Determining Large Scale Actual Evapotranspiration Using Agro-Meteorological and Remote Sensing Data in the Northwest of Sao Paulo State, Brazil

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Abstract

The best irrigation management depends on accurate estimation of reference evapotranspiration (ET_0) and then selection of the appropriate crop coefficient for each phenological stage. However, the evaluation of water productivity on a large scale can be done by using actual evapotranspiration (ET_a), determined by coupling agrometeorological and remote sensing data. This paper describes methodologies used for estimating ET_a for 20 centerpivots using three different approaches: the traditional FAO crop coefficient (K_c) method and two remote sensing algorithms, one called SEBAL and other named TEIXEIRA. The methods were applied to one Landsat 5 Thematic Mapper image acquired in July 2010 over the Northwest portion of the Sao Paulo State, Brazil. The corn, bean and sugar cane crops are grown under center pivot sprinkler irrigation. ET_0 was calculated by the Penman-Monteith method with data from one automated weather station close to the study site. The results showed that for the crops at effective full cover, SEBAL and TEIXEIRA's methods agreed well comparing with the traditional method. However, both remote sensing methods overestimated ET_a according to the degree of exposed soil, with the TEIXEIRA method presenting closer ET_a values with those resulted from the traditional FAO K_c method. This study showed that remote sensing algorithms can be useful tools for monitoring and establishing realistic K_c values to further determine ET_a on a large scale. However, several images during the growing seasons must be used to establish the necessary adjustments to the traditional FAO crop coefficient method.

INTRODUCTION

The results of human activities upon water resources were seen under the strict local scale vision. Nowadays, these resources can be analysed at the hydrological basin scale, where the planning and occupation is an increasing necessity in society with rising water use, compromising the environment by the coupled effects of climate and land use changes.

Water demand already exceeds supply in many parts of the world and as population continues to rise, many areas are expected to experience water scarcity (Gousbesville, 2008). This scarcity is accompanied with continuous pollution of the rivers in developing countries.

To achieve sustainable water resources development and secure water availability to competing user groups, future water management may notice the water accounting approach, which recognizes the various inhabitants of a basin and water flows in terms of production and water consumption (Cai et al., 2002)

Rising conflicts are expected as populations expand, economies grow, and the competition for limited water supplies intensifies. Basin-level dialogues among different users are required for the water allocation criterion. These dialogues requires a deep knowledge and rely on the available hydrological, land use, water consumption, and yield data for each agro-ecosystem in the area of interest.

Several ways of water use can be found together with the increase of population and the need of food production in the Northwest of São Paulo State. This region is characterized by dry winter and a moderate and wet summer, presenting the highest evapotranspiration rates of the State. Some periods with absence of rains may limit the water productivity due to water deficiencies which can happen at durations as long as eight months (Hernandez et al., 1995; Santos et al., 2010). Hernandez et al. (2003) reported high probabilities of natural water scarcity for crop growing, making irrigation an essential practice for agricultural development under these conditions. Several irrigation systems are being used for different crops, involving centerpivots in corn, bean and sugar cane.

Although irrigation favors the success of these crops, several situations reveal poor water management, contributing to excessive erosion which can adversely affect water availability and quality. These effects together can make the expansion of irrigated agriculture unlikely. Thus, studies considering water use quantification on a large scale are important to secure water supply in the future. The coupled use of satellite and agro-meteorological data can improve irrigation water management, as well as the conditions of water resources in general, making possible to monitor the impact of the intensive irrigated agriculture on the environment.

Evapotranspiration (ET) is one of the most important mediator of the weather and climate at both local and regional scale, connecting the energy and the water balances. It is estimated that 60 to 80% of the precipitation water goes back to the atmosphere through ET, which works then as a fundamental regulator agent for the availability of surface and underground water (Braun et al., 2001).

Experimentally, the calculation of ET can be made accurately using the Bowen ratio method, eddy covariance technique and scintillometers. The Bowen ratio method has been applied in agricultural crops and natural vegetation (Scott et al., 2003; Inmar-Balber et al., 2003; Lee et al., 2004; Teixeira et al., 2007). Examples of eddy covariance measurements can be also found (Cleverly et al., 2002; Humphreys et al., 2003, Lund and Soegaard, 2003; Prueger et al., 2004; Villalobos et al., 2004; Testi et al., 2004; Simmons et al., 2007; Teixeira et al., 2008a, 2008b). All these field methods however provide values for specific sites and cannot estimate ET at a regional scale. On large scales, the spatial variability is significant and direct extrapolation of energy balance data from flux towers to a surrounding environment can lead to inaccurate regional estimates.

Among the models to obtain the ET at regional scale using satellite images is the SEBAL (Surface Energy Balance Algorithm for Land), which uses the spatial variability of several key parameters and can be applied to various ecosystems (Teixeira et al., 2009b). This method requires surface spectral data in the visible, near infrared and thermal infrared wavebands. However, the disadvantage of the SEBAL algorithm is the need for identification of extreme conditions. This identification is not required in the TEIXEIRA algorithm, which makes use of the modelled ratio of the actual (ET_a) to the reference (ET_0) evapotranspiration (Teixeira, 2010). On the other hand, one of the problems in relation to the applicability of the satellite energy balance models, aiming the end users, is the need of the background knowledge in radiation physics involved inside these algorithms. The use of the fraction ET_a/ET_0 is highlighted by the model METRIC, where it is applied to extrapolate instantaneous values of ET_a to larger time scales (Allen et al., 2007).

The SEBAL algorithm was calibrated and validated with field measurements with hydrological contrast in the semi-arid region of Brazil (Teixeira, 2009; Teixeira et al., 2009a, 2009b). Although the model presented a good performance, the challenge for its applicability is the need of the characterization of the energy balance components under extreme conditions during the rainy season, because under these circumstances one cannot assume a zero value for the latent heat fluxes at the hot pixel.

Considering the simplicity of application and the absence of the need of either crop classification or extreme conditions, the new TEIXEIRA algorithm was tested against the SEBAL model and the traditional FAO crop coefficient method. This application is done with one Landsat image for ET analyses at daily scale, which is useful for decision making policies in conditions of quick land and water use changes of the Northwestern São Paulo region.

MATERIAL AND METHODS

The research was carried out in the Northwest of São Paulo State in a commercial area with central coordinates of 20°41’40”S, 50°59’02”W, where there are 20 center pivots covering an irrigated area of 2,111 ha (Bonança Farm) under rain-fed corn, bean, soybean, sugar cane, and pasture. One Landsat TM5 image for 12 July 2010 (80 days after the last rain) was used together with data from an agrometeorological station close to the study area. The reference evapotranspiration (ET_0) was calculated by the Penman-Monteith equation (Allen et al., 1998).

Crop water requirements in each pivot were estimated following the tabled values of crop coefficients from the FAO 56 bulletin (Allen et al., 1998) and the actual evapo-transpiration (ETa) was acquired applying the SEBAL (Bastiaanssen et al., 1998) and the TEIXEIRA (Teixeira, 2010) algorithm. Table 1 summarizes the steps for the application of the TEIXEIRA model to obtain the regional ET in the Northwestern São Paulo.

After converting the spectral radiances into surface reflectance and applying atmospheric corrections, maps of NDVI, α_0 and T_0 are the only input parameters for estimating the instantaneous values of the ratio ET/ET_0 without the need of the regional radiation balance. The instantaneous values of this ratio are multiplied by the daily grids of ET_0 to estimate the regional values of ET_a for 24 hours.

RESULTS AND DISCUSSION

Water use results obtained using the SEBAL and TEIXEIRA algorithms for each center pivot compared with those obtained from the FAO 56 methodology are presented in Table 2. In general, the results from both models compared well with those from the FAO methodology during the period of maximum crop water requirements (“mid-season stage”).

On the other hand, the FAO Kc values used for corn in the center pivots 10,15 and 16 were lower than those resulted from the remote sensing methods, indicating a possible degree of water deficiency. In addition, the Kc values for the “late season” stage were applied during the irrigation season, while in fact the crop should have been in their “mid-season” stage. This resulted in a water use estimate that was 42% less than the corn water requirements (Table 2). Satellite measurements can accurately identify these stages and the results clearly indicate that the crop stages should be defined with more accuracy and objectively, as by using relations between the crop coefficient and the accumulated degree days. According to Teixeira (2009), the advantage of the use of this relationship is the transfer of Kc values to different thermal conditions.

The generalized low values of standard deviation (SD) indicate uniformity in water application in the areas covered by the center pivots, with the exception of the pivot 9 (resting field) mainly for the SEBAL method. One reason for this is that only part of this pivot was irrigated and the TEIXEIRA method can minimize the effects of water applied to the soil on the passage of the satellite. Since the center pivot has not finished the complete rotation cycle, the SEBAL standard deviation (0.69) is much greater than the TEIXEIRA (0.29). Also compared to the crop coefficient, which in this situation was 0.3, SEBAL indicated 1.1 (value not true), while TEIXEIRA was 0.5 confirming the superiority of the latter method in this soil cover condition.

The maps of ETa in the Northwest of São Paulo State obtained by the application of the two remote sensing algorithms are shown in Figure 1. One can clearly see the higher sensibility for the TEIXEIRA method in relation to SEBAL. The highest ETa values are for the pivots with corn, because the plants are in their "mid season" stage.

Figure 2 shows the histogram values of ETa (center pivot 3 and 11) under different soil cover (almost bare soil in 3, at 5 days after planting and 11, with total soil coverage at 12 days after planting), showing the greater uniformity of the data obtained by TEIXEIRA's simplest method.

CONCLUSIONS

The crop coefficient values used for the irrigation management following FAO in the study area needed adjustments to better quantify the crop stages. The satellite measurements combined with agrometeorological data presented coherence with these stages, However, under partial soil cover, the TEIXEIRA model showed more consistence than SEBAL. The results are promising, stimulating the use of several images during the crop growing seasons for subsidizing the water managers at the large scale.

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Tables

Table 1. Summary of the applied equations: Surface albedo - α_0, Planetary albedo - α_p, Surface temperature - T_0, Brightness temperature - T_{sat}, Atmospheric emissivity, Normalized Difference Vegetation Index - NDVI, Actual evapotranspiration - ET_a, and reference evapotranspiration - ET_0.

Parameter	Equation	a	b	R^2
α_0	$\alpha_0 = a\alpha_p + b$	0.70	0.06	0.96
T_0	$T_0 = aT_{sat} + b$	1.11	-31.89	0.95
ET/ET_0	$ET/ET_0 = \exp\{a + b[T_0/(\alpha_0 NDVI)]\}$	1.00	-0.008	0.91

Table 2. Daily actual evapotranspiration (ET_a) and its ratio to reference evapotranspiration (ET_0) by different methods for each center pivot.

PIVOT	AREA	CROP	DAP	FAO	SEBAL	TEIXEIRA	FAO	SEBAL	TEIXEIRA	SEBAL	TEIXEIRA
	ha			ET_a/ET_o			ET_a (mm.d^{-1})			SD (mm.d^{-1})	
1	109	Corn	78	1.4	1.2	1.2	4.9	4.7	4.5	0.13	0,10
2	75	Corn	86	1.4	1.1	1.2	4.8	4.3	4.5	0.26	0.13
3	109	Bean	5	0.4	1.3	0.5	1.4	4.8	2.0	0.35	0.18
4	109	Corn	83	1.4	1.3	1.2	4.9	4.8	4.4	0.18	0.10
5	69	Bean	13	0.5	1.3	0.6	1.8	4.9	2.3	0.21	0.12
6	120	Corn	76	1.4	1.1	1.2	4.9	4.3	4.6	0.12	0.08
7	75	Corn	88	1.3	1.2	1.2	4.5	4.4	4.4	0.25	0.16
8	75	Corn	89	1.2	1.1	1.2	4.3	4.3	4.5	0.21	0.11
9	120	Resting stage	-	0.3	1.1	0.5	1.1	4.1	2.0	0.69	0.28
10	75	Corn	116	0.5	1.2	1.1	1.8	4.6	4.1	0.20	0.13
11	95	Corn	121	0.5	1.1	1.1	1.8	4.3	4.2	0.13	0.10
12	95	Corn	95	1.0	1.2	1.2	3.4	4.5	4.4	0.18	0.16
13	162	Corn	102	0.7	1.2	1.2	2.4	4.4	4.5	0.16	0.10
14	100	Corn	91	1.1	1.2	1.2	4.0	4.4	4.6	0.14	0.11
15	100	Corn	106	0.5	1.2	1.2	1.8	4.4	4.4	0.21	0.13
16	117	Corn	117	0.5	1.2	1.1	1.8	4.5	4.3	0.12	0.11
17	145	Sugar cane	-	-	0.9	0.8	-	3.4	3.1	0.32	0.35
18	120	Sugar cane	-	-	1.0	1.0	-	3.8	3.8	0.12	0.14
19	120	Sugar cane	-	-	1.0	1.0	-	4.0	3.7	0.26	0.36
20	120	Sugar cane	-	-	0.9	0.9	-	3.4	3.3	0.21	0.24
Mean	106	-	-	0.9	1.1	1.0	3.1	4.3	3.9	0.22	0.16

* DAP: Days after planting, SD: Standard deviation.

Figures

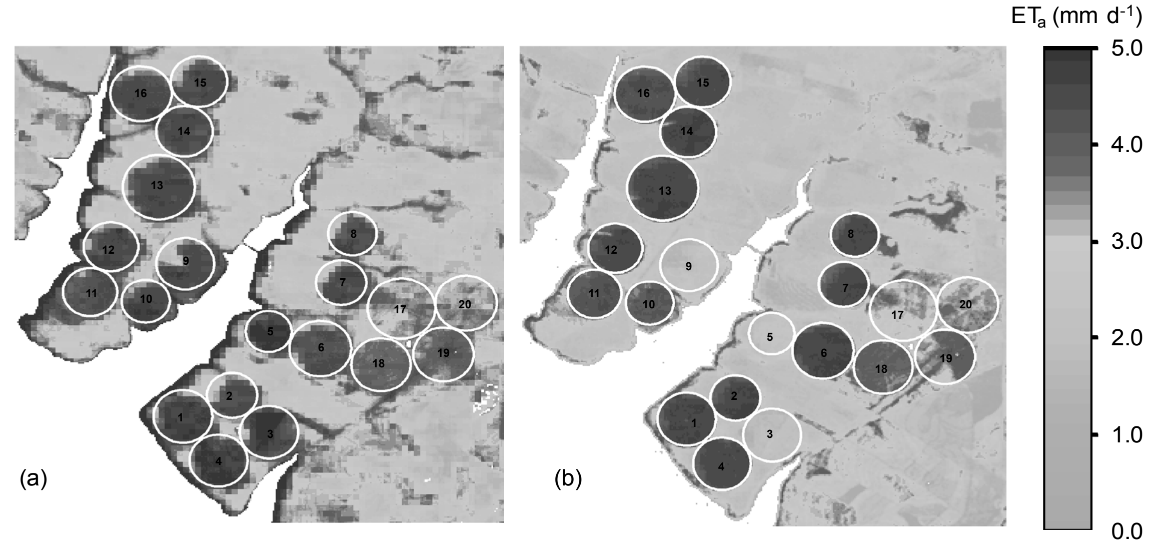

Fig. 1. Daily actual evapotranspiration (ET_a) in the study area of the Northwestern São Paulo by SEBAL (a) and TEIXEIRA (b) models.

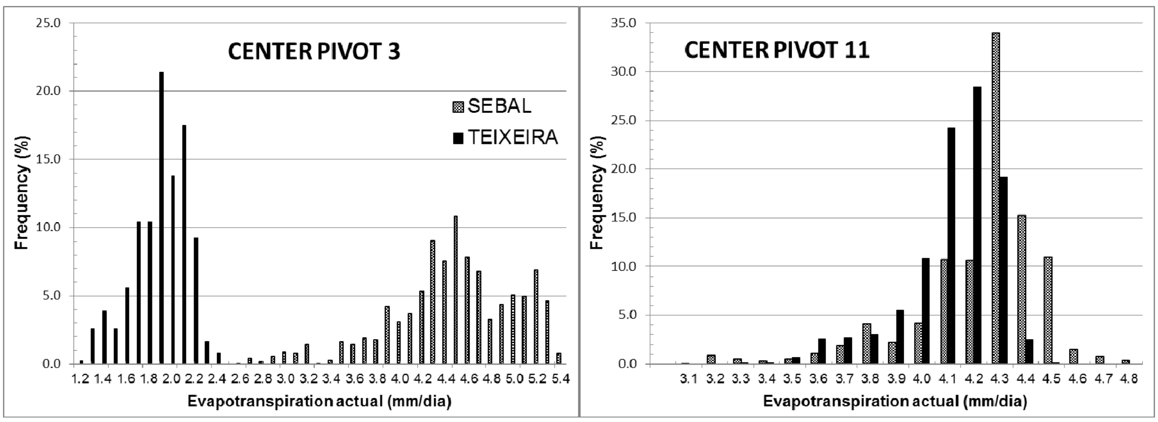

Fig. 2. Histograms of daily actual evapotranspiration (ET_a) in the study area of the Northwestern São Paulo, Brazil: center pivot 3 and 11.