

Stochastic methodology for estimation of the potential and depleted yield in corn

Metodologia estocástica na estimativa da produtividade potencial e deplecionada da cultura do milho

Metodología estocástica para estimar la productividad potencial y agotada de cultivos de maíz

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ABSTRACT

The objective of this research was to compare four methodologies of parameters simulation used in the corn potential and depleted yield in Rio Grande do Sul State. Had been used the daily mean air temperature, insolation and rain precipitation of sixteen localities of the Rio Grande do Sul State, as changeable of entrance in the modified model of the agroecological zone considered by De Wit. The data base was formed by 100 simulated values of the variable in each one of the eighth dates proposals (01/oct, 11/oct, 21/oct, 01/nov, 11/nov, 21/nov, 01/dec and 11/dec). The data had been through four cases of simulation: (i) average insolation and temperature (normal truncated); (ii) average insolation and temperature (triangular non-symmetrical); (iii) average insolation and temperature (triangular symmetrical) e (IV) insolation (triangular symmetrical). To verify was that: (i) the adaptation of the method (considered for De Wit) of the agroecological zone makes possible to define the order of magnitude of the maize potential and depleted productivities, in Rio Grande do Sul State; (ii) the random procedure process an in agreement variability time of sowing and evaluated place; (iii) the procedure (b) average insolation and temperature (triangular anti-symmetrical) and (d) insolation (triangular symmetrical) does not divergem how much the classification, being that the last one overestimates the values of potential and depleted productivity.

Keywords: Probability Distribution. Agroecological Zone. Simulation. Productivity

RESUMO

O objetivo dessa pesquisa foi comparar quatro metodologias de simulação de parâmetros utilizados na estimação da produtividade potencial e deplecionada da cultura do milho no Estado do Rio Grande do Sul por meio do modelo modificado da zona agroecológica proposto por De Wit. Utilizaram-se os dados de temperatura média do ar, insolação e precipitação pluvial de dezesseis localidades do Es-

tado do Rio Grande do Sul. O banco de dados foi formado por 100 valores simulados das variáveis em cada uma das oito datas propostas (01/out, 11/out, 21/out, 01/nov, 11/nov, 21/nov, 01/dez e 11/dez). Os dados foram obtidos por meio de quatro casos de simulação: (a) insolação média e temperatura (normal truncada); (b) insolação média e temperatura (triangular assimétrica); (c) insolação média e temperatura (triangular simétrica) e (d) insolação (triangular simétrica). Verificou-se que: (i) a adaptação do método (proposto por De Wit) da zona agroecológica possibilita definir a ordem de grandeza das produtividades potencial e deplecionada da cultura de milho, no Estado do Rio Grande do Sul; (ii) o procedimento estocástico possui uma variabilidade conforme época de semeadura e local avaliado; (iii) o procedimento (b) insolação média e temperatura (triangular assimétrica) e (d) insolação (triangular simétrica) não divergem quanto à classificação, sendo que o último superestima os valores de produtividade potencial e deplecionada.

Palavras-chave: Distribuições de Probabilidade. Zona Agroecológica. Simulação. Produtividade.

RESUMEN

El objetivo de esta investigación fue comparar cuatro metodologías de simulación de parámetros utilizados para estimar la productividad potencial y agotada de cultivos de maíz en el Estado de Rio Grande do Sul a través del modelo modificado de zona agroecológica propuesto por De Wit. Se utilizaron datos de temperatura media del aire, insolación y precipitaciones de dieciséis localidades del Estado de Rio Grande do Sul. La base de datos estuvo formada por 100 valores simulados de las variables en cada una de las ocho fechas propuestas (01/Oct, 11/Oct, 21/Oct, 01/Nov, 11/Nov, 21/Nov, 01/Dic y 11/Dic). Los datos se obtuvieron a través de cuatro casos de simulación: (a) insolación y temperatura promedio (normal truncada); (b) insolación y temperatura promedio (triangular asimétrico); (c) insolación y temperatura promedio (triangular simétrico) y (d) insolación (triangular simétrico). Se encontró que: (i) la adaptación del método (propuesto por De Wit) a la zona agroecológica permite definir el orden de magnitud de la productividad potencial y agotada de los cultivos de maíz en el Estado de Rio Grande do Sul; (ii) el procedimiento estocástico tiene variabilidad dependiendo del momento de siembra y lugar evaluado; (iii) el procedimiento (b) insolación y temperatura promedio (triangular asimétrico) y (d) insolación (triangular simétrico) no difieren en términos de clasificación, sobreestimando este último los valores de productividad potencial y agotada.

Palabras clave: Distribución de Probabilidad. Zona Agroecológica. Simulación. Productividad

1 INTRODUCTION

Modeling techniques for estimating grain yield are useful in reducing costs, in the agricultural planning of a region, in addition to providing a better understanding of the determinants of grain yield. Among the sciences that interact with the modeling of agricultural productivity, plant physiology, agrometeorology and statistics should be mentioned. These sciences are fundamental for understanding the mechanisms of energy interception from the environment, assimilation and its conversion to dry phytomass. However, as environmental variations are large, this must be considered using data simulation techniques that describe the behavior of environmental parameters. Water and temperature were found to be the most important constraints on biophysical limits (Andrea *et al.*, 2018).

When the probability levels of an event are not considered, a deterministic model of grain yield estimation is used. The advantages of estimation through this type of model are the speed of the calculations performed, the simplicity of testing the proposed model and the reduced number of variables and input parameters that are required (compared to the stochastic method). The stochastic model, on the other hand, needs a historical series of input data, or the opinion of the “expert”, to provide the minimum parameters for the supply of data for the functioning of the model. In this case, the conclusions will have more technical-scientific support due to the number of simulations allowing the most diverse conditions by means of the confidence level. The growth simulation models and crop yield forecast allow long-term simulations to be carried out at a low cost, using soil characteristics and crop management practices during the period of historical climatological data available for a given location. The performance of models based on estimating solar radiation in large databases (AgCFSR, AgMERRA, NASA/POWER and XAVIER) are options for filling gaps in historical series (Bender; Sentelhas, 2018). In addition, the use of mathematical models can also estimate the best sowing times for corn-soybean successions, as presented by Nóia Júnior and Sentelhas (Nóia Júnior; Sentelhas, 2019). Além disso, alguns modelos de estimação de produtividade também consideram itens como as variações climáticas, interações

com microrganismos benéficos e o melhoramento genético (Razzaq *et al.*, 2021).

The steps for creating and/or adapting a model to certain environmental conditions are: model development, verification of the logic involved, calibration or adjustment of parameters and validation. Oreskes *et al.* (1994) proposed invalidating a model, but never “making it valid”. The model is considered to be a scientific theory and, as such, can be falsified, but never validated. From this, the last author proposes the use of the term “test of the model”, instead of “validation of the model”. The expolinear model of crop growth to predict changes in growth of soybean cultivars when subjected to water deficit at different phenological stages with good results (Confalone *et al.*, 2010). For the soybean crop, more complex models were used taking into account the soybean leaf area, with corrections for temperature, shading, senescence, CO², biomass partitioning, as well as the methods of simulating the climate variables of the “input” for the model. Mathematical models for predicting productivity are increasingly complex and globalized. With the addition of several variables and increasingly large databases, it is possible to model large-scale systems (Schweiger *et al.*, 2020).

The water balance was used to estimate the depleted yields (Martin *et al.*, 2012). The use of series of climatic data is frequent in the estimation of productivity, however, it is often not possible to obtain a long series of data that is representative of the reality of a place, thus, some inferences are impaired. The possibility of using some resources such as data simulation through the normal distribution (requires a long series), symmetric triangular distribution (minimum, maximum and mean) and asymmetric triangular distribution (minimum, maximum and mode), are little studied as possibilities making inferences about locations without a complete data series. Just as it is important to study climate variations in extreme events such as those that occur due to the presence of the El Niño Southern Oscillation (Nóia Júnior; Sentelhas, 2019).

The purpose of this research is to compare four methodologies of simulation of parameters used in the estimation of the potential and depleted productivity of the corn crop using meteorological data from the State of Rio Grande do Sul through the modified model of the agroecological zone proposed by De Wit.

2 METHODOLOGY

Data on temperature, insolation, solar radiation and rain were used, referring to sixteen municipalities in the State of Rio Grande do Sul. The data were obtained from FEPAGRO/RS (State Foundation for Agricultural Research, Rio Grande do Sul) and INMET/RS (National Institute of Meteorology, Rio Grande do Sul). The data collection stations are located in the following municipalities: Cruz Alta, Erechim, Irai, Júlio de Castilhos, Passo Fundo, Santa Maria, Santa Rosa, São Luiz Gonzaga, Taquari, Vacaria, Veranópolis, Caxias do Sul, Maquine, São Borja, São Gabriel and Uruguaiana.

Based on the relations between agroclimatic data and the conversion of solar energy that results in the production of dry matter phytomass, the model by Wit (1965) was adapted to estimate the productivity of the corn crop, through a mechanistic-deterministic model, as sequence as equations. For the calculation of the temperature correction factors, it is necessary that:

$$cTn_j = n_0 + n_1.T_j + n_2.T_j^2 \quad (1)$$

$$cTc_j = c_0 + c_1.T_j + c_2.T_j^2 \quad (2)$$

where n_0 , n_1 and n_2 and c_0 , c_1 and c_2 refer to the empirical parameters, being, (i) when the temperature is higher than 16.5°C: $n_0 = -4.16$; $n_1 = 0.4325^\circ\text{C}^{-1}$; and $n_2 = -0.00725^\circ\text{C}^{-2}$ and $c_0 = -9.32$; $c_1 = 0.865^\circ\text{C}^{-1}$; and $c_2 = -0.0145^\circ\text{C}^{-2}$ and (ii) when the temperature is less than or equal to 16.5°C: $n_0 = -1.064$; $n_1 = 0.173^\circ\text{C}^{-1}$; and $n_2 = -0.0029^\circ\text{C}^{-2}$ and $c_0 = -4.16$; $c_1 = 0.4325^\circ\text{C}^{-1}$; and $c_2 = -0.00725^\circ\text{C}^{-2}$. The average insolation (n_j , h d⁻¹) can thus be calculated:

$$n_j = \frac{n_{\min_j} + n_{\max_j}}{2} \quad (3)$$

where n_{min_j} and n_{max_j} refer to the minimum and maximum values, respectively, and insolation ($h\ d^{-1}$) on the median day of the j th ten-day period. The leaf area index (LAI_j , $m^2\ m^{-2}$) can thus be calculated:

$$IAF_j = \alpha_0\ Dr_j^3 + \alpha_1\ Dr_j^2 + \alpha_2\ Dr_j \quad (4)$$

where α_0 , α_1 , and α_2 refer to empirical parameters determined in regression analysis based on data obtained from Figueredo Júnior (2005), where $\alpha_0 = -27.139\ m^2\ m^{-2}$; $\alpha_1 = 25.999\ m^2\ m^{-2}$; and $\alpha_2 = 3.1745\ m^2\ m^{-2}$. The correction referring to the leaf area index ($cIAF$) can be calculated as follows:

$$cIAF_j = b_0 + b_1\ IAF_j - b_2\ IAF_j^2 \quad (5)$$

where b_0 , b_1 and b_2 refer to the empirical parameters, where $b_0 = 0.0093$; $b_1 = 0.185\ m^2\ m^{-2}$; and $b_2 = 0.0175\ m^4\ m^{-4}$.

As for the correction for maintenance and growth respiration, the dry matter consumed in the maintenance and growth respiration process throughout the crop cycle depends mainly on the average air temperature (T , $^{\circ}C$), with the correction (cR) being used to estimate the relative balance (ratio between net photosynthesis and gross photosynthesis) which can be expressed by:

$$cR = 0,5; \text{ if } T_j > 20 \quad (6)$$

$$cR = 0,6; \text{ if } T_j \leq 20 \quad (7)$$

A produtividade potencial bruta diária pode assim ser calculada:

$$PPBc_j = (107,2 + 0,36.Qo_j) \cdot \frac{n_j}{H_j} \cdot cTc_j \cdot cIAF_j \cdot cR_j \cdot D_j \quad (8)$$

$$PPBn_j = (31,7 + 0,219.Qo_j) \cdot \left(1 - \frac{n_j}{H_j}\right) \cdot cTn_j \cdot cIAF_j \cdot cR_j \cdot D_j \quad (9)$$

where PPB_{cj} and PPB_{nj} refer to the daily gross potential productivity corresponding to clear and cloudy days, respectively; Q_{oj} to extraterrestrial radiation; n_j to insolation (h d⁻¹); H_j to photoperiod; cT_{cj} and cT_{nj} to the correction factors corresponding to clear and cloudy days, respectively; cIAF_j to the correction referring to the leaf area index; cR_j to the correction referring to breathing on the average day of the jth ten-day period and D_j to the duration (days) of the j-th ten-day period. Based on the concept of Wit (1965), designed to estimate the potential productivity of the corn crop through the energy available in the considered location, we have that:

$$PPB_j = PPB_{c_j} + PPB_{n_j} \quad (10)$$

$$PPB_{ac_f} = \sum_{j=1}^f PPB_j \quad (11)$$

where PPB_j refers to the potential productivity (kg ha⁻¹) that occurs in the jth ten-day period; and PPB_{acf} to the gross potential yield accumulated up to the point of physiological maturity (kg ha⁻¹) of the maize crop.

It refers to the fraction of dry matter of the organ of interest (usually grains) harvested in relation to the total dry matter produced, which is obtained based on experimental data. According to data reported in the literature (Doorenbos; Kassam, 2000; Lima, 1995; Gadioli, 1999; Barros, 1998; Sá, 2011), the harvest index for maize (grains) ranges from 0.35 to 0.65, with a value of 0.55, considered satisfactory for obtaining high productivity. To calculate potential productivity (PP, kg ha⁻¹), we have:

$$cW = \frac{100}{100 - u} \quad (12)$$

$$PP = PPBaC_f . IC . cW \quad (13)$$

where u refers to the water content (%) in the botanical seed ($u = 13\%$); IC to the harvest index ($IC = 0.55 \text{ kg kg}^{-1}$) and cW to the correction factor referring to the water content in the seed.

To prepare the cyclical water balance, the procedure proposed by Thornthwaite and Mather (1955) was adopted, which allows estimating the storage of water in the soil in all ten days of the year. For this purpose, a constant and unitary crop coefficient ($K_c = 1$) and effective root system depth constant and equal to 40 cm (Z_e , cm) are used for any distribution of available climatological data. The choice of this procedure was based on results obtained by Camargo and Sentelhas (1995), which demonstrated its feasibility of use for the conditions of the State of São Paulo.

To prepare the sequential water balance, the procedure proposed by Thornthwaite and Mather (1955), which allows for a variation in the crop coefficient (K_c). ET_p was calculated using the following equation proposed by Thornthwaite and Mather (1955). The crop evapotranspiration of the crop is estimated by multiplying the potential evapotranspiration (ET_{pj} , $\text{mm ten}^{-\text{day}^{-1}}$) by the crop evapotranspiration coefficient (K_{cj}) in the j th ten-day period, that is:

$$ET_{c_j} = K_{c_j} . ET_{p_j} \quad (14)$$

where K_{cj} is obtained in the literature through tabulated values according to the phenological stage of the crop: (i) $K_{cj} = 0.40$ (if $0.00 \leq Dr_j < 0.24$); (ii) $K_{cj} = 0.80$ (if $0.24 \leq Dr_j < 0.50$); (iii) $K_{cj} = 1.15$ (if $0.50 \leq Dr_j < 0.61$); (iv) $K_{cj} = 0.80$ (if $0.61 \leq Dr_j < 0.74$); and (v) $K_{cj} = 0.50$ ($Dr_j \geq 0.74$).

The productivity depletion caused by soil water deficiency is calculated by the ratio between actual evapotranspiration (ET_r , mm day⁻¹) and crop evapotranspiration (ET_c , mm day⁻¹) in three different phases of the cycle:

$$rET_1 = \frac{\sum_{j=1}^k ET_{r,j,1}}{\sum_{j=1}^k ET_{c,j,1}} ; \text{ if } 0 \leq Dr_j < 0,5 \quad (15)$$

$$rET_2 = \frac{\sum_{j=k+1}^m ET_{r,j,2}}{\sum_{j=k+1}^m ET_{c,j,2}} ; \text{ if } 0,5 \leq Dr_j < 0,74 \quad (16)$$

$$rET_3 = \frac{\sum_{j=m+1}^q ET_{r,j,3}}{\sum_{j=m+1}^q ET_{c,j,3}} ; \text{ if } Dr_j \geq 0,74 \quad (17)$$

$$Fd_1 = 1 - ky_1 \cdot (1 - rET_1) ;$$

$$\text{if } 0 \leq Dr_j < 0,5 \quad (18)$$

$$Fd_2 = 1 - ky_2 \cdot (1 - rET_2) ;$$

$$\text{if } 0,5 \leq Dr_j < 0,74 \quad (19)$$

$$Fd_3 = 1 - ky_3 \cdot (1 - rET_3) ;$$

$$\text{if } Dr_j \geq 0,74 \quad (20)$$

$$Fd = \prod_{d=1}^3 F_d \quad (21)$$

where $rET1$, $rET2$ and $rET3$ refer to the relationship between actual evapotranspiration (ET_r , mm day^{-1}) and crop evapotranspiration (ET_c , mm day^{-1}); $Fd1$, $Fd2$ and $Fd3$ to potential productivity depletion factors based on water balance and $Ky1$, $Ky2$ and $Ky3$ to water deficiency sensitivity factors referring to phases 1 ($0 \leq Dr < 0.5$) ($ky1 = 0.2$), 2 ($0.5 \leq Dr < 0.74$) ($ky1 = 0.8$) and 3 ($Dr \geq 0.74$) ($ky1 = 1.0$), respectively. The depleted yield (PD , kg ha^{-1}) of maize grains is estimated by:

$$PD = PP.Fd \quad (22)$$

where PP refers to the potential productivity (kg ha^{-1}) estimated by the model and Fd to the productivity depletion factor obtained as a function of the water balance.

The database consisted of 100 simulated values of the variables on each of the eight proposed dates (Oct 1, Oct 11, Oct 21, Nov 01, Nov 11, Nov 21, Dec 1 and Aug 11). ten). The simulation was carried out through four cases, namely: (a) mean insolation and temperature (truncated normal); (b) average insolation and temperature (asymmetrical triangle); (c) mean insolation and temperature (symmetrical triangle) and (d) insolation (symmetrical triangle).

The triangular probability distribution is used in cases where it is possible to determine the most likely value of the random variable, the minimum and maximum values, and when a linear function seems appropriate for describing the distribution of error values of the variables. In such cases, the triangular distribution can be used, which is a good model between the normal and uniform distributions. According to Bressan (2002), the area under the curve of the normal distribution, in the mean interval minus one standard deviation to the mean plus one standard deviation, corresponds to 0.6827. The areas under the curves of the triangular and rectangular (or uniform) distributions are, respectively, 0.64983 and 0.57735, considering the same interval. This probability density distribution is often used when the objective is to obtain an approximation in the absence of data. This allows us to adjust a more adequate distribution, or when we only know the most probable (m), minimum (a) and maximum (b) values of the variable, but not much is known

about the empirical distribution of the data. For the symmetric triangular distribution, the parameters are the mean, maximum and minimum values.

The generated data were compared by means of the three-factor analysis of variance (sowing dates x simulation cases x locations) through the Duncan test, using the SAS® software (1997).

3 RESULTS AND DISCUSSIONS

From the observed results, it appears that the 100 simulations for each of the sampling cases of temperature and insolation values, resulted in a variation of a maximum of 319 kg ha⁻¹ for potential productivity and 846 kg ha⁻¹ for depleted productivity, in the four forms of sampling evaluated (Table 1, 2 and 3).

Table 1. Potential (PP, kg ha⁻¹) and depleted (PD, kg ha⁻¹) productivity, minimum, maximum, mean and 90% probability values for selected locations and dates.

		mean and 90% probability values for selected locations and dates:															
Case A		Cruz Alta		Iraí		Maquiné		Santa Maria		São Borja		São L.Gonzaga		Uruguaiana		Veranópolis	
Date	Statistical	PP	PD	PP	PD	PP	PD	PP	PD	PP	PD	PP	PD	PP	PD	PP	PD
1/out	Maximum	14613	9887	14089	13184	14950	10946	14578	9267	14645	12865	14371	13303	14456	9061	15113	13576
	Minimum	13080	37	12792	1095	13172	35	12688	0	12734	84	12636	2152	12455	17	13397	2309
	Mean	14088	3898	13665	8308	14010	6953	13633	4204	13751	6598	13497	8405	13613	4017	14266	7727
	90%	13583	1119	12965	4541	13447	1610	13124	1367	13189	2077	12786	4066	13121	1251	13690	2470
21/out	Maximum	14730	7349	14224	13077	14680	13345	14734	9901	14358	12431	14286	13403	14512	10754	15000	13346
	Minimum	13185	56	12869	540	13133	36	12882	178	12719	54	12841	2417	12815	23	13509	1945
	Mean	14040	3471	13976	8507	14079	8311	13761	4986	13609	6490	13777	8319	13660	4747	14235	7847
	90%	13546	1565	13780	4278	13513	3023	13145	2031	13052	2155	13408	4968	13125	1366	13867	2886
11/nov	Maximum	14694	10978	14355	13887	14969	13694	14450	11334	14245	13092	14265	13070	14403	11350	14871	12566
	Minimum	13335	643	13055	1521	13152	972	12585	137	12755	1	12696	948	12648	828	13374	1497
	Mean	14022	4429	13626	8314	14027	8354	13796	5867	13752	5930	13639	7566	13725	5705	14228	7300
	90%	13564	2069	13152	4073	13586	2062	13233	2215	13266	1913	13034	3509	13016	1529	13856	2805
1/dez	Maximum	14585	12288	14233	13359	14741	13913	14549	12936	14223	13180	14336	13011	14518	13700	14843	13150
	Minimum	13126	771	12936	2166	13010	2626	12641	97	12799	130	12726	1327	12447	498	13410	1374
	Mean	13994	7598	13376	9364	13750	10039	13707	8123	13610	6168	13528	7375	13747	8023	13998	8305
	90%	13430	1549	13041	6875	13292	2841	13059	3799	13001	1573	13026	3833	13107	2137	13677	4043
Case B		Cruz Alta		Iraí		Maquiné		Santa Maria		São Borja		São L.Gonzaga		Uruguaiana		Veranópolis	
1/out	Maximum	14659	7656	14119	12962	14776	13758	14498	10683	14487	12855	14758	13625	14439	11714	15130	13795
	Minimum	13177	46	12905	686	13257	43	13032	0	12924	88	12895	1723	13046	23	13379	1846
	Mean	14195	3164	14029	8051	14216	8276	13555	4332	13543	6463	13905	8457	13599	4406	14509	7759
	90%	13904	979	13996	3736	13545	915	13239	1217	13205	1795	13627	3562	13321	1053	14005	1942
21/out	Maximum	14690	8907	14160	13110	14649	13282	14455	10004	14362	12938	14632	12971	14336	9769	15010	13432
	Minimum	13526	26	13890	1332	13675	711	13077	389	12958	25	13144	2509	12975	636	13664	402
	Mean	14007	3907	14033	8193	14225	9067	13645	4909	13513	6093	13837	8237	13537	4600	14211	7522
	90%	13691	2076	13967	3922	13994	3939	13244	1706	13083	1433	13354	3856	13254	1895	13887	2730
11/nov	Maximum	14479	11347	14277	13061	14664	13444	14250	11519	14186	12948	14288	12984	14232	11386	14800	12721
	Minimum	13606	778	13114	1554	13332	1072	13547	134	13636	1	13002	909	12936	980	13572	1802

	Mean	14112	4488	13425	7992	14083	8306	13968	5907	13945	5960	13827	7627	13958	5563	14155	7324
	90%	13838	1836	13162	4261	13462	2443	13786	2243	13745	2205	13319	3604	13783	1571	13842	2761
1/dez	Maximum	14472	12518	14144	12341	14301	13639	14197	13115	14202	13113	14239	12660	14360	13381	14439	13270
	Minimum	13439	994	12985	2308	13076	2520	13102	101	12964	179	12920	1385	13024	615	13428	1398
	Mean	14050	7601	13150	9177	13573	9908	13871	8167	13911	6418	13796	7623	13971	8157	13920	8559
	90%	13803	1647	13070	6430	13250	2931	13674	4262	13761	1626	13228	3823	13816	2160	13667	5054

Source: Authors, 2025.

Table 2. Potential (PP, kg ha⁻¹) and depleted (PD, kg ha⁻¹) productivity, minimum, maximum, mean and 90% probability values for selected locations and dates.

mean and 90% probability values for selected locations and dates.																		
Case C		Cruz Alta		Iraí		Maquiné		Santa Maria		Santa Rosa		São Gabriel		Taquari		Vacaria		
Date	Statistical	PP	PD	PP	PD	PP	PD	PP	PD	PP	PD	PP	PD	PP	PD	PP	PD	
1/out	Maximum	14693	10096	14114	13731	11528	8103	3414	324	9133	14156	13353	14989	13031	14534	8543	15046	13945
	Minimum	13042	251	12877	1366	12823	38	12905	230	12699	53	12987	1045	12684	44	13222	1369	
	Mean	14009	4203	13945	9066	13988	6857	13594	3688	13518	6739	14201	7816	13548	4205	14337	8985	
	90%	13373	1282	13902	4929	13414	3065	13130	1078	12888	278	13635	3628	13202	1521	13779	3610	
21/out	Maximum	14683	8728	14230	13823	14651	13430	14498	9275	14567	13608	15066	12657	14486	10204	15127	13456	
	Minimum	13190	68	13667	1714	13200	16	12828	1192	12689	53	13329	1125	12755	166	13672	1900	
	Mean	14032	4227	13993	8721	14067	9279	13698	4466	13829	6715	14297	7502	13636	4505	14501	8628	
	90%	13551	1667	13869	3840	13510	3845	13210	1869	13378	1226	13858	3698	13218	1978	14022	3819	
11/nov	Maximum	14615	11798	14332	13051	11481	19136	2014	3701	10524	14430	14083	15043	13395	14303	10733	14995	13029
	Minimum	13325	893	13101	1760	13022	0	13010	519	12844	503	13425	1570	12768	27	13352	2101	
	Mean	14012	5409	13615	8592	13995	9040	13924	5582	13896	6751	14253	7328	13794	5532	14263	8085	
	90%	13675	2303	13161	4779	13463	5192	13373	2539	13271	1895	13793	3034	13044	1659	13843	3629	
1/dez	Maximum	14679	11819	14221	13639	14749	14154	14336	12732	14551	13234	14804	12932	14141	11240	5146	2912	686
	Minimum	13338	2084	12936	4633	12863	1883	12963	1885	12981	162	13233	107	12720	100	12559	461	
	Mean	14007	7650	13481	8722	13701	9806	13807	8276	13865	7173	14000	7277	13609	6727	13701	7966	
	90%	13652	3938	13050	5019	13219	6945	13391	4967	13479	1680	13541	3180	13017	2799	13247	4105	
Case D		Cruz Alta		Iraí		Maquiné		Santa Maria		Santa Rosa		São Gabriel		Taquari		Vacaria		
1/out	Maximum	15156	9201	15361	14614	14249	12592	15506	9841	16128	14221	16526	15792	16966	14213	16397	15289	
	Minimum	13217	36	13613	403	11565	1344	12002	1470	13300	168	13429	1046	13828	40	13818	3968	
	Mean	14151	4163	14464	9095	12805	8322	13696	5745	14673	6996	15196	10001	15282	6092	15279	9863	
	90%	13655	1261	14080	4261	12366	5252	12943	2068	14027	2676	14419	3724	14537	2029	14636	6026	
21/out	Maximum	15056	9726	15017	14420	14103	12713	15302	9237	16130	13135	16175	14650	16519	13256	16354	14619	
	Minimum	13021	63	13275	1632	11382	2085	11708	1345	12959	63	13046	412	13414	31	13771	3691	
	Mean	13979	4554	14063	8857	12642	9064	13518	6231	14449	7416	14903	10196	15023	6452	15012	9063	
	90%	13470	1783	13660	3532	12235	4298	12706	2758	13750	3161	14045	4606	14178	2877	14420	4079	
11/nov	Maximum	15312	10670	14931	13411	14332	12915	15413	10700	16218	14117	16625	15167	16856	14643	16403	12776	
	Minimum	13319	500	13288	2165	11641	1956	11843	2065	12911	30	12986	870	13476	652	13761	2537	
	Mean	14192	5498	14005	8804	12812	8858	13769	6629	14598	7115	15084	10311	15155	7703	15152	8564	
	90%	13634	1925	13544	3402	12356	4422	13010	3005	13955	2902	14248	5450	14319	1777	14560	4317	
1/dez	Maximum	15383	11958	14818	13158	14354	13392	15153	14003	15902	13739	16848	15531	16626	15322	16527	13259	
	Minimum	13436	42	13048	977	11814	4214	11816	2570	12729	282	12667	1512	13571	521	13875	538	
	Mean	14151	7066	13868	8075	12802	9306	13679	8433	14466	6930	15115	10704	15148	8636	15176	8449	
	90%	13605	3386	13520	1084	12387	6566	13035	4907	13901	1436	14253	7199	14237	2121	14469	3576	

Source: Authors, 2025.

Table 3. Comparison of averages for the main effects sowing date, stochastic methods and locations, for potential (PP, kg ha⁻¹) and depleted (PD, kg ha⁻¹) yield variables and PP/PD ratio.

Planting date	PP		PD		PP/PD
October 1st	14028.11	c	6274.52	h	2.24
October 11th	14145.02	a	6435.85	g	2.20
October 21st	14002.89	d	6726.79	f	2.08
November 1st	14042.37	b	6877.27	e	2.04
November 11th	14017.47	c	7029.02	d	1.99
November 21st	13949.21	e	7310.13	c	1.91
December 1st	13882.40	f	7550.26	b	1.84
December 11th	13254.88	g	7905.63	a	1.68
Stochastic Simulation	PP		PD		PP/PD
Mean insolation and temperature (truncated normal) (a)	13854.59	c	6729.49	d	2.06
Average insolation and temperature (asymmetrical triangle) (b)	13896.35	b	6940.15	b	2.00
Average insolation and temperature (symmetrical triangle) (c)	13800.87	d	6801.45	c	2.03
Insolation (symmetrical triangle) (d)	14119.72	a	7575.23	a	1.86
Localizations	PP		PD		PP/PD
Caxias do Sul	13913.1	e	8496.23	cb	1.64
Cruz Alta	14077.19	b	5316.26	l	2.65
Erechim	14079.72	b	6860.14	e	2.05
Irai	13713.67	h	8597.11	b	1.60
Júlio de Castilhos	13940.52	d	6666.28	f	2.09
Maquiné	13645.39	j	8964.79	a	1.52
Passo Fundo	13688.02	i	8846.73	a	1.55
Santa Maria	13742.4	g	6059.24	h	2.27
Santa Rosa	13786.81	f	8887.8	a	1.55
São Borja	13903.02	e	6667.23	f	2.09
São Gabriel	14385.68	a	3131.64	k	4.59
São Luiz Gonzaga	14029.72	c	8405.27	c	1.67
Taquari	13757.76	g	6212.61	g	2.21
Uruguaiana	14067.73	b	6120.21	hg	2.30
Vacaria	13526.8	k	4740.38	j	2.85
Veranópolis	14404.12	a	8071.41	d	1.78

Source: Authors, 2025.

Through the analysis of variance, it was verified that the triple interaction was significant, for the studies of sowing dates, simulation methods and studied places. However, in the study of the main effects, which concerns the methods of simulating temperature and insolation data, it is observed that the methods (b) average insolation and temperature (asymmetrical triangle) and (d) insolation (symmetrical triangle) presented the same ranking order (Duncan) for potential and depleted productivity. It is also verified that the method (d) insolation (symmetrical triangle) simulates both the potential and the depleted productivity the highest values of grain production. In contrast, the smallest average simulation of values for potential productivity is given by method (c) average insolation and

temperature (symmetrical triangle) and the smallest average for depleted productivity is given by method (a) average insolation and temperature (truncated normal). However, the different variations in the performance of the sampling cases do not follow a trend in all the evaluated cities, certainly due to the different behavior of the climatic conditions in the 16 evaluated locations.

The super-early cycle cultivars need 780-830 GD (degree-days), the early ones 831-890 GD and the normal one 890-1200 GD (20), however, in addition to the average daily temperature, it must - considering the photoperiod and insolation, as the reduction in the average number of light hours will result in a smaller amount of photosynthetically active radiation to carry out photosynthesis, consequently reducing the accumulation of carbohydrates. The reduction of direct solar radiation may occur due to cloudiness, but this often does not change the temperature, not affecting the accumulation of degree-days for flowering, but due to the reduced amount of photosynthetically active radiation, it leads to a reduction in photosynthesis gross, and consequently net photosynthesis, as maintenance respiration in the organs continues. Another case that should be closely observed in crop models is the fact that in the winter period in places like the Southeast there are days with high insolation, but the temperature tends to be reduced. However, this concept cannot be applied to the state of Rio Grande do Sul, which has well-defined seasons, with the winter period having the lowest temperature and lowest daily hours of sunlight. Due to this, it was determined that the sowing dates should start from October 1st, although in some years it is possible to carry out earlier sowings aiming at the second crop, but with greater risk of frost.

The main effect sowing date indicates a variability of 890 kg ha⁻¹ for potential productivity and 1631 kg ha⁻¹ for depleted productivity (Table 3), indicating that there is a great variability in the rainy season (rainy days and amounts) that reflects on depleted productivity. In practically all locations and sowing dates it is possible to verify values of depleted productivity very close to zero. This is due to the frequency and amount of rainfall in the proposed period being insufficient for the development of the crop. However, considering the average of the 100 simulations for the depleted productivity, it is noticed that the value obtained is slightly above the productivity verified in the state. By means of the average depleted productivity

curve, it can be seen that the sowing date varies for each locality according to local climatic availability. But, in general, it appears that the highest grain yields are obtained when sowing occurs on dates close to October 1st to November 1st for potential yield and from November 21st to December 11th for depleted yield. However, one should study the best sowing dates for each of the evaluated locations. The according with Andrea *et al.* (2018) the greater availability of water (first season), provides increased productivity, however greater and more variable yield gaps. Greater productivity gaps were verified where there is greater water availability and milder temperatures.

Considering the probability of occurrence of water deficit and the E_{tr}/E_{tp} ratio, for the corn crop, in different regions of the state of Rio Grande do Sul, Da Silva *et al.* (2010) concludes that with the density adjustment, the sowing time with the lowest risk to grain production due to water deficit for the corn crop is August and December. On the other hand, the corn production seasons with the highest risk are September and October. According to Table 2, it is verified that the depleted productivity is more than twice lower than the potential productivity in the period from October 1st to November 11th. The authors indicate that the locations that present the lowest risk to production are Passo Fundo and Veranópolis, and similar results were obtained in this study. Da Silva *et al.* (2006) aimed to evaluate the components of grain yield and shoot dry mass in corn. Among the results obtained, the authors concluded that it is possible to obtain high yields of irrigated corn by increasing plant density both in early and late sowings. In addition to aspects of agricultural zoning, cost reduction, the proposed model presents four types of simulation that can be used in the absence of data for one of the evaluated variables. The different types of data simulation serve in specific cases where there is not a complete historical data series. As a 30-year historical series is not always available for the most diverse climatic variables, resources that enable the solution of the problem of lack of data must be used. Each simulation methodology requires its own parameters, which can be the historical series (truncated normal), minimum, maximum and average values (symmetrical triangular distribution) and minimum, maximum and mode values (asymmetrical triangular distribution). In the case of regional planning, the stochastic simulation results become more useful

compared to the simulation given by a deterministic model. In addition, a database with historical gaps can be used using the Xavier grid to carry out projections and carry out climate change studies (Bender; Sentelhas, 2018).

The use of different types of sampling for the corn crop was carried out by Assis *et al.* (2006), where the authors used two cases to characterize the temporal distribution, the truncated normal distribution ± 1.96 standard deviation, with variable daily average temperature, and constant daily global solar radiation (a); and with constant average daily temperature and variable daily global solar radiation (b). The authors found differences in results depending on the case used, but they carried out the study for only one location. Among other results, they observed that the estimation methodology allows defining the order of magnitude of potential corn yield, in a given location, based on temperature and solar radiation data. And the proposed stochastic procedure allows estimating the potential corn yield associated with a given probability. For simulations that take into account the El Niño phenomenon, Nória Júnior *et al.* (2020) highlight that its impacts can be minimized by the correct sowing date in the soybean crop.

Tables 1 and 2 show the values of potential and depleted corn productivity for 8 of the 16 evaluated cities, in 4 of the 8 sowing dates, in the four cases of simulation and data sampling. Through these tables it is verified that the results of minimum, maximum, average values and 90% of the values are above a determined value, for the four types of simulation. When comparing the simulated values through the four simulation cases, for Santa Maria, for example, it is verified that the average productivity is 13,633 kg ha⁻¹ (Case A), 13,555 kg ha⁻¹ (Case B), 13,594 kg ha⁻¹ (Case C) and 13,696 kg ha⁻¹ (Case D), for the first sowing date (October 1). As in the other situations (minimum, maximum, 90%, sowing dates and locations) the values observed from the four types of simulation are quite close, which makes it difficult to differentiate which data simulation method is used preferential. It is verified, however, that in simulation case D, the observed values of potential and depleted productivity are 69% greater than the simulation of case C, 70% greater than the simulation of case B and 74% greater than the values simulated in case A. Then, case D of data simulation has the characteristic of overestimating potential and depleted productivity values. In that regard, (6) used

an expolinear model of crop growth to predict changes in growth of soybean cultivars when subjected to water deficit at different phenological stages with good results. In addition to environmental variability, the variability and genetic potential of cultures must also be considered to overcome problems and improve the purposes of predicting productivity of agricultural crops (Razzaq *et al.*, 2021).

The asymmetric triangular distribution can behave like the symmetric triangular distribution, and require few input parameters, this simulation method becomes interesting, making the modeling of agricultural productivity can be estimated through a stochastic model that has a greater degree of reliability of the results. When comparing deterministic and stochastic models, one must remember for what purpose each one is used. It is reasonable to always start the set of calculations with a deterministic model, which facilitates understanding, streamlines the computational process and maximizes programming time. From the deterministic model, the second part is the implementation of a stochastic model through the simulation of input data in the model.

Historical series of climate data follow a certain probability distribution. This probability distribution of climate data can vary according to where the data originates. Martin *et al.* (2008) evaluated for 18 locations in the state of São Paulo, under the probability distributions for the rainfall variable and it was verified that, for the rainfall variable, the probability distributions that best adhered to the data were the Weibull distribution (94, 61%), log-normal (94.55%), normal (91.99%), gamma (89.89%) and exponential (77.66%). The same author, through the results obtained, printed the stochastic characteristic for the input variables in the model, causing the simulated variables to have the same distribution as the original variable. Among the various probability distributions, the normal distribution is the most important, from the perspective of agronomic knowledge, because a large number of phenomena can be studied with this model. Assis *et al.* (2006), considered two cases in the truncated normal probability distribution (extreme values: mean - 1.96 standard deviation and mean + 1.96 standard deviation): variable daily mean temperature and constant daily global solar radiation, and constant daily mean temperature and variable daily global solar radiation. The authors concluded that the estimation methodology allows defining the order of

magnitude of the potential corn yield at a given location, based on temperature and solar radiation data. The proposed stochastic procedure allows associating potential corn yield with a given probability. As a continuation of these researches, the applications proposed by Nóia Júnior and Sentelhas (2019) can be carried out, which determined the best sowing times depending on the soybean-corn succession according to the climate variability, productivity and economic profitability of the crops.

4 CONCLUSION

Based on the results obtained, it is concluded that: (i) the adaptation of the method (proposed by De Wit) of the agroecological zone makes it possible to define the order of magnitude of the potential and depleted productivity of the corn crop, in the State of Rio Grande do Sul, and produces consistent results, as well as allows identifying the best sowing time; (ii) the stochastic procedure has variability according to sowing time and evaluated location; (iii) the procedure (b) mean insolation and temperature (asymmetrical triangle) and (d) insolation (symmetrical triangle) do not differ in terms of classification, with the latter overestimating the values of potential and depleted productivity. These results are important to assist decision-making by technicians and producers at field level, providing data for better use of available genotypes. In addition, they validate a method for estimating corn crop productivity that will support future research. The main limitation of this research was the restriction that only one region of Brazil should have more super-early, early and late corn cultivars to be used. For future work, it is recommended to use a greater number of corn cultivars and a greater evaluation of variables.

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