Evapotranspiration mapping of commercial corn fields in Brazil using SAFER algorithm

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ABSTRACT: SAFER (Simple Algorithm for Evapotranspiration Retrieving) is a relatively new algorithm applied successfully to estimate actual crop evapotranspiration (ET) at different spatial scales of different crops in Brazil. However, its use for monitoring irrigated crops is scarce and needs further investigation. This study assessed the performance of SAFER to estimate ET of irrigated corn in a Brazilian semiarid region. The study was conducted in São Desidério, Bahia State, Brazil, in corn-cropped areas in no-tillage systems and irrigated by central pivots. SAFER algorithm with original regression coefficients (a = 1.8 and b = –0.008) was initially tested during the growing seasons of 2014, 2015, and 2016. SAFER performed very poorly for estimating corn ET, with RMSD values greater than 1.18 mm d^{-1} for 12 fields analyzed and NSE values < 0 in most fields. To improve estimates, SAFER regression coefficients were calibrated (using 2014 and 2015 data) and validated with 2016 data, with the resulting coefficients a and b equal to 0.32 and –0.0013, respectively. SAFER performed well for ET estimation after calibration, with r^2 and NSE values equal to 0.91 and RMSD = 0.469 mm d^{-1}. SAFER also showed good performance (r^2 = 0.86) after validation, with the lowest RMSD (0.58 mm d^{-1}) values for the set of 14 center pivots in this growing season. The results support the use of calibrated SAFER algorithm as a tool for estimating water consumption in irrigated corn fields in semiarid conditions.

Keywords: Landsat, water consumption, maize, remote sensing

Introduction

The knowledge of crop evapotranspiration (ET) is critical for irrigation management (Gheysari et al., 2017). At field level, ET can be measured using conventional techniques, such as the Bowen ratio, eddy covariance, soil water balance and lysimetric procedure (Costa et al., 2018; Gharsallah et al., 2013). However, these techniques are complex, costly, and require specific equipment and are thus generally applied only in scientific research (Gharsallah et al., 2013) and limited to homogeneous surfaces (Costa et al., 2018). On the other hand, over heterogeneous surfaces, water consumption can be monitored with the scintillation technique (Ezzahar et al., 2007) and especially using ET models/algorithms, based on remote sensing data. The latter is widely used because the algorithms allow estimating ET for larger and more heterogeneous areas (Hssaine et al., 2018; Sun et al., 2011; Teixeira et al., 2013) and provide knowledge about spatial-temporal distribution of ET (Cao et al., 2018; Liaqat et al., 2015). Furthermore, operational costs are relatively lower.

In the last decades, several methods to estimate ET using remote sensing data have been developed, such as Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998) and Mapping ET at High Resolution with Internalized Calibration (METRIC) (Allen et al., 2007). The Simple Algorithm for Evapotranspiration Retrieving (SAFER) is a remote sensing algorithm set recently developed to calculate ET (Teixeira, 2010; Teixeira et al., 2017, 2013). Estimation of ET with SAFER at satellite overpass time is based on the modeled fraction of actual (ET) to ref-

erence (ETo) evapotranspiration, ET$_f$, usually called crop coefficient. Calculation is made using visible, near infrared, and thermal infrared bands in conjunction with reference evapotranspiration data (ETo) estimated with meteorological station data (Teixeira, 2010; Teixeira et al., 2017, 2013).

SAFER algorithm applications involving large heterogeneous areas have shown very good performance (Coaguila et al., 2017; Dehziari and Sanaienejad, 2019; Teixeira et al., 2019, 2017, 2013). However, when applied to irrigated annual crops, which are more homogenous, SAFER provides unsatisfactory ET estimates during the early stages of crop growth (Althoff et al., 2019; Lima et al., 2019) thus requiring calibration and validation of SAFER algorithm.

This study assessed the performance of SAFER algorithm to estimate ET of irrigated corn crop in a Brazilian semiarid region by comparing with the modified FAO method (MFAO), a method used under these climatic conditions in Brazil. If the original SAFER algorithm did not function correctly, the additional objective was to calibrate the regression coefficients of the algorithm and verify its application in irrigated commercial cornfields using MFAO as a reference.

Materials and Methods

Study site

The study was conducted on a commercial farm in the municipality of São Desidério, western region of the state of Bahia, a semiarid region in Brazil (Figure 1). The site is located in the rectangle bounded by geographic coordinate pairs (Datum SIRGAS 2000): 12°28′08″ S,
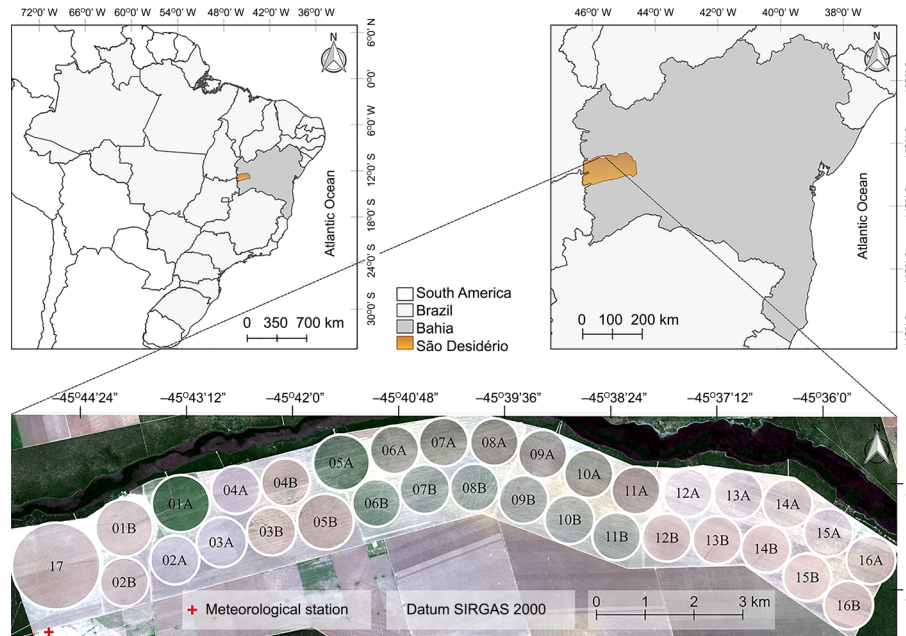
Figure 1 – Location of study site, nomenclature and distribution of center pivots in the fields. Meteorological station is in red.

45°45′12″ W, 12°25′40″ S, 45°34′55″ W, with an average altitude of 750 m. According to Köppen classification (Alvares et al., 2013), the climate of the region is Aw, that is, tropical with rainy summers and dry winters, with annual precipitation 1003.4 mm (INMET, 2018), concentrated in the rainy season (Oct to Apr). The farm covers an area of 1598 ha and has 17 center pivots, 16 towable, indicated by letters A and B in Figure 1.

Meteorological and crop data

The field data refer to corn (*Zea mays* L.) crop under the no-tillage system and were collected during the growing seasons 2014, 2015, and 2016. Meteorological data, such as air temperature (T, °C), wind speed at 2 m height (U_2, m s^{-1}), solar radiation (Ra, MJ m^2 d^{-1}), relative humidity (RH, %), and rainfall (mm) were obtained from an automated meteorological station, near the center pivots (Figure 1). These data were used to determine daily reference evapotranspiration (ETo) and actual corn evapotranspiration (ET). Additionally, data were acquired for sowing and harvest dates, applied irrigation depth, and the hybrid cultivated under each center pivot by year (Table 1).

Satellite Images: Landsat 8 OLI/TIRS and Landsat 7 ETM+ data

We used cloud-free surface reflectance images from the Enhanced Thematic Mapper Plus (ETM+) sensor onboard Landsat 7 and images from the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) sensors onboard the Landsat 8 satellite (path 220 and row 69), downloaded from the archives of the USGS Earth Explorer website (http://earthexplorer.usgs.gov/). For the

ETM+ sensor, we used multispectral bands 1 to 5, with a spatial resolution of 30 m, and thermal band 6, with a spatial resolution of 60 m, resampled to 30 m (USGS, 2018).

For the Landsat 8 OLI sensor, we used multispectral bands 2 to 7, with a spatial resolution of 30 m, and for the TIRS sensor, we used thermal band 10, with a spatial resolution of 100 m, resampled to 30 m (USGS, 2016). Access and full descriptions of the products can be found online in the Landsat data users' handbooks of USGS. We acquired 46 images, including from OLI/TIRS sensors and the ETM+ sensor, for the three cropping seasons, with 18, 15, and 13 images for 2014, 2015, and 2016, respectively.

Estimation of actual crop evapotranspiration (ET)

Modified FAO method

Corn ET was estimated using the modified FAO method (MFAO) (Bernardo et al., 2019; Mantovani et al., 2006). The MFAO method has been widely used in scientific studies in Brazil (Santos et al., 2018; Silva et al., 2018c; Venancio et al., 2019; Vicente et al., 2017). In addition, it has been widely applied in several Brazilians farms and in other countries by the company IRRIGER (http://www.irriger.com.br/en-US/) (IRRIGER, 2019). This method is based on single-crop coefficient method (Allen et al., 1998; Doorenbos and Pruitt, 1977) and is a simple method to estimate potential evapotranspiration and manage practical irrigation water at field level. The water stress coefficient (K_s) and localized water application coefficient (K_L) were added to MFAO to increase the

Table 1 – Sowing date (SD), harvest date (HD), applied irrigation (Irr) and hybrid (H) for each center pivot (CP) analyzed in the growing seasons of 2014, 2015, and 2016.

CP	SD	HD	H	Irr	CP	SD	HD	Irr	H	CP	SD	HD	Irr	H
				mm				mm					mm	
		2014					2015					2016		
01B	04/23	09/05	H8	820.2	01A	05/20	10/17	745.0	H1	03B	05/06	09/25	703.6	H2
02B	04/29	09/05	H9	747.5	04A	05/21	10/17	737.9	H7	04B	05/05	10/04	780.1	H9
03B	04/27	09/05	H9	747.2	05A	04/25	09/16	587.4	H9	05B	05/04	10/04	847.4	H9
04B	04/25	09/05	H9	790.8	06B	05/28	10/19	768.8	H9	06A	05/02	09/18	688.2	H6
05B	04/26	09/05	H3	807.4	07B	05/27	10/18	766.0	H9	07A	04/29	09/14	707.4	H6
06A	05/10	09/16	H3	821.6	08B	05/26	10/17	771.4	H9	08A	04/27	09/09	733.9	H7
07A	05/10	09/16	H3	826.7	09B	05/25	10/16	747.2	H9	09A	04/25	09/25	756.7	H3
08A	05/09	09/16	H3	832.6	10B	05/24	10/15	772.4	H9	10A	04/22	09/25	766.0	H3
09A	05/08	09/16	H7	796.5	11B	05/23	10/14	772.5	H9	11A	04/20	09/08	676.3	H10
10A	05/05	09/16	H7	810.8	12A	05/09	10/04	710.4	H9	12B	04/04	08/31	686.0	H9
11A	05/03	09/16	H7	784.6	13A	05/13	10/05	708.6	H9	13B	04/06	08/31	698.0	H9
12A	05/01	09/16	H6	760.3	14A	05/14	10/08	750.7	H9	14B	04/12	09/05	754.7	H9
-	-	-	-		15A	05/15	10/08	698.7	H9	15B	04/14	09/25	714.2	H9
-	-	-	-		16A	05/16	10/08	737.0	H9	16B	04/18	09/24	756.8	H9

The row spacing adopted at the farm was 0.5 m. Hybrids names: Dekalb DKB 390 Pro (H1), Dow AgroSciences 2B810 (H2), Pioneer 30F35 (H3), Pioneer 30F53 (H4), Pioneer 3431 (H5), Pioneer P2830 (H6), Pioneer P3646 (H7), Maximus Viptera 3 (H8), Status Viptera 3 (H9), and Supremo Viptera (H10).

performance of the single-crop coefficient method, according to the following equation:

$$ET = ETo \times K_c \times K_s \times K_L \tag{1}$$

where: ET is actual crop evapotranspiration (mm d^{-1}), ETo is reference evapotranspiration according to the FAO Penman-Monteith method (Allen et al., 1998) (mm d^{-1}), K_c is crop coefficient, K_s is water stress coefficient (Bernardo et al., 2019), K_L is the localized water application coefficient (Keller and Bliesner, 1990), K_L is 1 when the entire cultivated area is wetted by an irrigation system (e.g., areas are irrigated by center pivots).

The K_c values used in MFAO to determine corn ET were calibrated locally and derived from values recommend by the FAO-56 approach (Allen et al., 1998) (Figure 2). K_s is used to incorporate the water stress effect to reduced crop transpiration, and daily K_s estimation in the root zone (Bernardo et al., 2019) is computed according equation 2. The K_s values and estimated soil moisture based on soil water balance for four selected center pivots in each growing season are presented in Figures 3 and 4, respectively.

$$K_s = \frac{\ln(1 + CSWS)}{\ln(1 + SWS)}$$

where: SWS is total soil water storage (mm), which corresponds to TWA given in FAO-56 Bulletin (Allen et al., 1998); and CSWS is the current soil water storage (mm).

The CSWS is calculated from the difference between SWS and ETc accumulated considering certain period (1 or more days), both in millimeters. When soil moisture is at field capacity, CSWS is equal to SWS and, consequently, K_s is equal to 1.
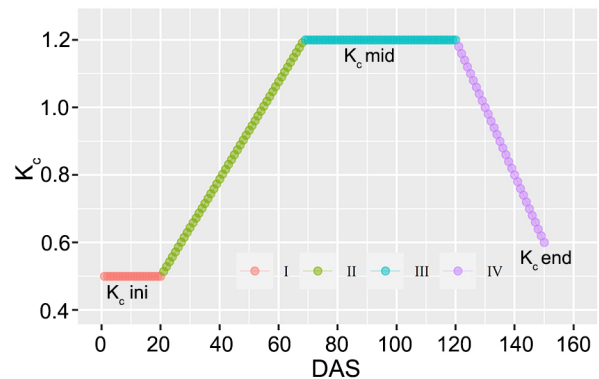
Figure 2 – Crop coefficient (K_c) curve regarding days after sowing (DAS) for corn used in ET estimation. Source: Adapted by the author from Allen et al. (1998). Growth stages: I (initial); II (crop development); III (midseason) and IV (late season).

### Simple Algorithm for Evapotranspiration Retrieving (SAFER)

SAFER combines remote sensing data, namely, the normalized difference vegetation index (NDVI), surface albedo (α_0), and surface temperature (T_0) with the ETo according to the FAO Penman-Monteith method (Allen et al., 1998). Calculations are made using data from weather stations. The steps for applying SAFER are described according to Teixeira (2010).

For the surface temperature calculation, bands 6 (Landsat 7) and 10 (Landsat 8) were first converted from spectral radiance to brightness temperature by applying the inverse of Planck equation to the radiation estimated.

$$T_b = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)}$$

where: T_b is satellite brightness temperature (K), L_λ is

TOA spectral radiance (W m^{-2} sr^{-1} μm^{-1}) for thermal bands (6 and 10), and K_1 and K_2 are the band-specific
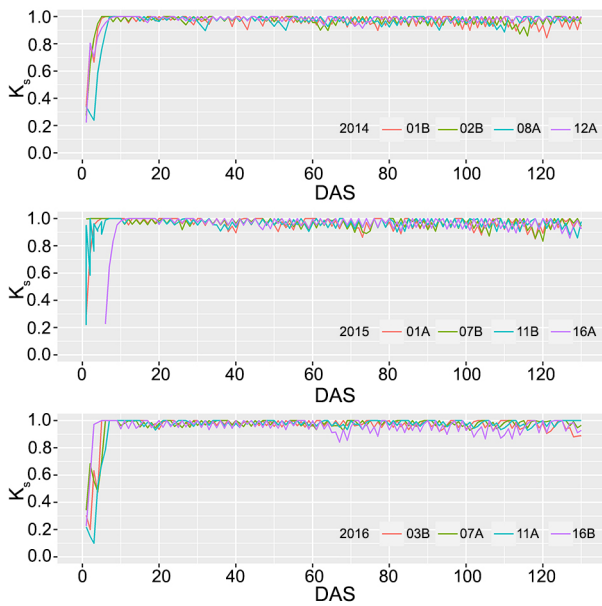
Figure 3 – Temporal evolution of water stress coefficient (K_s) obtained in selected center pivots in 2014, 2015, and 2016.

thermal conversion constants from metadata (specific for each sensor).

Afterward, surface temperatures of bands 6 and 10 were obtained according to the equation parameterized by Teixeira (Teixeira, 2010).

$$T_0 = 1.11 \times T_b - 31.89 \qquad (4)$$

where: T_0 is surface temperature (K) and T_b is satellite brightness temperature (K). Then, temperature was converted from Kelvin to Celsius degrees to be applied in equation 8.

For estimating surface albedo, first, top-of-atmosphere albedo (α_{TOA}) data were obtained by equation 5. Then, α_{TOA} was transformed to surface albedo data (Teixeira, 2010) using equation 6.

$$\alpha_{TOA} = \Sigma(\omega_p \times \rho_\lambda) \qquad (5)$$

$$\alpha_0 = 0.7 \times \alpha_{TOA} + 0.06 \qquad (6)$$

where: ω_ρ is the weight coefficient for each band and ρ_λ is surface reflectance of bands 1, 2, 3, 4, 5, and 7 (ETM+) and of bands 2, 3, 4, 5, 6, and 7 (OLI). Weight coefficients for ETM+ and OLI sensors were extracted from Allen et al. (2002) and Silva et al. (2016), respectively.
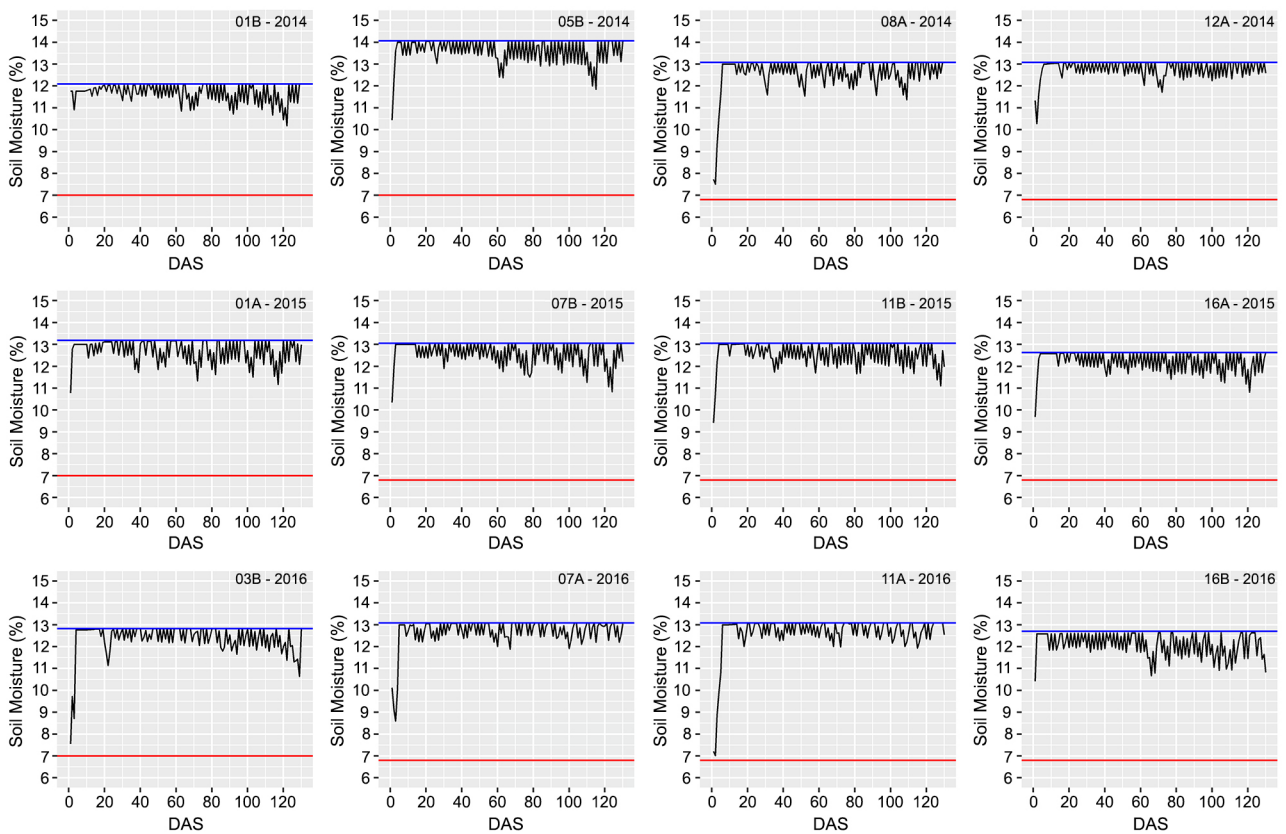
Figure 4 – Temporal evolution of estimated soil moisture obtained in selected center pivots in 2014, 2015, and 2016. Blue and red line refers to field capacity and wilting point, respectively.

$$NDVI = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}} \qquad (7)$$

where: ρ_{NIR} and ρ_{red} refer to reflectance of the near-infrared band and the red band, respectively.

Applying SAFER algorithm, the ratio of the actual (ET) to the reference (ET_o) evapotranspiration, ET_f, was modeled at the satellite overpass time (Teixeira, 2010; Teixeira et al., 2017, 2013) as follows:

$$ET_f = \exp\left[a + b\left(\frac{T_0}{\alpha_0 \times NDVI} \right) \right] \qquad (8)$$

where: "a" and "b" are regression coefficients, 1.8 and –0.008, respectively, applicable for the Brazilian semiarid conditions, according to Teixeira et al. (2013).

This equation (ET_f) was established for Brazilian semiarid conditions involving irrigated crops and natural vegetation under different meteorological and hydrological conditions, based on simultaneous field data from four flux towers and Landsat images (Teixeira, 2010). The main physical basis behind this equation is that ET_f values modeled from NDVI, α_0, and T_0 can express crop development and soil moisture condition, similar to crop coefficient (K_c) multiplied by water stress coefficient (K_s), as demonstrated in the FAO 56 approach and the MFAO method.

Based on ET_f and ETo data collected from the meteorological stations, crop ET (mm d^{-1}) was estimated by equation 9, providing daily ET values for each center pivot pixel.

$$ET = ET_f \times ET_O \qquad (9)$$

SAFER calibration and validation

First, the SAFER algorithm with regression coefficients recommended by Teixeira et al. (2013) for the study region (a = 1.8 and b = –0.008) was tested during the growing seasons of 2014, 2015, and 2016, involving 42 center pivots (12, 15, and 15 in 2014, 2015, and 2016, respectively), covering an area of 3357 ha. The results were very poor, especially during the first 30 days after sowing (DAS) (see Results and Discussion), mainly because of low ET_f values. Thus, we continued with the additional objective of this study, using data from 2014 (12 center pivots) and 2015 (15 center pivots), to calibrate and data from 2016 (15 center pivots) to validate. Calibration, based on adjusting empirical parameters (a and b) described in equation 8, was performed using the solver tool in Microsoft Excel, which uses the nonlinear optimized generalized reduced gradient (GRG) algorithm (Lasdon et al., 1978).

The empirical parameters (a and b) of ET_f was adjusted using $K_c \times K_s$ data from the modified FAO method as a standard, since $K_c \times K_s$ and ET_f are related to crop development and soil moisture conditions (Teixeira, 2010). Thus, $K_c \times K_s$ was called ET_{fMFAO}, while ET_f derived from SAFER was called ET_{fSAFER}. In the

calibration process, the original values of parameters a and b were used as initial values for the process of adjustment. The solver tool changes the parameter values to reduce the distance between the ET_{fSAFER} and ET_{fMFAO} through an iterative process. This distance was measured by the mean square error (MSE).

Statistical analysis

To assess accuracy of SAFER algorithm in corn ET modeling, we calculated the statistical indicators root mean square deviation (RMSD), mean bias error (MBE), mean absolute error (MAE), Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), and coefficient of determination (r^2). In addition, to avoid influence of field border, we used a 30-m buffer.

Results and Discussion

SAFER input parameters

Figure 5 shows the distribution of α_0 data based on a boxplot for center pivots cultivated in the growing seasons of 2014, 2015, and 2016. The albedo ranged between 0.13 and 0.18, agreeing with data reported in the literature for cornfields, 0.14 and 0.22 (Allen et al., 2002). The average value remained close to 0.15 for the three seasons, corroborating results reported in the literature for corn (Bsaibes et al., 2009; Eichelmann et al., 2016).

During the growing season of 2015, α_0 data had a low amplitude. This occurred because only one corn hybrid was cultivated in center pivots 05A to 16A, differently from 2014 and 2016 seasons, where five different hybrids were planted (Table 1). As α_0 value decreases, surface increases its absorption of solar energy and local surface temperature increases (Richardson et al., 2013), contributing to a relative increase in water consumption. Thus, the use of α_0 in SAFER algorithm is essential to provide more accuracy to ET estimation.
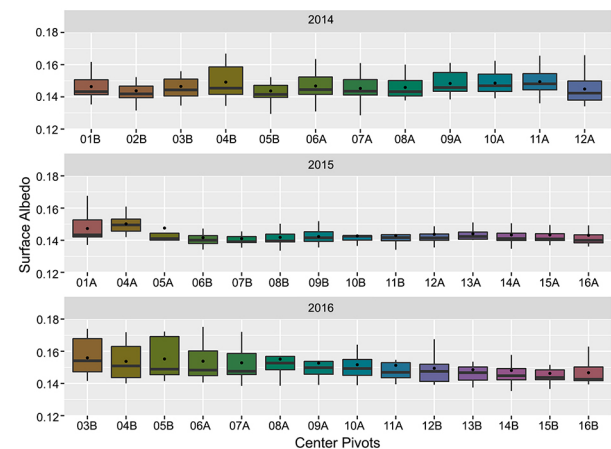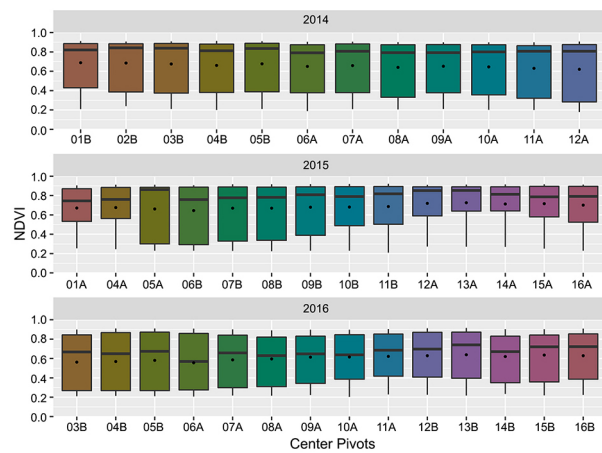

Figure 5 – Boxplot of surface albedo values for center pivots cultivated in the growing seasons of 2014, 2015, and 2016.

NDVI values were similar in the three growing seasons. During 2014 and 2015 seasons, the average was greater than in 2016, indicating high NDVI values for a longer time in the first two seasons (Figure 6). Maximum NDVI values remained at approximately 0.9, while minimum values were close to 0.2, with an average value of approximately 0.7. Minimum value, approximately 0.2, was commonly observed near the sowing date, while the maximum value was observed in the entire period covered. Other authors have reported similar results (Nagy et al., 2018; Nguy-Robertson et al., 2013; Wang et al., 2016).

Figure 7 shows a boxplot of surface temperature values for center pivots in the growing seasons of 2014, 2015, and 2016. T_0 ranged from 20 to 36 °C. Most fields of center pivots had an average surface temperature of approximately 25 °C. Maximum values of surface temperature were observed during the season beginning, when there is much exposed soil background.

Overall, there was very low variability of α_0, NDVI, and T_0 between fields. However, high variability
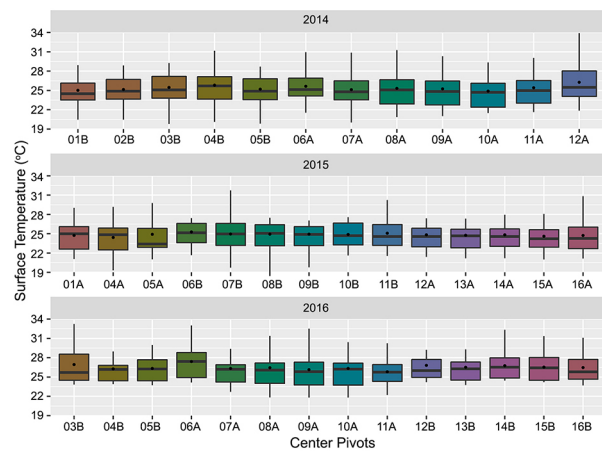
was observed within the same field over season, especially in NDVI values. According to Venancio et al. (2019), in these cornfields, a high technological level is adopted, resulting in well-managed irrigation and fertilization. Thus, variability of these parameters within the same field is more influenced by the different crop phenological stages, unlike natural vegetation, where variability of these parameters can primarily be attributed to variations in global solar radiation and surface moisture conditions (Teixeira et al., 2017).

SAFER: ET_f and corn ET with original regression coefficients

Figure 8 shows a boxplot of ET_f values. Pixel values ranged from 0 to 1.7, with 25 % of the data (third quartiles) normally between 1.3 and 1.7 (2014 and 2015). In 2016, maximum values were lower (≈1.4). The center pivots in this study were well managed regarding water use, causing Ks values to remain within the range from 0.9 to 1.0 (Figure 3) and soil moisture close to field capacity (Figure 4). Thus, ET_f was expected to be close to K_c values recommended for corn crops. However, resulting values varied greatly from normal K_c values.

These results indicate ET_f is not adequately sensitive to represent the behavior of crop coefficient adjusted to the water stress ($K_c \times K_s$) in irrigated cornfields. To overcome this problem, the best option is to adjust the empirical coefficients, considering suitable the input of remote sensing parameters, additional objective of this study. In irrigated cornfields, Teixeira et al. (2015) verified some pixels with ET_f values close to 1.40, with values normally ranging between 0.2 and 1.2; however, regression coefficients used in this study were 1.0 and −0.008 for a and b, respectively. Silva et al. (2018b) applied SAFER in sugarcane crops in the central-western part of São Paulo State, Brazil, and reported that some ET_f values were close to zero, as observed in this study.

Figure 6 – Boxplot of NDVI values for center pivots cultivated in the growing seasons of 2014, 2015, and 2016.
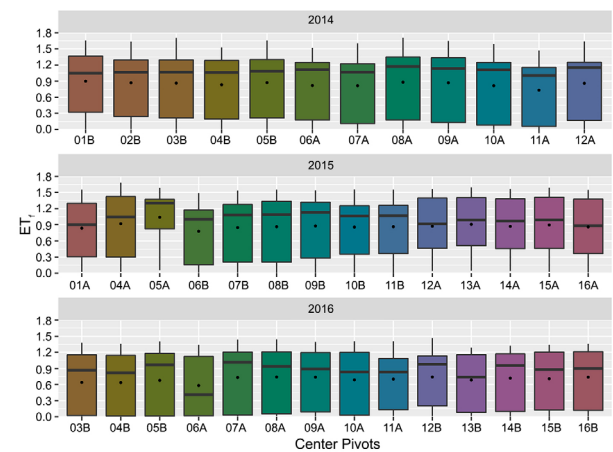

Figure 7 – Boxplot of surface temperature values for center pivots cultivated in the growing seasons of 2014, 2015, and 2016.

Figure 8 – Boxplot of fraction between actual (ET) to reference (ETo) evapotranspiration, ET_f values, for center pivots cultivated in the growing seasons of 2014, 2015, and 2016.

Figures 9A to 9L show scatter plots with statistical parameters between ET_{MFAO} and ET_{SAFER} for four center pivots selected in each of the three growing seasons (2014, 2015, and 2016). Considering only the r^2 values, agreement between ET_{SAFER} and ET_{MFAO} can be considered reasonable, with values greater than 0.8 in some pivots, such as 08A and 12A in 2014 (Figures 9C and 9D, respectively) and 03B in 2016 (Figure 9I). However, the analysis of r^2 along with RMSD, MBE, MAE, and NSE shows that SAFER algorithm performed very poorly to estimate corn ET. For instance, in 03B pivot in 2016 (Figure 9I), r^2 was good (0.85); however, the RMSD value reached almost 2.00 mm d^{-1}, MAE was equal to 1.70 mm d^{-1}, and NSE was –1.79.

Similar results for 03B pivot were also verified in the other fields, mainly for RMSD, which remained high (greater than 1.18 mm d^{-1}), and MAE (greater than 0.93 mm d^{-1}), considering the magnitude of corn ET in the region. In recent years, many authors have compared ET from remote sensing-based methods with other methodologies, taking into account RMSD value to infer accuracy of estimation. Paço et al. (2014), for example, compared METRIC (Allen et al., 2007) and FAO-56 dual

K_c approach (Allen et al., 1998) and considered an RMSD value less than 0.44 mm d^{-1} to be low. Silva et al. (2018a) compared SEBAL and FAO-56 (single K_c approach) and considered SEBAL results to be satisfactory because the difference in the estimates was less than or equal to 1.00 mm d^{-1}. Generally, RMSD values or differences in the estimates greater than 1 mm d^{-1} are not satisfactory.

An equilibrium was observed for MBE, as SAFER underestimated corn ET for all center pivots in 2015 (Figures 9E, 9F, 9G and 9H) and for 03B in 2016 (Figure 9I), and overestimated ET for the rest of the pivots analyzed. For NSE, most values were below zero, showing that the mean value of variable observed obtained higher accuracy than the values simulated (Moriasi et al., 2007). In addition, SAFER algorithm results in major underestimations, with values practically equal to zero, when evapotranspiration estimated from ET_{MFAO} is lower than 3 mm d^{-1} (Figures 9A to 9L), which normally occurs early in the growing season. In summary, the statistical parameters discussed in Figures 9A to 9L demonstrate the poorness of SAFER algorithm to estimate corn ET with original regression coefficients.
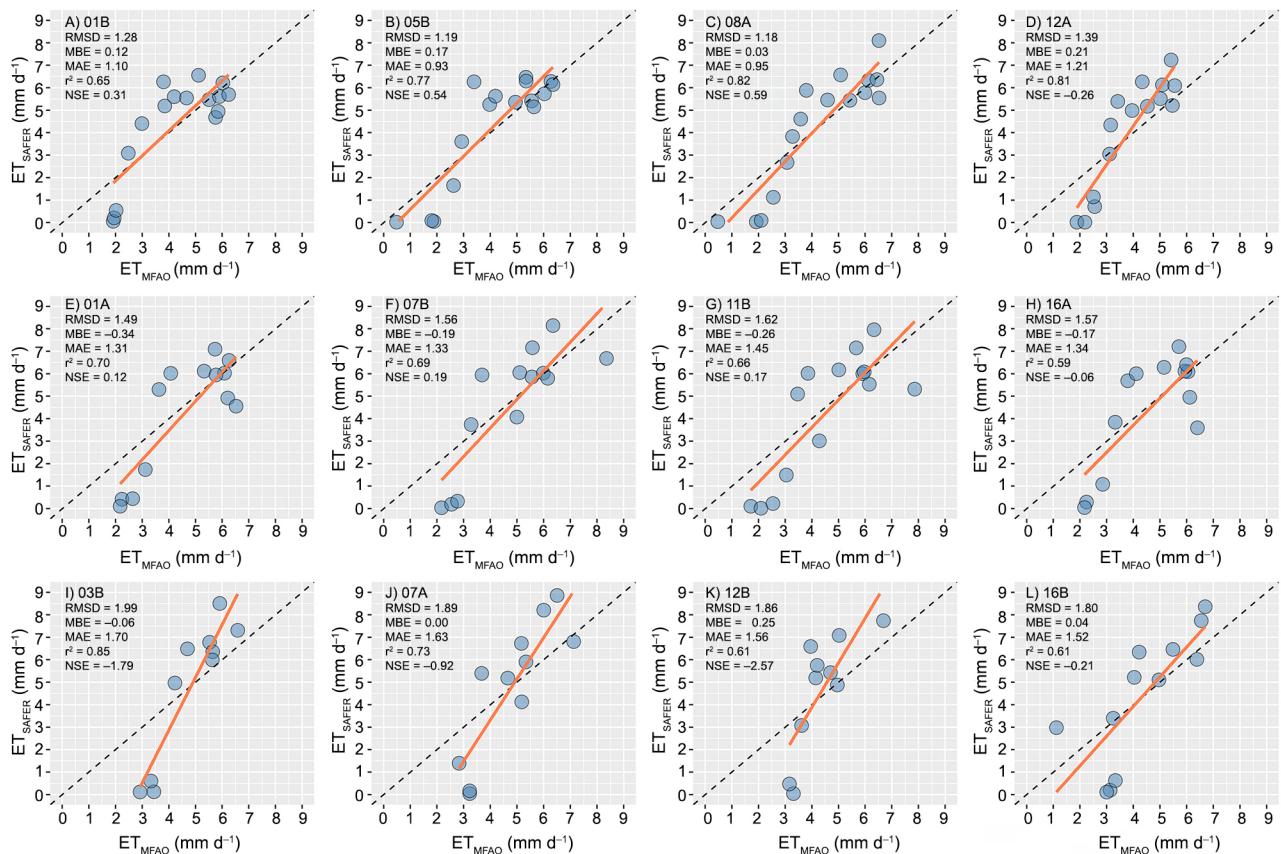
Figure 9 – Comparison between daily corn evapotranspiration (ET) estimated by SAFER algorithm (ET_{SAFER}) and modified FAO method (ET_{MFAO}) at four center pivots selected in the growing seasons of 2014, 2015, and 2016. Letters A, B, C, and D refer to center pivots 01B, 05B, 08A, and 12A, respectively, selected in growing season of 2014. Letters E, F, G, and H refers to center pivots 01A, 07B, 11B, and 16A, respectively, selected in growing season of 2015, and letters I, J, K, and L refer to center pivots 03B, 07A, 12B, and 16B, respectively, selected in growing season of 2016.

Figures 10A, 10B, and 10C show the seasonal cycle of daily ET_{SAFER} and ET_{MFAO} for 2014, 2015, and 2016 growing seasons, respectively. For both methodologies, daily ET had a strong seasonal cycle, with low values in the initial stage, high values during crop development and midseason stages, and a decrease in the late-season stage until harvest, normally between 135 and 150 days after sowing, in Brazil.

When data were analyzed separately in each phenological phase, valuable information could be extracted (Figures 10B and 10C). First, we observed very low ET_{SAFER} (close to zero) during the first 30 DAS, similar to the findings of Althoff et al. (2019), while ET_{MFAO} remained between 2 and 3 mm d^{-1}. The main reason for the lower ET values could be the large area of exposed soil background during this period, since after this time, when the corn enters the development phase, ET values increase quickly until 70-80 DAS. Thus, as NDVI has a high positive correlation with soil cover (Barati et al., 2011; Jiang et al., 2006; Zhang et al., 2006) among the input variables to SAFER (α_0, NDVI and T_0), it is possible to affirm that SAFER algorithm has a high dependence on NDVI values. Moreover, in bare soils, surface temperature is greater than in soils with vegetation cover (Song et al., 2015), favoring low ET_f values determined by equation 8.

During crop development stage (II), the opposite of the initial phase occurred, with SAFER algorithm presenting higher ET values in comparison to the MFAO method (Figures 10A, 10B and 10C). In addition, during the last two stages (III and IV), there was more agreement between the data; however, with ET_{SAFER} slightly greater than ET_{MFAO}. In summary, these results indicate that SAFER algorithm does not have capacity to estimate ET accurately, especially during the initial (underestimates) and crop development stages (overestimates).

The results of ET_f in Figure 8 show the poor agreement for corn ET based on the statistical parameters (Figures 9A to 9L) along with poor estimation for the first 30 DAS and overestimation during the crop development stage (Figures 10A, 10B and 10C). Thus, showing that SAFER algorithm is not

appropriate for this environment with the original parameters (a and b). We performed the second object of the study, that is, re-calibration of coefficients to increase SAFER performance for corn ET estimation at the farm level in a Brazilian semiarid region.

SAFER calibration

After calibration, the values determined for "a" and "b" coefficients were 0.32 and –0.0013, respectively, with final MSE of 0.0105. Both coefficients were very different to the value for semiarid environments (a = 1.8 and b = –0.008) recommended by Teixeira et al. (2013). Because the region in our study is also semiarid, we considered these differences high. The study of Teixeira et al. (2013), as well as others using SAFER (Dehziari and Sanaienejad, 2019; Teixeira, 2010; Teixeira et al., 2017), were conducted in large areas (e.g., river basins), which are very heterogeneous under water scarcity and natural vegetation, totally different from irrigated corn plantations. Thus, many of these differences can be attributed to these facts. In addition, comparison with areas similar to our study site (monoculture and irrigated) is difficult because this is the first study to use SAFER algorithm with newer-calibrated coefficients.

Figure 11A shows correlations between ET_{fSAFER} with calibrated regression coefficients and ET_{fMFAO} along with statistics for the comparison. Figure 11B also presents a scatter plot graph; however, the comparison is the actual crop evapotranspiration data. Calibration of ET_{fSAFER} showed reasonable agreement with estimates relatively close to 1:1 line and r^2 and NSE values equal to 0.75 (Figure 11A). Values of RMSD (0.102) and MAE (0.092) were low, with MBE = –0.001, the calibrated SAFER algorithm tended to underestimate the data; however, the difference was almost non-significant. Overall, these results show a good improvement compared to previous results (without calibration).

Crop ET after calibration showed excellent agreement, with r^2 and NSE values equal to 0.91 (Figure 11B). RMSD and MAE were similar, with values lower than 0.5 mm d^{-1}, considered very good values. MBE for ET was slightly negative (–0.030), meaning, in general
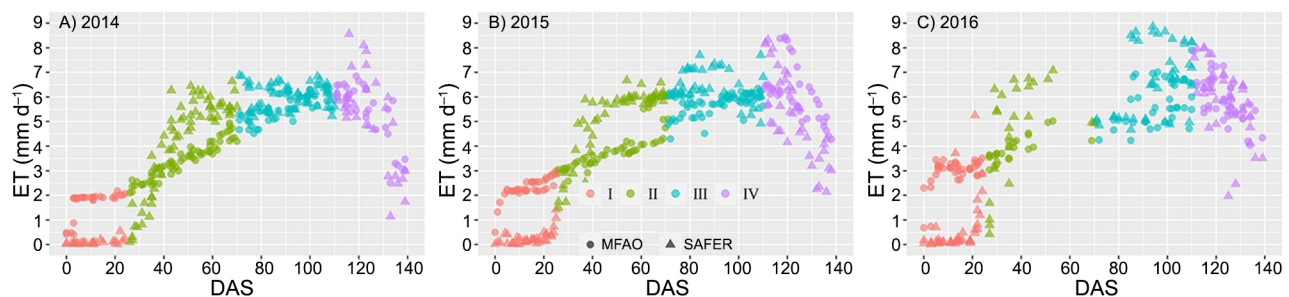
Figure 10 – Temporal evolution of daily corn evapotranspiration (ET) estimated by SAFER algorithm and modified FAO method for all center pivots cultivated during the growing seasons of 2014 (A), 2015 (B), and 2016 (C) regarding days after sowing (DAS). Growth stages: I (initial); II (crop development); III (midseason) and IV (late season).
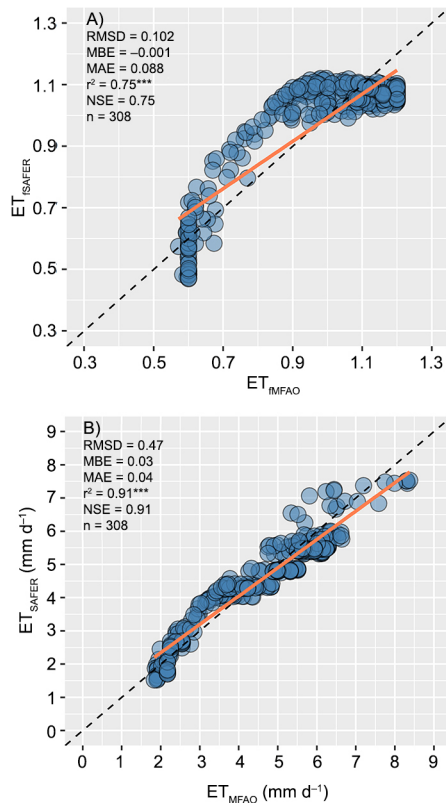
Figure 11 – Comparison of fractions between actual (ET) and reference (ET$_o$) evapotranspiration (ET$_f$) estimated by SAFER with calibrated regression coefficients (ET$_{fSAFER}$) and ET$_f$ estimated by the modified FAO method (ET$_{fMFAO}$) (A). The ET estimated by SAFER with calibrated regression coefficients (ET$_{SAFER}$) and ET estimated by the modified FAO method (ET$_{MFAO}$) (B), using data of all center pivots cultivated during the growing seasons of 2014 and 2015. In the figure, $***$ indicates regression significance at $p < 0.001$.

terms, a slight underestimation of ET data by SAFER algorithm (Figure 11B). This comparison between MFAO and SAFER methodologies is very satisfactory, as MFAO considers the water stress effect (using the K$_s$) on crop transpiration and crop coefficient calibrated under field conditions, meaning that ET represents an accurate estimation of ET under field conditions.

SAFER validation

Figures 12A to 12N show comparison between ET$_{SAFER}$ with calibrated regression coefficients and ET$_{MFAO}$ for each center pivot and one involving all center pivots in the growing season (GS) of 2016 (Figure 12O). The validation results showed good agreement, with estimates close to 1:1 line, and, based on r^2 value, ET values from SAFER explained between 66 and 97 % of data variation estimated by the modified FAO method (Figures 12A to 12N). Only one field, 13B (Figure 12K), presented r^2 value lower than 0.7 (r^2 = 0.66), with most values greater than 0.77. In general, the results

determined for r^2 can be classified as very good and excellent, since most center pivots had r^2 values above 0.84, and some had r^2 values above 0.9. NSE values reinforced the very good agreement based on r^2, with values reaching 0.92 for center pivot 04B (Figure 12B) and most fields with values greater than 0.7. Thus, SAFER algorithm can be classified as good (0.65 ≤ NSE ≤ 0.75) or very good (NSE > 0.75) according to Moriasi et al. (2007) for estimating ET in an irrigated corn crop.

Overall, SAFER algorithm tended to overestimate slightly corn ET, since MBE was positive for 10 out of 14 center pivots analyzed. Regarding the magnitude, the highest MBE (0.68 mm d^{-1}) was verified in pivot 11A (Figure 12I). MAE was low, close to 0.5, ranging between 0.34 and 0.68. Given that the ET average value for corn crop in the study site was approximately 4.2 mm d^{-1} from Apr to Oct, MBE and MAE could be considered low.

Center pivots in the 2016 growing season were also analyzed together and the results were similar to those observed for individual pivots (Figure 12O). NSE was 0.82, with 83 % of scatter close to 1:1 line (r^2 = 0.84). RMSD was 0.58 and MAE was 0.48 mm d^{-1}. MBE was positive (MBE = 0.18 mm d^{-1}), indicating that SAFER algorithm tended to overestimate corn ET, as mentioned above. These results are considered very good and allow to confirm calibration accuracy and assert that SAFER algorithm is capable of estimating corn ET accurately in a semiarid region and in other environments with similar conditions.

Very few studies have been published in the scientific literature with SAFER algorithm involving large areas with monocultures under full irrigation (e.g., corn) in semiarid regions. Most studies available to the scientific community were conducted in large areas involving different crops, cultivation systems, and edaphoclimatic conditions (Andrade et al., 2016; Coaguila et al., 2017; Dehziari and Sanaienejad, 2019; Teixeira et al., 2017), that is, heterogeneous areas. Thus, our field study is somewhat novel, also demonstrating that SAFER algorithm needs to be evaluated carefully before its application in irrigated monoculture areas, since the algorithm underestimated (first 30 DAS) and overestimated (after 30 DAS) ET$_f$ and, consequently, ET.

The authors acknowledge that a more robust validation study could have been conducted if we had used field data measured by an eddy covariance system or lysimeters, for example. However, these approaches do not represent the reality of Brazilian farms to estimate evapotranspiration for irrigation management purposes. On the other hand, the MFAO method has been applied with success in Brazil by scientific research as well as hundreds of irrigators by means of IRRIGER company for over 14 years, becoming the main irrigation management methodology in Brazilian farms. Therefore, the MFAO method is considered a reliable source of field-level ET data.
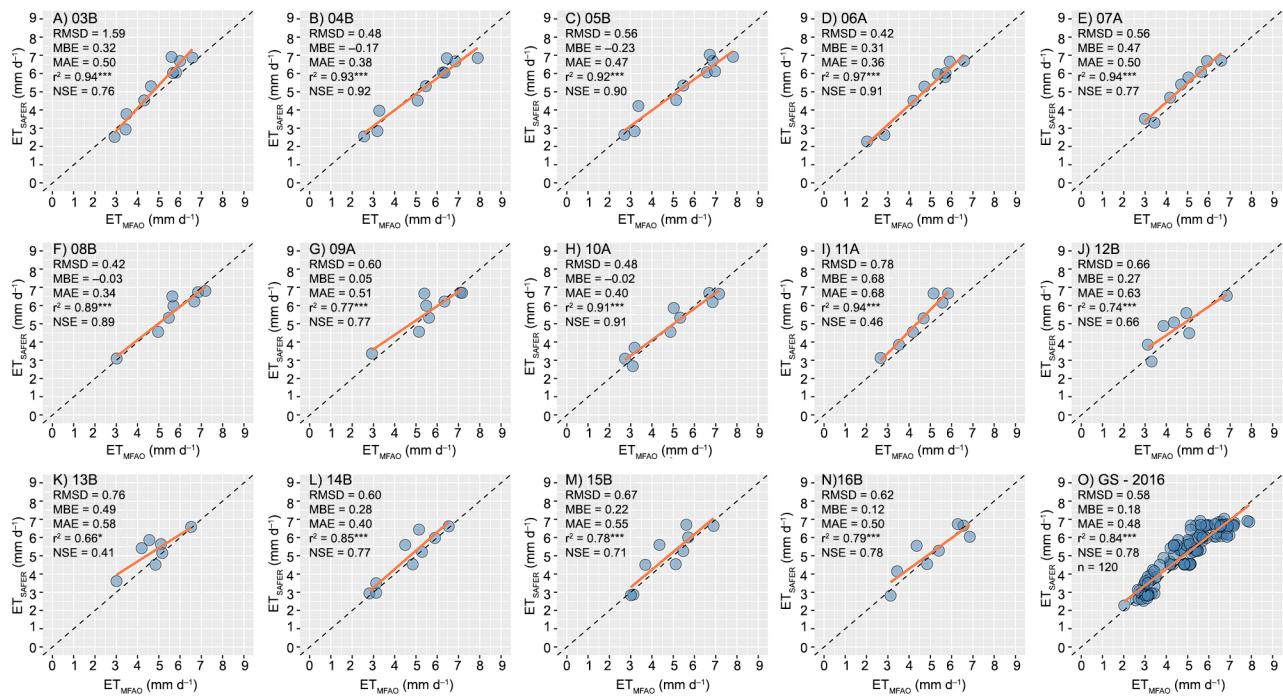
Figure 12 – SAFER algorithm validation results using corn evapotranspiration (ET) data estimated by the modified FAO method collected during the growing season of 2016. Letters A, B, C, D, E, F, G, H, I, J, K, L, M, N, and O refer to center pivots 01B, 04B, 05B, 06A, 07A, 08A, 09A, 10A, 11A, 12B, 13B, 14B, 15B, 16B and all center pivots harvested in this season, respectively. *indicates regression significance at $p < 0.05$, **indicates regression significance at $p < 0.01$ and ***indicates regression significance at $p < 0.001$.

Last, we used an extensive field-level dataset of actual corn (*Zea mays* L.) evapotranspiration from a farm that consisted of 17 irrigated fields (center pivots), 12, 15, and 15 cultivated fields in 2014, 2015, and 2016 growing seasons, respectively. Thus, there were 42 cultivated fields in three seasons covering an area of 3,357 and conferring variability and repeatability of the analyses.

Conclusions

The SAFER algorithm was tested on fully irrigated corn crop in the western region of Bahia State, a semiarid region in Brazil, under climatic and vegetation conditions that were slightly different from the conditions of algorithm validation (relatively larger areas in a semiarid region involving irrigated crops and natural vegetation). For these cornfield conditions, SAFER algorithm without calibration performed very poorly to estimate corn ET. The RMSD value was greater than 1.8 mm d^{-1} in four fields and was always higher than 1.18 mm d^{-1} for 12 fields analyzed, and the NSE values were lower than zero in most fields.

Regarding the periods, up to 30 DAS, SAFER was very inconsistent, with ET values close to zero. When regression coefficients of ET$_f$ were calibrated, there was good agreement (RMSD = 0.012, MBE = −0.001,

MAE = 0.008 and r^2 = NSE = 0.85). Validation with ET data from 2016 provided good performance of SAFER algorithm (r^2 = 0.84), with low RMSD (0.58 mm d^{-1}), MBE (0.18 mm d^{-1}), and MAE (0.48 mm d^{-1}) values for the set of 14 center pivots cultivated in this growing season. Using validation data (2016 growing season) and taking into account all center pivots harvested in this season, cumulative ET for SAFER and MFAO was 616.44 and 595.15 mm, respectively. An overestimate of only 3.5 % of SAFER in comparison to the MFAO method.

SAFER integration with field observations can be very beneficial for precision irrigation, allowing better water use in irrigation management, particularly in environments where water is scarce.

Acknowledgements

Authors' Contributions

Conceptualization: Venancio, L.P.; Mantovani, E.C.; Neale, C.M.U. **Data acquisition:** Venancio, L.P.; Mantovani, E.C. **Data analysis:** Venancio, L.P.; Mantovani, E.C.; Neale, C.M.U.; Amaral, C.H.; Cunha, F.F. **Design of methodology:** Venancio, L.P.; Mantovani, E.C.; Neale, C.M.U. **Software development:** Venancio, L.P.; Filgueiras, R.; Gonçalves, I.Z. **Writing and editing:** Venancio, L.P.; Mantovani, E.C.; Neale, C.M.U.; Amaral, C.H.; Gonçalves, I.Z.

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