Water productivity assessment by using MODIS images and agrometeorological data in the Petrolina municipality, Brazil

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ABSTRACT

The municipality of Petrolina, located in the semi-arid region of Brazil, is highlighted as an important agricultural growing region, however the irrigated areas have cleared natural vegetation inducing a loss of biodiversity. To analyze the contrast between these two ecosystems the large scale values of biomass production (BIO), evapotranspiration (ET) and water productivity (WP) were quantified. Monteith´s equation was applied for estimating the absorbed photosynthetically active radiation (APAR), while the new SAFER (Simple Algorithm For Evapotranspiration Retrieving) algorithm was used to retrieve ET. The water productivity (WP) was analysed by the ratio of BIO by ET at monthly time scale with four bands of MODIS satellite images together with agrometeorological data for the year of 2011. The period with the highest water productivity values were from March to April in the rainy period for both irrigated and not irrigated conditions. However the largest ET rates were in November for irrigated crops and April for natural vegetation. More uniformity of the vegetation and water variables occurs in natural vegetation, evidenced by the lower values of standard deviation when comparing to irrigated crops, due to the different crop stages, cultural and irrigation managements. The models applied with MODIS satellite images on a large scale are considered to be suitable for water productivity assessments and for quantifying the effects of increasing irrigated areas over natural vegetation on regional water consumption in situations of quick changing land use pattern.

Keywords: evapotranspiration, biomass production, surface albedo, surface temperature, NDVI, surface resistance.

1. INTRODUCTION

The municipality of Petrolina has becoming an important growing region, as a result of the development of irrigation technologies at the vicinities of the São Francisco River, in the semi-arid region of Brazil. The dominant vegetation cover is "Caatinga", which is a natural semiarid vegetation type encountered mainly in the Brazilian Northeast region. The dry period is characterized by brown vegetation, however, during the rainy period, it turns a verdant green. The main commercial irrigated crops are grapes, mangos, guava and banana. Intensification of agriculture has caused widespread land cover changes during the last decades. Water use from irrigated plots exceeds that from the natural ecosystems, promoting a reduction of the river stream flow by the increasing of biomass production (BIO) and evapotranspiration (ET) rates outside the rainy periods.

In these situations of fast land use change, estimations of BIO, ET and water productivity (WP) on a large scale are becoming very important in developing semi-arid regions for supporting policy planning and decision-making about natural resources uses. The main ways for these estimations include satellite remote sensing-based calculations, which provide suitable alternatives to obtain the biophysical parameters involved on these processes[1].

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The energy captured during photosynthesis is represented in part by the total dry matter on a unit area of the vegetated surface at any given time. An important step towards quantifying the net production (dry matter minus respiration) is the net CO_2 uptake in vegetation systems, termed net primary production (NPP) or BIO, which even though a crude measure, it is useful for making comparisons of different land areas and use. For obtaining estimates of carbon balance the light-use efficiency concept devised based on radiation interception can be applied[2]. The degree of radiation interception is variable throughout the year and during the crop growing periods[3,4].

Satellite remote sensing is an efficient tool for crop area and BIO estimates, providing spatial and temporal information on the location and state of vegetation[1]. The high correlation between spectral bands and vegetation parameters provides information for BIO estimations over a wide area[5]. MODIS data were processed in combination with precipitation, temperature and elevation for mapping BIO in forest from California[6]. BIO was also estimated from MODIS images in Guandong, China, to evaluate the feasibility of setting up new biomass power plants and to optimize the locations of plants[7]. In Brazil BIO estimations have been made in São Francisco[1] and Amazon[8] basins by using Landsat images.

The BIO model proposed based on global solar radiation (R_G) and canopy development has acceptable accuracy[9], and it can be used together with any satellite data for quantifying the spatial and temporal variation of BIO in composite landscapes[10-12]. Besides BIO, one need to quantify also ET to reach at the water productivity (WP), which in the current research is considered as the ratio of BIO to ET for both natural vegetation and irrigated crops. From field measurements, the calculation of ET has been made in these mixed agro-ecosystems in the semiarid region of Brazil by using the Bowen ratio (BR) method, eddy covariance and (EC) techniques[4,13-15]. However, the spatial variability is significant and extrapolation of ET data directly from flux tower to a surrounding landscape environment can lead to inaccurate large scale estimates.

The spatial variability is significant and the variation is caused by different amounts of precipitation, seepage, flooding, irrigation, hydraulic characteristics of soils, vegetation types and densities. The temporal changes in ET can be ascribed to weather conditions and vegetation development[1]. Remote sensing, excluding the need of quantifying other complex hydrological processes, is a suitable means for determining and mapping the spatial and temporal structure of ET on a large scale. The use of satellite images to measure ET from mixed ecosystems has been done also in distinct climate regions[16-18]. Aiming to increase the spatial scales of field measurements in the Brazilian semiarid region, ET was obtained by means of Landsat images with application of the SEBAL algorithm[18] following processes of calibration and validation[11,12].

Although the SEBAL model performed well in the Brazilian semiarid region with Landsat images[12], its application problem lies on the assumption of zero ET for dry pixels, which is difficult during the rainy season in the Brazilian semiarid region, because during this period the regional moisture status is homogeneous in the mixed ecosystems of irrigated crops and natural vegetation. On the other hand, although Landsat images having a good spatial resolution, the difficult of their use is the poor temporal re-visit period of 16 overpass days.

Considering the simplicity of application, and its needing neither crop classification nor extreme conditions, the algorithm now called SAFER (Simple Algorithm For Evapotranspiration Retrieving) for acquiring ET has been developed and validated with field data from four flux stations and Landsat images involving irrigated crops and natural vegetation, in the Brazilian semi-arid conditions[14,19].

The basic inputs for the SAFER model are surface albedo, surface temperature and NDVI, which can be obtained from MODIS images together with interpolated weather data[19]. Although with a worse spatial resolution than that for Landsat images, the MODIS sensor views the entire surface of the Earth every one to two days, being appropriate for retrieving vegetation and water variables on the large scale.

The objective of this paper is to combine the well known model of Monteith's BIO model[9] with the new SAFER algorithm[19] to demonstrate that MODIS satellite measurements, combined with agro-meteorological data, can be used for water productivity assessments in a mixed agro-ecosystems with irrigated and natural vegetation on a large scale. The municipality of Petrolina, Pernambuco state, Brazil, having a net of 10 automatic agrometeorological stations is the study area of the current research.

2. MATERIAL AND METHODS

MODIS images together with 10 agrometeorological stations were used, with 6 being for 2010 and 9 for 2011, following field calibrations and interpolations. Energy balance measurements in irrigated crops and natural vegetation, during 2002 and 2004[14], were used to develop regression equations for surface albedo (α_0) and for surface temperature (T_0). Figure 1 shows the locations of the Petrolina municipality, Pernambuco (PE) state, Northeast Brazil and the agrometeorological stations.

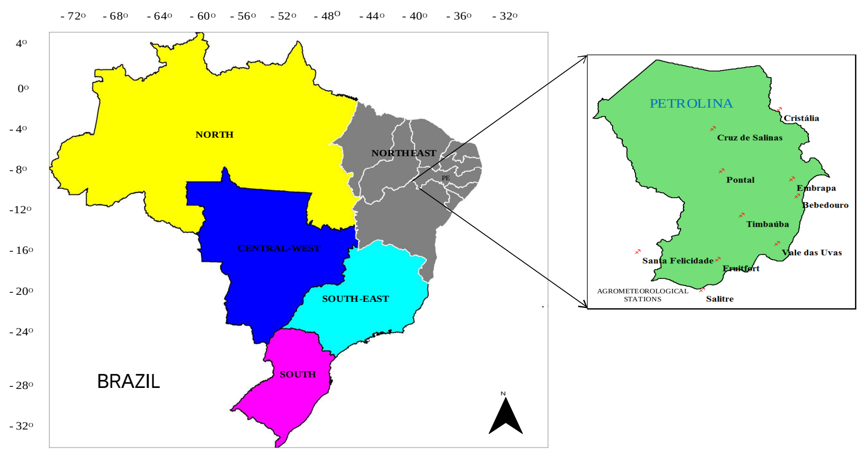

Figure 1. Location of the Petrolina municipality, Pernambuco (PE) state, Northeast Brazil, and the agrometeorological stations used for the interpolation processes.

MODIS is an instrument onboard Terra platform with 36 spectral bands between 0.405 and 14.385 µm, acquiring data at three spatial resolutions (250m, 500m and 1,000m). The land product used in the current study was Level-1B (L1B) data set, which contains radiances for these bands. Only four (two reflectance and two thermal bands) were used. These are reflective solar bands (Bands 1 and 2, red and near infrared) with a spatial resolution of 250m and the thermal emissive bands (Bands 31 and 32) with a spatial resolution of 1,000m.
For α_0 calculations the reflectance values for band 1 and 2 were used, according to the following linear model[20]:

$$\alpha_0 = a + b\alpha_1 + c\alpha_2 \tag{1}$$

where α_1 and α_2 are the planetary albedo for the bands 1 and 2 from MODIS satellite measurements, and a, b, and c are regression coefficients obtained comparing these measurements with field data[14], thus including the atmospheric effects through the radiation path. The values found for the Brazilian semiarid conditions were, respectively, 0.08, 0.41 and 0.14.

For the surface temperature (T_0), the thermal emissive bands 31 and 32 were used. After trying the split technique, comparing with the aerodynamic T_0 data from the same energy balance experiments as for α_0[14], it was observed that several terms of the model tested[21] could be neglected for the semi-arid conditions of the current study and the simpler regression equation could be applied with reasonable accuracy in relation to the field experimental data:

$$T_0 = aT_1 + bT_2 \tag{2}$$

where T_1 and T_2 are the brightness temperature from the bands 31 and 32 and the regression coefficients a and b were equally 0.50, also including already the atmospheric effects through the radiation path.

For both BIO and ET estimations, the Normalized Vegetation Index (NDVI) was an input, because it is a measure of the amount of vegetation at the surface:

$$\mathrm{NDVI} = \frac{\alpha_{p_{(2)}} - \alpha_{p_{(1)}}}{\alpha_{p_{(2)}} + \alpha_{p_{(1)}}} \qquad (3)$$

where $\alpha_{p(2)}$ and $\alpha_{p(1)}$ represent the planetary albedo over ranges of wavelengths in the near infrared (MODIS band 2) and red (MODIS band 1) regions of the solar spectrum, respectively.

With the images of α_0, T_0 and and NDVI, ET was obtained by the SAFER algorithm[19]

$$\frac{\mathrm{ET}}{\mathrm{ET}_0} = \exp\left[a + b\left(\frac{T_0}{\alpha_0 \mathrm{NDVI}}\right)\right] \qquad (4)$$

where ET_0 is the reference evapotranspiration with the values interpolated from the 10 agrometerological stations (Figure 1) calculated by the Penman-Monteith method[22] and a and b are regressions coefficients, which for the Brazilian semiarid conditions were found to be 1.8 and - 0.008, respectively.

The 24-hour values of the net radiation (R_n) can be described by the 24-hour values of net shortwave radiation, with a correction term for net longwave radiation for the same time scale:

$$R_n = (1 - \alpha_0) R_G - a\tau_{sw} \qquad (5)$$

where R_G is the incident global solar radiation and a is the regression coefficient of the relationship between net long wave radiation and atmospheric transmissivity (τ_{sw}) at the daily scale. The regression equation between the a coefficient and air temperature (T_a) was used[14]. Values of R_G and T_a were interpolated from the 10 agrometeorological stations showed in Figure 1[11].

The maps of the daily values of R_G were used to estimate the large scale Photosyntetically Active Radiation (PAR) for the same time scale:

$$\mathrm{PAR} = aR_G \qquad (6)$$

where a = 0.44 is the constant of the regression equation found under the Brazilian semiarid conditions that reflects the portion of R_G that can be used by leaf chlorophyll for photosynthesis[11].
The values of Absorbed Photosyntetically Active Radiation (APAR) can be approximated directly from PAR:

$$\mathrm{APAR} = f\mathrm{PAR} \qquad (7)$$

The factor f was estimated from the NDVI values[10,12]:

$$f = a\mathrm{NDVI} + b \qquad (8)$$

It was considered the coefficients a and b of 1.257 and -0.161, respectively, reported for a mixture of arable crop types[10].
BIO was then obtained as:

$$\mathrm{BIO} = \varepsilon_{max} E_f \mathrm{APAR}\ 0.864 \qquad (9)$$

Where E_F is the ratio of the latent heat flux (λE) to R_n, being λE acquired by transforming ET into energy units; ε_{max} is the maximum light use efficiency, which was considered 2.5 g MJ^{-1} for the majority c4 species in the study area; and 0.864 is a unit conversion factor[12].

For water productivity (WP) analyses involving both irrigated crops and natural vegetation the following indicator was used[23]:

$$WP = \frac{BIO}{ET} \tag{10}$$

For classifying irrigated crops and natural vegetation at the municipality level, the following model was applied by using a selected MODIS image during the naturally driest period of the year[24].

$$r_s = \exp\left[a\left(\frac{T_0}{\alpha_0}\right)(1 - NDVI) + b\right] \tag{11}$$

where a and b are regressions coefficients, which were found to be respectively 0.04 and 2.72 for the Brazilian semi-arid conditions. The r_s values were obtained from field experiments by inverting the Penman-Monteith equation[14] and the model represented by the Equation 11 was applied for MODIS images by using threshold values of 1500 s m^{-1} and 10,000 s m^{-1} together with logical functions in a GIS environment. r_s values bellow or equal to the left end of this range should be irrigated crops and above this limit and bellow the right end of the range, was considered to be natural vegetation. The superior limit was to exclude other features of the images which are not from vegetation.

When along the analysed year of 2011 there were no cloud free images, the ET/ET_0 and NDVI images from 2010 together with weather data for 2011 were used to fill the gaps, and successive interpolations were done until there were at least 3 images for each month. The average image for each month was then used together with the monthly grids of R_G, T_a and ET_0 from the 10 agrometeorological stations showed in Figure 1.

3. RESULTS AND DISCUSSION

As the weather driving forces for biophysical variables are solar radiation and precipitation, first the monthly behaviour of these meteorological parameters during the year of 2011 were analysed (Figure 2). For this purpose the data used were from the agrometeorological station of Pontal which was installed at the end of 2010 in the Petrolina municipality, Pernambuco (PE) state, Brazil (Lat. 09°02'30" S; Long. 40°32'56"W, see Figure 1).

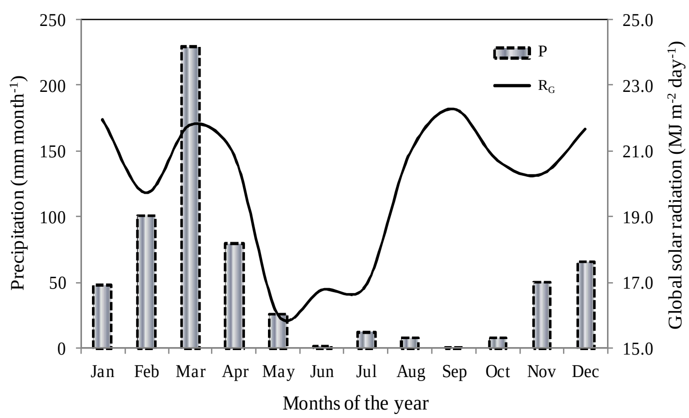

Figure 2. Monthly averaged daily values of global solar radiation (R_G) and totals of precipitation (P) during the year of 2011 at Petrolina, Pernambuco (PE) state, Brazil.

Having sufficient solar radiation and soil moisture, both, natural vegetation and irrigated crops will produce large amounts of biomass. For natural vegetation these best conditions occurred in March, while for irrigated crops they were in September as the plants developments are not dependent on precipitation. For the year of 2011 the total rainfall of

630 mm was 11% higher than the historical value registered at the older conventional station in Bebedouro (see Figure 1). Higher levels of R_G happened during the first and the last four months of the year. During the second semester the amount of rainfall is lower and the quick rise of R_G is appropriate for starting the growing seasons of irrigated crops. In the middle of the year, the naturally driest conditions and the lowest solar energy availability are less favourable for BIO considering both irrigated and not irrigated conditions.

The PAR being around 44% of R_G[11], is very high, and with the availability of water, this radiation is intercepted by the crop leaves for photosynthesis. With these levels of PAR, natural vegetation will produce large amounts of BIO during the rainy period, while outside this period there is a strong contrast with irrigated crops. After E_F and APAR calculations, the monthly and annual values of BIO were obtained applying Equation 9. Figure 3 presents the spatial variation of the BIO monthly values in the mixed agro-ecosystems for the year of 2011.

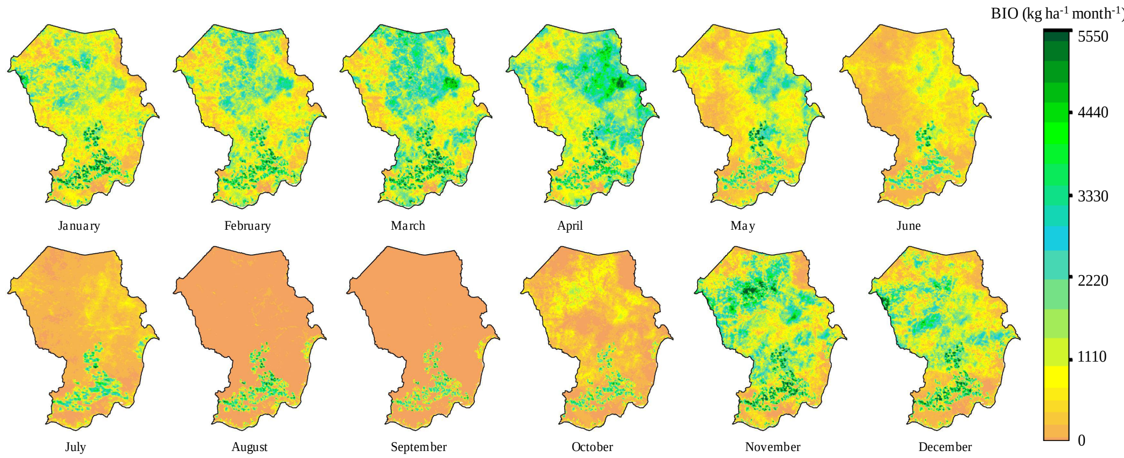

Figure 3. Spatial distribution of the monthly values of Biomass production (BIO) for the mixed agro-ecosystems during the year of 2011 in the Petrolina municipality, Pernambuco (PE) state, Brazil.

Considering the Petrolina municipality as a whole, the spatial and temporal variation of BIO along the year is evident, mainly when observing the wettest period from February to April with the driest one, from July to September. The maximum values occur in April, with some areas with BIO higher than 4,000 kg ha^{-1} $month^{-1}$, including irrigation and natural conditions, with an average BIO of 1,134 kg ha^{-1} $month^{-1}$ for the total area. Another pick with a mean value of 1,533 kg ha^{-1} $month^{-1}$ is verified in November, when the rain starts inducing the "Caatinga" species to a quick development and the crops are still well irrigated using the high energy availability during this month. On the other hand, the lowest BIO values occur in September, due to low soil moisture in natural vegetation, with a spatial average of 142 kg ha^{-1} $month^{-1}$ for the whole municipality.

Precipitation from January to April provided much water storage to the root zones of the "Caatinga" species, keeping this natural ecosystem wet and green, while from July to September, irrigated crops produced large amounts of BIO, as the soils are moist during the irrigation periods in absence or with little amount of rainfall. During the period outside the rainy period, from June to September the irrigated crops are very well highlighted from the natural vegetation. After this period the rain starts slowly and R_G increases quickly since July (see Figure 2) as a consequence of the apparent movement of the sun that reaches the zenith position under the conditions of low cloud cover.

The conjugated effect of increasing soil moisture and solar radiation contributes to an increment in the regional values of BIO. The highest standard deviation (STD) occurred in November, reaching to a STD value of 1,237 kg ha^{-1} $month^{-1}$, showing the largest heterogeneity during the year. On the other hand, as the majority of the Petrolina municipality areas are with "Caatinga", the driest month of September presents the lowest STD value of 519 kg ha^{-1} $month^{-1}$ as the natural species are at the dormancy stage. Considering the whole year, the BIO averaged value for mixture of agro-ecosystems was 11.7 ± 8.4 t ha^{-1} $year^{-1}$. According to previous studies with Landsat images, the range under the Brazilian semiarid region was from 14.0 to 34.0 t ha^{-1} year^{-1}, being the highest values for irrigated mango orchards (50 - 100 t ha^{-1} year^{-1}) and vineyards (30 - 100 t ha^{-1} year^{-1})[12].

Figure 4 presents the spatial distribution of the monthly ET pixel values for the year of 2011 at Petrolina municipality, Pernambuco (PE) state, Brazil.

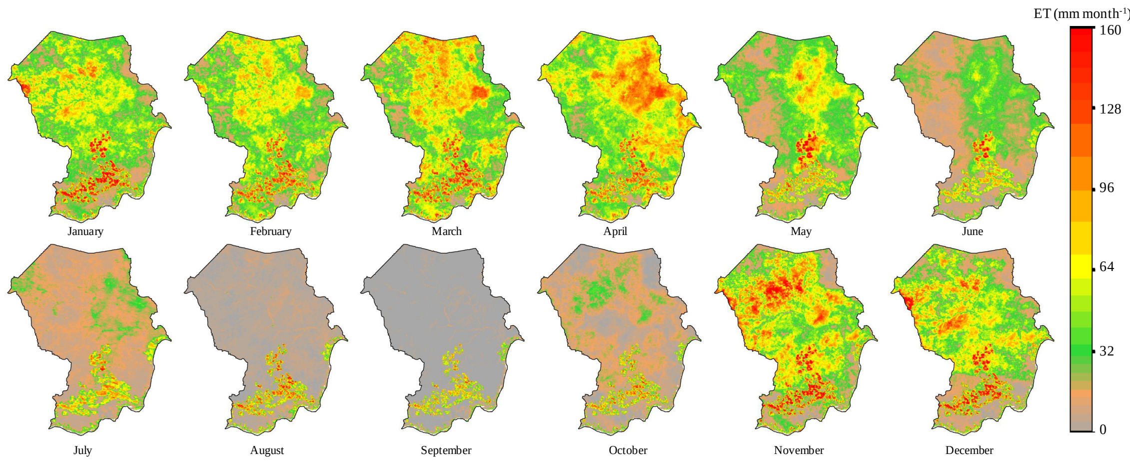

Figure 4. Spatial distribution of the monthly values of evapotranspiration (ET) for the mixed agro-ecosystems for the year of 2011 in the Petrolina municipality, Pernambuco (PE) state, Brazil.

As there is a relation between BIO and ET, similar trend for ET values are evident along the year. During the rainy period the maximums are verified in April, with a municipality average of 61 mm month^{-1}. In November there is another pick with a mean of 58 mm month^{-1}. Intermediate ET values in natural vegetation occur just after the rainy season, from May to June, because antecedent precipitation from January to April still keeps the natural vegetation brushes wet and green. As a consequence of the higher portions of the available energy reducing E_F, during the driest period of the year from July to October, the natural vegetation presents the lowest ET values, while the irrigated fields show the highest ones. Stomata close during dry natural conditions limiting transpiration and photosynthesis, and, in general, irrigation intervals are short (daily irrigation), with a uniform water supply, reducing the heat losses to the atmosphere in irrigated plots.

According to Figures 1 and 4, the effect of the soil moisture in the magnitude of the ET rates is strong. Pixels with values lower than 1.0 mm month^{-1} occur during the dry season representing the "Caatinga" species. The highest STD value of 35 mm month^{-1} occurred in November, as a consequence of the coupled effect of the start of the rains and the heterogeneity caused by differences in the irrigated crop stages. As in the case of BIO, the driest month of September presents the lowest STD of 17 mm month^{-1}. Considering the whole year and the averaged monthly ET, the annual value for mixture of agro-ecosystems was 438 ± 235 mm year^{-1}. Previous study in the semiarid conditions of the Brazilian Northeast reported the highest annual ET values for table grapes and mango orchards with those for natural vegetation close to the amounts of annual rainfall[12].

Figure 5 presents the spatial distribution of the WP monthly values for the year of 2011 at Petrolina municipality, Pernambuco (PE) state, Brazil.

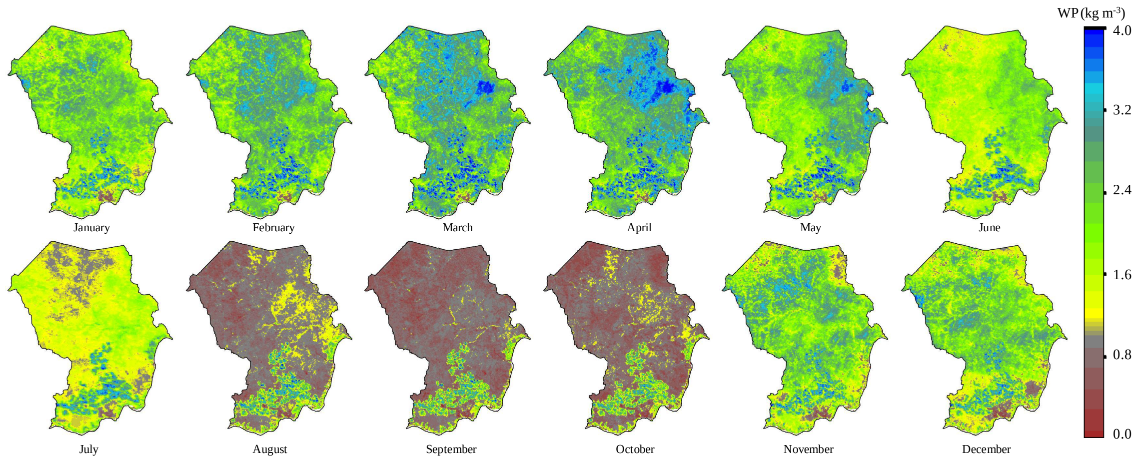

Figure 5. Spatial distribution of the monthly values of water productivity (WP) for the mixed agro-ecosystems for the year of 2011 in the Petrolina municipality, Pernambuco (PE) state, Brazil.

The maximum WP values occurred during the rainy period from March to April, around 2.7 kg m^{-3} with some areas reaching till 4.0 kg m^{-3}, including both irrigation and natural conditions. Another pick of an average of 2.2 kg m^{-3} happened in November, with maximums pixel values for irrigated crops, as a consequence of the high R_G levels. The lowest WP occurred from September to October, with an average value of 0.9 kg m^{-3}, because of the driest soil moisture conditions of the year and the smaller irrigated area in relation to that for natural vegetation. The largest variation is verified in November and the lowest one for June, with STD values of 0.6 and 0.5 kg m^{-3}, respectively. Considering the whole year, the WP averaged value for mixture of agro-ecosystems was 1.90 ± 0.4 kg m^{-3}. Maximum values are for irrigated crops, which multiplying by the harvest index it is possible to estimate the crop water productivity. Values for this index were found to be around 0.60 for vineyards and 0.80 for mango orchards under the semiarid conditions of the Brazilian Northeast[12].

After using Equation 11 and the conditional functions in a GIS environment, the vegetation was classified into irrigated crops and natural vegetation. Table 1 presents the mean values and standard deviations of the biophysical parameters in Petrolina municipality, Pernambuco (PE) state, Brazil.

Table 1. Averaged monthly values and standard deviations of the biophysical parameters for the year of 2011 in Petrolina Municipality, Pernambuco (PE) state, Brazil: Biomass production (BIO); evapotranspiration (ET); and water productivity (WP).

Months/Year	BIO ($t\ ha^{-1} month^{-1}$)		ET ($mm\ month^{-1}$)		WP ($kg\ m^{-3}$)	
	IC	NV	IC	NV	IC	NV
January	2.84 ± 1.67	1.01 ± 0.73	95.1 ± 41.0	42.2 ± 19.9	2.76 ± 0.60	2.08 ± 0.47
February	2.82 ± 1.44	1.17 ± 0.80	86.8 ± 31.7	43.6 ± 19.3	3.06 ± 0.58	2.41 ± 0.50
March	3.19 ± 1.62	1.49 ± 0.99	94.3 ± 34.0	52.4 ± 24.4	3.20 ± 0.60	2.60 ± 0.55
April	2.90 ± 1.33	1.70 ± 1.07	87.3 ± 27.5	57.9 ± 25.0	3.18 ± 0.55	2.69 ± 0.55
May	2.35 ± 1.40	0.91 ± 0.80	74.3 ± 37.2	36.6 ± 20.7	3.04 ± 0.58	2.28 ± 0.54
June	2.02 ± 1.14	0.40 ± 0.53	66.9 ± 29.5	22.5 ± 12.1	2.86 ± 0.53	1.77 ± 0.35
July	1.92 ± 1.11	0.07 ± 0.27	66.1 ± 26.7	14.6 ± 8.4	2.73 ± 0.55	1.38 ± 0.28
August	1.94 ± 1.39	0.01 ± 0.14	68.8 ± 34.0	4.5 ± 5.6	2.50 ± 0.67	0.90 ± 0.26
September	1.34 ± 1.18	0.01 ± 0.08	49.5 ± 29.7	1.6 ± 3.5	2.37 ± 0.73	0.75 ± 0.23
October	1.56 ± 1.20	0.18 ± 0.39	58.8 ± 31.8	11.9 ± 7.9	2.28 ± 0.63	0.78 ± 0.26
November	2.85 ± 1.73	1.36 ± 1.12	96.7 ± 42.1	53.4 ± 30.7	2.66 ± 0.61	2.10 ± 0.60
December	2.62 ± 1.66	1.04 ± 0.96	90.5 ± 42.0	43.4 ± 27.0	2.60 ± 0.61	1.99 ± 0.58
Year	28.48 ± 14.35	9.87 ± 4.89	937.9 ± 351.2	385.0 ± 140.6	2.77 ± 0.53	1.81 ± 0.31

*IC - Irrigated crops; NV - Natural Vegetation

Considering both irrigated crops and natural vegetation, the period from March to April during the rainy period is highlighted with the highest averages for BIO and WP values because high rainfall amounts and solar radiation levels. However November presented the highest mean ET value for irrigated crops, while April had the largest one for natural vegetation. Considering the STD, values, the highest spatial variations of BIO and ET for both irrigated and not irrigated conditions, are in November. In the case of WP values, the largest spatial variation in irrigated crops happened in September, while for natural vegetation it occurred in November

4. CONCLUSIONS

Coupling remote sensing parameters from MODIS satellite images and weather data from agrometeorological stations allowed the water productivity assessments on a large scale along the year of 2011 in a mixture of agro-ecosystems in the Petrolina municipality, Pernambuco state, Brazil. These assessments may subsidize a better understanding of the dynamic of the biophysical parameters, what are important for appraising the impact of land use changes on the regional scale energy and water balances. It could be concluded that, taking the year of 2011 as a reference, the period with the highest water productivity values were from March to April in the rainy period for both irrigated and not irrigated conditions. However the largest ET rates were in November for irrigated crops and April for natural vegetation.

It was demonstrated that the water productivity can be analyzed from instantaneous measurements of visible and thermal radiations by using only four MODIS bands, throughout modelling the ratio of the actual to reference evapotranspiration at the satellite overpass time once having daily weather data available. The combination of these images and agrometorological stations proved to be useful for monitoring vegetation and water parameters, contributing to the sustainability of the rational agro-ecosystems exploration in the future.

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