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Cientific Paper

Simplify the triangle method for estimating evapotranspiration and its use in agrometeorological modeling

Daniela Fernanda da Silva Fuzzo [1]
Jansle Vieira Rocha [2]

Abstract

An aim of this paper was to assess the accuracy in estimating soybean yield proposed by Doorenbos and Kassam over a region in Brazil using the evapotranspiration fraction (EF) obtained from a simplified version of the triangle model, the counties analyzed were Toledo, Vera Cruz do Oeste, Cascavel, Campo Bonito, Medianeira and Serranópolis Iguaçu, in Paraná state, for crop years 2002/03 to 2011/12. A high accuracy of the data was found, the model values for the parameter d1 ("d1" modified Willmott) were between 0.8 and 0.95 in most counties, whereas the root mean squared error showed that there was low variation between 149,60 to 358,60 (kg ha^{-1}). This means that the average of the data from the modified model (using the remotely determined evapotranspiration fraction) were statistically equal the average of the measured soybean crop data. The remote sensing input can be used as tools in the absence of surface information, serving as input data for assisting in agrometeorological modeling in order to estimate agricultural productivity of soybean.

Key words: crop yield; MODIS image; remote sensing; vegetation index.

Resumo

Simplificar o método do triângulo para a estimativa da evapotranspiração e sua utilização em modelagem agrometeorológica

O objetivo deste trabalho foi avaliar a precisão na estimativa do rendimento de soja proposto por Doorenbos e Kassam em uma região do Brasil, utilizando a fração de evapotranspiração (EF) obtida a partir de uma versão simplificada do modelo triangular, os municípios analisados foram Toledo, Vera Cruz do Oeste, Cascavel, Campo Bonito, Medianeira e Serranópolis Iguaçu, no estado do Paraná, para os anos de safra 2002/03 a 2011/12. Foi encontrada uma alta precisão dos dados, os valores do modelo para o parâmetro d1 ("d1" modificado Willmott) estavam entre 0,8 e 0,95 na maioria dos condados, enquanto que o erro quadrático médio mostrou que houve uma variação baixa entre 149,60 e 358 , 60 (kg ha^{-1}). Isso significa que a média dos dados do modelo modificado (usando a fração de evapotranspiração remotamente determinada) era estatisticamente igual à média dos dados de colheita de soja medidos. A entrada de sensoriamento remoto pode ser usada como ferramentas na ausência de informações de superfície, servindo como dados de entrada para auxiliar na modelagem agrometeorológica, a fim de estimar a produtividade agrícola da soja.

Palavras-chave: produtividade agrícola; imagem MODIS; sensoriamento remoto; índice de vegetação.

Resumen

Simplificar el Método del Triángulo para la estimación de la evapotranspiración y su utilización en el modelado agrometeorológico

El objetivo de este trabajo fue evaluar en una región de Brasil, la precisión en la estimación del rendimiento de soja propuesto por Doorenbos y Kassam utilizando la fracción de evapotranspiración (EF) obtenida a partir de una versión simplificada del modelo triangular. Os municipios analizados fueron

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[1] Graduada em Geogragia. Dra. Prof. Universidade Estadual de Campinas - UNICAMP - Cidade Universitária Zeferino Vaz - Barão Geraldo, Campinas - SP, 13083-970. Email: silva.danielaf@gmail.com

[2] Eng. Agrônomo. PhD. Applied Remote Sensing. Prof. Universidade Estadual de Campinas - UNICAMP - Cidade Universitária Zeferino Vaz - Barão Geraldo, Campinas - SP, 13083-970. Email: jansle.rocha@feagri.unicamp.br

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Toledo, En el estado de Paraná, para los años de cosecha 2002/03 a 2011/12. Vera Cruz del Oeste, Cascavel, Campo Bonito, Medianera y Serranópolis Iguaçu, en el estado de Paraná. Se encontró una alta precisión de los datos, los valores de la plantilla para el parámetro d1 ("d1" modificado Willmott) estaban entre 0,8 y 0,95 en la mayoría de los condados, mientras que el error medio cuadrático mostró que hubo una variación baja entre 149,60 y 358, 60 (kg ha^{-1}). Esto significa que el promedio de los datos del modelo modificado (usando la fracción de evapotranspiración remotamente determinada) era estadísticamente igual a la media de los datos de cosecha de soja medidos. La entrada de sensoriamiento remoto puede ser usada como herramientas en ausencia de información de superficie, sirviendo como datos de entrada para auxiliar en el modelado agrometeorológico, a fin de estimar la productividad agrícola de la soja.

Palabras clave: productividad agrícola; imagen MODIS; detección remota; índice de vegetación.

Introduction

Several studies have been developed in this area in order to improve and complement programs related to agriculture either based on meteorological data obtained from conventional weather stations, or even spectral models based on satellite images. As examples, work by Jiang et al. (2001), Mkhabela et al. (2011), Brunsel et al. (2011), Garcia et al. (2014) and Silva-Fuzzo et al. (2015b).

Physical processes and with greater realism led to the development of the land surface modeling systems proposed for application, for example, using images of temperature surface (Ts) and fractional vegetation (Fr), to provide moisture content in the soil surface (Mo), and evapotranspiration fractional (EF), the ratio of evapotranspiration ET to net radiation (Rn), through a methodology known as the "triangle method". The approach of the triangle method is based on a contextual interpretation of a scatter plot derived from the relationship between radiant surface temperature (Ts) and vegetation index (IV).

However, according to Carlson (2013), a new methodology based on simple and purely geometric, physical arguments obviating the use of complex models. So, this new methodology is termed herein as "simplified triangle method”. Thus, derived parameters are obtained by means of radiative temperature and vegetation index measurements from satellite or aircraft that are largely self contained and internally consistent within the triangular pixel space. The aim of this paper was to test the agrometeorological model for soybean yield estimates, substituting the variable relative evapotranspiration (actual evapotranspiration/potential evapotranspiration) obtained from a climatological water balance by fractional evapotranspiration (EF), obtained by the simplified triangle method.

A recent class of remote sensing models utilize the triangle configuration of pixels in Ts/Fr space to generate these variables (CARLSON, 2007; PETROPOULOS et al., 2009). Referred to as the triangle model the boundaries of the triangle constrain the solution for Mo and EF. The geometrical constraint to the dispersion of pixels, when plotted as Ts versus Fr, allows solutions for EF and Mo to be determined solely from the shape of the pixel configuration, which tends to resemble a triangle (or sometimes a trapezoid). The simplified geometrical solution proposed by Carlson (2013) is especially useful for survey of large regions where little or no surface data is available.

Material and Methods

The universe of analysis encompasses Paraná state - Brazil, located in the southern region of the country between latitudes 22° 29' S and 26° 43' S and the meridians 48° 2’ W and 54° 38'W (Figure 1).

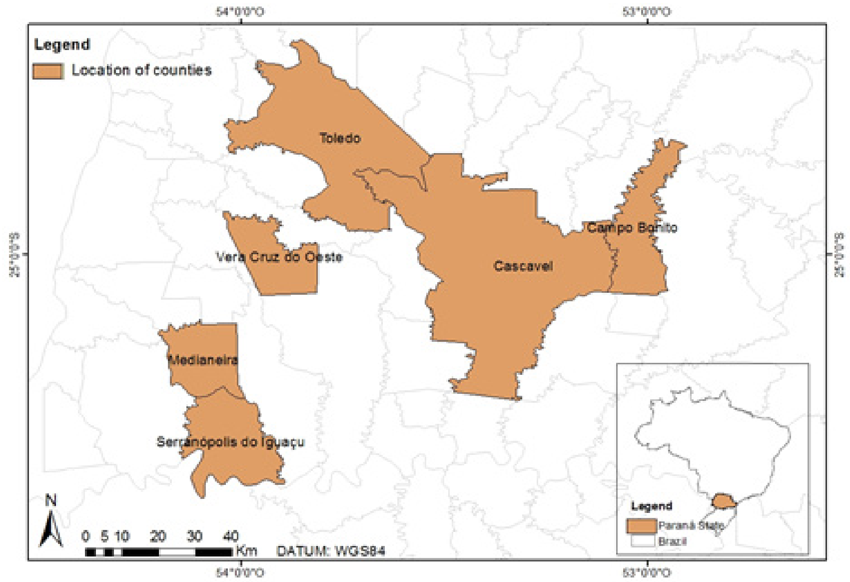

Figure 1. Location of study area.

The counties selected were based on data of crop yeld from the SEAB (Department of Agriculture and Supply of State of Paraná). To estimate relevant parameters using the triangle method, images from sensor MODIS, products MOD13A2 and MOD11A2, "tile h13v11, were used. These products are the compositions of images of 16 days of Vegetation Index NDVI and images of 8 days with Surface Temperature, respectively, with spatial resolution of o1 (one) kilometer.

Mathematical operations were made by changing the digital values of the image pixels, the MOD11A2 products are for 16-bits images, and are converted primarily expressed in Kelvin temperature, and then for values in degrees Celsius (°C). The MO13A2 products were converted to and scale of -1 to 1 by dividing 10,000 by the image. With the NDVI values converted from the digital product and the raw temperatures converted to degrees Celsius, calculations of the important boundary parameters, NDVIs, NDVIo, NDVImax, and NDVImin, were performed from the NDVI images, where NDVIs and NDVIo are, respectively, the highest values represent 100% coverage of vegetation and the lowest values represent by bare soil. Similarly, the extraction of Tmax values are obtained, for the warmest pixels with bare soil or urban area while Tmin represents the lowest temperatures appropriate to areas with well watered dense vegetation as, proposed by Carlson, 2007.

Subsequent scatterplots are shown with axes representing scaled quantities, T* and fractional vegetation cover, Fr, where T* is defined as equation 1.

$$T^* = \{ Ts - Tsmin \ / \ Tsmax - Tsmin \} \qquad (1)$$

Ts, as defined above, is surface radiant temperature, Tsmin is the value of Ts for wet bare soil or dense well watered vegetation, and Tsmax is the corresponding value of Ts for dry, bare soil characteristic of an urban center, for example. Fractional vegetation cover is obtained from NDVI through the equation 2 (CARLSON, 2007).

$$Fr = \{ NDVI - NDVIo \ / \ NDVIs - NDVIo \} \qquad (2)$$

Where: NDVIo is the NDVI value corresponding to bare soil; and, NDVIs is the value corresponding to the maximum coverage of vegetation (bare soil) (GILLIES and CARLSON, 1995). Thus, the method of the triangle, determined from its simple geometric form, yields the availability of surface soil moisture (Mo) and the evapotranspiration (ET) expressed as a fraction of the net radiation (Rn), referred to as the evapotranspiration fraction (EF), as exemplified in Carlson (2013). Eqs. 3 and 4 define these terms as follows:

$$Mo = \{1 - T^* (pixel) \ / \ T^* \ warmedge \} \qquad (3)$$

Ftotal = { Efsoil * (1-Fr) + Fr (pixel) * EFveg } (4)

where: EFveg - value appropriate for vegetation alone, the potential evapotranspiration (assumed to be equal to 1.0); and, T* - scaled surface radiant temperature evaluated along the warm edge. Thus. Ef soil = Mo and Ef veg = 1.

The original agrometeorological model comes from the multiplicative model based on Doorenbos and Kassam (1979). This model considers the product of the ratio, ETr / ETp is very similar to the evapotranspiration fraction EF, which is estimated by the triangle method. Typically, in agrometeorological modeling, the ETr and ETp values are obtained with the calculation of climatic water balance, with data obtained from conventional meteorological stations. Here, we test the use of EF in place of this ratio by replacing the ETr/ETp values in the agrometeorological model with EF. Thus, the ETr / ETp were replaced by the value of EF, estimated by the simplified triangle method, consequently the model was modified according to Eq.5.

Ya/Yp = { ∏i=4 [1 - Ky (1 – EF) i (5)

Where: EF is fractional evapotranspiration.

Subsequently, the meteorological data (rainfall and average temperature) of the surface stations, assigned by the Technological Institute SIMEPAR in counties scale for the years from 2002/03 to 2010/11 were obtained for Toledo and Cascavel city for data comparison. Calculation of Potential Productivity (Yp) depends on the technological level applied to the crop, as was also done by Rose (2007) and Fuzzo-Silva et al. (2015a). Were obtained values of yield potential (Yp) above 3.000 kh ha^{-1} for the cities studied, highlighting the counties of Medianeira, Serranópolis do Iguaçu, e Vera Cruz do Oeste, which had values above 4.000 kg ha^{-1}.

To investigate the method, the values estimated by the modified agrometeorological model were compared using data from evapotranspiration fractional (EF), with the conventional model using the values of relative evapotranspiration (the radio of actual evapotranspiration to potential evapotranspiration (ETr/ETp) obtained by the climatological water balance of Thornthwaite and Mather (1955).

Statistical analyzes were performed to verify the correctness and accuracy of the data, using a simple linear regression model and its coefficient of determination (R^2), MAE (mean absolute error) may be most appropriate for checking the correctness or accuracy of estimated scalar data (e) in relation to the (measured) data (o). The RMSE (root square error) is used to estimate the quality of the classifier. To verify the final quality of the estimator model, although the statistic d1, as described by Willmott et al. (1985) called index Willmott modified, and random and systematic error.

Results and Discussion

In Figure 2 we observe the dispersion of pixels in their typical triangular configuration the dashed red line indicating the warm (dry) edge of the triangle, and the dotted line in blue the cold (wet) edge. Hot and cold ends, respectively, correspond to the driest and wettest pixels for a given value of Fr. These scatterplots can be interpreted in the context of Eqs 3 and 4 as follows: Each pixel within these triangles represents a different value of surface soil water content (Mo) and evapotranspiration fraction (EF). The former varies linearly (along any straight line at constant Fr) from zero (dry) at the warm edge (the sloping red line) to 1.0 (wet) at the cold edge (the vertical blue line). EF varies linearly from zero at the lower right hand vertex to 1.0 along the cold edge. Fractional vegetation cover varies linearly from zero at the base of the triangle to 1.0 at the upper vertex.

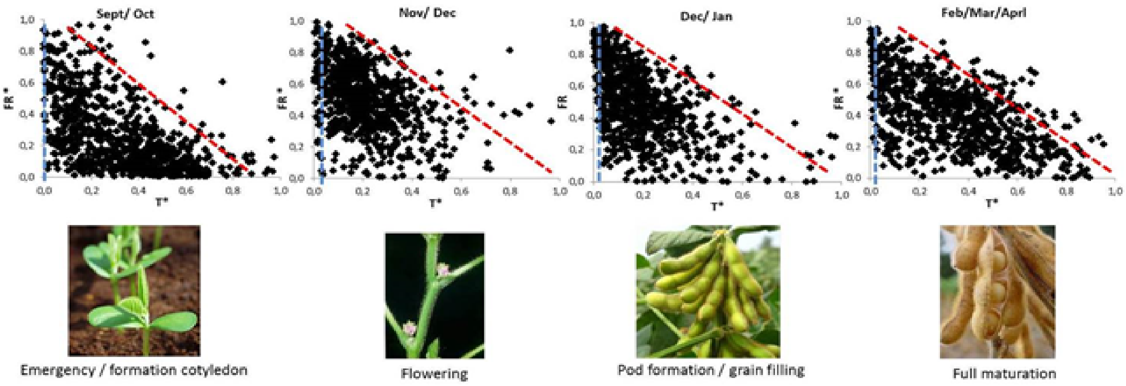

Figure 2. Schematic representation of triangle method and phenological cycle of the soybean crop.

Tian et al. (2013) conducted studies with the triangle method using MODIS images for a bowl of Heibe River, located in the arid region of northeastern China during the growing season of 2009. The results showed that pixel envelope formed in the surface temperature and vegetation index yielded an estimate of the evapotranspiration and showed the Pearson correlation coefficient ranging from 0.94 to 1.0 for 10 days of evapotranspiration estimates and different domain scales.

According to Carlson (2013), the sloping warm side of the triangle (the warm edge) indicates higher bare soil temperature than in areas of higher vegetation, because the soil is more shielded from the sun by the vegetation. We note with triangular graphs that the warm edge has many more pixels near the lower part of the warm edge (signifying more dry, canopy visible to the radiometer), for the months with the greatest amount of exposed soil, i.e. the months of sowing (Sept / Oct) and months regarding the harvesting season (Mar / Apr).

We then tested the agrometeorological model of Doorenbos and Kassam (1979), which includes EF values obtained from the simplified triangle method. Agricultural productivity of the soybean crop was evaluated by considering the estimated values of EF using the simplified triangle method, and substituting these for the values of ETr/ETp (ratio between actual evapotranspiration/potential evapotranspiration) previously used in the original model, whose input was based on surface, rainfall and climate data as described earlier in this paper).

Table 1. Statistical Analysis performance of the agro-meteorological model (Eq. 6) modified for simplified triangle method, from 2002/03 to 2011/12 in kg ha^{-1}, and data measured by SEAB.

	Vera Cruz			Serranópolis			Medianeira			Toledo			Cascavel			Campo Bonito		
Anos	Obs	Est	Diff %	Obs	Est	Diff %	Obs	Est	Diff %	Obs	Est	Diff %	Obs	Est	Diff %	Obs	Est	Diff %
2002/03	3652	3488	4.7	3200	3059	4.6	3500	3142	11.4	3470	3569	-2.8	3300	3156	4.6	3223	3159	2.0
2003/04	2300	2369	-2.9	2700	2506	7.7	2500	2455	1.8	2400	2569	-6.6	2750	2658	3.5	3100	2986	3.8
2004/05	2400	2578	-6.9	2000	2368	15.5	2350	2887	18.6	2650	2454	8.0	2355	2159	9.1	2850	2698	5.6
2005/06	2231	2125	5.0	2480	2369	4.7	2355	2942	20.0	2230	2349	-5.1	2700	2659	1.5	3100	3015	2.8
2006/07	3000	3180	-5.7	3595	3359	7.0	3427	3083	11.2	3100	3136	-1.1	2851	2658	7.3	3300	3059	7.9
2007/08	2900	2827	2.6	2880	2435	18.3	3000	2914	3.0	3479	3258	6.8	2988	2956	1.1	3100	3258	-4.8
2008/09	2000	2127	-6.0	1363	1987	31.4	1240	2077	40.3	2300	2632	12.6	2580	2798	-7.8	2400	2368	1.4
2009/10	3400	3259	4.3	3744	3689	1.5	3719	3217	15.6	3500	3347	4.6	3322	3256	2.0	3347	3156	6.1
2010/11	3497	3012	16.1	3618	3598	0.6	3500	3223	8.6	3200	3185	0.5	3200	2986	7.2	3325	2968	12.0
2011/12	3298	3015	9.4	3100	3059	1.3	2949	2962	-0.4	3124	2968	5.3	2726	2365	15.3	3000	2832	5.9

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d1	0.96	0.95	0.55	0.96	0.92	0.92
R^2	0.89	0.86	0.81	0.88	0.80	0.80
MAE	180.60	223.50	358.60	149.60	155.70	155.70
RMSE	59.21	80.04	112.59	51.85	57.26	57.26
Ea	52.62	71.66	106.80	45.48	54.88	54.88
Es	27.15	35.64	35.67	24.91	16.34	16.34

Table 1, express the differences between measured and estimated yield is expressed as a percentage 100 (b-a)/a, d1 and d2, are the concordance indices, which indicates the model performance, R2 is the coefficient of determination, (the correlation coefficient). MAE is the mean absolute error, RMSE is the root squared error, Ea is the systematic error, Es is the non-systematic error, and the p-value is an assessment of the significance significant difference between the mean values of the estimated data and the mean values of the measured data. Error here is defined as the difference between estimated and measured crop productivity.

The performance of the modified model, and in accordance with Figure 3, showed satisfactory results, in accordance with the concordance index "d1" which measured the dispersion of data at line 1:1, namely the accuracy of the values estimated from agrometeorological model (based in the simplified triangle method) as compared to measured values (SEAB). This table shows that the values were between 0.8 and 0.95 in most municipalities, i.e. a high accuracy of the data.

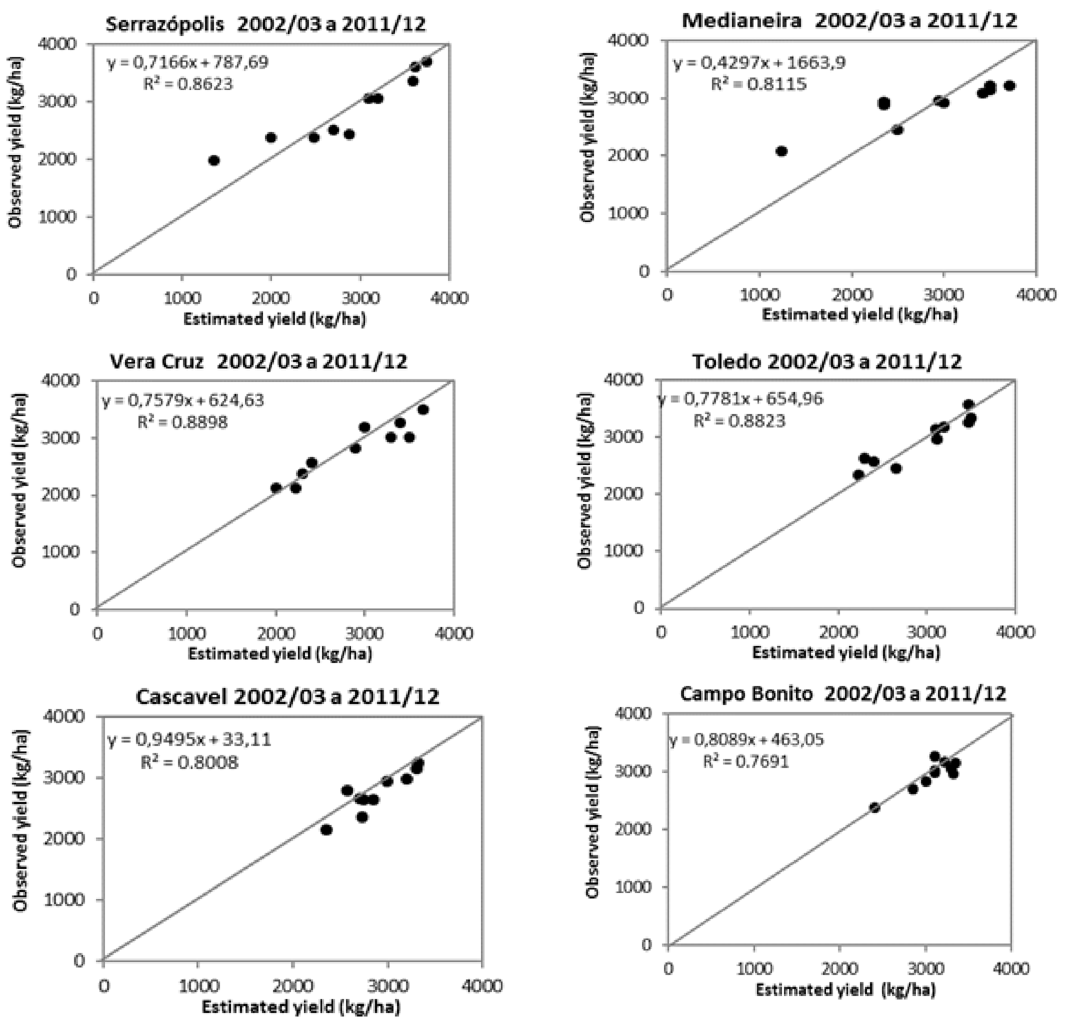

Figura 3. Yield (kg ha^{-1}) measured and estimated by the agrometeorological model (based in the simplified triangle method) for the period from 2002/03 to 2011/12.

By analyzing the coefficients of confidence "c", the values ranged from 0.9 (c> 0.85) for some counties as, Toledo, Vera Cruz, and Campo Bonito, showing good agreement. Analyzing the MAE it was found that the values were underestimated by 358.60 kg ha^{-1} in Medianeira. The RMSE showed that on average there was variation between 48,86 kg ha^{-1} to 112.59 kg ha^{-1}. The R^2 values ranged from 0.77 in Campo Bonito, to 0.89 in Vera Cruz do Oeste.

Ren et al. (2008) have generated regional spectral models for estimating yield of winter wheat based on MODIS NDVI profiles for 11 counties in China from 2002 to 2004, noting that the linear relationship between NDVI and productivity values was significant, with R^2 values being 0.66 to 0.88., These data were compared with official field data, showing good accuracy of the estimated data. Random errors were higher than those of systematic errors, indicating that the exactness of the measurements was better than the accuracy.

Johann (2012) tested a spectral agrometeorological model based on MODIS EVI for the state of Paraná - Brazil, from 2004/05 to 2007/08 seasons. Altogether 317 counties were analyzed, using two statistical methods, "stepwise" and "best subset", showing correlations ranging from 0.57 to 0.85 and R^2 set values ranged between 33.31 and 66.90% for the same data set. The reliability values "d" shown that the values estimate straight lines approximating 1:1, showing the absence of systematic error in the estimates.

Table 2 shows the statistical analysis for 2 counties regions with SIMEPAR data Comparing the three tests (Table 5 on the modified model with EF method triangle, Table 6, and agro-meteorological Doorembos and Kassan, with point data), we can say for Toledo and Cascavel, that are repeated in the three analyzes showed similar statistical performance in the three analyzes. Regarding the concordance index "d1", which measures the dispersion of data and accuracy, we can say that it showed better agreement (values above 0.9) using EF obtained from the simplified triangle method (in agrometeorological model) than for the other two tests.

Table 2. Statistical performance of the agrometeorological model conventional by Doorembos and Kassan (1979) (Eq. 5), based on SIMEPAR data (point data) for the years 2002/03 to 2011/12, for Toledo and Cascavel city.

	Toledo			Cascavel		
Anos	Obs	Est	Diff %	Obs	Est	Diff %
2002/03	3470	3500	-0.9	3300	3421	- 3.5
2003/04	2400	2800	-14.3	2750	2965	-7.3
2004/05	2650	2100	26.2	2355	2411	-2.3
2005/06	2230	2400	-7.1	2700	2963	-8.9
2006/07	3100	2800	10.7	2851	3057	-6.7
2007/08	3480	3563	-2.3	2988	3356	-11.0
2008/09	2300	2800	-17.9	2580	3210	-19.6
2009/10	3500	3500	0.0	3322	3211	3.5
2010/11	3200	3300	-3.0	3200	3358	-4.7
2011/12	3124	3080	1.4	2726	3058	-10.9
d1	0.89			0.78		
d2	0.99			0.95		
R^2	0.77			0.63		
MAE	245.20			246.00		
RMSE	102.97			76.61		
Ea	90.36			65.92		
Es	49.37			39.04		

In general, the results show performance improvements when EF was obtained from the simplified triangle method than when ETr / ETp was obtained from the climatic water balance. We believe that this result is due to the scale of the data, i.e., SIMEPAR data is point data, whereas EF from triangle method pertain to a spatial resolution of 1km. The agro-meteorological model uses as database agricultural productivity data that consider the counties boundary as whole. It is appropriate, therefore, to claim that this improvement in performance is due to compatibility with the agro-meteorological data scales used.

Regarding errors, it was verified with the largest values based on data SIMEPAR tests, the MAE, with values, were from between 245.20 kg ha^{-1} to 246.00 kg ha^{-1}. The RMSE, which shows the differences between measured and estimated data values were from 102.97 kg ha^{-1} to 76.61 kg ha^{-1}.

Conclusions

1. The variable fractional evapotranspiration (EF), developed with a simplified method for treating remote sensing measurements of vegetation index and radiometric surface temperature (referred to here as the simplified triangle method), can be used in replacement of relative evapotranspiration (ETr/ETp), obtained from the method of climatic water balance, often used in agrometeorological models to estimate agricultural productivity.

2. The agrometeorological model for the estimation of agricultural productivity of soybean showed better performance when (EF) is used in place of the ratio of actual evapotranspiration and potential evapotranspiration (ETr/ETp).

3. Thus the use of remotely sensed variables such as NDVI and surface radiant temperature, as obtained, for example from MODIS, can be used as reliable tool to calibrate agrometeorological models, such as for predicting soybean yield estimates. This type of data source is especially useful in the absence of ancillary data or surface information for monitoring and forecasting of agricultural crop yields.

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