil and absorbed by the lower part of the vegetation (PAR_{ra}) and transmitted (PAR_t), in the years 2009, 2011, 2013, 2016, 2017 and 2019, in the Vale do Submédio São Francisco.

Concerning reflected radiation, although the adjustments found to show the lowest values of R^2 (Table 6), it is noted that there is a triangular formation in the dispersion of the data, indicating a tendency to decrease the reflected radiation as it increases the leaf area index, waiting for behavior according to the data shown in Figure 10. Concerning there was a variation from 0.42 to 0.76, configuring a moderate to strong correlation (Table 6).

The fraction transmitted from PAR and LAI presented, with an R^2 ranging from 0.90 to 0.98 and r and from 0.95 to 0.99, characterizing a very strong correlation, in which there is greater

radiation transmission through the canopy in areas that have a lower leaf area index, since the leaves are attenuating agents of this component through interception and, in their absence, allows PAR to reach the soil more easily, corroborating with Parker et al. (2005), who found higher transmittance values in the dry season, in deciduous forests, which, due to their lack of leaves (absence of LAI), allowed a greater amount of radiation to pass through the canopy. Results also found by Andrade et al. (2014) who describe a reduction in radiation that is transmitted through the canopy as the LAI increases in Atlantic Forest areas in Alagoas.

Table 7. Coefficients of the second-order polynomial model equation ($ax^2 + bx + c$), determination coefficient (R^2) and Pearson's correlation coefficient (r) obtained between the Leaf Area Index (LAI) and the components of the PAR balance.

Year	Component	a	b	c	R^2	r
2009	PAR _a	-43.41	191.24	8	0.98**	0.99**
	PAR _r	10.96	-32.89	64.4	0.55**	0.74**
	PAR _{ra}	-2.93	12.90	0.5	0.98**	0.99**
	PAR _t	35.31	-170.81	240.9	0.98**	0.99**
2011	PAR _a	-62.24	231.58	-3.3	0.99**	0.99**
	PAR _r	30.68	-72.37	72.8	0.58**	0.76**
	PAR _{ra}	-4.20	15.62	-0.2	0.99**	0.99**
	PAR _t	35.49	-174.23	242.6	0.97**	0.99**
2013	PAR _a	-20.06	174.48	11	0.95**	0.97**
	PAR _r	5.57	-39.58	74.6	0.35**	0.59**
	PAR _{ra}	-1.35	11.77	0.7	0.95**	0.97**
	PAR _t	15.76	-146.09	242.6	0.96**	0.98**
2016	PAR _a	-19.74	168.52	14	0.90**	0.95**
	PAR _r	6.54	-44.77	79	0.27**	0.52**
	PAR _{ra}	-1.33	11.37	0.9	0.90**	0.95**
	PAR _t	14.44	-134.58	239.2	0.93**	0.97**
2017	PAR _a	-20.43	165.30	11.6	0.89**	0.94**
	PAR _r	5.25	-33.62	68.2	0.18**	0.42**
	PAR _{ra}	-1.38	11.15	0.8	0.89**	0.94**
	PAR _t	16.50	-142.46	239.8	0.90**	0.95**
2019	PAR _a	-20.40	174.49	19.4	0.95**	0.97**
	PAR _r	4.62	-33.24	77.8	0.33**	0.57**
	PAR _{ra}	-1.38	11.77	1.3	0.95**	0.97**
	PAR _t	17.08	-152.53	256.4	0.96**	0.98**

PAR_a - photosynthetically active radiation absorbed; PAR_r - photosynthetically active radiation reflected; PAR_{ra} - photosynthetically active radiation reflected by the soil and absorbed by the lower part of the vegetation; PAR_t - photosynthetically active radiation transmitted.

** significant adjustment to 1% probability ($p < 0.01$) by the t-student test.

According to what can be seen in Figure 15, it is noted the importance of the existence of foliage in the fractionation and use of PAR, thus highlighting the relevance of existing vegetation cover, especially in urban areas, because of the benefits of vegetable thermoregulation. In studies carried out in Caatinga by Fernandes et al. (2019), seeking to characterize the energy balance, it was found greater fractions of the radiation balance being directed to sensitive heat in areas of thinner vegetation and of smaller ones in areas of higher

density, indicating greater surface heating in less dense areas.

Regarding the balance of photosynthetically active radiation in favor of the different classes of vegetation, it can be seen in Figure 16 that as the density of vegetation increases (class 3 - thin shrubby shrub vegetation to 11 - very dense tree) there is a decrease in PAR_t and PAR_r and, an increase in PAR_a and PAR_{ra}, on all the dates, analyzed.

Figure 16. Average fractionation of Photosynthetically Active Radiation (PAR) in areas of natural vegetation, in the Valley of the Submédio São Francisco, in the years 2009, 2011, 2013, 2016, 2017, and 2019.

The data shown in Figure 16 validates the information already mentioned related to how the dense vegetation cover has a greater absorption capacity, less reflection, and less transmission of photosynthetically active radiation. Therefore, there is greater use of this resource when compared to the lower levels of plant density. Besides, it is noted in the distribution of the PAR that the largest proportion, in this type of land cover, is transmitted, corresponding to 50 to 80% of the incident PAR. While the other components vary from 5 to 30% for PAR_a , from 17 to 20% for PAR_r , and from 0.4 to 2% for PAR_{ra} . It is worth mentioning that the distribution of PAR is similar on all the dates analyzed for the coverage of native forests.

More dense areas, such as class 11 (very dense tree vegetation) have the average fractionation of the PAR in 50% transmitted, 30% absorbed, 17% reflected, and 2% reflected by the soil and absorbed by the lower part of the canopy.

In contrast, areas with sparse vegetation, such as class 3 (thin shrubby shrub vegetation) have the average fraction of PAR in 80% transmitted, 8% absorbed, 20% reflected, and 0.5% reflected by the soil and absorbed by the part bottom of the canopy.

The PAR subdivisions in the MapBiomass classification consider the different types of land cover existing in the studied area and can be seen in Figure 1. It is noted that the distribution pattern is similar on the dates evaluated, in which there are different fractions between the classes.

In areas of natural vegetation (3 - Forest Formation, 4 - Savanna, and 12 - Countryside Formation) the largest portions of PAR are destined to the PAR_t and PAR_a components, followed by PAR_r and PAR_{ra} . In agricultural areas (15 - Pasture, 20 - Sugar cane, 21 - Agriculture and Pasture and 41 - Temporary crops), it is observed that 40 to 50% of PAR is transmitted, applying the same proportion to the portion absorbed, while approximately 20% corresponds to the PAR_r and

PAR_{ra} components. Areas of permanent cultivation (36) are more similar to the proportions of areas of

natural vegetation, due to their size and leaf area. (Figure 17).

Figure 17. Average fractionation of Photosynthetically Active Radiation (PAR) in classes of land use and cover, in the Vale do Submédio São Francisco, in the years 2009, 2011, 2013, 2016, 2017, and 2019.

According to Parker et al. (2005) deciduous forests in Mexico, denser than the Caatinga, absorb about 95% of the incident photosynthetically active radiation, of which 50% is absorbed by the leaves, 25% by non-leaf tissues, 20% by the soil, the 5% remaining is reflected by the canopy. In contrast, exclusive areas of natural vegetation in the Vale do Submédio São Francisco (Figure 17), have about 25% of absorbed radiation, 13% reflected, and 62% transmitted.

In general, it is noted that the type of cover directly affects the distribution of photosynthetically active radiation on the surface, which is more used in vegetations that have higher densities. From the data exposed, it is observed that

most of the incident PAR is not absorbed by the plants, therefore, it is intended for other purposes such as heating the soil and water, reflected the atmosphere, among others.

According to the data presented, the need for further studies that seek to analyze the radiative processes in native forests is emphasized, mainly aimed at characterizing the impacts of the removal of this vegetation cover and its conversion in areas with other purposes on the availability of energy on the surface and altering biophysical processes once imbalanced in the ecosystem. So that there is the supply of more information to assist environmental planning aiming at the preservation of the biome.

Conclusion

The vegetation in the Vale do Submédio São Francisco region has great heterogeneity, ranging from thin shrub to very dense tree classifications, thus presenting a complex relationship with the balance of photosynthetically active radiation on the surface.

The spatio-temporal analysis of the components of the photosynthetically active radiation balance over the seasonally dry tropical forest showed that most of the incident PAR was destined for transmission (from 50 to 80%), followed by absorption (5 to 30%) and reflection (17 to 20%), varying according to the density of the vegetation.

The relationship between the Leaf Area Index indicates that as the density of vegetation increases, there is a decrease in PAR_t and PAR_r and an increase in PAR_a and PAR_{ra} . Thus, the dense vegetation cover has a greater absorption capacity, less reflection, and less transmission of photosynthetically active radiation, configuring a greater use of this resource when compared to the lower levels of plant density.

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