AGROMETEOROLOGICAL MODELING TO ESTIMATE SOYBEAN YIELD IN THE SOUTHERN CONE OF RONDÔNIA

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ABSTRACT

Agrometeorological modeling is crucial to predict the impact of climatic conditions on agricultural production. However, its application in large regions faces challenges due to the lack of weather stations and limited access to real-time data. In this study, the multiplicative agrometeorological model was used to estimate soybean yield in the seven municipalities of the Southern Cone of Rondônia in the 2020/21 to 2022/23 harvests. This model considers the relationships between actual and potential evapotranspirations and water conditions during different phenological stages. Ten-year water balances were developed for each municipality, using air temperature data from ERA5-Land from the ECMWF and precipitation data estimated by NASA's GPM_v06 satellite. The results showed satisfactory performance of the model, with coefficients of determination ranging from 0.48 to 0.88 and agreement indices from 0.41 to 0.90 compared to the data observed by IBGE.

Keywords: Evapotranspiration; Water balance; Climate variability; ERA5-Land; GPM_v06.

1. INTRODUCTION

The agricultural sector is extremely important socially and economically, accounting for 24.4% of Brazil's GDP in 2023, according to the Brazilian Center for Advanced Studies in Applied Economics (CEPEA/ESALQ/USP, 2023). According to Leite-Filho *et al.* (2021), agricultural productivity is closely linked to edaphoclimatic conditions, especially to the distributions of precipitation volumes, which present great spatial-temporal variability, even between farms and neighboring municipalities.

Due to this variability, agrometeorology is a very important science for agriculture, as it correlates meteorological information with the development of agricultural crops. Agrometeorological modeling predicts productivity through mathematical models (MONTEIRO, 2009). These models correlate climatic variables with their respective influences on plants. Production is a correlation between the potential productivity of a specific crop in a given region (considering optimal conditions for the plant to express its maximum genetic potential) with the penalty suffered by the crop from water conditions (ARAÚJO *et al.*, 2011).

Crop yield forecasting is extremely valuable for producers, for the market to plan for storing and selling the produce, and for public administrators to manage and implement agricultural and public policies (CRESTANI MOTA *et al.*, 2024). Therefore, for several decades, agrometeorological models have been used to estimate crop yield and characterize the effects of climate variations on agriculture (CAMARGO *et al.*, 1986; FONTANA & BERLATO, 1998; BERKA & RUDORFF, 2003; RIZZI & RUDORFF, 2005;

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ROJAS *et al.*, 2005; SILVA-FUZZO *et al.*, 2015).

The state of Rondônia (RO) has become a major grain-producing state, especially in the northern region of the country, with an estimated production of 3.74 thousand tons in the 23/24 harvest, of which about 2 tons will be soybeans, which represents 54.5% of the amount of grain produced in the state (CONAB, 2023). The soybean crop generates capital and attracts investments to RO. According to the Brazilian Institute of Geography and Statistics (IBGE, 2023), the region known as the Southern Cone of the RO (SCRO) is central to oilseed production in the state, accounting for about 51.2% of the 22/23 harvest. Due to its importance for soybean production, the SCRO needs a model to monitor, even simplistically, the relationships between plant physiology, environmental variables, and impediments that occur during the different phenological stages to indicate periods and regions that are adverse to cultivation (RIZZI & RUDORF, 2005).

According to Mota *et al.* (2019), crop yield estimation models must meet regional needs, be objective, and require as few data sources as possible. This is due to limitations in monitoring information on-site and the robustness and constancy of surface surveys, which pose challenges in modeling agricultural crops. The same authors noted that in Brazil, inferences about harvest progress and crop yields are predominantly and subjectively made by public agencies and institutions, based on interviews with sector-related agents (traders). This approach hampers accurate error analysis and leads to speculation.

However, the use of agrometeorological models in vast regions is limited due to the lack of weather stations and the challenge of accessing real-time data, especially in areas of agricultural hinterlands, making timely decisions difficult (MOTA *et al.*, 2019), as is the case of SCRO. In addition, station readings are limited and often scarce (INMET, 2023). The need for spatial interpolation can result in significant discrepancies from real conditions on the earth's surface. Therefore, Silva-Fuzzo *et al.* (2015) indicate that the limited information from surface meteorological stations in the estimation of soybean yield can be reliably replaced by meteorological data from reanalysis and satellite estimates for air temperature and precipitation variables to obtain a greater coverage area.

Thus, possible options include databases from the ERA5-Land for air temperature at 2 m from the earth's surface and the Global Precipitation Measurement (GPM_v06) space mission for precipitation accumulations. Among the recent studies that prove the satisfactory accuracy of these estimates are those by Alves and Victoria (2020), who proved the feasibility of using data from the GPM_v06 space mission for ten-day or monthly performance on accumulated precipitation. Furthermore, Araújo *et al.* (2021) validated that the air temperatures obtained by reanalysis of ERA5-Land were similar to data from weather stations.

ERA5-Land is a high-resolution global climate data set that is part of the ERA5 series, developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) (MUÑOZ SABATER, 2019) and provides detailed information on several meteorological and environmental variables. GPM_v06 is an updated and improved version of the Global Precipitation Measurement GPM_v5 mission. This earth observation satellite was developed by an international collaboration, led by the National Aeronautics and Space Administration (NASA), an agency of the United States federal government responsible for research and development of space exploration technologies and programs, and the Japan Aerospace Exploration Agency (JAXA). It was designed to measure precipitation worldwide with high accuracy on 0.1º × 0.1º spatial and daily temporal scales (HUFFMAN *et al.*, 2019).

Thus, considering the presented scenario and the possibility of estimating soybean production through an agrometeorological model, this study was conducted in the hydroclimatic conditions of the region known as the Southern Cone of the state of Rondônia. The objective was to estimate soybean productivity in the SCRO in the 2020/21, 2021/22, and 2022/23 harvests from an agrometeorological model, with emphasis on the penalty resulting from water scarcity at different phenological stages of the crop. The data on average air temperature was obtained from ERA5-Land reanalyzes, and daily accumulated precipitation was estimated using data from the GPM_3IMERGDL_v06 satellite.

2. MATERIALS AND METHOD

The SCRO is a region formed by the seven municipalities located to the Southeastern RO, between the geographical coordinates 10°989'S to 13°693'S latitude and 62°115'W to 59°774'W longitude. The municipalities included are Cabixi, Cerejeiras, Chupinguaia, Colorado do Oeste, Corumbiara, Pimenteiras do Oeste, and Vilhena (Table 1). The region was chosen due to its relevance as a soybean producer, responsible for more than half of the soybeans produced in the entire state of RO (IBGE, 2023). The predominant climate is the Am type (ALVARES *et al.*, 2013), with an average annual precipitation ranging from 1,340 mm to 2,340 mm with a mean of 1,906.5 mm. The region has two well-defined seasons: the rainy season, from October to April, with almost 90% of the total precipitation, and the dry season, from May to September, with scarce precipitation (SILVA *et al.* 2015). The average altitude of the SCRO is 313.79 m (EROS, 2017).

Municipality	Latitude (S)	Longitude (W)	Altitude (m)
Cabixi	13°474'	60°639'	236.55
Cerejeiras	13°201'	61°259'	223.43
Chupinguaia	12°537'	60°901'	345.44
Colorado	13°159'	60°551'	390.30
Corumbiara	12°927'	61°092'	294.95
Pimenteiras	13°381'	61°717'	205.57
Vilhena	12°09'	60°2493'	600.00

Table 1. Information on latitude, longitude, and average altitude of the municipalities that make up the SCRO.

The agrometeorological variables adopted in this research considered a set of data referring to three soybean crops 2020/2021, 2021/2022, and 2022/2023 (from October 1 to January 31 of the following year). The study covered 12 ten-day periods, which coincide with 120 days of the phenological development cycle (stages of vegetative development, flowering, grain filling, and maturation) and the agricultural calendar of the crop in the seven municipalities of the SCRO for early and semi-early cycle cultivars (Table 2).

Ten-day	O1	O2	O3	N1	N2	N3	D1	D2	D3	J1	J2	J3
Phenology	V	V	V	F	F	-	-	-	GF	GF	M	M
DAE	10	20	30	40	50	60	70	80	90	100	110	120

V = Vegetative development, F = Flowering, GF = Grain filling, M = maturation, DAE = Days after emergence.
Source: Oliveira Junior *et al.* (2016)

Table 2. Relationship between the ten-day period analyzed, the phenological stage in which the crop is found, and the number of days after emergence (DAE).

Two databases were used to obtain meteorological information. The first database containing the air temperature 2 m above the earth's surface was obtained from ERA5-Land (global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecast - ECMWF), available on the Copernicus platform. The other was obtained from NASA's GPM space mission and used to generate the database of accumulated daily precipitation estimates, employing the IMERG v6. alagorithm. Both the air temperature reanalysis data and the estimated precipitation data were extracted from their respective systems in the "netCDF" format through the Python Spyder software (anaconda3) version

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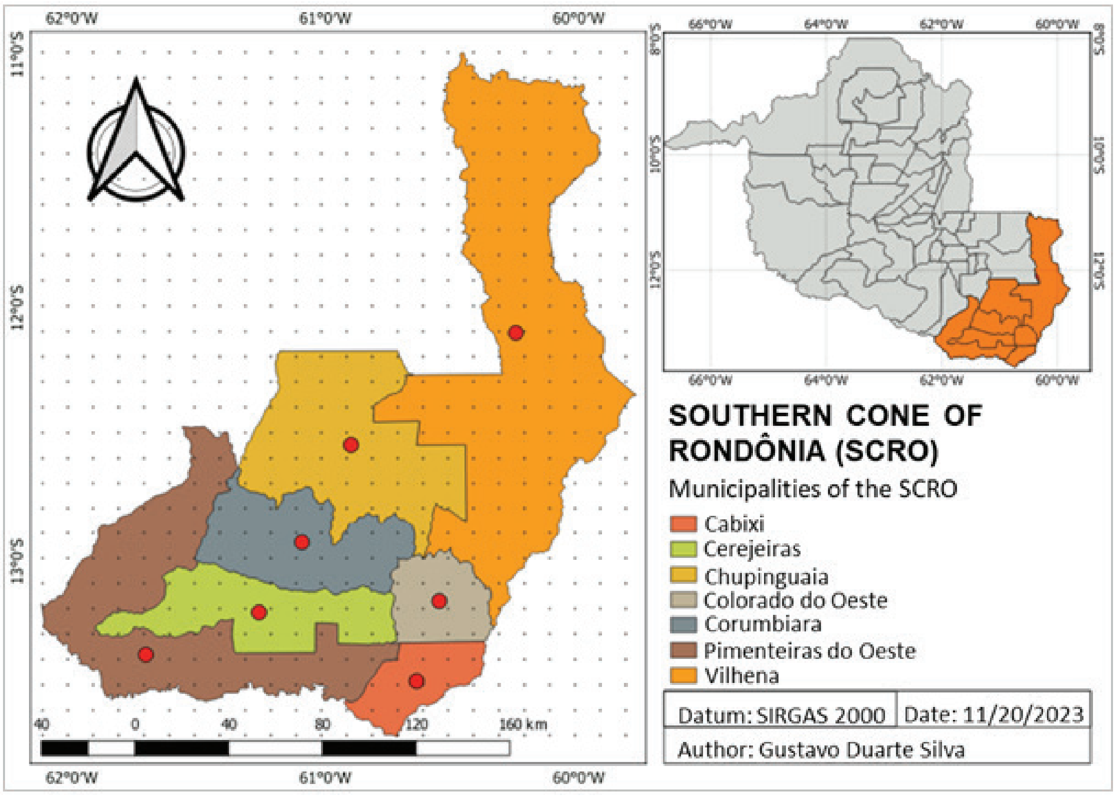

Figure 1. Regular grid for the municipalities in the Southern Cone of Rondônia (SCRO) with a spatial resolution of 0.10° or 9 km horizontal resolution representing the ERA5-Land reanalysis data for the average daily air temperature at 2 m above the earth's surface and estimated daily precipitation accumulated by GPM_3IMERGDL_v06 for the SCRO. Red circles (centroids) indicate the latitudes and longitudes to which the Climatological Water Balances of Thornthwaite and Mather (1955) were projected, and the average soybean yields in the 2020/2021 to 2022/2023 harvests in each SCRO municipality.

2020.11.0.0 in the domain from 10.989°S to 13.693°S latitude and from 59.774°W to 62.115°W longitude (an area covering the seven SCRO municipalities) on hourly and daily scales, respectively, with a spatial resolution of 0.10° or 9 km of horizontal resolution (Figure 1).

The first set of data had to be transformed into a daily average scale in Python Spyder. The second data were already in accumulated daily precipitation (mm day^{-1}). Both files were converted to ".txt" and from ".txt" to Comma Separated Values (CSV) pixel by pixel (each pixel contained a pair of daily average air temperature and daily accumulated precipitation information, always linked to a grouping of georeferenced points of spatialized latitude and longitude for the seven SCRO municipalities in the QGIS geographic information system). The data were grouped in ten-day periods for the development of the Climatological Water Balance (CWB). Temperatures were converted from Kelvin (K) to Celsius (°C) by subtracting 273.15.

The CWB used was the Normal Climatic Water Balance, proposed by Thornthwaite and Mather (1955), with a ten-day temporal analysis providing the most refined monitoring of conditions. The model estimates information on soil water storage (SWS), actual evapotranspiration (AE), water surpluses (WSP), and water deficiencies (DEF). The Available Water Capacity (AWC) was considered to be 100 mm for the entire region, based on data from the Irrigation Atlas (ANA, 2021).

Multiplicative model proposed by Doorenbos and Kassam (1979) and modified by Camargo *et al.* (1986) was the agronomic model employed to estimate soybean crop productivity in the SCRO (Equation 1). This considers the penalty suffered by the crop due to the water surplus (fe) (Equation 2) instead of just the deficit.

$$\frac{y_r}{y_p} = \prod_{i=1}^{n} \left[1 - ky_i \left(1 - \frac{RE}{PE} \right) * \left[1 - ke_i (1 - fe_i) \right] \right] \quad \text{(Eq. 1)}$$

Where y_r is the real soybean yield (kg ha^{-1}); y_p is the potential soybean yield in the region (kg ha^{-1}); $\prod$ is the product, $\frac{RE}{PE}$ is the relationship between real evapotranspiration and potential evapotranspiration, respectively; i is an index for growth stage and n is total number of crop growth stages; k_y is the crop penalty coefficient for water deficiency; and ke is the crop penalty coefficient for water surplus. Both ky the ke and vary according to the phenological stage of the crop, due to the different water requirements of plants according to their development. The different water requirements were represented based on the tabulated values of k_y proposed by Doorenbos and Kassam (1979) (Table 3) and presented by Camargo *et al.* (1986) (Table 4).

$$fe = \left[1 - \frac{(WSP - PE)}{WSP} \right] \quad \text{(Eq. 2)}$$

The surplus factor femeasures the influence of water surplus on crop productivity by correlating water surplus (WSP) and potential evapotranspiration (PE). This factor is only used under the condition that the WSP is equal to or greater than PE; otherwise, the fe will be equal to the unit, regardless of the result (CAMARGO *et al.*, 1986).

Table 3. Values of the productivity coefficients (ky) used in the multiplicative model.

Phenological Stage	Productivity Coefficient (ky)
Vegetative	0.2
Flowering	0.8
Grain filling	1.0
Maturation	0.2

Source: Doorenbos and Kassam (1979) and Camargo *et al.* (1986).

Table 4. Values of the productivity penalty coefficients for water surplus (ke) used in the multiplicative model.

Phenological Stage	Penalty coefficient (ke)
Vegetative	0.0
Flowering	0.1
Grain filling	0.1
Maturation	0.1

Source: Camargo *et al.* (1986).

The calculation of y_p is determined by the technological level applied to the crop, with a maximum value defined for the cultivation conditions, provided there are no climatic constraints. To estimate y_p , 10% was added to the y_r of each municipality for each harvest analyzed. This approach resulted in a more accurate model adjustment for the SCRO, due to the limited historical information available (data series with only three harvests) on soybean cultivation. This method differs from that proposed by Silva-Fuzzo *et al.* (2015), who added 10% to the highest observed crop yield in the historical series, as they analyzed at least ten agricultural harvests in their studies. According to Moraes *et al.* (1998) and Carvalho *et al.* (2005), the 10% increase in yield aims to account for any environmental effects that might interfere with the yield potential.

To evaluate the performance of the multiplicative model, linear regression analyses were conducted, involving the coefficient of determination (R^2) and the concordance index "d" as proposed by Willmott *et al.* (1985). These analyses relate the estimated values to the observed values, allowing for the assessment of the model's accuracy and precision, which together indicate the consistency of the estimated data with the measured data. Precision, represented by the coefficient of determination (R^2), reflects the degree of dispersion of the estimated values around the mean and measures random error, without considering systematic error. The concordance index "d" numerically quantifies the model's accuracy by evaluating how well it simulates the observed values (Equation 3). This index ranges from 0 to 1, with values closer to 1 indicating better agreement with the observed data. The "d" index reflects the deviation from the ideal 1:1 line in scatter plots,

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measuring the difference between the slope of the regression line and the ideal value of 1, as well as the deviation of the line's intercept from zero.

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (Pi - Oi)^2}{\sum_{i=1}^{n} (|Pi - O| + |Oi - O|)^2} \right] \quad \text{(Eq. 3)}$$

Where Pi is the value estimated by the model, Oi is the observed value, and O is the average of the observed values.

Additionally, the evaluation model proposed by Willmott *et al.* (1985) provides other important information, such as systematic error (SE) and non-systematic (random) error (RAE), which are components of the mean absolute error (MAE). MAE measures the average magnitude of the differences between the estimated and observed values, offering a comprehensive view of the model's performance by considering both systematic and random errors.

The statistical analysis performed to evaluate the model also considered the coefficient, as defined by Camargo and Sentelhas (1997), which is calculated by multiplying the correlation coefficient (R) by Willmott's index "d" (Equation 4). According to the authors, its interpretation is as follows: "excellent" (c > 0.85); "very good" (0.76 ≤ c ≤ 0.85); "good" (0.66 ≤ c ≤ 0.75); "fair" (0.61 ≤ c ≤ 0.65); "poor" (0.51 ≤ c ≤ 0.60); "bad" (0.41 ≤ c ≤ 0.50); and "very bad" (c< 0.40).

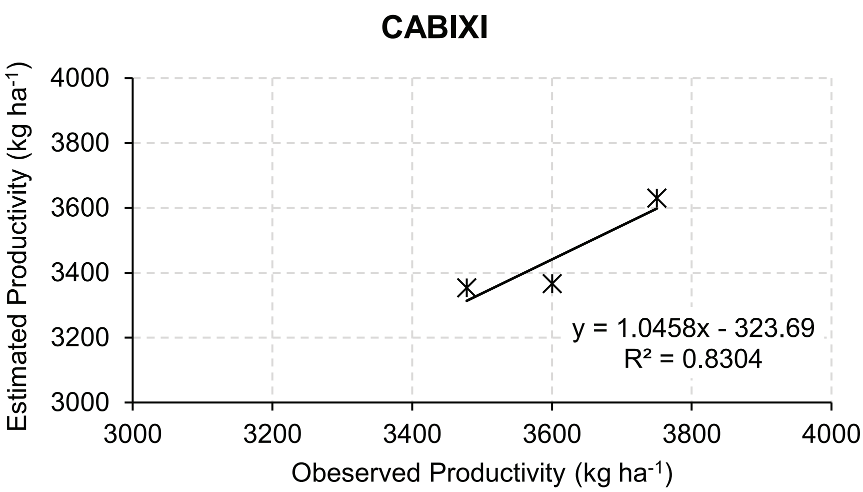
$$c = R^2 * d \quad \text{(Eq. 4)}$$

Results and Discussion

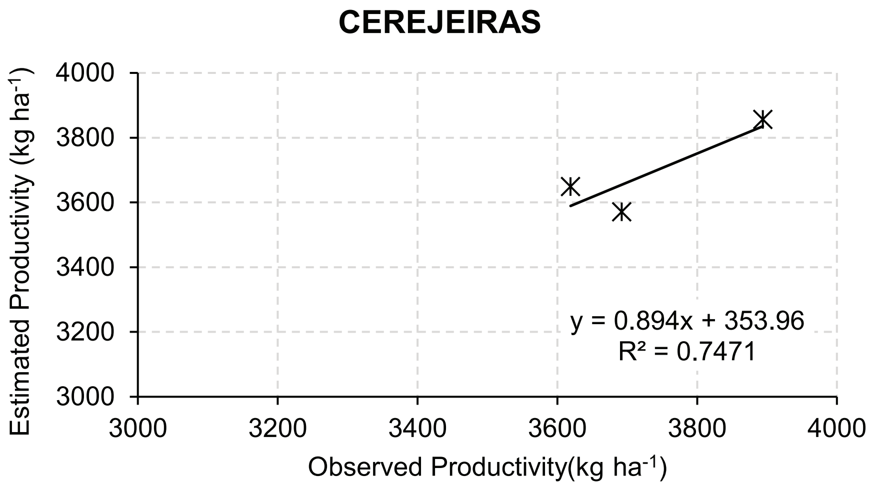
The graphical representation of the analyzed data for the 2020/21 to 2022/23 harvests (Figure 2) illustrated the variation in the observed real values (y_r) from 3,350 to 3,900 kg ha^{-1}, while the values estimated by the agronomic model (y_e) ranged from 3,354 to 3,975 kg ha^{-1}, demonstrating a very close relationship. The lowest y_r value was recorded in the 2020/21 harvest, while the highest occurred in the 2022/23 harvest, both in Colorado do Oeste, indicating a gradual increase in yield attributable to the municipality's agricultural development. This trend of gradually increased yield was also observed in the municipalities of Cabixi, Corumbiara, and Chupinguaia.

Figure 2. Comparison between the yields observed (y_r) observed by IBGE and yields estimated (y_e) by the multiplicative agrometeorological model for the seven municipalities in the Southern Cone of Rondônia during the 2020/21, 2021/22, and 2022/23 harvests.

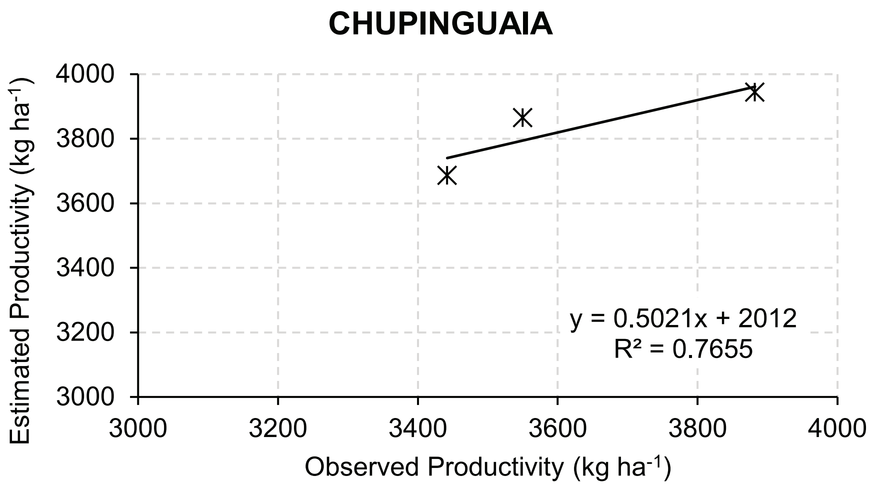
2-A



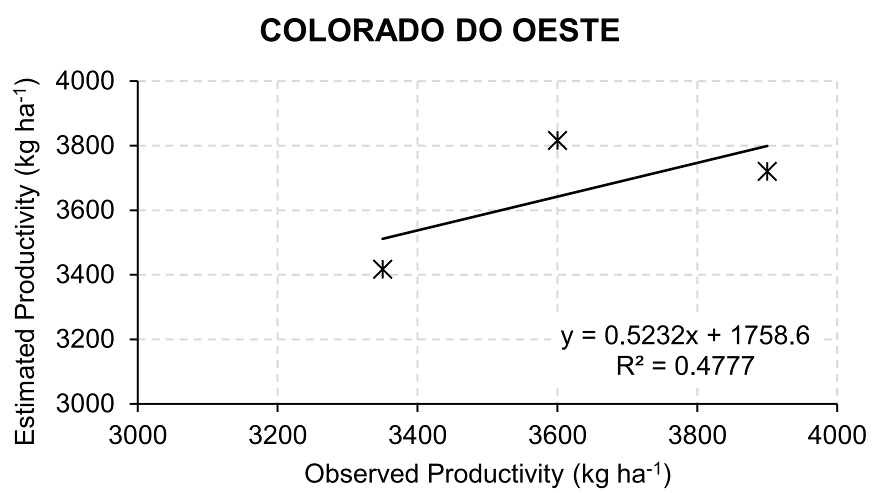
2-B


CEREJEIRAS
Estimated Productivity (kg ha-1)
4000
3800
3600
3400
3200
3000
y = 0.894x + 353.96
R² = 0.7471
3000
3200
3400
3600
3800
4000
Observed Productivity(kg ha-1)

2-C


CHUPINGUAIA
Estimated Productivity (kg ha-1)
4000
3800
3600
3400
3200
3000
y = 0.5021x + 2012
R² = 0.7655
3000
3200
3400
3600
3800
4000
Observed Productivity (kg ha-1)

2-D


COLORADO DO OESTE
Estimated Productivity (kg ha-1)
4000
3800
3600
3400
3200
3000
y = 0.5232x + 1758.6
R² = 0.4777
3000
3200
3400
3600
3800
4000
Observed Productivity (kg ha-1)

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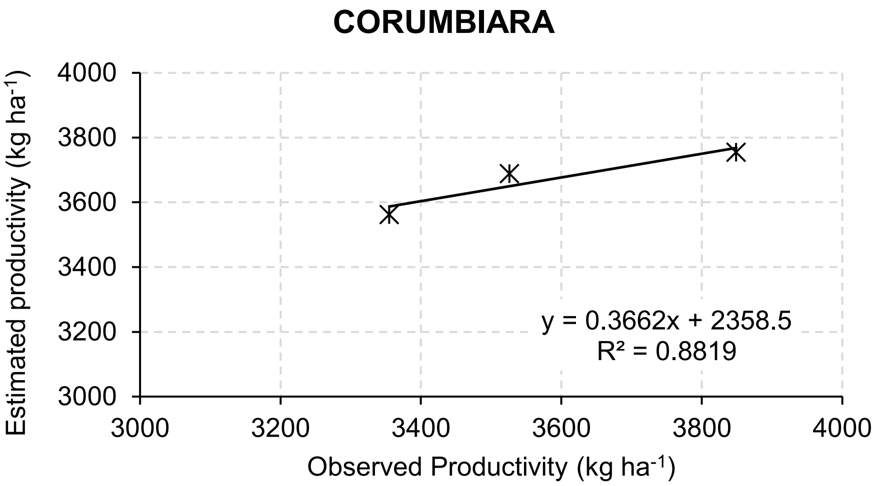
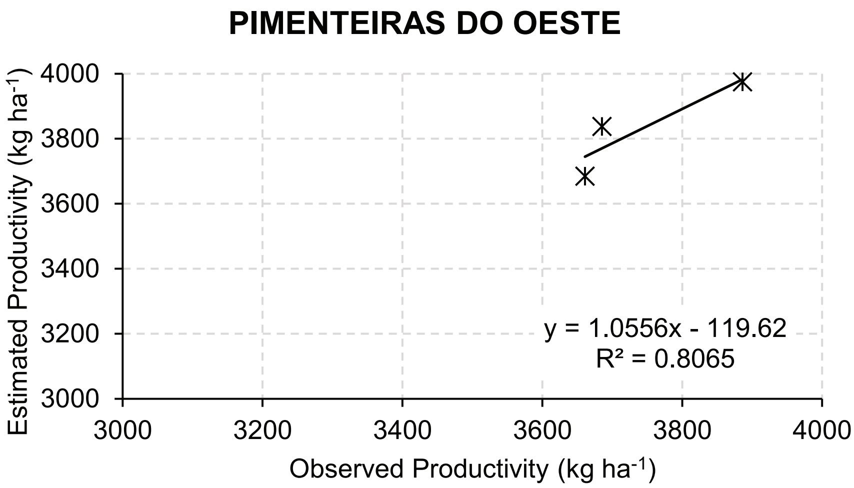
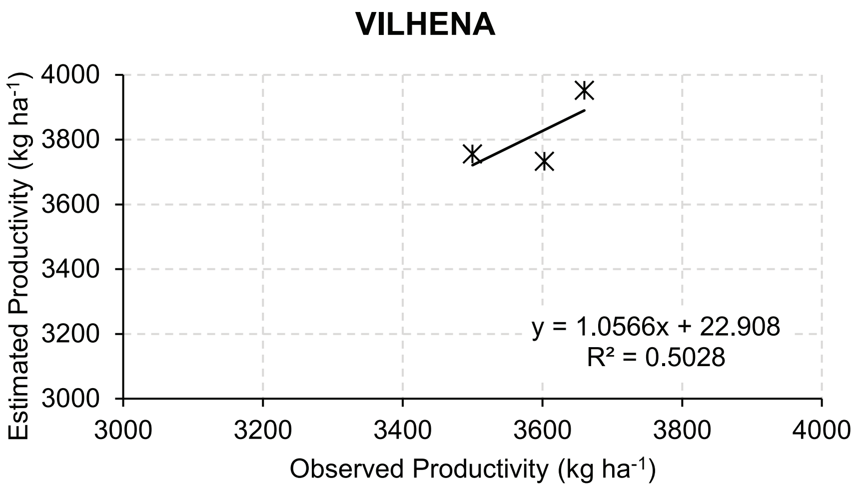
2-E



2-F



2-G



The coefficient of determination (R^2) indicated that the results did not deviate significantly from the adjusted regression line, with the model explaining more than 74% of the data variation for all municipalities, as well as for the study by Camargo *et al.* (1986). Exceptions include Colorado do Oeste (48%) (Figure 2-D) and Vilhena (50%) (Figure 2-G), which showed the lowest values, though these still presented considerable significance. This indicator revealed that the municipalities with the lowest data divergence were Corumbiara, with 88% (Figure 2-D), Cabixi, with 83% (Figure 2-A), and Pimenteiras do Oeste, with 81% (Figure 2-F), in terms of the variance explained by the model. According to the confidence index (*c*) used by Camargo and Sentelhas (1997), the results achieved a median to good performance (Table 5).

Table 5. Performance of the multiplicative agrometeorological model using air temperature reanalysis data from ERA5-Land and estimated precipitation from GPM_v06 in the 2020/21, 2021/22, and 2022/23 soybean harvests in the Southern Cone of Rondônia.

			kg ha^{-1}	
	d	*c*	*MAE*	*RAE*
Cabixi	0.65	0.54	151.21	151.21
Cerejeiras	0.9	0.67	62.64	42.01
Chupinguaia	0.67	0.51	207.18	-207.18
Colorado	0.8	0.38	154.07	-34.11
Corumbiara	0.73	0.64	154.45	-91.7
Pimenteiras	0.83	0.67	88.53	-88.53
Vilhena	0.41	0.2	225.96	-225.96

d =Willmott agreement index; c =Camargo and Sentelhas confidence index (1997); MAE =mean absolute error; RE = random error.

Mean absolute error (MAE) and random error (RAE) demonstrated an inversely proportional relationship with the agreement index "d" . Municipalities with higher values of *d* also exhibited lower errors, such as Cerejeiras ("d"=0.90, MAE=62.64, RAE=42.1) (Figure 2-B) and Pimenteiras do Oeste ("d"=0.83, MAE=88.53, RAE= -88.53) (Figure 2-F). Conversely, Vilhena ("d"=0.41, MAE=225.96, RAE=42.1) (Figure 2-G) and Chupinguaia ("d"=0.67, MAE =207.18, RAE= -207.18) (Figure 2-C) showed higher errors with lower d values. The average MAE for all municipalities indicates that the model had an average error of less than two and a half bags per hectare, which represents less than 5% of the region's crop yield.

The agreement index *d* exhibited excellent results, where six of the seven municipalities obtained values between 80 and 95% of correlation, including Cabixi with 87% correlation (Figure 2-A), Chupinguaia 95% (Figure 2-B), Chupinguaia 81% (Figure 2-C), Colorado do Oeste 89% (Figure 2-D), Corumbiara 85% (Figure 2-E) and Pimenteiras do Oeste with 91% (Figure 2-F). The lowest value (Figure 2-G) showed 64% correlation, thus validating the efficiency of the model.

CONCLUSIONS

Despite the limited volume of data, due to the analysis of only three harvests and the lack of detailed information on the cultivars sown in each of the seven municipalities analyzed, the multiplicative agrometeorological model effectively estimated soybean yield in the SCRO. The average error was less than two and a half sacks per hectare. This confirms the accuracy of both the prediction model and the air temperature data obtained from ERA5-Land reanalysis, as well as the precipitation data provided by the GPM_v06 space mission remote sensing. Freely available online, these products are powerful tools for assisting in agricultural planning and management in the region.

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REFERENCES

ALVARES, C. A.; STAPE, J. L.; SENTELHAS, P. C.; MORAES, J. L. G.; SPAROVEK, Gerd. 2013. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift.** v.22, n.6, p.711-728. Available at: <https://doi.org/10.1127/0941-2948/2013/0507>. Accessed on: 17.nov.2023.

ALVES, G. F.; VICTORIA, D. C. 2020. Avaliação da precipitação estimada pelo gpm late run para estações meteorológicas no Brasil. **Anais do 14º Congresso Interinstitucional de Iniciação Científica – CIIC**, Campinas, São Paulo, 2020. Available at: <https://ainfo.cnptia.embrapa.br/digital/bitstream/item/218833/1/RE20604-CIIC-2020.pdf>. Accessed on: 02.nov.2023.

ANA, Agência Nacional das Águas. 2021. **Atlas Irrigação:** uso da água na agricultura irrigada. 2. ed. Brasília: ANA, 2021. Available at: <http://atlasirrigacao.ana.gov.br>. Accessed on: 15.nov.2023.

ARAÚJO, C. S. P.; ALMEIDA, C. D. G. C.; LOPES, P. M. O.; SOUZA, W. M.; SILVA, L. M. C.; SILVA, M. R. B. 2021. Normal and Sequential Climatological Water Balance for the Municipality of Palmares-PE by ERA5-land Reanalysis. **VII Inovagri Meeting Virtual.** Available at: <https://www.researchgate.net/publication/358988148>. Accessed on: 02.nov.2023.

ARAÚJO, M. A.; SOUZA, J. L. M.; TSUKAHARA, R. Y. 2011. Modelos agro-meteorológicos na estimativa da produtividade da cultura da soja na região de Ponta Grossa, Estado do Paraná. **Acta Scientiarum. Agronomy.** Maringá, v.33, n.1, p.23-31. Available at: <https://10.4025/actasciagron.v33i1.5062> Accessed on: 02.nov.2023.

BERKA, L. M. S.; RUDORFF, B. F. T. 2003. Estimativa de área plantada com soja através de imagens Landsat em municípios do norte do Paraná. **Anais XI do Simpósio Brasileiro de Sensoriamento Remoto (SBSR).** São José dos Campos, INPE, p.27-31. Available at: <http://marte.sid.inpe.br/attachment.cgi/ltid.inpe.br/sbsr/2002/11.18.18.36/doc/01_469.pdf>. Accessed on: 03.nov.2023.

CAMARGO, A. P., SENTELHAS, P. C. 1997. Avaliação do desempenho de diferentes métodos de estimativa da evapotranspiração potêncial no estado de São Paulo, Brasil. **Revista Brasileira de Agrometeorologia.** Santa Maria, v.5, n.1, p.89-97. Available at: <http://www.leb.esalq.usp.br/agmfacil/artigos/artigos_sentelhas_1997/1997_RBAgro_5(1)_89-97_ETPM%E9todosSP.pdf>. Accessed on: 17.nov.2023.

CAMARGO, M. B. P.; BRUNINI, O.; MIRANDA, M. A. C. 1986. Modelo agrometeorológico para estimativa da produtividade para a cultura da soja no Estado de São Paulo. **Bragantia.** v.45, n.2, p.279–292. Available at: <https://doi.org/10.1590/S0006-87051986000200007>. Accessed on: 17.nov.2023.

CARVALHO, L. G. de; SEDIYAMA, G. C.; CECON, P. R.; ALVES, H. M. R. 2005. Aplicação da Análise Harmônica por Séries de Fourier para a Previsão de Produtividade da Cultura do Café no Estado de Minas Gerais. **Engenharia Agrícola**, v.25, p.732-741. Available at: < https://doi.org/10.1590/S0100-69162005000300019>. Accessed on: 03.nov.2023.

CEPEA/ESALQ/USP, Centro de Estudos Avançados em Economia Aplicada. 2023. **Pib do Agronegócio Brasileiro**. Available at: <https://www.cepea.esalq.usp.br/br/pib-do-agronegociobrasileiro.aspx>. Accessed on: 02.nov.2023.

CONAB, Companhia Nacional de Abastecimento. 2023. **Safras.** Available at: <https://www.conab.gov.br/info-agro/safras>. Accessed on: 02.nov.2023.

COPERNICUS CLIMATE CHANGE SERVICE. **European Center for Medium-Range Weather Forecast**: ECMWF Reanalysis v5 (ERA5). Available at: <https://www.ecmwf.int/en/forecasts/datasets/browse-reanalysis-datasets>. Accessed on: 10.nov.2023.

CRESTANI MOTA, M.; ANTONIO CANDIDO, L.; VIANNA CUADRA, S.; ANTONIO MARENCO, R.; MAITO TOMÉ, A.; BACK DE ANDRADE LOPES, A.; LOPES DE LIMA, F.; REIS, J.; MORBEQUE BRIZOLLA, R. 2024. CROPGRO-soybean model – Validation and application for the southern Amazon, Brazil. Computers and Electronics in Agriculture. **Computers and Electronics in Agriculture.** v.216, n.108478. Available at: <https://doi.org/10.1016/j.compag.2023.108478>. Accessed on: 14.jan.2024.

DOORENBOS, J.; KASSAM, A. H. 1979. Yield response to water. Rome: FAO. 197p.

EROS - Earth Resources Observation and Science Center. 2017. Global 30 Arc-Second Elevation (GTOPO30). U.S. Geological Survey. Available at: <https://doi.org/10.5066/F7DF6PQS>. Accessed on: 15.oct.2023.

FONTANA, D. C., BERLATO, M. A. 1998. Modelo agrometeorológico-espectral para a estimativa do rendimento de soja no Rio Grande do Sul: um estudo preliminar. **Anais IX Simpósio Brasileiro de Sensoriamento Remoto (SBSR).** Santos, INPE, p.17-24. Available at: <http://marte.sid.inpe.br/col/sid.inpe.br/deise/1999/02.08.09.35/doc/3_150o.pdf>. Accessed on: 18.nov.2023.

HUFFMAN, G. J.; STOCKER, E. F.; BOLVIN, D. T.; NELKIN, E. J.; TAN, J. 2019. GPM IMERG Late Precipitation L3 1 day 0.1 degree x 0.1 degree V06. **Goddard Earth Sciences Data and Information Services Center (GES DISC).** Available at: <https://doi.org/10.5067/gpm/imergdl/day/06>. Accessed on: 10.nov.2023

IBGE, Instituto Brasileiro de Geografia e Estatística. 2023. **Produção agrícola – lavoura temporária.** IBGE. Available at: <https://cidades.ibge.gov.br/brasil/ro/dor=10370&ano=2022&localidade1=110092>. Accessed on: 02.nov.2023.

INMET, Instituto Nacional de Meteorologia. 2023. **Mapas.** Available at: <https://mapas.inmet.gov.br/>. Accessed on: 02.nov.2023.

LEITE-FILHO, A. T.; SOARES-FILHO, B. S.; DAVIS, J. L.; ABRAHÃO, G. M.; BÖRNER, J. 2021. Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. **Nature Communications.** v.12, n.2591, p.1-7. Available at: <https://doi.org/10.1038/s41467-021-22840-7>. Accessed on: 02.dec.2023

MONTEIRO, J. E. B. A. (org.). 2009. **Agrometeorologia dos cultivos: o fator meteorológico na produção agrícola**. Brasília: INMET, 2009. 530 p. Available at: <https://www.embrapa.br/documents/1355291/37056285/Bases+climatol%C3%B3gicas_G.R.CUNHA_Livro_Agrometeorologia+dos+cultivos.pdf/13d616f5-cbd1-7261-b157-351eaa31188d?version=1.0>. Accessed on: 02.nov.2023.

MORAES, A. V. C.; CAMARGO, M. B. P.; MASCARENHAS, H. A. A.; MIRANDA, M. A. C.; PEREIRA, J. C. V. N. A. 1998. Teste e Análise de Modelos Agrometeorológicos de Estimativa de Produtividade para a Cultura da Soja na Região de Ribeirão Preto. **Bragantia**, v.57, p.393-406. Available at: <https://doi.org/10.1590/S0006-87051998000200021>. Accessed on: 15.oct.2023.

MOTA, M. C.; RIZZI, R.; HÄRTER, F. P.; DAMÉ, R. C. F. 2019. Precipitações Estimadas pela Missão TRMM e Observadas em Superfície no Estado do Rio Grande do Sul. **Revista Engenharia na Agricultura**. v.27, n.3, p.237-247. Available at: <https://doi.org/10.13083/reveng.v27i3.890>. Accessed on: 02.nov.2023.

MUÑOZ SABATER, J. 2019. ERA5-Land hourly data from 1950 to present. **Copernicus Climate Change Service (C3S)/Climate Data Store (CDS).** Available at: <https://cds.climate.

DOI: 10.37856/bja.v99i2.4356

copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=overview>. Accessed on: 17.nov.2023.

OLIVEIRA JUNIOR, A; CASTRO, C.; PEREIRA, L. R.; DOMINGOS, C. S. 2016. **Estádios fenológicos e marcha de absorção de nutrientes da soja.** Folders, Embrapa Soja. Available at: <https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1047123/estadios-fenologicos-e-marcha-de-absorcao-de-nutrientes-da-soja>. Accessed on: 17.nov.2023.

RIZZI, R., RUDORFF, B. 2005. Estimativa da área plantada com soja no Rio Grande do Sul por meio de imagens Landsat. **Revista Brasileira de Cartografia.** v.3, n.57, p.226-234. Available at: <https://doi.org/10.14393/rbcv57n3-43538>. Accessed on: 17.nov.2023.

ROJAS, O., REMBOLD, F., ROYER, A.; NEGRE, T. 2005. Real-time agrometeorological crop yield monitoring in Eastern Africa. **Agronomie.** v.25, v.1-15, p.63-77. Available at: <https://doi.org/hal.science/hal-00886252>. Accessed on: 17.nov.2023.

SILVA, M. J. G.; SARAIVA, F. A. M.; SILVA, A. A. G.; SANTOS NETO, L. A.; QUERINO, C. A. S. 2015. Clima. In: MARCALAN, A. L.; ESPÍNDULA, M. C. (ed.). **Café na Amazônia.** Brasília, EMBRAPA. p.41-54. Available at: <https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1023755/cafe-na-amazonia>. Accessed on: 17.nov.2023.

SILVA-FUZZO, D. F.; PRELA-PANTANO, A.; CAMARGO, M. B. P. 2015. Modelagem agrometeorológica para estimativa de produtividade de soja para o Vale do Médio Paranapanema-SP. **Irriga.** v.20, n.3, p.490-501. Available at: <https://doi.org/10.15809/irriga.2015v20n3p490>. Accessed on: 19.nov.2023.

THORNTHWAITE, C. W.; MATHER, J. R. 1955. The water balance. In: CENTERTON, N. J. (ed.). **Drexel Institute of Technology - Laboratory of Climatology.** Publications in Climatology. 104p.

WILLMOTT, C. J.; CKLESON, S. G.; DAVIS, R. E.; FEDDEMA, J. J.; KLINK, K. M.; LEGATES, D. R.; O'DONNELL, J.; ROWE, C. M. 1985. Statistics for evaluation and comparison of models. **Journal of Geophysical Research**, v.90, n.C5. p.8995-9005. Available at: <https://doi.org/10.1029/JC090iC05p08995>. Accessed on: 02.nov.2023.

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