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WATER PRODUCTIVITY ASSESSMENTS WITH LANDSAT 8 IMAGES IN THE NILO COELHO IRRIGATION SCHEME

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1 ABSTRACT

The Nilo Coelho (NC) irrigation scheme, located in the Brazilian semi-arid region, is an important irrigated agricultural area. Land use change effects on actual evapotranspiration (ET), biomass production (BIO) and water productivity (WP) were quantified with Landsat 8 images and weather data in this scheme covering different thermohydrological conditions. The SAFER algorithm was used for ET acquirements while the Monteith's radiation model was applied to retrieve BIO. For classifying irrigated crops and natural vegetation, the SUREAL model was used with a satellite image representing the driest period of the year. The average values for ET, BIO and WP in irrigated crops, ranged, respectively, from 1.6 ± 1.9 to 4.2 ± 1.9 mm day^{-1}; 59 ± 86 to 146 ± 91 kg ha^{-1} day^{-1}; and 2.0 ± 1.5 to 3.0 ± 1.2 kg m^{-3}. The corresponding ranges for natural vegetation ("Caatinga") were from 1.2 ± 1.8 to 2.6 ± 1.8 mm day^{-1}; 43 ± 78 to 76 ± 78 kg ha^{-1} day^{-1}; and 1.6 ± 1.4 to 2.7 ± 1.1 kg m^{-3}. The incremental values, which represent the effects of the replacement of natural vegetation by irrigated crops, were 40, 54 e 23%, for ET, BIO e WP, respectively.

Keywords: evapotranspiration, biomass production, land use change

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ANÁLISES DA PRODUTIVIDADE DA ÁGUA COM IMAGENS LANDSAT 8 NO PERÍMETRO DE IRRIGAÇÃO NILO COELHO

2 RESUMO

O perímetro de irrigação Nilo Coelho (NC), localizado na região semiárida do Brasil, é uma importante área de agricultura irrigada. Os efeitos da mudança de uso da terra na evapotranspiração atual (ET), na produção de biomassa (BIO) e na produtividade da água (PA) foram quantificados com imagens Landsat 8 e dados climáticos neste perímetro cobrindo diferentes condições termo hidrológicas. O algoritmo SAFER foi usado para a obtenção da ET enquanto que o modelo da radiação de Monteith foi aplicado para a estnimativa da BIO. Para classificação em culturas irrigadas e vegetação natural o modelo SUREAL foi usado na imagem representativa do período mais seco do ano. Os valores médios da ET, BIO e PA nas culturas irrigadas variaram respectivamente de 1,6 ± 1,9 a 4,2 ± 1,9 mm dia^{-1}; 59 ± 86 a 146 ± 91 kg ha^{-1} dia^{-1}; e 2,0 ± 1,5 a 3,0 ± 1.2 kg m^{-3}. Os valores correspondentes para vegetação natural

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("Caatinga") foram de 1,2 ± 1,8 a 2,6 ± 1,8 mm dia^{-1}; 43 ± 78 a 76 ± 78 kg ha^{-1} dia^{-1}; e 1,6 ± 1,4 a 2,7 ± 1,1 kg m^{-3}. Os valores incrementais, representativos dos efeitos da substituição da vegetação natural por culturas irrigadas foram de 40, 54 e 23%, para respectivamente ET, BIO e PA.

Palavras-chave: Evapotranspiração, produção de biomassa, mudança de uso da terra.

3 INTRODUCTION

The natural vegetation in the Brazilian semi-arid region, the "Caatinga", has been replaced by crops because of the development of irrigation technologies at the vicinities of the São Francisco River. In the main irrigation scheme, the Nilo Coelho and water use from irrigated plots exceeds that from the natural species, promoting a reduction of the São Francisco river stream flow by the increasing of actual evapotranspiration (ET) and biomass production (BIO). Considering the situation of land use changes, it is becoming important the development and application of tools for quantifying the water productivity (WP) components, ET and BIO. Experimentally, ET acquirements in the Brazilian semi-arid region have been done by using energy balance techniques (TEIXEIRA et al., 2007; 2008). However, the difficulties to measure the water fluxes from mixed ecosystems by field experiments make the use of remote sensing by satellite images (TEIXEIRA et al., 2014a; b).

For WP analyses based on ET, it is also necessary to obtain BIO, which is a key indicator for any agro-ecosystem (WU et al., 2010), being highly variable in both space and time (ADAK et al., 2013). For BIO quantification, the light-use efficiency concept (LUE), devised based on radiation interception, can be applied (CLAVERIE et al., 2013). Although uncertainties arise in connection with LUE values, due to their spatiotemporal variations, the model's accuracy has been considered acceptable for large-scale applications with satellite data (BASTIAANSSEN & ALI, 2003; ZWART et al., 2010).

WP mapping, based on remote sensing parameters, can be found for several agro-ecosystems, combining these parameters with weather variables (ZWART et al., 2010; TEIXEIRA et al., 2014b). Landsat 8 (L8) was launched on February 11, 2013 and normal operations started on May 30, 2013. L8 has a ground track repeat cycle of 16 days with an equatorial crossing time at 10:00 a.m. The Operational Land Imager (OLI) on L8 is a nine-band push broom scanner with a swathwidth of 185 km (VANHELLEMONT & RUDDICK, 2014). In this paper seven 30 m - visible bands were used to estimate surface albedo (α_0) and two thermal bands at 100 m spatial resolution were used for retrieving the surface temperature (T_0).

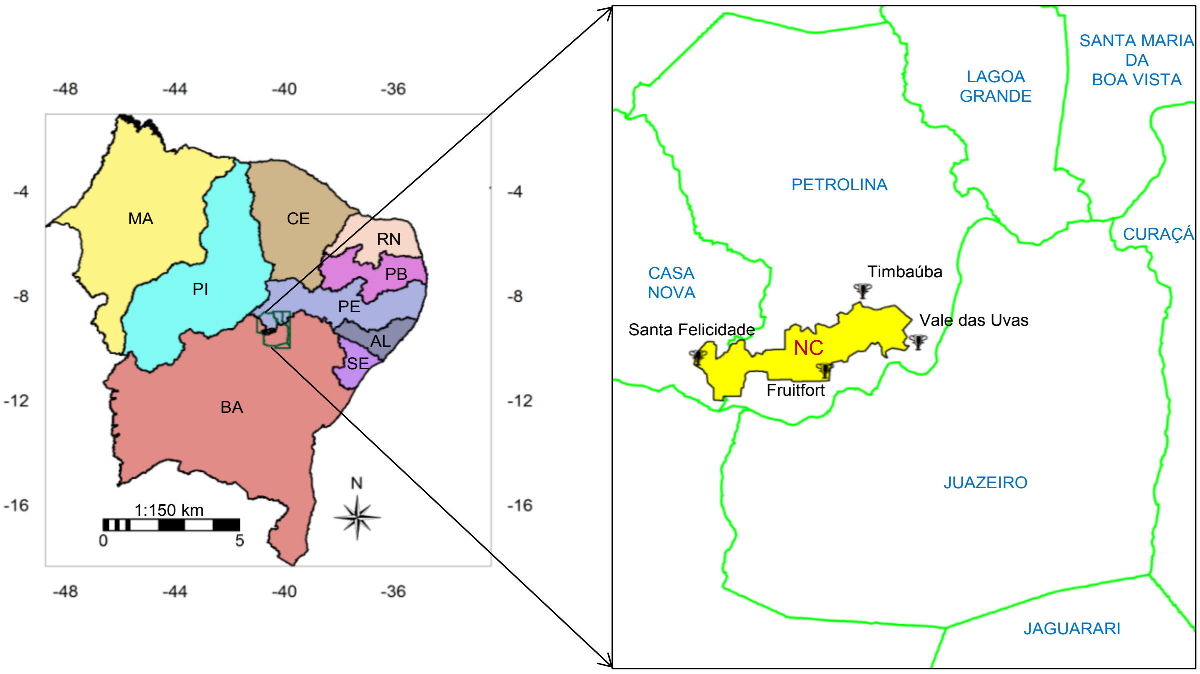
Despite several WP studies with satellites having different spatial and temporal resolutions, research is needed with applications of the new L8 satellite images to evaluate the combined ET and BIO models, especially for operational monitoring in different agro-ecosystems under rapid land use change and having high temporal and spatial thermohydrological variations. The objective of the current research was to combine L8 measurements and agrometeorological data to model the WP components under these situations in the Brazilian semi-arid region.

4 MATERIAL AND METHODS

The large-scale modelling is done in the Nilo Coelho (NC) irrigation scheme located in the semiarid region of Brazil, aiming to subsidize the monitoring of the water use effects by agriculture introduction, which has replaced natural vegetation in the São Francisco river basin.

Figure 1 shows the locations of the NC scheme in Northeast Brazil and the agrometeorological stations used to model the WP components.

Figure 1. Location of the Nilo Coelho (NC) Irrigation scheme and the agro-meteorological stations in the Northeast region of Brazil.



Data from four automatic agro-meteorological stations were used together with 8 Landsat 8 (L8) images, being two for 2013 (September 03 and October 05) and six for 2014 (January 09, January 25, June 02, July 04, August 05 and September 22). Grids of global solar radiation (R_G), air temperature (T_a) and reference evapotranspiration (ET_0) were used together with remotely sensed retrieved parameters during the estimation of the large-scale WP components.

The bands 1 to 7 of the L8 satellite were used to retrieve the surface albedo (α_0), while for the surface temperature (T_0), the bands 10 and 11 were used, following the methodology described in TEIXEIRA (2009) for the Landsat 5 and 7 but considering the wavelengths and the conversion constants for the L8.

Daily R_n can be was calculated as:

$$R_n = (1 - \alpha_0) R_G - a_L \tau_{sw} \quad (1)$$

where τ_{SW} is the atmospheric transmissivity and a_L the regression coefficient (TEIXEIRA, 2009).

The SAFER (Simple Algorithm for Evapotranspiration Retrieving) algorithm was used for modeling the instantaneous values of the ratio of actual (ET) to the reference (ET_0) evapotranspiration, which was then multiplied by ET_0 from the agro-meteorological stations for estimating the daily ET large-scale values:

$$\frac{ET}{ET_0} = exp\left[a_S + b_S\left(\frac{T_0}{\alpha_0 NDVI}\right)\right] \quad (2)$$

where NDVI is the Normalized Difference Vegetation Index, and a_S and b_S are the regressions coefficients, being 1.8 and -0.008, respectively, for the Brazilian Northeast conditions (TEIXEIRA et al., 2014a; b).

Eq. 2 do not work for water bodies, i.e. when NDVI < 0. Thus, the concept of equilibrium evapotranspiration (RAUPASCH, 2001) is applied in the SAFER algorithm under these conditions, and the latent heat flux (λE) is retrieved throughout conditional functions further being transformed in mm of water:

$$\lambda E = \frac{s\left(R_n - G\right)}{s + \gamma} \quad (3)$$

where s is the slope of the curve relating saturation water vapor pressure to temperature, G is the ground heat flux and γ is the psychometric constant. Under these conditions, the surface moisture availability is not constrained and the water vapor transfer is limited only by available energy.

For BIO calculations on large scales, the Monteith's LUE model was applied. The evaporative fraction (E_f) is included to take into account the soil moisture effects. E_f is defined as the latent heat flux (λE) divided by the available energy, with in turn is the difference between R_n and soil heat flux (G).

$$E_f = \frac{\lambda E}{R_n - G} \quad (4)$$

where λE from Eq. 2 is obtained by transforming ET into energy units.

For the daily G values, the equation derived by TEIXEIRA et al., (2014a; b) was used:

$$\frac{G}{R_n} = a_G \, exp\left(b_G \alpha_0\right) \quad (5)$$

where a_G and b_G are regression coefficients found to be 3.98 and -25.47, respectively, for the Brazilian Northeast conditions.

The Absorbed Photosyntetically Active Radiation (APAR) was approximated directly from PAR:

$$APAR = f_{PAR} PAR \quad (6)$$

The factor f_{PAR} was estimated from the NDVI values (BASTIAANSSEN & ALI, 2003, TEIXEIRA, 2009):

$$f_{PAR} = bNDVI + c \tag{7}$$

The coefficients b and c of 1.257 and -0.161, were considered (BASTIAANSSEN & ALI, 2003, TEIXEIRA, 2009), and the BIO was quantified as:

$$BIO = \varepsilon_{max} E_f APAR\ 0.864 \tag{8}$$

where ε_{max} is the maximum light use efficiency, which depends if the vegetation are c3 or c4 species; and 0.864 is a unit conversion factor (TEIXEIRA, 2009).

WP based on ET was calculated by:

$$WP = \frac{BIO}{ET} \tag{9}$$

For classification of the vegetated surface as irrigated crops and natural vegetation, the SUREAL (Surface Resistance Algorithm) model was applied[24]:

$$r_s = exp\left[a_r \left(\frac{T_0}{\alpha_0} \right) \left(1 - NDVI \right) + b_r \right] \tag{10}$$

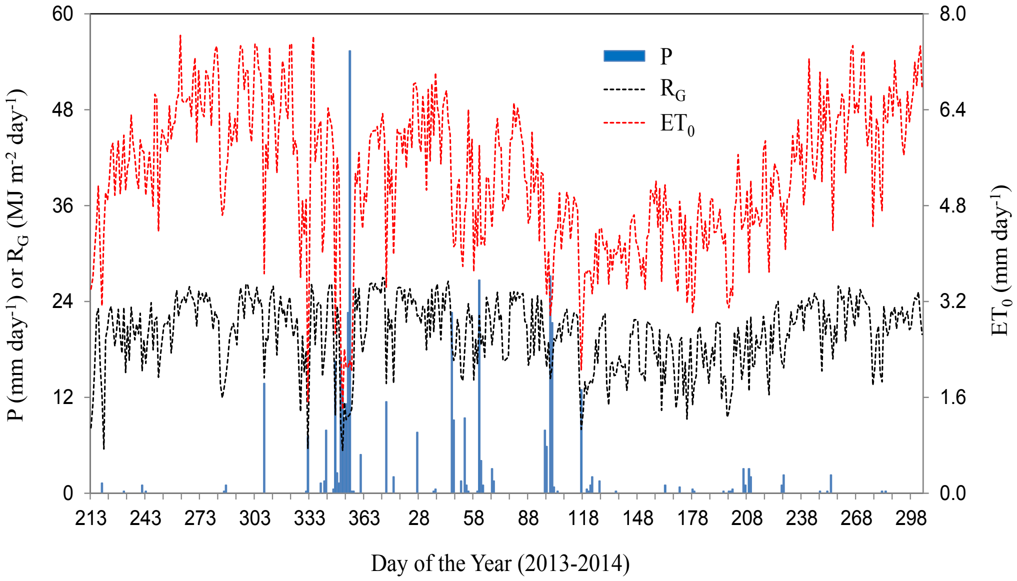
where a_r and b_r are regression coefficients, considered respectively 0.04 e 2.72 for the Brazilian Northeast condition. Pixels with r_s values bellow 800 s m^{-1} and NDVI above or equal to 0.40 were considered as irrigated crops. If r_s was in between 1000 and 10000 s m^{-1} they should be natural vegetation. The high end of this last range was considered to eliminate humankind structures

5 RESULTS AND DISCUSSION

Whereas the weather-driving forces for ET and BIO are R_G, precipitation (P) and the atmospheric demand (ET_0), the trend of these weather parameters on a daily scale, during the period comprising the acquisitions of the satellite images (August 2013 to September 2014), were first analysed.

Figure 2 shows these weather parameters in terms of Day/Year, with data from Timbaúba agrometeorological station (see Figure 1).

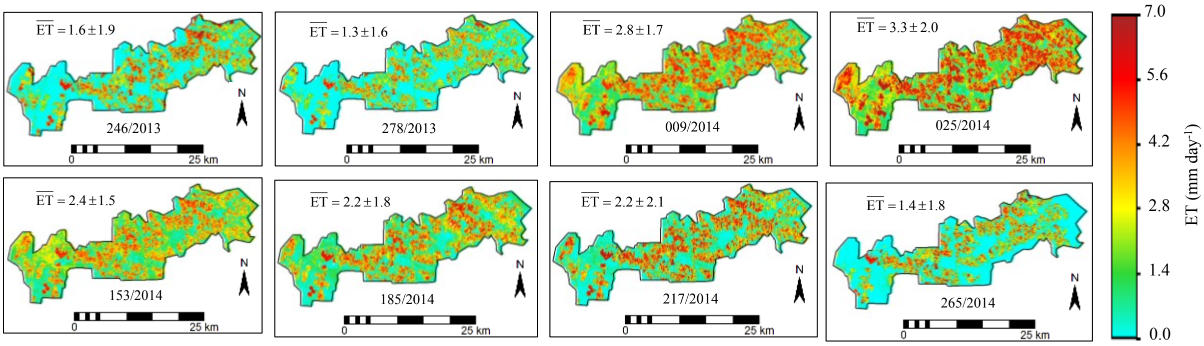
Figure 2. Daily values precipitation (P), global solar radiation (R_G) and reference evapotranspiration (ET_0) during the period involving the Landsat 8 (L8) images, from August/2013 to September/2014, in the Nilo Coelho (NC) irrigation scheme.



Considering the natural water input, P was the most variable weather parameter. The concentrations of rains were from Day/Year 303/2013 to 120/2014, mainly during the end of 2013. The driest periods were from Days 210 to 300 in both years. By the ET_0 daily values, the largest atmospheric demands happened in two periods, from days 248 to 323 of 2013 and between 242 and 304 of 2014, when they stayed above 7.0 mm day^{-1}. In these situations, the sun was in the zenith position with low cloud cover. R_G daily values were higher than 25 MJ m^{-2} day^{-1} at the end of both years, and bellow 10 MJ m^{-2} day^{-1} in the middle of 2014, with the highest ones also being related to the sun astronomical position. Under conditions of high P, ET_0 and R_G, natural vegetation and agricultural crops were in favour for large both ET and BIO.

Figure 3 presents the spatial distribution of the daily ET values in the mixed agro-ecosystems inside the NC irrigation scheme, from September 2013 to September 2014.

Figure 3. Spatial distribution of the daily values for actual evapotranspiration (ET) from the mixed agro-ecosystems of the Nilo Coelho (NC) irrigation scheme, in the semi-arid of Brazil, Northeast region, from September 2013 to September 2014.

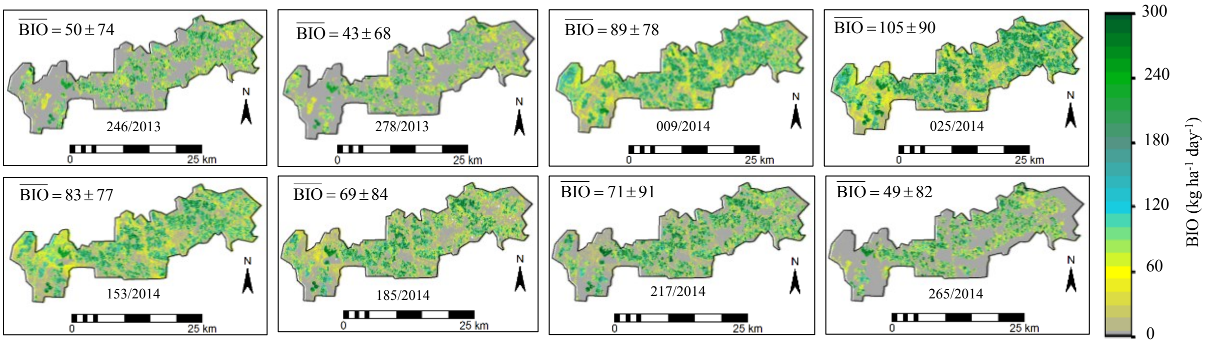


Spatial and temporal ET variations throughout the different thermo hydrological conditions are evident, mainly when observing the wettest period represented by the images for the days 009 and 025 of 2014, with the driest ones of the images Day/Year 278/2013 and 265/2014. During the rainy season, ET maximums represent irrigated crops, because the joint effect of water from rains and irrigation under high atmospheric demands. Intermediate ET values in “Caatinga” occurred just after the rainy period, as shown in image from Day/Year 153/2014, because antecedent precipitation still keeps the natural species wet and green.

Because the largest fractions of the available energy used as sensible heat fluxes (H), during the driest period of the year (Day/Year 278/2013 and 265/2014), the natural vegetation presented the lowest ET (bluish pixels). Stomata of “Caatinga” species, under these conditions, so limiting both transpiration and photosynthesis, while, in general, irrigation intervals in crops are short (daily irrigation), with a uniform water supply, thus reducing the heat losses to the atmosphere.

Figure 4 presents the spatial distribution of the daily BIO values in the mixed agro-ecosystems inside the NC irrigation scheme, from September of 2013 to September of 2014.

Figure 4. Spatial distribution of the daily values for biomass production (BIO) from the mixed agro-ecosystems of the Nilo Coelho (NC) irrigation scheme, in the semi-arid of Brazil, Northeast region, from September 2013 to September 2014.



Considering that there is a relation between ET and BIO (YUAN et al., 2013), the spatial and temporal variations of this last vegetation parameter are also influenced by the thermo hydrological conditions. The largest areas with the highest BIO values were during the rainy season, as showed in the images for the days 009 and 025 of 2014. During this period, there were several BIO rates bigger than 200 kg ha^{-1} day^{-1}, including both natural vegetation and irrigated crops. The lowest ones occurred during the driest period, from September to October (Day/Year 278/2013 and 265/2014), with the mean pixel values bellow 50 kg ha^{-1} day^{-1} for the “Caatinga” species.

On the one hand, P at the end of 2013 to the start of 2014 provided enough water storage in the root zones of the natural species to keep their continuous vegetative development. On the other hand, during the driest conditions, irrigated crops presented larger BIO, as with absence of rains; the soil moisture is close to the field capacity due to the general daily irrigation. These last conditions make irrigated crops very well visible. Similarly, irrigated corn crop presented the double of BIO values when comparing with natural alpine meadow in the Heihe River basin (WANG et al., 2012), being irrigation considered the main reason for these strong differences.

Table 1 shows the daily averages values of ET, BIO and WP together with the standard deviations (SD) for irrigated crops (IC) and natural vegetation (NV) from the selected L8 images under different thermo hydrological conditions during the year 2014, in the NC irrigation scheme.

Table 1. Daily average values and standard deviations (SD) of the water productivity parameters, under different thermohydrological conditions for Landsat 8 (L8) selected days during the year 2014, in the Nilo Coelho (NC) irrigation scheme, Northeast Brazil: actual evapotranspiration (ET); biomass production (BIO); and water productivity (WP).

Day/Year	ET (mm day^{-1})		BIO (kg ha^{-1} day^{-1})		WP (kg m^{-3})	
	IC	NV	IC	NV	IC	NV
025/2014	4.2 ± 1.9	2.6 ± 1.8	146 ± 91	76 ± 78	3.0 ± 1.0	2.3 ± 0.9
153/2014	2.6 ± 1.6	2.2 ± 1.5	95 ± 81	75 ± 72	3.0 ± 1.2	2.7 ± 1.1
265/2014	1.6 ± 1.9	1.2 ± 1.8	59 ± 86	43 ± 78	2.0 ± 1.5	1.6 ± 1.4
Mean	2.8 ± 1.8	2.0 ± 1.7	100 ± 86	65 ± 76	2.7 ± 1.2	2.2 ± 1.2

*IC – Irrigated crops; NV – Natural Vegetation

For both irrigated crops and natural vegetation, the largest ET values were during the rainy season represented by the image of day 025/2014, while the lowest rates occurred in September (image Day/Year 265/2014). During the wettest period, irrigated crops consumed 1.6 mm day^{-1} more water than "Caatinga" species, while, in average, this extra consumption was 0.8 mm day^{-1}. Considering both ecosystems, the lowest standard deviation (SD) was during the period after the rainy season, represented by the image of Day/Year 153/2014.

During the period with the highest BIO (Day/Year 025/2014), the average value was above 140 kg ha^{-1} day^{-1} in irrigated crops and the lowest ones, in the driest period, the average value for "Caatinga" was below 45 kg ha^{-1} day^{-1}. The incremental BIO ranged from 16 to 70 kg ha^{-1} day^{-1}, respectively, for the driest and wettest conditions of the year, with an average annual value of 35 kg ha^{-1} day^{-1}. As in the case of ET, the lowest SD values for irrigated crops occurred after the rainy period (Day/Year 153/2014). Plants from both ecosystems are strongly sensitive to the spatial distribution of P and soil water content (CLAVERIE et al., 2012), however, the BIO and SD values for irrigated crops are also influenced by different levels of fertilization, crop stages and irrigation (WU et al., 2010).

Analyzing WP values only for irrigated crops, although less strongly than in the case of ET and BIO, differences between the ecosystems can also be identified. However, the highest WP values for both, irrigated crops and "Caatinga" species, happened after the rainy period (Day/Year 153/2014). Multiplying BIO by the harvest index (HI) make it possible to estimate the crop water productivity based on ET (CWP_{ET}). HI values were found to be around 0.60 for vineyards and 0.80 for mango orchards under the Brazilian semi-arid conditions, which returned high CWP_{ET} values, around 2.8 kg m^{-3} and 3.4 kg m^{-3}, respectively (TEIXEIRA, 2009). These previous results are confirmed by the current WP values under irrigation conditions taking into account the highest both ET and BIO values from Figures 3 and 4, which cover several irrigated vineyards and mango orchards. In the semi-arid Inner Mongolia, CWP_{ET} values of 1.1 to 1.3 kg m^{-3} for oats; 1.5 to 2.6 kg m^{-3} for sunflower; 0.5 to 1.1 kg m^{-3} for legumes; and 3.1 to 4.4 kg m^{-3} for potato, were reported (YUAN et al., 2013). For oil seed crop, under the semi-arid conditions of India, CWP_{ET} ranged from 1.9 to 2.3 kg m^{-3} (ADAK et al., 2013).

6 CONCLUSIONS

Remote sensing parameters from Landsat 8 (L8) satellite images and data from a net of agrometeorological stations were coupled. This combination allowed the large-scale water productivity assessments in a mixture of the Brazilian semi-arid agro-ecosystems located in the Nilo Coelho irrigation scheme, during the period from September/2013 to September/2014. It was demonstrated that these analyzes can be done from instantaneous measurements of the visible, near infrared and thermal radiations of the L8 bands. This was possible by modeling the ratio of the actual to reference evapotranspiration at the satellite overpass time, and with the availability of daily weather data, providing temporal information on vegetation growth rates as well plant responses to dynamic weather and irrigation conditions.

7 REFERENCES

ADAK, T.; KUMAR, G.; CHAKRAVARTY, N. V. K.; KATIYAR, R. K.; DESHMUKH, P.S. Biomass and biomass water use efficiency in oilseed crop (*Brassica Jnceae* L.) under semi-arid microenvironments**. Biomass and Bioenergy**, v. 51, p. 154-162, 2013.

BASTIAANSSEN, W. G. M.; ALI, S. A new crop yield forecasting model based on satellite measurements applied across the Indus Basin, Pakistan. **Agriculture, Ecosystems & Environment**, v.94, n.3, p. 32-340, 2003.

CLAVERIE, M.; DEMAREZ, V.; DUCHEMIN, B.; HAGOLLE, O.; DUCROT, D.; MARAIS-SICRE, C.; DEJUOUX, JEAN-FRANÇOIS; HUC, M.; KERAVEC, P.; BÉZIAT, P.; FIEUZAL, R.; CESCHIA, E.; DEDIEU, G. Maize and sunflower biomass estimation in southwest France using spatial and temporal resolution remote sensing data. Remote **Sensing of Environment**, v.124, p. 884-857, 2012.

RAUPASCH, M. R. Combination theory and equilibrium evaporation. **Quarterly Journal of the Royal Meteorological Society**, v. 127, p. 1149-1181, 2001.

TEIXEIRA, A. H. de C.; BASTIAANSSEN, W. G. M.; BASSOI, L. H. Crop water parameters of irrigated wine and table grapes to support water productivity analysis in Sao Francisco River basin, Brazil, **Agricultural Water Management**, v. 94, p. 31-42, 2007.

TEIXEIRA, A. H. de C.; BASTIAANSSEN, W. G. M.; MOURA, M. S. B., SOARES; J. M., AHMAD, M. D.; BOS, M. G. Energy and water balance measurements for water productivity analysis in irrigated mango trees, Northeast Brazil, **Agricultural and Forest Meteorology**, v. 148, p. 1524-1537, 2008.

TEIXEIRA, A. H. de C., 2009. **Water productivity assessments from field to large scale: a case study in the Brazilian semi-arid region**, LAP Lambert Academic Publishing: Saarbrücken, Germany; 226 p.

TEIXEIRA, A. H. de C.; HERNANDEZ, F. B. T.; ANDRADE, R. G.; LEIVAS, J. F.; BOLFE, E. L. Energy balance with Landsat images in irrigated central pivots with corn crop in the São

Paulo State, Brazil. **Proceedings of SPIE - International Society for Optical Engineerin**g, v. 9239, p. 923900-1-92390O-10, 2014a.

TEIXEIRA, A. H. de C.; VICTORIA, D. de C.; ANDRADE, R. G.; LEIVAS, J. F.; BOLFE, E. L.; CRUZ, C. R. Coupling MODIS images and agrometeorological data for agricultural water productivity analyses in the Mato Grosso state, Brazil. **Proceedings of SPIE - International Society for Optical Engineering**, v. 9239, p. 92390W-1-92390W-14, 2014b.

VANHELLEMONT, Q.; KEVIN RUDDICK, K. Turbid wakes associated with offshore wind turbines observed with Landsat 8. **Remote Sensing of Environment**, v. 145, p. 105-115, 2014.

WANG, X.; MA, M.; HUANG, G.; VEROUSTRAETE, F.; ZHANG, Z.; SONG, Y.; TAN, J. Vegetation primary production estimation at maize and alpine meadow over the Heihe River Basin, China. **International Journal of Applied Earth Observation Geoinformation**, v. 17, p. 94-101, 2012.

WU, C.; MUNGER, J. W.; NIU, Z.; KUANGA, D. Comparison of multiple models for estimating gross primary production using MODIS and eddy covariance data in Havard Forest. **Remote Sensing of Environment**, v. 114, p. 2925-2939, 2010.

YUAN, M.; ZHANG, L.; GOU, F.; SU, Z.; SPIERTZ, J. H. J.; WERF, W. VAN DER. Assessment of crop growth and water productivity for five C3 species in the semi-arid Inner Mongolia. **Agricultural Water Management**, v. 122, p. 28-38, 2013.

ZWART, S. J.; BASTIAANSSEN, W. G. M.; FRAITURE de F.; MOLDEN, D. J. WATPRO: A remote sensing based model for mapping water productivity of wheat. **Agricultural Water Management**, v.97, p. 1628-1636, 2010.