Retrieving water productivity parameters by using Landsat images in the Nilo Coelho irrigation scheme, Brazil

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ABSTRACT

The Nilo Coelho irrigation scheme, located in the semi-arid region of Brazil, is highlighted as an important agricultural irrigated perimeter. Considering the scenario of this fast land use change, the development and application of suitable tools to quantify the trends of the water productivity parameters on a large scale is important. To analyse the effects of land use change within this perimeter, the large-scale values of biomass production (BIO) and actual evapotranspiration (ET) were quantified from 1992 to 2011, under the naturally driest conditions along the year. Monteith´s radiation model was applied for estimating the absorbed photosynthetically active radiation (APAR), while the SAFER (*Simple Algorithm For Evapotranspiration Retrieving*) algorithm was used to retrieve ET. The highest incremental BIO values happened during the years of 1999 and 2005, as a result of the increased agricultural area under production inside the perimeter, when the average differences between irrigated crops and natural vegetation were more than 70 kg ha^{-1} d^{-1}. Comparing the average ET rates of 1992 (1.6 mm d^{-1}) with those for 2011 (3.1 mm d^{-1}), it was verified that the extra water consumption doubled because of the increments of irrigated areas along the years. More uniformity along the years on both water productivity parameters occurred for natural vegetation, evidenced by the lower values of standard deviation when comparing to irrigated crops. The heterogeneity of ET values under irrigation conditions are due to the different species, crop stages, cultural and water managements.

Keywords: evapotranspiration, biomass production, photosyntetically active radiation, surface resistance.

1. INTRODUCTION

On a large scale, agricultural crops in the irrigations schemes have rapidly replaced the natural vegetation of the Brazilian semiarid region, the “Caatinga”. Among the most important of them is the Nilo Coelho, located in the left bank of the São Francisco River. Its construction was finalized in 1990 and since then, irrigated agriculture has increased mainly with fruit crops for external markets. The water is pumped from the river and applied throughout different irrigation methods mainly drip and micro sprinklers systems. The rainy period is concentrated from January to April, with the lowest area under irrigation occurring in February and the largest area under happening in July[1].

Considering the changes in land use inside the irrigated schemes, it´s becoming important to develop tools for quantifying water productivity parameters, with analyses of the dynamics of the agro-ecosystems that characterize these schemes in the São Francisco river basin. The water consumption of irrigated crops in the Brazilian semi-arid region is higher than for the “Caatinga” species during the naturally driest period of the year, inducing an increment in biomass production (BIO) and evapotranspiration (ET) rates on large scales[2].

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For BIO estimations, the concept of light use efficiency based in solar radiation interception can be applied[3], being the degree of this interception variable along the year and crop stages[2,4]. Remote sensing by satellites is an efficient tool for these estimations, providing spatiotemporal information, location and state of different agro-ecosystems[2]. The high correlation between the spectral bands and biophysical parameters allow mapping and quantifying BIO on a large scale[5].

Images from MODIS satellite, combined precipitation, temperature and elevation data have been used for mapping forests in California[6]. The same satellite was used in Guandong, China, aiming 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[2] 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 also needs to quantify ET to obtain the water productivity (WP), which in the current research, is defined as the ratio of BIO to ET for both natural vegetation and irrigated crops. 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 carried out in distinct climate regions[2,13-14].

The SAFER (Simple Algorithm For Evapotranspiration Retrieving) algorithm for retrieving ET has been developed and validated with field data and Landsat images applied to irrigated crops and natural vegetation, in the Brazilian semi-arid conditions[15-16]. One of the advantages of the SAFER model is that data from both automatic and conventional agro-meteorological stations can be used, allowing a larger temporal evaluation of BIO and ET. A second biophysical model was also developed for the estimation of the surface resistance to water fluxes (r_s) on a large scale, which established threshold values are useful for classifying the vegetation into irrigated crops and natural vegetation[17].

The objective of this paper is to combine Monteith's BIO model[9] with the SAFER algorithm[16] to demonstrate that when they are combined with Landsat satellite inputs and agro-meteorological data are useful for water productivity assessments in mixed agro-ecosystems containing irrigated crops and natural vegetation. The Nilo Coelho irrigation scheme in Northeast Brazil was used as a reference site for the application of the models which have been successfully applied in other areas.

2. MATERIAL AND METHODS

Data from one conventional and 5 automatic agro-meteorological stations were used together with 10 Landsat images for growing periods outside the rainy season from 1992 to 2011. Figure 1 shows the locations of the Nilo Coelho scheme and the stations. The conventional station was used to estimate interpolated values of the daily weather parameters before 2003 by applying simple regression equations, due to the absence of automated stations before this year. This allowed the use of grids of incident solar radiation ($RS\downarrow$), air temperature (T_a) and reference evapotranspiration (ET_0), together with remotely sensed retrieved parameters during the estimation of the radiation and energy balance components on a large scale.

The remote sensing retrieved parameters involved the surface albedo (α_0), surface temperature (T_0) after simple atmospheric corrections and NDVI, which were used to acquire ET and r_s[16-17]. ET was estimated using the SAFER algorithm[16]

$$\frac{ET}{ET_0} = \exp\left[a + b\left(\frac{T_0}{\alpha_0 NDVI}\right)\right] \qquad (1)$$

where ET_0 is the reference evapotranspiration with the values interpolated from the 5 automatic agro-meteorological stations (Figure 1) calculated by the Penman-Monteith method[18] and a and b are regressions coefficients, which for the Brazilian semiarid conditions were found to be 1.8 and - 0.008, respectively[16].

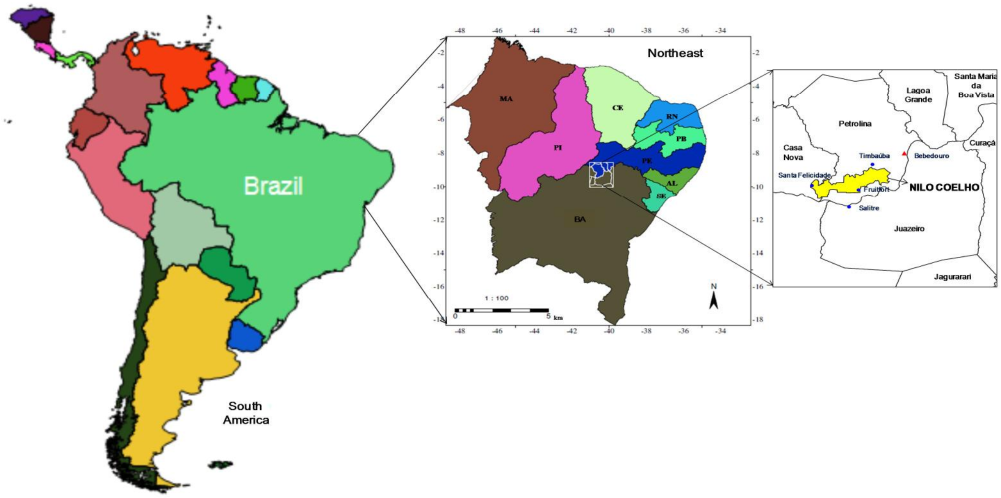

Figure 1. Location of the Nilo Coelho Irrigation scheme and the agro-meteorological stations. The round points represent the automated stations while the triangle indicates the location with both a conventional and an automated station.

The daily 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[11,15]:

$$R_n = (1 - \alpha_0) RS\downarrow - a_l \tau_{sw} \qquad (2)$$

where a_l is the regression coefficient of the relationship between net long wave radiation and atmospheric short-wave transmissivity (τ_{sw}) on a daily scale[11,15].

Because of the T_a dependency on longwave radiation via the Stephan Boltzmann equation, a previous study investigated further whether the variations of the a_l coefficient of the Equation 3 could be explained by variations in 24 hours T_a values[15]:

$$a_l = cT_a - d \qquad (3)$$

where c and d are regression coefficients found to be 6.99 and 39.93, respectively for the Brazilian semi-arid conditions[15]. Interpolated T_a data from the agro-meteorological stations from Figure 1 were then using with Equation 3.

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:

$$PAR = eRS\downarrow \qquad (4)$$

where e = 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[2].
The values of Absorbed Photosyntetically Active Radiation (APAR) can be approximated directly from PAR:

$$APAR = fPAR \qquad (5)$$

The factor f was estimated from the NDVI values[12,19]:

$$f = gNDVI + h \qquad (6)$$

The coefficients g and h of 1.257 and -0.161, respectively, reported for a mixture of arable crop types[19] were used. BIO was then obtained as:

$$BIO = \varepsilon_{max} E_f APAR\ 0.864 \tag{7}$$

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 as 2.5 g MJ^{-1} for the majority c4 species in the study area and 0.864 is a unit conversion factor[12].

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[17].

$$r_s = \exp\left[i\left(\frac{T_0}{\alpha_0}\right)(1 - NDVI) + j \right] \tag{8}$$

where i and j 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[15] and the model represented by Equation 8 was applied to Landsat images by using threshold values of 800 s m^{-1} and 10,000 s m^{-1} together with logical functions in a GIS environment. r_s values below or equal to the lower end of this range should be irrigated crops and above this limit and below the upper end of the range, was considered to be natural vegetation. The upper limit was to exclude other features of the images that were not vegetation.

3. RESULTS AND DISCUSSION

The difficulty of identifying land use change effects on water variables by using only NDVI is the variability of this vegetation indicator with the thermo-hydrological conditions. On the other hand, besides NDVI and accumulated precipitation (P_{ac}), ET and BIO depend also on the absorbed photosyntetically active radiation (APAR), which in turn is conditioned by RS↓ levels. Figure 2 shows the variation of these parameters along the analysed days and years.

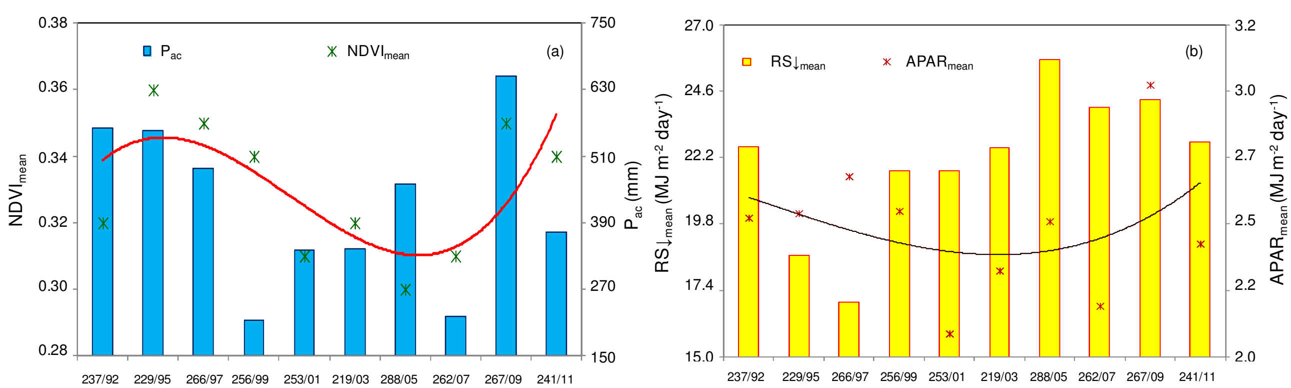

Figure 2. Averaged values of vegetation indicators and weather parameters for the period from 1992 to 2011 for each Day/Year: (a) Normalized Difference Vegetation Index (NDVI) and accumulated Precipitation (P_{ac}); Absorbed Photosythetically Active Radiation (APAR) and incident Solar Radiation (RS↓).

In Figure 2, P_{ac} data were from the conventional station of Bebedouro (see Figure 1), while the other parameters are mean pixel values. Although the years of 1992, 1995 and 1997 had lower irrigated areas in relation to the other years, high amounts of precipitations during the rainy period left the root zone of the "Caatinga" species wet (Figure 2a). On the other hand, lower P_{ac} between 1999 and 2007 was not favourable for vegetation development. Figure 3b reinforces the dependence of plant development with moisture conditions, as high values of APAR are observed with low levels of

RS↓ in 1997, as an example, while the highest mean RS↓ value did not correspond to the largest APAR, which occurred in 2009, when both high P_{ac} and RS↓ occurred.

To clarify more how the changes in vegetation alone could explain the variation of the water variables, the trend of NDVI along the years was analysed. Figure 3 presents the spatial variation of its values within the Nilo Coelho irrigation scheme during the period from 1992 to 2011, for the satellite overpass dates during the driest period of the year.

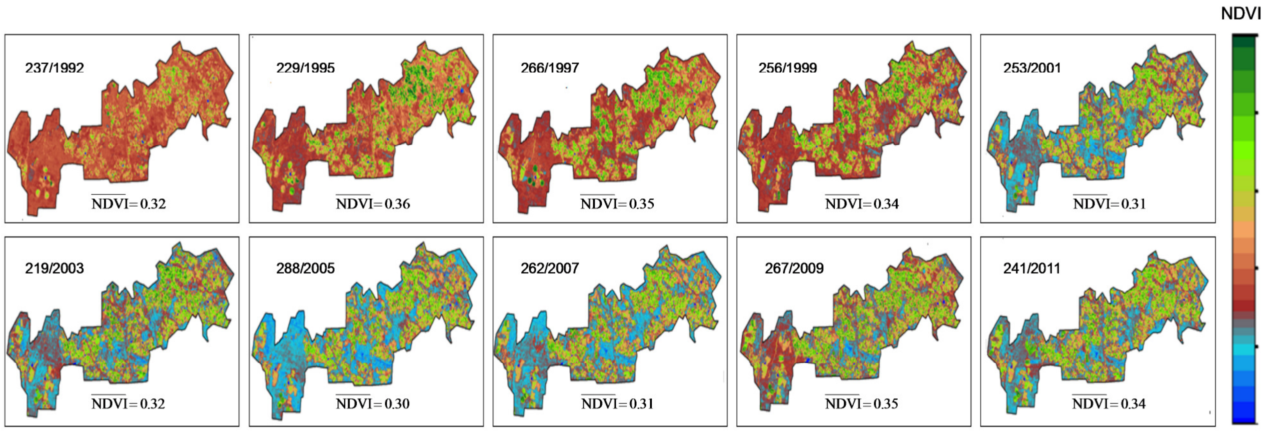

Figure 3.Spatial distribution of the Normalized Difference Vegetation Index (NDVI) at the Landsat satellite overpass time during the driest period of the year for each Day/Year from 1992 to 2011, in the Nilo Coelho irrigation scheme, Brazil, The bars mean averaged values of the pixels.

The increments of the NDVI values along the years as a result of irrigated crops replacing the natural vegetation are evident, mainly when observing the images for 1992 and 2011, which are for similar days of the year (Day/Year 237/1992 and 241/2011, respectively). Considering all the period represented within Figure 3, the mean NDVI for the perimeter was of 0.33, although irrigated areas had the highest values close to 0.80. The spatial heterogeneity also increased with the standard deviations (SD) ranging from 0.008 in 1992 to 0.17 in 2011.

Figure 4 shows the spatial distribution of the ET daily values for the same days as for the NDVI, within the driest period of the year from 1992 to 2011, at the Nilo Coelho irrigation scheme, Brazilian Northeast.

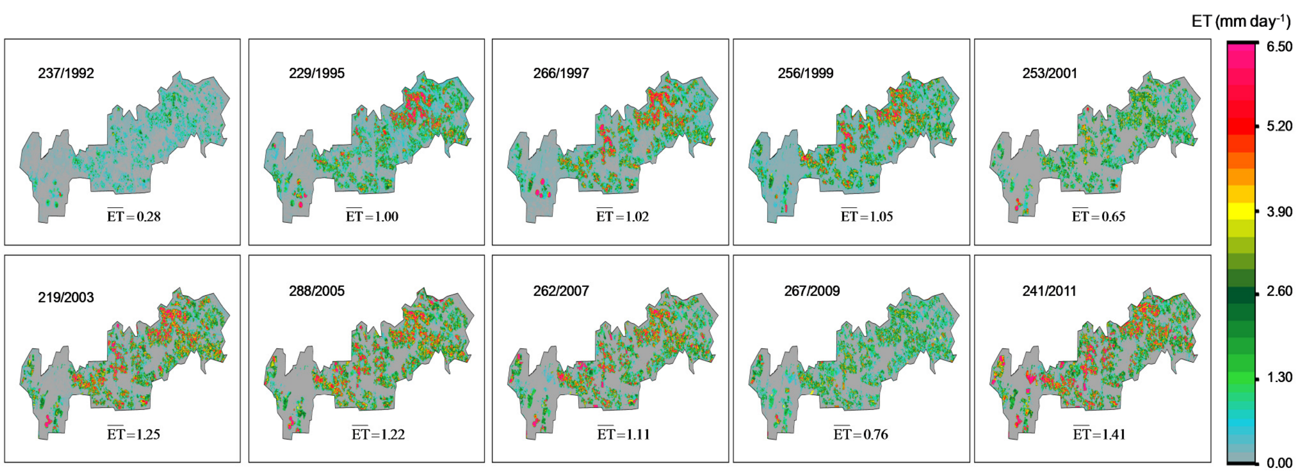

Figure 4.Spatial distribution of daily evapotranspiration (ET) during the driest period of the year for each satellite overpass date from 1992 to 2011, in the Nilo Coelho irrigation scheme, Brazil. The bars mean averages values of all the pixels.

Clearly one can distinguish irrigated areas from the natural vegetation by the higher values of ET in the first ecosystem. Because the highest portion of the available energy is used as sensible heat flux by the "Caatinga" species during the driest and hottest period of the year, this result in ET values lower than 1.00 mm day^{-1}, while the corresponding values for irrigated crops are above 3.50 mm day^{-1}. Considering the whole perimeter, the increments throughout the years are evident; around 350% when comparing 1992 with 2011, however, some variations occurred due to the combined effects of land use change and different thermo-hydrological conditions.

Figure 5 shows the spatial distribution of the BIO daily values for the same days as for NDVI and ET, within the driest period of the year from 1992 to 2011, in the Nilo Coelho irrigation scheme.

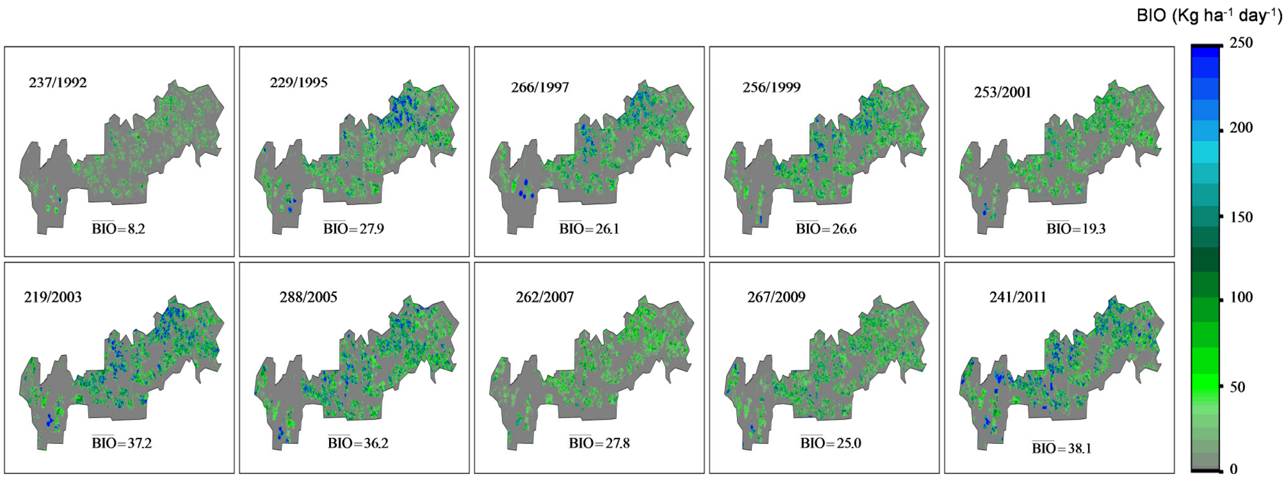

Figure 5.Spatial distribution of biomass production (BIO) during the driest period of the year for each overpass date from 1992 to 2011, in the Nilo Coelho irrigation scheme. The bars represent averages values of the pixels.

With high large-scale values of APAR and absence of rains during the driest periods of the year, natural vegetation species presented low BIO daily values, while irrigated crops showed the highest ones, promoting strong contrast between these ecosystems. In some irrigated areas, Bio reached values above 200 kg ha^{-1} day^{-1}.The average pixel daily values ranged from 8 to 38 kg ha^{-1} day^{-1} from 1992 to 2011, accounting for an increment of 475% as a result of increased irrigated areas. The spatial variation is large, with SD values changing from 21 to 70 kg ha^{-1} day^{-1}.

For irrigated and natural vegetation, the variation of the mean and SD values were analysed along the years (Table 1).

Table 1. Averaged daily values and standard deviations of the water productivity parameters for the period of 1992-2011 in Nilo Coelho irrigation perimeter: evapotranspiration (ET); and Biomass production (BIO).

Day/Year	ET (mm day^{-1})		BIO (kg ha^{-1} day^{-1})	
	IC	NV	IC	NV
237/92	1.8 ± 0.8	0.2 ± 0.3	12.6 ± 24.7	8.5 ± 21.9
229/95	2.8± 1.8	0.4± 0.6	42.5± 70.3	23.0 ± 51.8
266/97	3.5 ± 1.6	0.4 ± 0.5	33.3± 61.9	25.7 ± 53.2
256/99	2.7 ± 1.5	0.2 ± 0.2	73.2± 63.7	2.1 ± 3.2
253/01	2.6 ± 1.0	0.5 ± 0.5	28.8 ± 47.1	21.8 ± 41.3
219/03	3.0 ± 1.8	0.2 ± 0.4	41.0 ± 71.5	34.8 ± 69.0
288/05	2.9 ± 1.6	0.1 ± 0.2	88.5 ± 73.7	1.1 ± 2.8
262/07	3.3 ± 1.8	0.4± 0.6	30.2 ± 57.2	28.8 ± 58.7
267/09	2.6 ± 1.1	0.5± 0.4	98.0 ± 56.7	11.0 ± 11.0
241/11	3.4 ± 1.9	0.3± 0.6	42.1 ± 72.7	37.4 ± 70.2

*IC - Irrigated crops; NV - Natural Vegetation

Considering irrigated crops, the mean BIO values along the driest period of the years were between 10 and 100 kg ha^{-1} day^{-1}, being bellow 25 kg ha^{-1} day^{-1} only for the year of 1992. The highest values happened in 2009, however the largest spatial variation, as determined by the SD value was for 2011. For “Caatinga”, there was a bigger oscillation of the BIO values, with the average values ranging from 1 to 40 kg ha^{-1} day^{-1}, with the lowest values occurring in 1999 and 2005, highlighting the year of 2011 with the highest mean value.

The ET rates almost doubled, when comparing 1992 with 2011. On the other hand, the rates for "Caatinga" species were more stable and lower, with the natural vegetation converting the largest part of R_n towards warming the air near the surface during the driest and hottest periods of the year.

Comparing the BIO lowest values for the years of 1999 and 2005 for natural vegetation with the weather conditions depicted in Figure 2, one can see that for the first year, the lower values were a consequence of low rainfall amounts; however in 2005, the low BIO values happened even with high levels of both P and RS↓. Analysing Equation 7 it is clear that E_f, including the soil moisture conditions, also have a strong influence upon the magnitude of BIO. The lowest E_f value in natural vegetation during the analysed period, with a mean of 0.02 in 2005, indicates the utilization of only 2% of the available energy, being this the main reason for the BIO decline in that year for the "Caatinga" species.

Incremental ET, represented by the different water fluxes between irrigated crops and natural vegetation, ranged from 1.6 in 1992 to 3.1 mm day^{-1} in 2011, doubling the water consumption because of the introduction of the commercial irrigated agriculture. According to SD values of irrigated crops, one can see the largest heterogeneity of water consumption than that for natural vegetation, due to different crop management and growth stages.

4. CONCLUSIONS

The coupled use of Landsat images and agro-meteorological data allowed the quantification and analyses of tendencies on water productivity parameters, during the period from 1992 to 2011, in the Nilo Coelho irrigation scheme, Brazilian Northeast. The analyses may lead to a better understanding of the dynamics of biophysical properties from the agro-ecosystems, important for evaluation of land use changes effects upon the water resources.

From the viewpoint of incremental evapotranspiration, extra water consumption resulted from the introduction of irrigated crops doubling the water withdrawn from the São Francisco river, taking into account the driest periods of the year in the Nilo Coelho irrigation scheme.

Analyzing the biomass production (BIO) within the whole Nilo Coelho perimeter, we conclude that the values are more strongly dependent on accumulated antecedent precipitation than on solar radiation levels. As there is a strong relationship between water fluxes and BIO, similar tendencies along the years of study were verified, with averaged BIO values presenting an increment of 475% during the analyzed period as a result of the introduction of irrigated crops.

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