# Irrigation performance assessments for corn crop with Landsat images in the São Paulo state, Brazil

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**Abstract:** Actual evapotranspiration (ET) and crop coefficient (Kc) were modelled in a commercial farm with corn crop. The plots were irrigated by central pivots for grain and silage, in the north-western side of São Paulo State, Brazil. For ET acquirements, the SAFER (Simple Algorithm For Evapotranspiration Retrieving) algorithm was applied to Landsat satellite images during growing seasons (GS) from March to August of 2010. Polynomial functions relating Kc and the accumulated degree-days ($DD_{ac}$) allowed the estimation of evapotranspiration under potential conditions (ETp). Adding data on reference evapotranspiration (ET0), precipitation (P), irrigation (I) and productivity ($Y_p$), irrigation performances were assessed. The Relative Evapotranspiration ($R_{ET}$) ranged from 0.78 to 1.00 and the Water Deficit (WD) presented a maximum of 110 mm $GS^{-1}$. The Relative Water Supply ($R_{WS}$) with values from 1.1 to 1.4 indicated high drainage rates. The physical values of water productivity, based on ET ($WP_{ET}$) ranged from 1.4 to 2.8 kg $m^{-3}$ for grains and from 8.8 to 14.1 kg $m^{-3}$ for silage, with the corresponding monetary ones for grains from 0.34 to 0.68 US$ $m^{-3}$, showing high return when comparing with other annual crops.

**Keywords:** Remote sensing, evapotranspiration, crop coefficient, degree-days.

# Acessos ao desempenho de irrigação da cultura do milho com imagens Landsat no estado de São Paulo, Brasil

**Resumo:** A evapotranspiração atual (ET) e coeficiente de cultura (Kc) foram modelados em uma fazenda comercial com a cultura do milho. As parcelas foram irrigadas por pivôs centrais para grãos e silagem, no lado noroeste do Estado de São Paulo, Brasil. Para obtenção da ET, o algoritmo SAFER (*Simple Algorithm For Evapotranspiration Retrieving*) foi aplicado em imagens do satélite Landsat durante os ciclos produtivos (CP) de março a agosto de 2010. Funções polinomiais relacionando o coeficiente de cultura (Kc) com os graus-dias acumulados ($GD_{ac}$) permitiram a estimativa da evapotranspiração em condições potenciais (ETp). Adicionando dados de evapotranspiração de referência (ET0), precipitação (P), irrigação (I) e produtividade ($Y_p$), os desempenhos de irrigação foram analisados. A Evapotranspiração Relativa ($R_{ET}$) ficou entre 0,78 e 1,00 enquanto que a Deficiência Hídrica (WD) apresentou um máximo de 110 mm $CP^{-1}$. O Suprimento de Água Relativo (RWS) com valores de 1,1 a 1,4 evidenciou altas taxas de drenagem. Os valores físicos da produtividade da água, baseada na ET ($PA_{ET}$) estiveram entre 1,4 e 2,8 kg $m^{-3}$ para grãos e de 8,8 a 14,1 kg $m^{-3}$ para silagem, com os monetários correspondentes para grãos de 0,34 a 0,68 US$ $m^{-3}$, apresentando elevado retorno quando comparados com outras culturas anuais.

**Palavras Chave:** Sensoriamento remoto, evapotranspiração, coeficiente de cultura, graus-dias.

## Introduction

In the Southeast region of Brazil, one of the main crops is corn (*Zea mays* L.), which has been cultivated in two periods during the year. The first period (first harvest crop) starts in October or November, coinciding with the beginning of rainfalls, whereas the second period (second harvest crop) starts in February or March.

Soil moisture is important for maintaining yield at optimum levels, thus the soil water deficit (WD) is the main risky factor for the second harvest corn crop, which can be attenuated at high altitudes, because the lower values of air temperature reduce the evapotranspiration rates (Ko and Piccinni, 2009). Water stress can affect the plant development and the physiological processes, reducing yield, with this last parameter being a linear function of evapotranspiration (Traore et al., 2000; Payero et al., 2006), both included in irrigation performance indicators.

For irrigation performance assessments, it is important to dicern the concepts of reference evapotranspiration (ET0), potential evapotranspiration (ETp) and actual evapotranspiration (ET) adopted in the current study. ET0 is the evapotranspiration rate from a reference surface, which in this paper is grass. $ET_p$ may be referred as the water flux from crops growing in large fields under optimum soil moisture, excellent management and environmental conditions, achieving full production under the given climatic conditions. ET involves all situations of the vegetated surface (Allen et al., 1998). ET can deviate from ETp due to the presence of pests and diseases, soil salinity, low soil fertility, water shortage or water logging. The deviations from the optimum conditions affect the productivity and quality of the harvested products. The water fluxes characteristics that distinguish field crops from grass are integrated into crop coefficient (Kc), which multiplied by ET0 gives ETp. The upper envelope of ET/ET0 values during a growing season may represent the seasonal behaviour of the Kc values (Teixeira et al., 2008a; Teixeira, 2009).

One suitable way to make the rational irrigation management is throughout the Kc approach (Allen et al., 1998). Kc can be determined throughout field measurements (Teixeira et al., 2008b; Teixeira, 2009); however, remote sensing by satellite images is another powerful way for its modelling (Tasumi and Allen, 2007). Acquiring the Kc values during the growing seasons is the first step and challenge for the researchers when aiming an efficient water management. The second one is related to the extension services for disseminating its use with sufficient accuracy.

Irrigation performance in agriculture must be efficient to feed the growing population and for the rational water resources management (Bos et al., 2005). Contributions from remote sensing by satellite images give opportunities for evaluating this performance at different spatial and temporal scales (Teixeira et al., 2009; Teixeira, 2010; Teixeira et al., 2013). The use of satellite images for diagnostic study on irrigation performance was already carried out in a Brazilian irrigation scheme by using the visible, near-infrared and thermal bands of NOAA images (Bastiaanssen et al., 2001). However, the spatial resolution of these images is 1.1 km implying that many pixels cover a mixture of land use. Bastiaanssen et al. (2001) used SEBAL (Surface Energy Balance Algorithm for Land) for ET acquirements (Bastiaanssen et al., 1998) and the empirical Prestley and Taylor equation (Priestly and Taylor, 1972) to derive ETp.

Considering that corn crop and its growing areas in the south-eastern region of Brazil are inside of the priorities from the Brazilian Ministry of Agriculture, the irrigation performance assessments in commercial farms for grain and silage are relevant, especially in the north-western side of São Paulo State. In scenarios of high probabilities of water scarcity for agriculture (Hernandez et al., 2003), rational irrigation is an essential practice for crop development.

Several remote sensing algorithms have been developed for ET estimations, being based largely on the energy balance theories, highlighted by some advantages and shortcomings. The Surface Energy Balance Algorithm for Land—SEBAL (Bastiaanssen et al. 1998), the Surface Energy Balance Index—S-SEBI (Roerink et al. 2000), and the Surface Energy Balance System - SEBS (Su 2002), are some examples. Those techniques can be applied to several conditions without the need of crop classification, what is considered difficulty to be done in mixed agro-ecosystems.

The disadvantage of many remote sensing energy balance methods is the need to identify hydrological extreme conditions. Other problem in relation to the applicability of the energy balance models, aiming at the end users, is the need of background knowledge in radiation physics involved inside these algorithms. Although the worldwide known SEBAL algorithm had been calibrated and validated with field radiation and energy balance measurements, presenting a good performance in the Brazilian semi-arid region (Teixeira et al. 2009a,b), the major difficult for its applicability for a whole year is the assumption of zero latent heat flux (λE) for dry pixels.

Considering the simplicity of application and the absence of the need of neither crop classification nor extreme conditions, a model for ET acquirements based on the modelled ratio ET/ET$_0$, called SAFER (Simple Algorithm For Evapotranspiration Retrieving) was developed and validated with field data from four flux stations involving irrigated crops and natural vegetation, in Brazil (Teixeira, 2010, Teixeira et al., 2013, Teixeira et al., 2014a). In the current research, it was used to estimate ET, whereas to take into account ETp, specific relations for grains and silage between crop coefficients (Kc) and the accumulated degree-days (DD$_{ac}$) were elaborated. Then ETp was calculated multiplying ET0 by Kc.

The main goal of this research was to assess the irrigation performance for corn crop, irrigated by central pivots, at the north-western side of the Brazilian São Paulo State. Weather, irrigation and yield data were used together with the SAFER algorithm and Landast images. The analyses is meant to subsidize a rational water management, generating agrometeorological indicators for up-scaling water variables to other regions of the country.

## Materials and Methods

Fig. 1 shows the locations of the irrigation central pivots and the agrometeorological station from the São Paulo University State (UNESP) used in the north-western side of São Paulo state, Brazil (latitude 20°25' S; long 51°21' W). This area is characterized by a dry winter and a moderate and wet summer, presenting the highest ET rates of the State. According to the Koepën climatic classification this region is Aw type, defined as a tropical wet climate, with the dry season lasting as
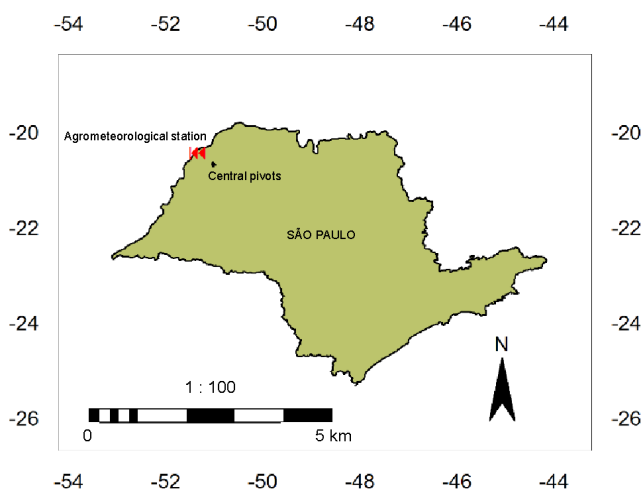
long as eight months (Santos et al., 2010). The long-term rainfall range is from 13 to 239 mm month$^{-1}$ and the corresponding one for the mean air temperature from 21.7 to 26.9 °C. The average total for annual precipitation is 1260 mm while that for the average relative humidity is 62.4%.

The SAFER algorithm was applied to Landsat 5 satellite images from March 22, April 07, April 23, June 10, June 26, July 12 and August 29 of 2010. For ET acquirements, only the visible and near infrared bands were used together with agrometeorological data.

Weather data for 2010 were used together with the images and successive interpolations of these images were performed to cover the complete corn crop growing seasons at each central pivot, resulting in ten images involving the entire farm. For Kc modelling, six pivots for grains and eight for silage were considered; further selecting five of each commercial proposal, for irrigation performance assessments.

Fig. 2 shows the flowchart for ET acquirements by using the SAFER algorithm with the red and infrared bands of the Landsat images together with agrometeorological stations.

The daily values of surface albedo ($\alpha_0$) were calculated according to Teixeira (2010):

$$\alpha_0 = a\alpha_p + b \qquad (1)$$

where $\alpha_p$ is the planetary albedo and a and b are regression coefficients, which for a 24 hour period were respectively 1.70 e 0.13.

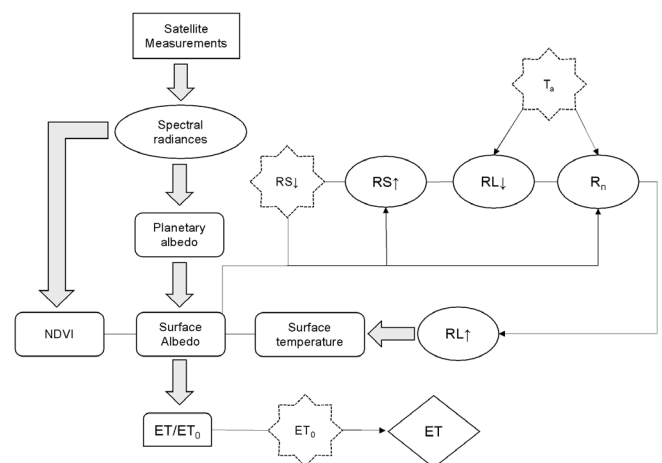The Normalized Difference Vegetation Index (NDVI) was calculated with the bands 3 and 4 of the



**Figure 1**. Location of the irrigation corn crop central pivots and the weather station used in the north-western side of São Paulo (SP) State, Brazil



**Figure 2**. Flowchart for evapotranspiration (ET) acquirements by using the SAFER (Simple Algorithm For Evapotranspiration Retrieving) algorithm by using the red and infrared bands of the Landsat images together with agrometeorological stations

Landsat images (Teixeira et al., 2009; Teixeira, 2010; Teixeira et al., 2014a):

$$NDVI = \frac{\alpha_{p_{(4)}} - \alpha_{p_{(3)}}}{\alpha_{p_{(4)}} + \alpha_{p_{(3)}}} \qquad (2)$$

where $\alpha_{p(4)}$ and $\alpha_{p(3)}$ represent the planetary albedo over ranges of wavelengths in the near infrared (band 4) and red (band 3) regions of the solar spectrum, respectively.

For better analyses at the pivot scales, instead of using the thermal band from Landsat 5 (120 m), the surface temperature ($T_0$) in the current study was physically estimated as a residual in the radiation balance equation with only the visible and near infrared bands (spatial resolution of 30 m) (Teixeira et al., 2014b,c).

The radiation balance equation may be described as:

$$R_n = RS\downarrow - RS\uparrow + RL\downarrow - RL\uparrow \qquad (3)$$

where and $RS\downarrow$ and $RS\uparrow$ are shortwave components representing respectively the incident and reflected solar radiation; and the longwave components $RL\downarrow$ and $RL\uparrow$ are the radiation emitted by the atmosphere and the surface, respectively.

$RS\downarrow$ was measured at the agrometeorogical station and $RS\uparrow$ is given by:

$$RS\uparrow = \alpha_0 RS\downarrow \qquad (4)$$

$RL\downarrow$ was calculated by the Stefan-Boltzmann low:

$$RL\downarrow = \sigma \varepsilon_a T_a \qquad (5)$$

where $\sigma$ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$); $\varepsilon_a$ is the atmospheric emissivity and $T_a$ is the air temperature measured at the agrometeorological station.

$\varepsilon_a$ was calculated as following (Teixeira, 2010; Teixeira et al., 2014a):

$$\varepsilon_a = a_a \left(-\ln \tau_s\right)^{b_a} \qquad (6)$$

where $\tau_s$ is the short-wave transmissivity calculated as the ratio of $RS\downarrow$ to the incident solar radiation at the top of the atmospheric; and $a_a$ and $b_a$ are regression coefficients taking as 0.94 and 0.10 according to Teixeira et al. (2014a).

The regression coefficients for Eq. 6 for the current research are between those in Idaho ($a_a = 0.85$ and $b_a = 0.09$; Allen et al., 2000) and in Egypt ($a_a = 1.08$ and $b_a = 0.26$; Bastiaanssen et al.,1998).

The Slob equation (Teixeira et al, 2013, 2014a,b,c) for acquiring the daily values of $R_n$, is described as:

$$R_n = \left(1 - \alpha_0\right) RS\downarrow - a_1 \tau_s \qquad (7)$$

where the regression coefficient $a_1$ was obtained throughout its relation with $T_a$:

$$a_1 = b_1 T_a - c_1 \qquad (8)$$

where $b_1$ and $c_1$ are regression coefficients found to be 6.99 and 39.93, respectively under different thermohydrological conditions in the Brazilian semi-arid region (Teixeira, 2010; Teixeira, 2013, Teixeira, 2014a,b,c). Originally $a_1$ coefficient was considered constant (Bastiaansssen et al., 1998), Eq. 8 was derived by Teixeira et al. (2008b) throughout field experiments, having the advantage of taking into account different thermal conditions.

Having the $RL\uparrow$ daily values as a residual in Eq. 3, $T_0$ was estimated:

$$T_0 = \sqrt[4]{\frac{RL\uparrow}{\varepsilon_0 \sigma}} \qquad (9)$$

where $\varepsilon_0$ is the surface atmospheric emissivitiy calculated as:

$$\varepsilon_0 = a_0 \ln NDVI + b_0 \qquad (10)$$

where $a_0$ and $b_0$, are the regression coefficients considered 0.06 and 1.00 from Teixeira (2010) and Teixeira et al. (2014a,c) obtained under different thermohydrological conditions. The original coefficients for Eq. are $a_0 = 0.047$ and $b_0 = 1.009$ (Bastiaanssen et al., 1998).

Even with small differences between the regression coefficients in the emissivities of Eq. 6 and 10 in relation to others sites, possible errors in the Northwest side of São Paulo state are self-minimized in Eq 3 when taking into account all radiation balance components.

Having calculated the input parameters for the SAFER algorithm, the daily ET was acquired with ET0 data for the same time scale:

$$\frac{ET}{ET_0} = \exp\left[a_s + b_s\left(\frac{T_0}{\alpha_0 NDVI}\right)\right] \qquad (11)$$

where $a_s$ and $b_s$ are regressions coefficients, which for the north-western side of São Paulo were considered 1.0 and - 0.008, respectively (Teixeira et al., 2014a).

The average values of the ET/ET0 ratio in the buffered areas of the irrigation pivots and without water deficits (Allen et al., 1998) allowed the Kc modelling as a function of the accumulated degree-days ($DD_{ac}$) taking the basal temperature of 10 °C and considering

both commercial situations, corn for grains (subscript G) and for silage (subscript S):

$$Kc_{G,S} = a_{G,S}DD_{ac}^2 + b_{G,S}DD_{ac} + c_{G,S} \qquad (12)$$

where $a_G$, $a_S$, $b_G$, $b_S$, $c_G$ and $c_S$ are the regression coefficient determined in the current research.

The values of evapotranspiration under potential conditions (ETp) for grains and silage were estimated as:

$$ETp_{G,S} = Kc_{G,S}ET_0 \qquad (13)$$

Following Bastiaanssen et al. (2001) and Teixeira et al. (2008a) the irrigation performance indicators applied were the relative evapotranspiration ($R_{ET}$) relative water supply ($R_{WS}$), water deficit (WD) and water productivity based on evapotranspiration ($WP_{ET}$) and irrigation ($WP_I$):

$$R_{ET} = \frac{ET}{ETp} \qquad (14)$$

$$R_{WS} = \frac{I+P}{ETp} \qquad (15)$$

$$WD = ETp - ET \qquad (16)$$

$$WP_{ET,I} = \frac{Y_{G,S}}{ET,I} \qquad (17)$$

Where I is the water applied through irrigation, P is the precipitation and $Y_{G,S}$ is the grain (G) or silage (S) yield.

With the availability of prices for grains, the economic indicator was the monetary value of grain production over ET and I ($WP\$_{ET}$) and ($WP\$_I$) (Bos et al., 2005; Teixeira et al. 2008a).

## Results and Discussion

### Weather drivers

Fig. 3 shows the monthly variations of RS↓, ET0 and P through the year of 2010 at the study area. RS↓ represents the main energy source for the evaporative processes. Lower levels happened from May to September, around 16.2 MJ m$^{-2}$ day$^{-1}$, at the winter solstice in the South hemisphere, and higher ones were from October to December, averaging 23.4 MJ m$^{-2}$ day$^{-1}$, when the sun is near the zenith position with low cloud cover. High RS↓ values during this last period contributed to strong atmosphere demand and biomass production.
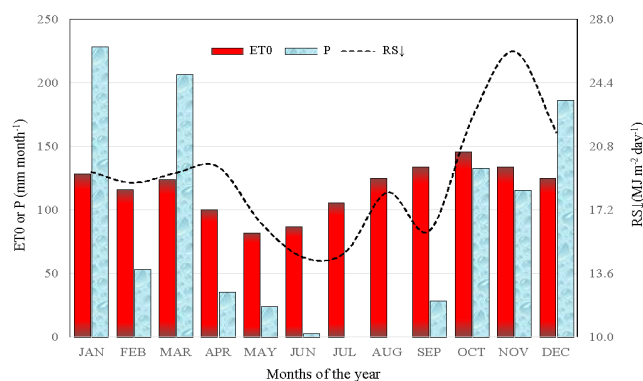


**Figure 3**. Monthly totals of reference evapotranspiration (ET0) and precipitation (P), together with the monthly average daily values of incident global solar radiation (RS↓) at the agrometeorological station, during the year of 2010, in the north-western side of São Paulo State, Brazil

Although the largest ET0 rates occurring at the end of the year, reaching to more than 145 mm month$^{-1}$ in October, their variations along the year are not so high when comparing with those for P. The only months with ET0 lower than 100 mm month$^{-1}$were May and June. Considering P as the natural input in the water balance, much more temporal variation were verified, reaching to rates above 200 mm month$^{-1}$, from February to March, while between July and August there were absence of rains.

Taking the difference between P and ET$_0$ as a crude measure of water availability, in 2010 there were climatic water excesses (P > ET0) only during the months of January (100 mm), March (82 mm) and December (61 mm), while water deficit (P – ET0 < 0) reached to 125mm month$^{-1}$ from July to September. As the stages of the second harvest corn crop are concentrated from April to September, the need of irrigation is evident, which should be based on the crop water requirements.

### Crop coefficient modelling

Fig. 4 shows the spatial distributions of the ET/ET0 pixel values for several days of the year (DOY) during 2010, in an area involving the corn plots, located in the northwestern side of São Paulo state. This area includes irrigated pivots, natural vegetation and water.

Clearly one can distinguish irrigated pivots from the natural vegetation by the highest ET/ET0 values, with some pixels reaching close to 1.40. For the current study, to relate Kc as a function of the accumulated degree-days ($DD_{ac}$) for corn crop, the ET/ET0 values from SAFER results were used, considering six pivots for grain corn and eight for silage, under optimum soil moisture conditions (Fig. 5).
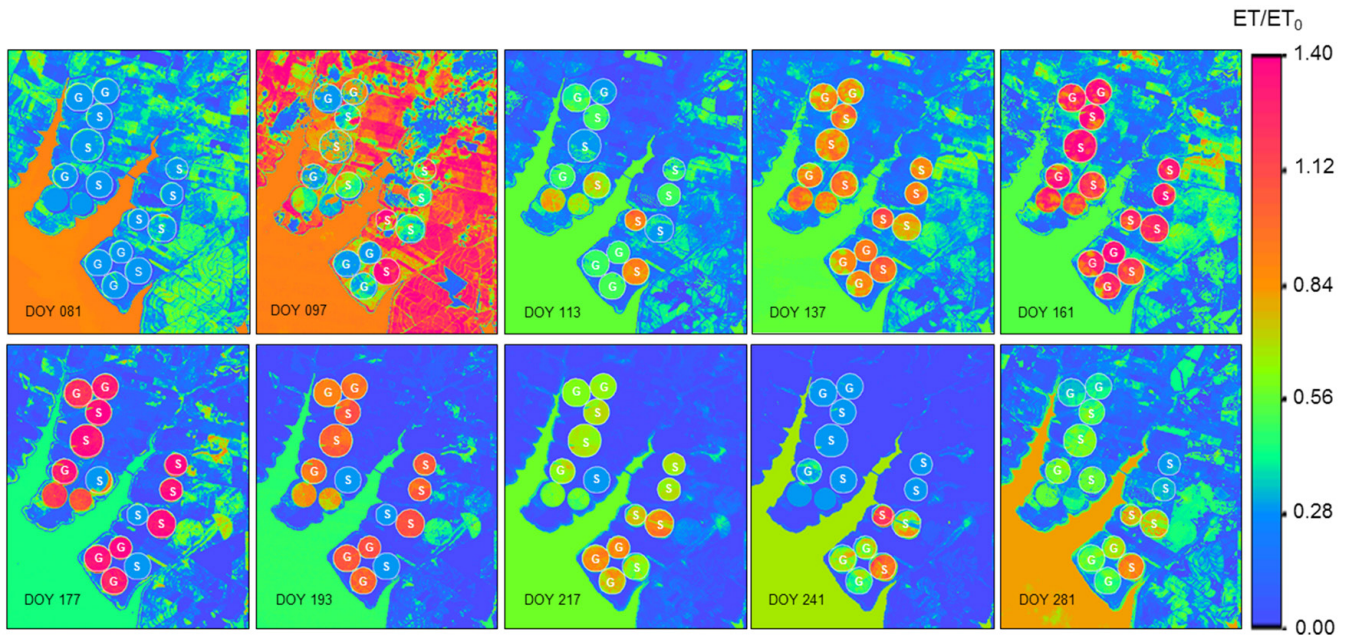
**Figure 4**. Spatial distribution of the ET/ET0 ratio in an area involving the corn plots, located at the north-western side of São Paulo State, Brazil. DOY means days of the year and the letters G and S are Grain and Silage, respectively
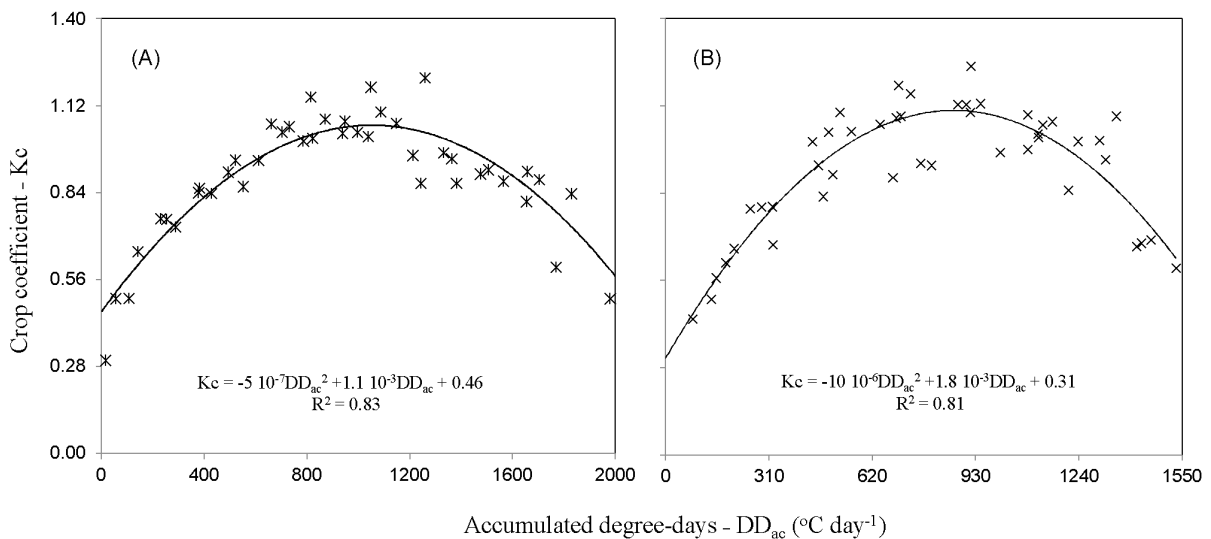


(A) $Kc = -5\ 10^{-7}DD_{ac}^2 + 1.1\ 10^{-3}DD_{ac} + 0.46$
$R^2 = 0.83$

(B) $Kc = -10\ 10^{-6}DD_{ac}^2 + 1.8\ 10^{-3}DD_{ac} + 0.31$
$R^2 = 0.81$

Accumulated degree-days - $DD_{ac}$ (°C day$^{-1}$)

**Figure 5**. Relations between crop coefficients (Kc) and the accumulated degree-days ($DD_{ac}$) for corn crop. Grains (A); silage (B)

The Kc values, considered as the average ET/ET0 pixels in the buffered pivot areas, at different corn crop stages, were between 0.3 and 1.2. This range is in agreement with that reported by DeJonge et al. (2012) during their ET modelling improvements in Colorado (USA) and with the tabled values from the standard work from Allen et al. (1998). One of the advantages of the models showed in Fig. 5 is the possibility of up scaling of the Kc values to different thermal conditions (Teixeira, 2009), as their values are related to $DD_{ac}$. In the current research, these regression equations were used to estimate ETp, which in turn, together ET, are keys parameters for the irrigation performance assessments.

**Irrigation performance assessments**

The input parameters for SAFER algorithm are $\alpha_0$, NDVI and $T_0$ that are used to model the ET/ET0 ratios at the satellite overpass time. This ratio was also applied to acquire the daily ET values multiplying it by ET0 from the agrometeorological station (see Fig. 1). Teixeira (2010) reported no significant differences between the Landsat overpass and daily values of this ratio from field experiments involving irrigated crops and natural vegetation in the Brazilian semi-arid region. For irrigation performance assessments, ten pivots were selected, five for grains and five for silage. Fig. 6 shows the spatial variations of the ET totals for a growing season (Figure 6A) and the seasonal mean
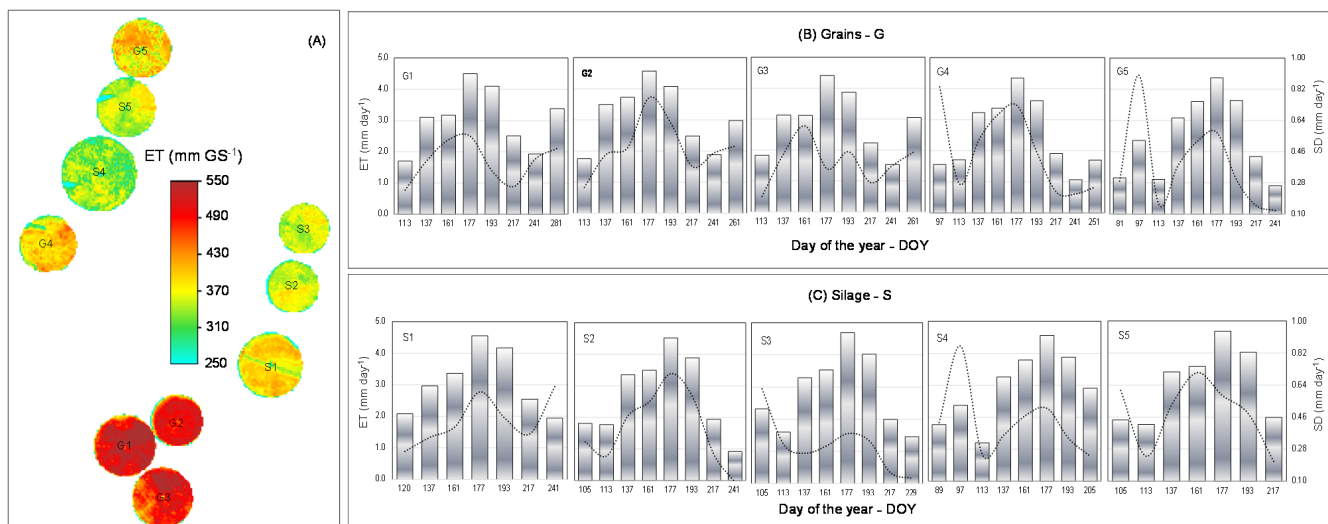
**Figure 6**. Evapotranspiration for ten corn crop irrigation pivots. (A): spatial variation of the growing season (GS) totals for grains (G) and silage (S) corn pivots; (B): seasonal variation of the daily pixel values for grains corn pivots; and (C): seasonal variation of the daily pixel values for silage corn pivots. DOY is day of the year

daily pixel values for each of them (Figures 6B and 6C).

The highest ET values were for the pivots 1, 2 and 3, due to the strongest atmospheric demands involving DOY from 108 - 285 for grains and from 105 - 241 for silage. However, for G1, G2 and G3 several pixels presented total ET above 450 mm; while for S1, S2 and S3 most pixels presented total ET bellow than 400 mm. The larger ET values for grain than for silage are due to the different season lengths, which were in average, respectively 160 and 120 days.

According to the Figures 6B and 6C the highest daily ET rates were on DOY 177, grain-filling stage, while the lowest ones were verified on DOY 241, at the end of the growing seasons. The daily values were in the range from 0.9 and 4.7 mm day$^{-1}$ for both grains and silage. In the Northwest of China, Ding et al. (2013) throughout field measurements and modelling, found similar daily rates, averaging 3.5 mm day$^{-1}$, what brings confidence of using the SAFER algorithm with only the Landsat visible and near infrared bands in the current research.

Knowledge on the water input and output in each pivots allowed the corn irrigation performance assessments, including the water productivity. The indicators are summarized in Table 1 for grain (A) and for silage (B).

**Table 1.** Irrigation performance indicators of corn crop for grain (A) and for silage (B). Area; Growing season (GS); water applied through irrigation ($V_I$); precipitation (P), relative evapotranspiration ($R_{ET}$); water deficit (WD); relative water supply ($R_{WS}$); productivity ($Y_p$) and water productivity based on evapotranspiration ($WP_{ET}$) and on irrigation ($WP_I$)

| Pivots | Area (ha) | GS (days) | $V_I$ (mm) | P (mm) | $R_{ET}$ (-) | WD (mm) | $R_{WS}$ (-) | $Y_p$ (t ha$^{-1}$) | $WP_{ET}$ (kg m$^{-3}$) | WPI (kg m$^{-3}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| (A) Irrigation performance indicators for grain | | | | | | | | | | |
| G1 | 108.0 | 169 | 436.9 | 240.0 | 0.98 | 11.8 | 1.3 | 7.2 | 1.4 | 1.7 |
| G2 | 74.0 | 155 | 498.2 | 48.0 | 0.96 | 20.0 | 1.1 | 10.3 | 2.1 | 2.1 |
| G3 | 108.0 | 168 | 463.7 | 242.0 | 0.93 | 36.5 | 1.4 | 8.0 | 1.6 | 1.7 |
| G4 | 91.0 | 155 | 495.6 | 65.0 | 0.78 | 110.2 | 1.1 | 8.9 | 2.3 | 1.8 |
| G5 | 100.0 | 158 | 405.9 | 160.0 | 0.79 | 100.4 | 1.2 | 10.7 | 2.8 | 2.6 |
| Mean | 96.2 | 161 | 460.1 | 151.0 | 0.89 | 55.8 | 1.2 | 9.0 | 2.0 | 2.0 |
| (B) Irrigation performance indicators for silage | | | | | | | | | | |
| G1 | 118.0 | 123 | 454.9 | 57.0 | 0.99 | 2.6 | 1.3 | 33.3 | 8.8 | 7.3 |
| G2 | 77.1 | 129 | 443.2 | 77.0 | 0.90 | 40.7 | 1.3 | 31.2 | 8.9 | 7.0 |
| G3 | 75.0 | 124 | 442.1 | 77.0 | 0.95 | 20.5 | 1.4 | 36.5 | 10.3 | 8.3 |
| G4 | 157.2 | 111 | 358.6 | 95.0 | 0.99 | 2.6 | 1.4 | 46.5 | 14.1 | 13.0 |
| G5 | 100.0 | 114 | 361.8 | 52.0 | 1.00 | 0.0 | 1.2 | 48.2 | 13.8 | 13.3 |
| Mean | 105.5 | 120 | 412.1 | 71.6 | 0.97 | 13.3 | 1.3 | 39.1 | 11.1 | 9.5 |

The $R_{ET}$ indicator showed a gap between the demand and requirements of water only in the pivots G4 and G5, when ET was lower than 80% of ETp and the water deficits (WD) higher than 100 mm. In all other situations, $R_{ET}$ was close to 1.00, ranging from 0.78 to 1.00 with WD at a maximum of 110 mm $GS^{-1}$. $R_{WS}$ with values from 1.1 to 1.4 indicated some drainage rates, due to the sandy soil and rainfall events. Theses water percolations happened with more intensity in the pivots for silage than those for grains. These numbers imply that in general 10 to 40% more irrigation water was supplied than necessary to meet the crop water requirements.

Taking the water percolation rates as the differences between P, I and ET without corrections for soil storage changes, they were in average 159.3 mm (35% of ET) and 131.5 mm (37% of ET), for grains and silage, respectively. To reduce the water going to the water table, practices of mulching should be used (Ding et al., 2013) improving water productivity. It is important to note that even with $R_{WS}$ being higher than 1.0 for G4 and G5 pivots, low $R_{ET}$ and high WD values indicated some occasions when more water should be supplied. Teixeira et al. (2008a) reported similar gap between water requirements and water applied in a commercial mango orchard in the Brazilian semi-arid region.

Considering the pivot areas and the yield for each of then, the productivity in terms of grains ranged 7.2 to 10.7 t $ha^{-1}$, while for silage this range was between 31.2 and 48.2 t $ha^{-1}$. The water productivity based on evapotranspiration ($WP_{ET}$) showed good return, from 1.4 to 2.8 kg $m^{-3}$ for grains and between 8.8 and 14.1 kg $m^{-3}$ for silage. The best values for grains were verified with a certain WD, what is an indication that $WP_{ET}$ increases with some degree of water stress. In average, there were no significant differences when the WP was based on ET or I in the case of grains, however, for silage, $WP_{I}$ was 86% of $WP_{ET}$ indicating some room for water management improvements. The main reason for this should be the use of unappropriated Kc for silage. $WP_{ET}$ values for grains are higher than those for wheat and rice, reported by Zwart and Bastiaanssen (2004), which were from 0.5 to 1.5 kg $m^{-3}$.

With the availability of prices for grains, the corresponding $WP\$_{ET}$ and $WP\$_{I}$ values were respectively from 0.34 to 0.68 US\$ $m^{-3}$ and from 0.41 to 0.63 US\$ $m^{-3}$. On one hand, these values are much lower than for table grapes (8.1 and 2.2 US\$ $m^{-3}$, respectively) and mangos (1.8 and 1.3 US\$ $m^{-3}$) in the semi-arid region

of Brazil (Teixeira et al., 2009b), however, the higher values for fruit crops occur with larger production costs. On the other hand, Sakthivadivel et al. (1999) reported typical $WP\$_{ET}$ values for arable crops between 0.10 and 0.20 US\$ $m^{-3}$, lower than those found for corn crop in the current study.

Considering the importance for human and animal feed, mainly in rural environments, the water usage for this crop should be stimulated with sustainable irrigation managements, in areas such those with climatic aptitude in the São Paulo State.

## Conclusions

Evapotranspiration and crop coefficients were modelled in a corn crop commercial farm located in the north-western side of the Brazilian São Paulo State. Landsat images with only the visible and infrared bands were used together with the SAFER algorithm. The remote sensing parameters together with weather, irrigation, precipitation and yield data, allowed irrigation performance assessments of the irrigated pivots for grain and silage at a good spatial resolution. The balance between the input and output of water indicated high drainage rates, due to sandy soil together with rains events, promoting significant percolation rates. However, in some occasions, more water should be supplied by irrigation. For grains, there were no significant differences when the water productivity was based on evapotranspiration or irrigation, but, for silage, the differences indicated some room for water management improvements. The main reason for these differences in silage pivots should be the use of unappropriated crop coefficient. The results of this research can subsidize the rational irrigation water management, improving yield, while insuring agriculture sustainability.

## Acknowledgements

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