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Maize yield gain using irrigation in the state of Rio Grande do Sul, Brazil[1]

Ganho de produtividade de milho utilizando irrigação no estado do Rio Grande do Sul, Brasil

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HIGHLIGHTS:

Crop model had a less than 16% bias when comparing simulated and observed maize yield under rainfed and irrigated conditions.
The best sowing date varied by site when considered yield gain and irrigation demand.
Maize yield can be increased three-fold with irrigation of 342 to 565 mm per cycle.

ABSTRACT: The state of Rio Grande do Sul, Brazil, has a low maize production when compared to the total demand, particularly under water deficit conditions. This study aimed to estimate the yield gain of maize using irrigation. The FAO Agroecological zone model was used to simulate the yield after previous calibration and evaluation, following an experimental design of randomized blocks, with 40 growing seasons as replicates and 20 sites. Two water management (rainfall and irrigation), three sowing dates (Aug 15, Sept 15, and Oct 15), and three soil textures (sandy, sand-clayey, and clayey) were evaluated. The generic hybrid obtained from calibration based on multiple hybrids with a medium cycle of 150 d was utilized for the simulation. The model evaluation showed an absolute bias of 16% and an overestimated yield of 2%. The mean irrigated and rainfed yields were, respectively, 16,094 and 5,386 kg ha^{-1}. The irrigated yield had statistically superior values for the sowing dates Sep 15 and Oct 15, although it required a greater amount of irrigation. The yield gain reached a maximum value of 56% in the site of São Gabriel, with irrigation amount increasing 14% on the sowing date Oct 15 compared to that of Aug 15. The soil types showed statistical differences for rainfed conditions, and irrigation minimized the differences, while no statistically significant differences were found for the yield. Irrigation showed potential to increase the maize supply, and the response across sites can be considered in the agricultural management plan.

Key words: *Zea mays*, water deficit, sowing dates, crop model, agriculture plan

RESUMO: O Rio Grande do Sul apresenta baixa oferta de milho em relação à demanda, condição agravada com limitação hídrica. Assim, objetivou-se estimar o ganho de produtividade do milho utilizando irrigação. O modelo da zona agroecológica da FAO, calibrado e validado, foi utilizado para simulação, considerando um experimento de blocos casualizados, com 40 safras de repetições, e 20 locais, manejo irrigado e sequeiro, três datas de semeadura (15/Ago, 15/Set e 15/Out) para solos de textura arenosa, média e argilosa. Um híbrido genérico obtido na calibração com base em vários híbridos com ciclo médio de 150 dias foi considerado na simulação. Na validação, o modelo apresentou um erro absoluto relativo de 16%, superestimando a produtividade em apenas 2%. A produtividade média irrigada e de sequeiro foi, respectivamente, de 16.094 e 5.386 kg ha^{-1}. As datas de semeadura de 15 Set e 15 Out apresentaram valores estatisticamente superior para a condição irrigada. O uso da irrigação resultou em maior ganho de produtividade para 15 Set e 15 Out, com maior demanda de irrigação. O maior ganho de produtividade com uso de irrigação foi de 56%, em São Gabriel, com aumento de 14% na demanda de irrigação quando comparado 15 Out e 15 Ago. Os tipos de solos obtiveram diferenças significativas para a condição de sequeiro, enquanto que a irrigação minimizou as diferenças de produtividade, não apresentando diferença estatística. A irrigação demonstrou potencial para aumentar a oferta de milho, em que manejos locais podem ser considerados no plano agrícola.

Palavras-chave: *Zea mays*, déficit hídrico, data de semeadura, modelo de cultura, produção de alimento, planejamento agrícola

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Introduction

Maize production in the consumer market has gained attention because of the high prices of imported grain from other states. These prices limit the expansion of animal production and raise the final cost of the products. The state of Rio Grande do Sul produced 3.93 million tons of grain maize in the 2019/20 growing seasons (IBGE, 2020). Historically, the estimated total production deficit was between 9 and 12 million tons, making the animal protein production chain economically unfeasible (Camargo et al., 2022). This was caused by maize supply importation from other Brazilian states that resulted in R$ 400 million of taxes and logistics evasion in 2018 (Camargo et al., 2022).

The low production of maize in the state was associated with climatic limitation, where water deficit was responsible for the reduction of 58% of maize potential yield, along with limited crop management, as low fertilization reduced the maize potential yield by 22% (Battisti et al., 2012). To improve the crop and reduce yield variability between growing seasons, producers began using irrigation to counter the effects of the weather patterns in the state (Nóia Júnior et al., 2020). The yield gain from irrigation can be quantified using a crop model, which is a tool that simulates yield in response to environmental conditions and crop management, including that of irrigation (Battisti et al., 2018b). Crop models have equation and calculation steps that represent crop physiology in response to multiple inputs, such as weather, soil, sowing date, and water management (Silva & Giller, 2020). The FAO Agroecological zone has been widely used for evaluating yield responses to weather, sowing date, and irrigation management across sites (Battisti et al., 2020). The database enables quantification of the yield response for multiple growing seasons to obtain reliable results for agricultural planning (Sampaio et al., 2020).

Irrigation leads to yield stability and increases maize supply (Attia et al., 2021), ensuring the efficiency of resource use in the production system. The mean irrigated maize yield reported in farm plots ranged from 10,140 to 18,081 kg ha^{-1} in the state (Vian et al., 2016; Barcellos, 2017), with a maximum of 22,493 kg ha^{-1} measured in an area of agricultural precision (Vian et al., 2016). During the same period, the mean maize yield reported by IBGE (2020), considering the mean value by county, ranged between 3,133 and 7,518 kg ha^{-1} in the state (IBGE, 2020). Therefore, this study aimed to estimate the maize yield gain using irrigation and irrigation demand based on 40 years (1980–2020) of daily weather data for different sowing dates and soil types in 20 municipalities in the state of Rio Grande do Sul, Brazil.

Material and Methods

Yield and irrigation amounts were simulated for 20 municipalities in Rio Grande do Sul, Brazil that were defined based on the maize growing area and climatic region (Table 1). The simulation was performed following a randomized block design, with 40 growing seasons as replicates, 20 sites, two water management, three sowing dates, and three soil textures.

Weather data were obtained daily between 1980 and 2015 from Xavier et al. (2015) and between 2016 and 2020 from the NASAPOWER (https://power.larc.nasa.gov/dataaccess-viewer/), totaling 40 growing seasons. These weather databases were validated for crop modeling in Brazil (Duarte & Sentelhas, 2020). The weather data obtained included the mean, maximum, and minimum air temperatures, mean relative humidity, solar radiation on the surface, wind speed,

Table 1. Sites, Köppen climate classification, latitude (Lat), longitude (Long), altitude above sea level (Alt), minimum (min), mean and maximum (max) air temperature, solar radiation, rainfall, potential crop evapotranspiration (ETc), water deficit and surplus along maize cycle

Köppen climate[1]	Sites	Growing area[2] (ha)	Lat (°)	Long (°)	Alt (m)	Air temperature (°C)[3] min	Air temperature (°C)[3] mean	Air temperature (°C)[3] max	Solar radiation[3] (MJ m^{-2} day^{-1})	Rainfall[3] (mm cycle^{-1})	ETc[3] (mm cycle^{-1})	Water deficit[3] (mm cycle^{-1})	Water surplus[3] (mm cycle^{-1})
Cfa	Alegrete	3800	-29.82	-55.77	102	16.22	21.96	27.69	21.06	904	695	169	388
	Bagé	400	-31.34	-54.05	212	15.18	20.78	26.38	20.81	800	661	167	318
	Canguçu	16000	-31.41	-52.70	386	15.75	20.70	25.66	20.29	783	639	153	306
	Cruz Alta	5100	-28.69	-53.58	452	15.97	21.64	27.30	20.71	983	668	134	457
	Dr. M.Cardoso	6800	-27.50	-54.35	282	16.73	22.40	28.07	20.54	991	675	130	454
	Encruz. do Sul	3500	-30.53	-52.44	432	15.60	20.86	26.12	20.12	793	636	149	317
	Herval	1800	-32.03	-53.34	287	15.65	20.79	25.93	20.66	739	659	173	264
	Itaqui	6000	-29.10	-56.40	57	16.90	22.69	28.47	21.05	948	711	165	411
	Pal. das Missões	14500	-27.92	-53.32	639	16.27	21.87	27.47	20.58	975	672	130	440
	Santa Maria	190	-29.70	-53.80	113	16.29	21.82	27.36	20.60	943	668	144	428
	Santiago	2570	-29.21	-54.86	409	16.69	22.51	28.33	20.84	1006	693	148	468
	São Gabriel	2000	-30.37	-54.29	114	16.00	21.61	27.21	20.80	842	673	169	348
	São Luiz Gonzaga	11150	-28.44	-54.95	231	17.07	22.97	28.88	20.73	1026	701	149	482
	Torres	95	-29.31	-49.77	16	17.18	20.79	24.40	19.35	840	588	105	361
	Venâncio Aires	12000	-29.64	-52.19	210	15.64	20.74	25.83	19.96	860	621	124	372
Cfb	Bom Jesus	16000	-28.70	-50.40	1046	12.99	18.14	23.28	19.21	827	541	84	375
	Caxias do Sul	7000	-29.19	-51.15	817	14.28	19.36	24.44	19.55	870	576	95	395
	Erechim	1320	-27.65	-52.27	783	15.37	20.77	26.17	20.16	964	631	107	445
	Lagoa Vermelha	4500	-28.24	-51.53	797	14.50	19.88	25.26	19.81	931	601	101	437
	Soledade	800	-28.85	-52.48	726	15.34	20.66	25.98	20.31	936	636	123	430

[1]Obtained from Alvares et al. (2013); [2]2018/19 growing season obtained from IBGE (2020).[3]The values represent the mean of minimum (min), mean and maximum (max) for air temperature, the mean value for solar radiation and the mean accumulated values for rainfall, potential crop evapotranspiration (ETc), water deficit and surplus across maize cycle sowing on 15 Aug, 15 Sept and 15 Oct and a total cycle of 150 days for 40 growing seasons from 1980 and 2020

and rainfall. Table 1 shows the geographic location of each site (latitude and longitude), altitude above sea level, and the mean weather variables, potential crop evapotranspiration (ETc), water deficit, and water surplus over 40 years.

The attainable yield was simulated using the crop model of the FAO Agroecological zone (Doorenbos & Kassam, 1979), calibrated by Andrioli & Sentelhas (2009). The crop model was evaluated for maize in the Rio Grande do Sul state, considering the mean measured yield for 10 growing seasons (2009-2017) for 20 sites (IBGE, 2020) and eight irrigated yields from two regions (Vian et al., 2016; Barcellos, 2017). Crop model performance was evaluated by considering the correlation between simulated and measured yield (r), R^2, Willmott agreement index (d) indices, and absolute and relative bias (Wallach et al., 2006).

The simulations were performed using Microsoft Excel, where the general equations used to simulate the potential and attainable yield were as follows:

$$Yp = \sum_{i=1}^{m} GP \cdot \frac{LAI_i}{LAI_{ref}} \cdot C_{RESP} \cdot C_H \cdot \left(1 - C_W\right)^{-1} \quad (1)$$

$$Ya = Yp \cdot \prod_{i=1}^{n} \left[1 - Ky_i \cdot \left(1 - \frac{ETa_i}{ETc_i}\right)\right] \quad (2)$$

where:

Yp - potential yield (kg ha^{-1});

Ya - attainable yield (kg ha^{-1});

GP - gross photosynthesis (kg DM ha^{-1} per day), calculated as the sum of the gross photosynthesis for C_4 crop estimated in the fraction of clear and overcast skies based on extra-terrestrial solar radiation, photoperiod, and effective hours of sunshine, adjusted by the efficiency of the photosynthetic process depending on air temperature (Andrioli & Sentelhas, 2009);

LAI_i - leaf area index across the cycle (Müller et al., 2005; Battisti et al., 2018a), where $LAI_i = 0$ from sowing to seven days after sowing (DAS) and from 140 to 150 DAS; LAI_i increases linearly from 0 to 5 from 8 to 80 DAS; and $LAI_i = 5$, from 81 to 140 DAS; LAI_{ref} is the reference leaf area index of five in the GP simulation;

C_{RESP} - depletion coefficient from maintenance respiration, with a value of 0.6 when the air temperature is lower than 20 °C, and 0.5 above 20 °C (Doorenbos & Kassam, 1979);

C_H - crop harvest index, defined as 0.5 (Avila et al., 2016);

C_W - fraction of water content in the harvested part of the plant, defined as 0.13;

Ky_i - water deficit sensitivity index, defined by crop stage (0.40 for establishment to flowering; 1.4 during flowering; 0.5 during grain filling; and 0.2 for maturation) (Andrioli & Sentelhas, 2009);

ETa_i - actual evapotranspiration;

ETc_i - potential crop evapotranspiration;

i-day - crop cycle in Eq. 1, and the crop stage in Eq. 2;

m - number of days of the crop cycle from sowing to harvesting, totaling 150 days (generic hybrid with medium-late cycle); and,

n - number of crop stages (sowing to establishment, establishment to the beginning of flowering, flowering, grain filling, and maturation).

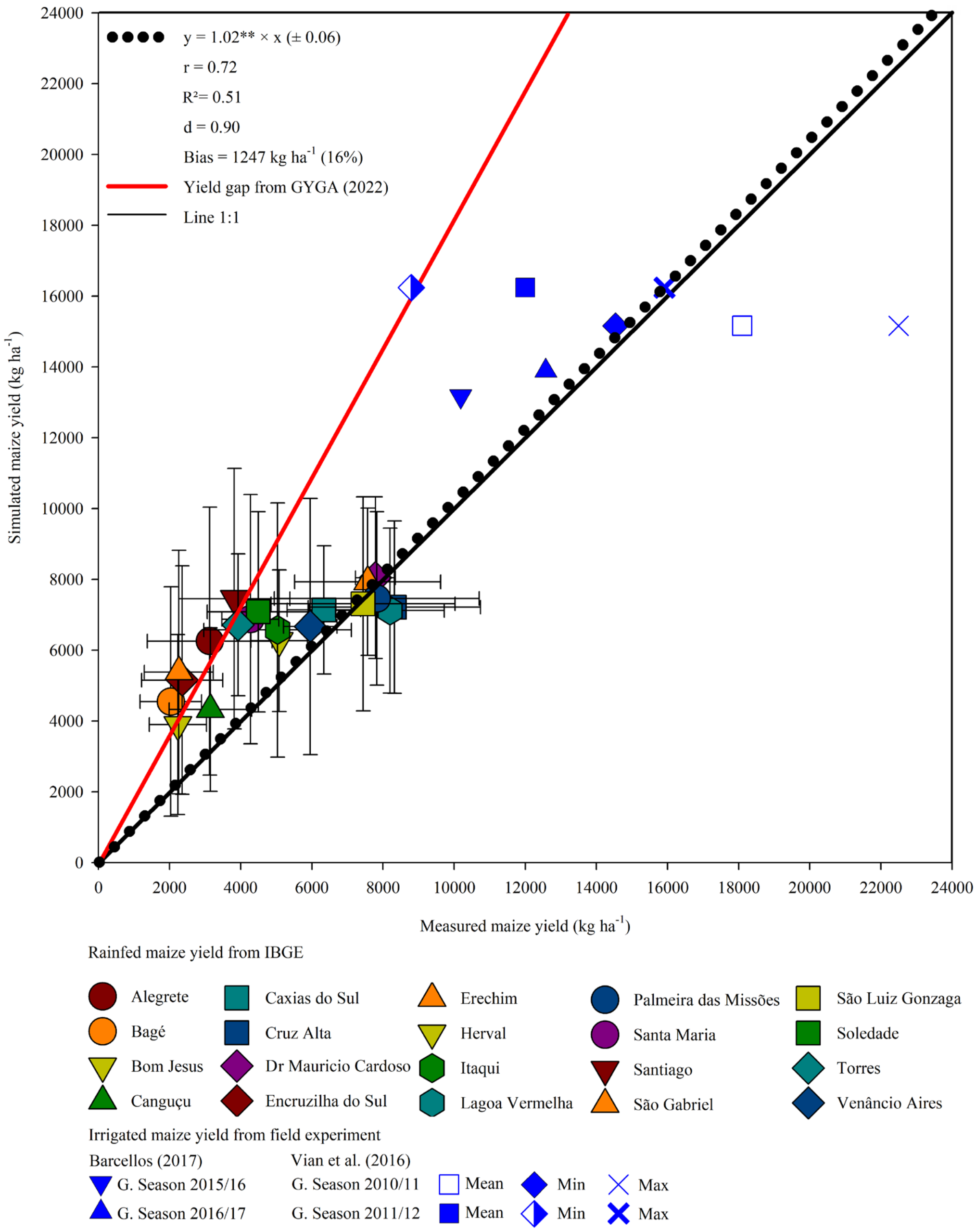
Potential crop evapotranspiration (ETc) was estimated from the reference evapotranspiration (ETo) by the Penman-Monteith method (Pilau et al., 2012), multiplied by the crop coefficient (Kc), of 0.56 from sowing to establishment (15 days), 0.56 to 1.2 from establishment to flowering (65 days), 1.2 during flowering and grain filling (55 days) and 1.2 to 0.6 during maturation (15 days) (Andrioli & Sentelhas, 2009). ETa was obtained using the water balance methodology of Thornthwaite and Mather adapted by Battisti et al. (2018a), where the initial root depth of 15 cm increased linearly to the maximum root depth of 80 cm at the beginning of flowering. The data required for water balance were daily rainfall and potential crop evapotranspiration amounts, including three soil types having soil water availabilities for the crop (texture) of 0.50 (sandy), 0.87 (sand-clayey), and 1.25 (clayey) mm cm^{-1} of root depth (Battisti et al., 2018b).

Sowing dates followed the recommendations of the Agricultural Zoning of Climate Risk of Aug 15, Sep 15, and Oct 15. The attainable yield under rainfed conditions was obtained based on the amount and distribution of rainfall, whereas that under irrigation was considered the additional amount of water applied by the irrigation system. The yield gain was determined as the difference between the yields under irrigation and rainfed conditions. Irrigation management was performed by applying 8 mm of water per day, which is the value used in the main maize production system in Rio Grande do Sul, the central pivot irrigation system. Irrigation was applied when the available soil water level decreased by 8 mm, to maintain the crop under optimal soil water content.

Maize yield, yield gain using irrigation, and the total amount of irrigation during the crop cycle were subjected to analysis of variance at $p \leq 0.05$, and the means were compared using the Scott-Knott test at $p \leq 0.05$. The analyses were performed using GENES software (Cruz, 2013).

Results and Discussion

The crop model showed an absolute bias of 1,247 kg ha^{-1}, representing 16%, with a high correlation (r = 0.72; d = 0.90) between the measured and simulated yields (Figure 1). The overprediction was 2%, with most of the data in the range of 1:1 to the mean yield gap of the Global Yield Gap Atlas (GYGA, 2022). The yield gap indicates the amount of yield losses that occur in the field by crop management with conditions that were not simulated by the crop model, which for maize represents a value of 44% for the Rio Grande do Sul state (GYGA, 2022). The crop model performance during evaluation using the yield from IBGE (2020) and irrigated areas in the Rio Grande do Sul state was similar to that of Andrioli & Sentelhas (2009), who obtained a bias from -5.7 to + 5.8%, with a general mean absolute error of 960 kg ha^{-1} (10%). Those authors calibrated the model for a generic hybrid, considering the inputs of 26 maize hybrids across different climate conditions and yields range from 7,000 to 11,000 kg ha^{-1}.



ns, * and **: Not significant, significant at p ≤ 0.05 and at 0.01 by F test; The bars in the points indicate de standard deviation to growing seasons analized

Figure 1. Simulated and measured maize yield for irrigated and rainfed method for sites and field experiment in the state of Rio Grande do Sul

The differences between the measured and simulated yields were linked to uncertainties in the simulation, including sowing dates, crop cycles, and weather variability from the field to the weather station. The dataset from the IBGE is also a source of uncertainty because it considers interviews to obtain yield results that represent the mean value across multiple plots that have greatly differing crop management methods (IBGE, 2020). This dataset also does not separate rainfed and irrigated areas, leading to crop model underprediction for the areas of Cruz Alta, São Luiz Gonzaga, and Palmeira das Missões, which have 12, 7, and 4%, respectively, of the agricultural area in the county irrigated by a central pivot (Martins et al., 2016).

The limitation in the simulation for the Vian et al. (2016) dataset was associated with natural yield variability under field conditions, where the results were obtained from a harvest map in an area of 35 ha, considering the minimum, mean, and maximum yields compared to a single simulated value. The crop model has a single result for which the simulation, where crop model parameters were calibrated for the mean yield condition, showed the importance of representing yield tendencies among different treatments (Paixão et al., 2021). Despite these limitations, the crop model showed a good yield tendency among multiple sites under rainfed and irrigated conditions and was therefore applicable to this study.

Water management showed a significant interaction ($p \leq 0.01$) for sites, water management, and sowing dates in terms of yield, while soils presented an interaction with water management (Table 2). The yield gain using irrigation and irrigation demand had significant interactions ($p \leq 0.01$) for sites and sowing dates, and for soil as an isolated factor (Table 2).

All sites had higher yields from the sowing dates of Sept 15 and Oct 15 than that of Aug 15 under irrigated conditions

Table 2. Analysis of variance summary for maize yield, yield gain by irrigation use, and irrigation demand during crop cycle

Sources of variation	Yield (kg ha^{-1})		Yield gain (kg ha^{-1})		Irrigation demand (mm cycle^{-1})	
	Df	Ms	Df	Ms	Df	Ms
Sites (st)	19	488975828**	19	1410705670**	19	1059696**
Water management (wm)	1	412737068000**	-	-	-	-
Soils (so)	2	1515693820**	2	2746278930**	2	3913287**
Sowing dates (sd)	2	2.021857330**	2	13105111800**	2	2008011**
st × wm	19	705352833**	-	-	-	-
st × so	38	1648179^{ns}	38	3529313^{ns}	38	1567^{ns}
st × sd	38	25364279**	38	42285641**	38	10657**
wm × so	2	1373139470**	-	-	-	-
wm × sd	2	6552555920**	-	-	-	-
so × sd	4	6315048^{ns}	4	11453600^{ns}	4	2307^{ns}
st × wm × so	38	1764656^{ns}	-	-	-	-
st × wm × sd	38	21142820**	-	-	-	-
st × so × sd	76	257574^{ns}	76	489254^{ns}	76	98^{ns}
wm × so × sd	4	5726800^{ns}	-	-	-	-
st × wm × so × sd	76	244627^{ns}	-	-	-	-
Residues	14040	5837846	7020	12929155	7020	4570
Total	14399		7199		7199	
CV	22%		33%		14%	

ns, * and ** - Not significant, significant at p ≤ 0.05, and at p 0.01 by F test; CV - Coefficient of variation; Df - Degree of freedom; Ms - Mean square

(Table 3). For example, a higher yield was observed in Itaqui, reaching 18,991 kg ha^{-1} on Oct 15, which was statistically similar to that of Sept 15 (Table 3), but differed from the value on Aug 15 of 15,994 kg ha^{-1}. This result relates to the interaction of available solar radiation and the maximum leaf area index under optimal water conditions (Liu et al., 2021), where the sowing dates of Sep 15 and Oct 15 had better matches between higher solar radiation and maximum maize leaf area.

The sites showed three sowing date patterns under rainfed conditions (Table 4). Thirteen sites had similar statistical yields for sowing dates of Aug 15, Sep 15, and Oct 15, and superior statistical performance was revealed on Aug 15 compared to Sep 15 and Oct 15 for six sites. The Aug 15 date was included as a strategy to avoid yield losses due to water deficit (Battisti et al., 2018b; Pilau et al., 2018). This strategy was effective in Alegrete, where the yield on Aug 15 was 5,828 kg ha^{-1} compared to 3,779 kg ha^{-1} on Sep 15 (Table 3). In contrast, Torres was the only site where the sowing date of Oct 15 had a better statistical performance than those of Aug 15 and Sep 15.

The mean maize yields were 5,386 and 16,094 kg ha^{-1}, respectively, for rainfed and irrigated conditions. The yield level differed significantly across sites for each water management type and sowing date. For example, São Luiz Gonzaga had a higher yield across sites for Aug 15 under irrigated conditions, reaching a mean of 16,054 kg ha^{-1} (Table 3), which was statistically similar to that of other sites, such as Alegrete and Cruz Alta. Based on this result, public policies can be developed by region for irrigation use and maize production improvement (Battisti et al., 2018b).

Table 3. Maize yield obtained for sites in the state of Rio Grande do Sul based on water management and sowing dates

[1]Sites	Irrigated			Rainfed		
	Aug 15	Sept 15	Oct 15	Aug 15	Sept 15	Oct 15
	Maize yield (kg ha^{-1})					
Alegrete	15245 aBα	18093 aAα	18671 aAα	5828 aAβ	3379 bBβ	4022 bBβ
Bagé	13553 bBα	16832 bAα	17643 bAα	4657 bAβ	3216 bAβ	3295 bAβ
Bom Jesus	9608 dBα	12689 dAα	13931 dAα	5174 bAβ	5675 aAβ	6762 aAβ
Canguçu	13438 bBα	16439 bAα	17239 bAα	4658 bAβ	3169 bAβ	3734 bAβ
Caxias do Sul	11649 cBα	14435 cAα	15382 cAα	6156 aAβ	5933 aAβ	7228 aAβ
Cruz Alta	15078 aBα	17574 aAα	18069 aAα	7052 aAβ	5191 aAβ	5794 aAβ
D. M. Cardoso	15664 aBα	17910 aAα	18305 aAα	7285 aAβ	5974 aAβ	5955 aAβ
Encr. do Sul	13614 bBα	16513 bAα	17317 bAα	5216 bAβ	3423 bAβ	3959 bAβ
Erechim	14089 bBα	16377 bAα	16868 bAα	7105 aAβ	6605 aAβ	7442 aAβ
Herval	13614 bBα	16810 bAα	17577 bAα	4114 bAβ	2533 bAβ	2933 bAβ
Itaqui	15994 aBα	18565 aAα	18991 aAα	6308 aAβ	4375 bBβ	4427 bBβ
Lagoa Vermelha	12790 bBα	15278 cAα	15955 cAα	6676 aAβ	6175 aAβ	7149 aAβ
Palmeira das Missões	15255 aBα	17607 aAα	18080 aAα	7203 aAβ	5865 aAβ	6056 aAβ
Santa Maria	14924 aBα	17597 aAα	18232 aAα	6453 aAβ	4214 bBβ	5139 aBβ
Santiago	15727 aBα	18226 aAα	18751 aAα	6908 aAβ	4794 aBβ	5497 aBβ
São Gabriel	14692 bBα	17626 aAα	18247 aAα	5168 bAβ	3027 bBβ	3367 bBβ
São Luiz Gonzaga	16054 aBα	18422 aAα	18898 aAα	6971 aAβ	5027 aBβ	5448 aBβ
Soledade	13772 bBα	16373 bAα	17018 bAα	6436 aAβ	5488 aAβ	6044 aAβ
Torres	13670 bBα	15752 cAα	16376 cAα	6201 aBβ	5247 aBβ	7300 aAβ
Venâncio Aires	13524 bBα	16146 bAα	16880 bAα	6205 aAβ	4898 aAβ	5673 aAβ

[1]Mean values followed by the same letter do not statistically differ by Scott-Knott test at p ≤ 0.05, where uppercase letters compare sowing dates in the same water management (irrigated or rainfed) and site, lowercase letter compare yield for sites in each water management and sowing date at the column, and greek letter compare yield between water management into the same site and sowing date

Table 4. Maize yield gain and total irrigation demand for sites in the state of Rio Grande do Sul based on sowing dates

[1]Sites	Yield gain (kg ha^{-1})			Irrigation (mm per cycle)		
	Aug 15	Sept 15	Oct 15	Aug 15	Sept 15	Oct 15
Alegrete	9416 aB	14715 aA	14649 aA	493 aB	554 aA	566 aA
Bagé	8896 bB	13616 bA	14348 aA	476 aB	539 aA	555 aA
Bom Jesus	4434 eB	7014 fA	7168 fA	342 eA	363 eA	364 fA
Canguçu	8780 bB	13270 bA	13505 bA	450 bB	507 bA	519 bA
Caxias do Sul	5493 dB	8501 eA	8155 eA	365 dB	393 dA	399 eA
Cruz Alta	8027 bB	12383 cA	12276 cA	450 bB	493 bA	501 bA
D. M. Cardoso	8379 bB	11936 cA	12350 cA	454 bB	493 bA	500 bA
Encr. do Sul	8398 bB	13089 bA	13358 bA	440 bB	499 bA	513 bA
Erechim	6983 cB	9771 dA	9426 eA	410 cA	433 cA	435 dA
Herval	9500 aB	14278 aA	14644 aA	471 aB	536 aA	551 aA
Itaqui	9686 aB	14190 aA	14564 aA	503 aB	558 aA	569 aA
Lagoa Vermelha	6114 dB	9103 eA	8807 eA	388 dB	415 dA	425 dA
Palmeira das Missões	8053 bB	11741 cA	12024 cA	448 bB	486 bA	497 bA
Santa Maria	8472 bB	13383 bA	13093 bA	455 bB	508 bA	519 bA
Santiago	8819 bB	13432 bA	13253 bA	480 aB	533 aA	540 aA
São Gabriel	9524 aB	14599 aA	14879 aA	484 aB	541 aA	553 aA
São Luiz Gonzaga	9082 aB	13395 bA	13450 bA	485 aB	536 aA	545 aA
Soledade	7336 cB	10885 dA	10975 dA	423 cB	460 cA	468 cA
Torres	7470 cB	10505 dA	9076 eA	382 dB	412 dA	413 eA
Venâncio Aires	7319 cB	11247 dA	11207 dA	411 cB	453 cA	462 cA

[1]Mean values followed by the same letter do not statistically differ by Scott-Knott test at p ≤ 0.05, where uppercase letter compare sowing dates in the same site, and lowercase letter compare yield for sites in each sowing date at the column

The yield gain using irrigation was higher on Sep 15 and Oct 15 than on Aug 15 for all sites (Table 4). A higher yield gain leads to a higher water demand for irrigation but with a greater water use efficiency. For example, São Gabriel had the higher yield gain on Oct 15, reaching a mean of 14,879 kg ha^{-1}, leading to an irrigation demand of 553 mm per cycle (Table 4) and in a yield gain of 26.9 kg ha^{-1} mm^{-1} of irrigation. This region had the highest water deficit across the study sites, with a mean of 169 mm per cycle (Table 1). In contrast, Bom Jesus had the lowest yield gain, with 4,434 kg ha^{-1}, and an irrigation demand of 342 mm per cycle (Table 4), resulting in a yield gain of 13.0 kg ha^{-1} mm^{-1} of irrigation. Bom Jesus was the coldest site analyzed in the state, with a mean air temperature during the maize cycle of 18.14 °C (Table 1). The climatic variability was associated with the effects of the macroscale climate phenomena that affect the state (Nóia Júnior et al., 2020).

The irrigated yield was statistically similar when simulated for soil texture (Table 5), but with different irrigation requirements: 516, 469, and 436 mm per cycle for sandy, sand-clayey, and clayey soils, respectively (Table 5). The use of irrigation helps to minimize the difference in absolute yield between soils by avoiding water deficits (Battisti et al., 2018b). However, rainfed yields were 6,427, 5,492, and 4,241 kg ha^{-1} for sandy, sand-clayey, and clayey soils, respectively, which were statistically different (Table 5). The soil types also differed statistically for yield gain (Table 5), with 11,831, 10,589, and 9,701 kg ha^{-1} for sandy, sand-clayey, and clayey soils, respectively. These patterns were the result of interactions between the total soil water content available to the crop and climate across the crop cycle (Pilau et al., 2018).

Table 5. Maize yield, maize yield gain and total irrigation demand across cycle obtained for soil types in the state of Rio Grande do Sul

Soil	Maize yield		Yield gain	Irrigation (mm cycle^{-1})
	Irrigated	Rainfed		
	(kg ha^{-1})			
Sandy	16073 aA	4241 cB	11831 a	516 a
Sand-Clayey	16080 aA	5492 bB	10589 b	469 b
Clayey	16129 aA	6427 aB	9701 c	436 c

[1]Mean values followed by the same letter do not statistically differ by Scott-Knott test at p ≤ 0.05, where uppercase letter compare yield irrigated and rainfed in the line for each soil, and lowercase letter compare results at the column

The simulated yield considers optimal crop management, and when compared with the actual mean yield of farmers, limited crop management was responsible for 46% of potential maize yield losses in Rio Grande do Sul (Battisti et al., 2012). Crop management can be improved with increased soil fertility, nitrogen adjustments for potential yield, efficient control of pests and diseases, improved quality of sowing, and the use of hybrids adapted to the environment (Andrea et al., 2018) in association with irrigation. Thus, considering the growing area in 2018/2019 of approximately 750,000 ha (IBGE, 2020) and a maize yield of 16,000 kg ha^{-1}, obtained in the simulation by irrigation and optimal management, the state could achieve a production of 12 million tons.

Conclusions

1. The crop model showed an acceptable relative bias (16%) and high correlation (r = 0.72) between the simulated and measured yields.
2. The maize yield was significantly increased by irrigation, with different patterns observed across sites for rainfed and irrigated management.
3. Yield gain and irrigation amount were influenced by the sowing dates, which determined climate conditions, and by soil types, due to the amount of soil water available to the crop.

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