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# Metodologia estocastica para estimar a produtividade potencial do milho

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

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## Authors' contribution

Reinaldo Antonio Garcia Bonnecarrère: Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing
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## Conflict of interest declaration

There is no conflict of interest for the publication of said article.

## 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, isolation 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 (October 1st, October 11th, October 21st, November 1st, November 11th, November 21st, December 1st, December 11th). 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 diverge how much the classification, being that the last one overestimates the values of potential and depleted productivity.

**Keywords**: probability distribution, agroecological zone, simulation.

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

## 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 Estado 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-chaves:** distribuições de probabilidade, zona agroecológica, simulação.

## 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 mass. 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 and 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 (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". Confalone *et al*. (2010) 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. 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 *et al*., 2020).

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. MATERIAL AND METHODS

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:

$$cTn_j = n_0 + n_1.T_j + n_2.T_j^2 \qquad (1) \qquad cTc_j = c_0 + c_1.T_j + c_2.T_j^2 \qquad (2)$$

where $\mathbf{n}_0$, $\mathbf{n}_1$ and $\mathbf{n}_2$ and $\mathbf{c}_0$, $\mathbf{c}_1$ and $\mathbf{c}_2$ refer to the empirical parameters, being, (i) when the temperature is higher than 16.5ºC: $\mathbf{n}_0$ = -4.16; $\mathbf{n}_1$ = 0.4325ºC$^{-}$1; and $\mathbf{n}_2$ = -0.00725ºC$^{-2}$ and $\mathbf{c}_0$ = -9.32; $\mathbf{c}_1$ = 0.865ºC$^{-1}$; and $\mathbf{c}_2$ = -0.0145ºC$^{-2}$ and (ii) when the temperature is less than or equal to 16.5ºC: $\mathbf{n}_0$ =-1.064; $\mathbf{n}_1$ = 0.173ºC$^{-1}$; and $\mathbf{n}_2$ = -0.0029ºC$^{-2}$ and $\mathbf{c}_0$ = -4.16; $\mathbf{c}_1$ = 0.4325oC$^{-1}$; and $\mathbf{c}_2$ = -0.00725ºC$^{-2}$. The average insolation (nj, h d$^{-1}$) can thus be calculated:

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

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 jth ten-day period. The leaf area index (LAIj, m2 $m^{-2}$) can thus be calculated:

$$IAF_j = \alpha_0 \ \mathrm{Dr}_j^3 + \alpha_1.\mathrm{Dr}_j^2 + \alpha_2.\mathrm{Dr}_j \qquad (4)$$

where $\alpha_0$, $\alpha_1$, and $\alpha_2$ refer to empirical parameters determined in regression analysis based on data obtained from Figueredo Júnior *et al.* (2005), where $\alpha_0$ = -27.139 m2 $m^{-2}$; $\alpha_1$ = 25.999 m2 $m^{-2}$; and $\alpha_2$ = 3.1745 m2 $m^{-2}$. The correction referring to the leaf area index (cIAF) can be calculated as follows:

$$\mathrm{cIAF}_j = b_0 + b_1.\mathrm{IAF}_j - b_2.\mathrm{IAF}_j^2 \qquad (5)$$

where $\mathbf{b}_0$, $\mathbf{b}_1$ and $\mathbf{b}_2$ refer to the empirical parameters, where $\mathbf{b}_0$ = 0.0093; $\mathbf{b}_1$ = 0.185 m2 $m^{-2}$; and $\mathbf{b}_2$ = 0.0175 m4 $m^{-4}$.

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**, °C), with the correction (cR) being used to estimate the relative balance (ratio between net photosynthesis and gross photosynthesis) which can be expressed by:

$$\mathrm{cR} = 0{,}5;\ \text{if } Tj > 20 \qquad (6) \qquad\qquad \mathrm{cR} = 0{,}6;\ \text{if } Tj \leq 20 \qquad (7)$$

A produtividade potencial bruta diária pode assim ser calculada:

$$\mathrm{PPBc}_j = (107{,}2 + 0{,}36.\mathrm{Qo}_j).\frac{n_j}{H_j}.\mathrm{cTc}_j.cIAF_j.cR_j.D_j \qquad (8)$$

$$\mathrm{PPBn}_j = (31{,}7 + 0{,}219.\mathrm{Qo}_j).\left(1 - \frac{n_j}{H_j}\right).\mathrm{cTn}_j.cIAF_j.cR_j.D_j \qquad (9)$$

where PPBcj and PPBnj refer to the daily gross potential productivity corresponding to clear and cloudy days, respectively; Qoj to extraterrestrial radiation; nj to insolation (h $d^{-1}$); Hj to photoperiod; cTcj and cTnj to the correction factors corresponding to clear and cloudy days, respectively; cIAFj to the correction referring to the leaf area index; cRj to the correction referring to breathing on the average day of the jth ten-day period and Dj 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:

$$\mathrm{PPB}_j = \mathrm{PPBc}_j + \mathrm{PPBn}_j \qquad (10) \qquad\qquad \mathrm{PPBac}_f = \sum_{j=1}^{f} \mathrm{PPB}_j \qquad (11)$$

where PPBj refers to the potential productivity (kg $ha^{-1}$) that occurs in the jth ten-day period; and PPBacf 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 and Kassam (1994), Lima (1995), Gadioli (1999), Barros (1998), Sá (2001), 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:

$$cW = \frac{100}{100 - u} \qquad (12) \qquad\qquad \mathrm{PP} = \mathrm{PPBac}_f.IC.cW \qquad (13)$$

where u refers to the water content (%) in the botanical seed (u = 13%); IC to the harvest index (IC = 0.55 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 (Kc = 1) and effective root system depth constant and equal to 40 cm (Ze, 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 (Kc). ETp 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 (ETpj, mm ten-day-1) by the crop evapotranspiration coefficient (Kcj) in the jth ten-day period, that is:

$$ETc_j = Kc_j.ETp_j \qquad (14)$$

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

The productivity depletion caused by soil water deficiency is calculated by the ratio between actual evapotranspiration (ETr, mm $day^{-1}$) and crop evapotranspiration (ETc, mm $day^{-1}$) in three different phases of the cycle:

$$\mathrm{rET_1} = \frac{\sum_{j=1}^{k} \mathrm{ETr_{j,1}}}{\sum_{j=1}^{k} \mathrm{ETc_{j,1}}} \text{; if } 0 \leq \mathrm{Dr_j} < 0{,}5 \qquad (15)$$

$$\mathrm{rET_2} = \frac{\sum_{j=k+1}^{m} \mathrm{ETr_{j,2}}}{\sum_{j=k+1}^{m} \mathrm{ETc_{j,2}}} \text{;if} 0{,}5 \leq \mathrm{Dr_j} < 0{,}74 \qquad (16)$$

$$\mathrm{rET_3} = \frac{\sum_{j=m+1}^{q} \mathrm{ETr_{j,3}}}{\sum_{j=m+1}^{q} \mathrm{ETc_{j,3}}} \text{; if } \mathrm{Dr_j} \geq 0{,}74 \qquad (17)$$

$$Fd_1 = 1 - ky_1.(1 - rET_1); \text{ if } 0 \leq \mathrm{Dr_j} < 0{,}5 \qquad (18)$$

$$Fd_2 = 1 - ky_2.(1 - rET_2); \text{ if } 0{,}5 \leq \mathrm{Dr_j} < 0{,}74 \qquad (19)$$

$$Fd_3 = 1 - ky_3.(1 - rET_3); \text{ if } \mathrm{Dr_j} \geq 0{,}74 \qquad (20)$$

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

where rET1, rET2 and rET3 refer to the relationship between actual evapotranspiration (ETr, mm $day^{-1}$) and crop evapotranspiration (ETc, mm $day^{-1}$); Fd1, Fd2 and Fd3 to potential productivity depletion factors based on water balance and and Ky1, Ky2 and Ky3 to water deficiency sensitivity factors referring to phases 1 ($0 \leq Dr < 0.5$) (ky1 = (21)

0.2) , 2 ($0.5 \le Dr < 0.74$) (ky1 = 0.8) and 3 ($Dr \ge 0.74$) (ky1 = 1.0), respectively. The depleted yield (PD, kg ha$^{-1}$) of maize grains is estimated by:

$$PD = PP.Fd$$

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 (October 1st, October 11th, October 21st, November 1st, November 11th, November 21st, December 1st, December 11th). 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 (SAS, 1997).

## 3. RESULTS AND DISCUTIONS

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.

| 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 |

**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.

| 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 | 15288 | 10334 | 14324 | 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 | 14819 | 13620 | 14370 | 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 | 12405 | 14629 | 12686 |
| | 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 |

**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 | I | 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 |

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 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 (Fancelli and Dourado Neto, 2000), 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 Etr/Etp 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*. (2010) 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 and 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, Nóia 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, Confalone *et al*. (2010) 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 derministic 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. CONCLUSIONS

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.

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