Received: 20 November 2024 | Accepted: 9 November 2025

DOI: 10.1002/agj2.70258

Agronomy Journal

ORIGINAL ARTICLE

Agronomy, Soils, and Environmental Quality

Identifying maize yield potential and farm yield gaps in Southern Brazil

Isabela Bulegon Pilecco[1] | **Leandro do Prado Ribeiro**[2] | **Matheus Cavalheiro Moreira de Camargo**[1] | **Cintia Piovesan Pegoraro**[1] | **Álvaro De Souza Carnellosso**[1] | **Nereu Augusto Streck**[1] | **Alencar Junior Zanon**[1]

[1]Departamento de Fitotecnia, Universidade Federal de Santa Maria, 1000 Roraima Avenue, Santa Maria, Rio Grande do Sul, Brazil

[2]Centro de Pesquisa para Agricultura Familiar, Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina, Chapecó, Santa Catarina, Brazil

Correspondence
Isabela Bulegon Pilecco, UFSM, Santa Maria, RS, Brazil.
Email: isabelabpilecco@gmail.com

Assigned to Associate Editor Erick Sebetha.

Funding information
Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Grant/Award Number: 10.13039/501100002386

Abstract

A comprehensive understanding of the interaction between genotype and environment at the local level, coupled with the development of effective management strategies, is imperative to meet the demand for maize (*Zea mays*) in Santa Catarina, Brazil, and elsewhere. This study estimated maize yield potential, water-limited yield potential, and yield gaps in the state. The study also identified the key biophysical and management factors contributing to yield gaps. The nine buffer zones selected encompass 63% of the total cultivated area dedicated to maize production. To ensure the appropriate balance between the quantity of data utilized and the representativeness of the study area, the Hybrid-Maize model and the method developed by the Global Yield Gap Atlas were employed. In the 2020–2021 and 2021–2022 agricultural years, surveys were conducted in 293 fields. A comparative analysis between high and low yields, in conjunction with regression tree analyses, enables the identification of management practices that warrant investment to elevate average yields and approach values approximating 75% of water-limited yield potential. The results indicated that the yield potential of maize in Santa Catarina is 17.4 Mg ha^{-1}, while the water-limited yield potential is 14.7 Mg ha^{-1}. Therefore, the attainable yield gap was estimated to be 4.0 Mg ha^{-1}. The primary management practices that constrain maize yield were identified, including the population of established plants, the rate of potassium fertilization, the sowing date, and the interval between lime applications. Improvements to these practices will enable an increase of 1.0 million Mg in the current crop area.

Abbreviations: BZ, buffer zone; CZ, climate zone.

Plain Language Summary

In southern Brazil, especially in Santa Catarina, maize is essential for livestock feed. But local production does not meet the state's demand. This study estimated how much maize could be produced and why current yields are lower than expected. Researchers used a crop simulation model and data from nearly 300 farms to investigate. They found that the yield gap is mainly due to farm management rather than weather. The main issues were low plant density, not the adequate sowing date, insufficient potassium fertilizer, and long intervals between liming. If farmers could reach 75% of the rainfed yield potential, they could produce 1 million Mg more of maize in the state. These findings can help farmers and policymakers develop better strategies to boost food production in ways that are environmentally responsible and reduce the need for imports or land expansion.

1 | INTRODUCTION

Maize is a key component of agricultural systems in southern Brazil, particularly as feed for intensive livestock production. In Santa Catarina, a subtropical state in southern Brazil, maize demand exceeds local production by approximately 6 million Mg annually. This deficit is covered by imports from other Brazilian regions, Paraguay, and Argentina (Marcondes, 2023). Such dependence raises production costs and reduces the competitiveness of pork, poultry, and dairy sectors. Moreover, long-distance transport significantly increases greenhouse gas emissions associated with grain supply (Marin et al., 2022).

Maize area expansion in Santa Catarina is limited by environmental and legal constraints related to its location in the Atlantic Forest biome. Over the past 15 years, the maize-cultivated area has declined by about 30,000 ha per year, while soybean area has increased by 26,000 ha annually (Instituto Brasileiro de Geografia e Estatística [IBGE], 2024). Under these conditions, increasing maize yields on existing farmland is the most effective and sustainable strategy to meet demand (Grassini et al., 2011; Van Wart et al., 2013). Identifying yield gaps and the biophysical and management factors that limit yield is essential to guide interventions (Grassini et al., 2011; Van Ittersum et al., 2013).

The yield potential (Yp) of a crop is dependent upon some factors, including the amount of incident solar radiation, the atmospheric CO_2 concentration, the temperature of the air, and the genetic characteristics of the crop (Cassman et al., 2003). These factors determine the maximum yield of the crop without limitations from water, nutrients, weeds, pests, and diseases (Cassman et al., 2003). The water-limited yield potential (Yw) considers both rainfall and the available soil water. The discrepancy between Yp and Yw illustrates the impact of both water quantity and distribution, in addition to soil characteristics (Lobell et al., 2009; Van Ittersum et al., 2013). The discrepancy between the actual farmer's yield (Ya) and each of the yield potentials represents the yield gaps (Ygs) (Cassman et al., 2003; Lobell et al., 2009). The Ygs indicate the potential for increased production in the current crop area, with or without supplementary irrigation.

This is the first study in Brazil to integrate estimates of maize yield potential (Yp and Yw) with actual on-farm yield data (Ya) and explanatory variables collected from commercial fields. Unlike previous studies based solely on crop modeling (e.g., Andrea et al., 2018), this approach allows a more realistic diagnosis of yield gaps and their drivers under local conditions. The inclusion of Santa Catarina is especially relevant due to its strategic role in Brazil's maize-livestock systems and its exclusion from prior national-scale assessments. Estimating yield potential and yield gaps in this context is essential, as large-scale studies often overlook key genotype-by-environment interactions at the local level (Andrea et al., 2018; Stuart et al., 2016).

Most of the prior research conducted in Brazil has concentrated on the consequences of individual management practices or restricted interactions, including cover cropping and nitrogen (N) fertilization (Pott et al., 2021), seed treatment (Segatto et al., 2023), biological inoculants (Guimarães et al., 2023), genotype and sowing time (Coelho et al., 2022), and pest and disease management (Ribeiro et al., 2023). While these studies are valuable in terms of technical recommendations, they do not fully capture the complexity of crop performance under real-world conditions. Multi-site, multi-year datasets facilitate a more comprehensive evaluation of the combined effects of biophysical and management factors on yield, as demonstrated in studies about soybean (*Glycine max*) (Tagliapietra et al., 2021; Winck et al., 2023), cassava (*Manihot esculenta*) (Zebalho et al., 2024), and irrigated rice (*Oryza sativa*) (Ribas et al., 2021) in Brazil.

It is imperative to enhance the competitiveness of the grain maize-based agro-industrial chain in the state of Santa

Catarina, Brazil. This has consequences for the security of the 81,200, 111,000, and 80,100 agricultural establishments involved in the cultivation of grain maize and the poultry and swine industries, respectively (Instituto Brasileiro de Geografia e Estatística [IBGE], 2024). It is hypothesized that the average maize yield in Santa Catarina can be significantly increased through targeted management adjustments, as observed in higher yielding farms, and that relatively simple changes in management practices are responsible for the existing yield gaps in the region. In this study, we sought to (i) determine the Yp, Yw, and Yg of maize in Santa Catarina State, Brazil; and (ii) identify the main biophysical and management factors associated with yield gaps. To achieve this objective, a methodology was employed that integrates site-year field data, process-based ecophysiological crop simulation models, and the most accurate climate and soil information. The findings of this study will inform the decision-making processes of farmers regarding the management practices and investments they adopt, as well as the design of research and public policy programs aimed at addressing yield gaps.

Core Ideas

- Water-limited yield potential ranges from 10.4 to 16.9 Mg ha^{-1} in Santa Catarina.
- The maize yield gap due to water restriction is 2.7 Mg ha^{-1}, while the attainable yield gap is 4.0 Mg ha^{-1}.
- The main cause of the maize yield gap was plant population.
- It is possible to produce an additional 1.0 million Mg in the current maize production area in Santa Catarina.

2 | MATERIALS AND METHODS

2.1 | Study site characterization

Santa Catarina is a state located in the southern region of Brazil (Figure 1A). The predominant climate, according to the Köppen system, is Cfa (humid subtropical climate) (Alvares et al., 2013). The state was selected as the study area due to its strategic role in Brazil's maize-livestock integration systems. Despite its relatively minor contribution to the country's total area dedicated to maize cultivation, the state is home to a significant concentration of highly intensive pork and poultry production chains that rely on maize as a source of feed. Furthermore, as demonstrated in a previous study (Andrea et al., 2018), the existence of a yield gap has been identified in the subtropical Brazilian region. The regionalized approach is conducive to the development of location-specific strategies for enhancing maize yield under both rainfed and irrigated conditions.

To represent the climate variability within the state, its territory was divided into homogeneous climate zones (CZs) using the spatial structure approach of the Global Yield Gap Atlas (for further details, please see www.yieldgap.org/; Van Wart et al., 2013). This approach considers three agroclimatic variables that impact maize production: (i) annual degree-day accumulations, (ii) annual aridity index (AI), and (iii) temperature seasonality (TS).

A total of seven CZs were identified within the state, comprising the following codes: 5801, 5901, 6701, 6801, 6901, 7801, and 7901. By overlaying the CZs map with the maize harvest area map (average harvest area from 2016 to 2020) (Instituto Brasileiro de Geografia e Estatística [IBGE], 2024) using QGIS version 2.18, it was possible to identify only those CZs that cover more than 5% of the maize crop area. Consequently, five CZs were selected, encompassing 89% of the maize crop area in Santa Catarina (Figure 1B). The buffer zones (BZs) were defined using the network of weather stations of EPAGRI/CIRAM (EPAGRI, 2020). Each BZ is associated with a reference meteorological station (reference weather station [RWS]), from which a 15-year series (2006–2020) of meteorological data was utilized. A BZ covers an area of up to 100 km in diameter, delineated by the boundaries of the CZ it represents. BZs with a coverage exceeding 1% of the maize area and an overlap of less than 20% with other BZs were selected, encompassing 63% of the maize crop area in Santa Catarina (Figure 1C).

2.2 | Field experiments for the evaluation of the Hybrid-Maize model simulation

The Hybrid-Maize model (H. S. Yang et al., 2004; H. Yang et al., 2017) has previously been employed to estimate both yield potential and water-limited yield potential in the context of the Global Yield Gap Atlas Project for Brazil (Antolin et al., 2025; Marin et al., 2022). The model was evaluated for its ability to simulate aboveground dry matter, phenology, and maize yield in Santa Catarina. To this end, the simulated data were compared with observations from experiments conducted in Chapecó, SC (latitude: 27.08 S; longitude: 52.63 W; and an elevation of 679 m above mean sea level) during the 2020/2021 and 2021/2022 growing seasons. The experiments were conducted under conditions free of weeds, pests, diseases, and nutritional stress, with the additional provision of supplementary irrigation (Figure 1D).

A random complete block design was used, with four replicates per hybrid. The hybrids were selected for inclusion

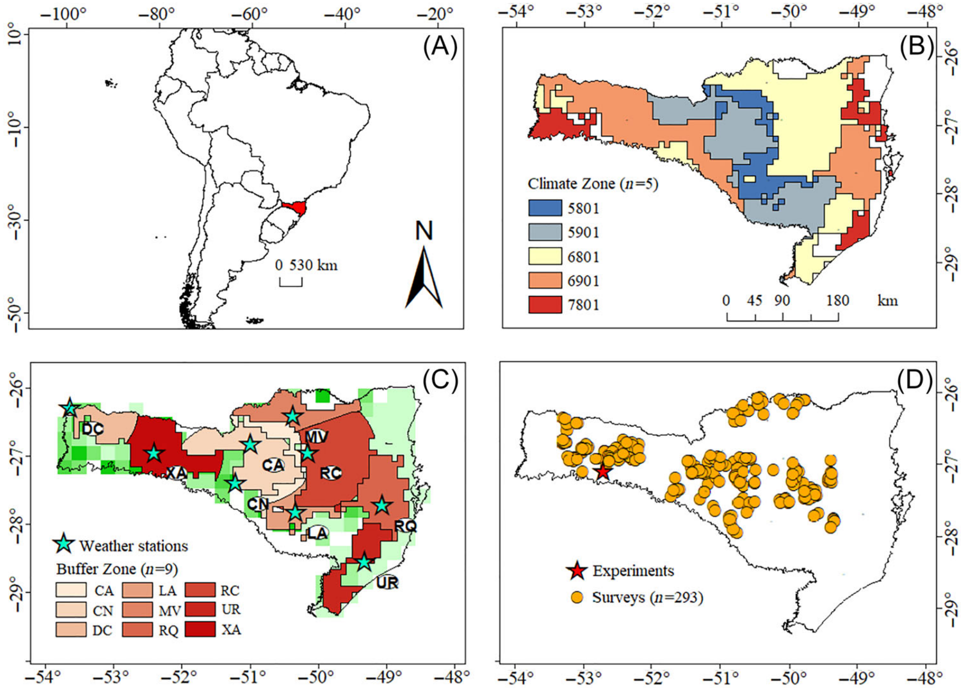

FIGURE 1 Geographic location of Santa Catarina state, Brazil, in South America (A); five climate zones (CZs) delineated in the state (B); nine buffer zones (BZs) and reference weather stations (RWSs) (indicated by the green stars) selected to represent the maize crop area from 2016 to 2020 (highlighted in green) (C); and location of the experiments (indicated by the red stars) and site-year field data surveys (indicated by the yellow circles) conducted in the 2021/2022 and 2022/2023 crop seasons (D).

in the study due to their prevalence in each maturity group (hyper-early, super-early, and early) among producers in Santa Catarina. The sowing dates were September 9, 2020, and September 15, 2021, which represent the typical range of maize sowing dates in southern Brazil. The objective was to achieve a sowing density of 75,000 plants per hectare in the 2020/2021 crop season and 90,000 plants per hectare in the 2021/2022 crop season. The row spacing was maintained at 0.45 m throughout both crop seasons.

Based on previous soil analysis, fertilizer application was adjusted to meet the requirements for an expected yield of 18 Mg ha^{-1}. At planting, monoammonium phosphate and a formulated fertilizer (NPK 09-33-12) were applied as base fertilization. Nitrogen (urea) and potassium (K) (potassium chloride) were then split into two topdressing fertilizations, respectively, at the V3/V4 and V7/V8 stages (Ritchie et al., 1989). Plant health management was conducted according to the recommendations established in the crop management plan. Irrigation was carefully managed to meet the crop's water needs in terms of both quantity and timing.

To evaluate aboveground dry matter, plants were sampled from a 1-m linear section within each plot at the R6 growth stage, during the 2020/2021 growing season (Ritchie et al., 1989). Following the separation of the plants into their constituent parts, namely, leaves, stems, and ears, the parts were subjected to drying at a temperature of 70˚C until a constant weight was achieved. Thereafter, the dry matter was quantified through weighing. Phenological evaluations were conducted on five marked plants in each plot, with the dates of emergence, silking (R1), and physiological maturity (R6) assessed (Ritchie et al., 1989). Yield estimates were calculated based on a pre-marked 5 m^2 area harvested from each plot to minimize external factors and adjusted to 13% grain moisture content. Meteorological inputs for the Hybrid-Maize model were obtained from the EPAGRI/CIRAM meteorological station located in the municipality of Chapecó, 50 m away from the experimental plots.

The root mean squared error (RMSE) and the normalized root mean squared error (NRMSE) were employed to ascertain the efficacy of the models in simulating maize growth, development, and yield (Y. Liu & Hwang, 2015). Both statistics quantify the magnitude of the discrepancy between observed and simulated values, with a value approaching zero indicating superior model performance in simulating field observations (Jacovides & Kontoyiannis, 1995).

2.3 | Simulation of yield potential and water-limited yield potential, and estimation of yield gaps

The input data utilized for the simulations of yield potential (Yp) and water-limited yield potential (Yw) were designed to represent the crop system of the areas covered by each

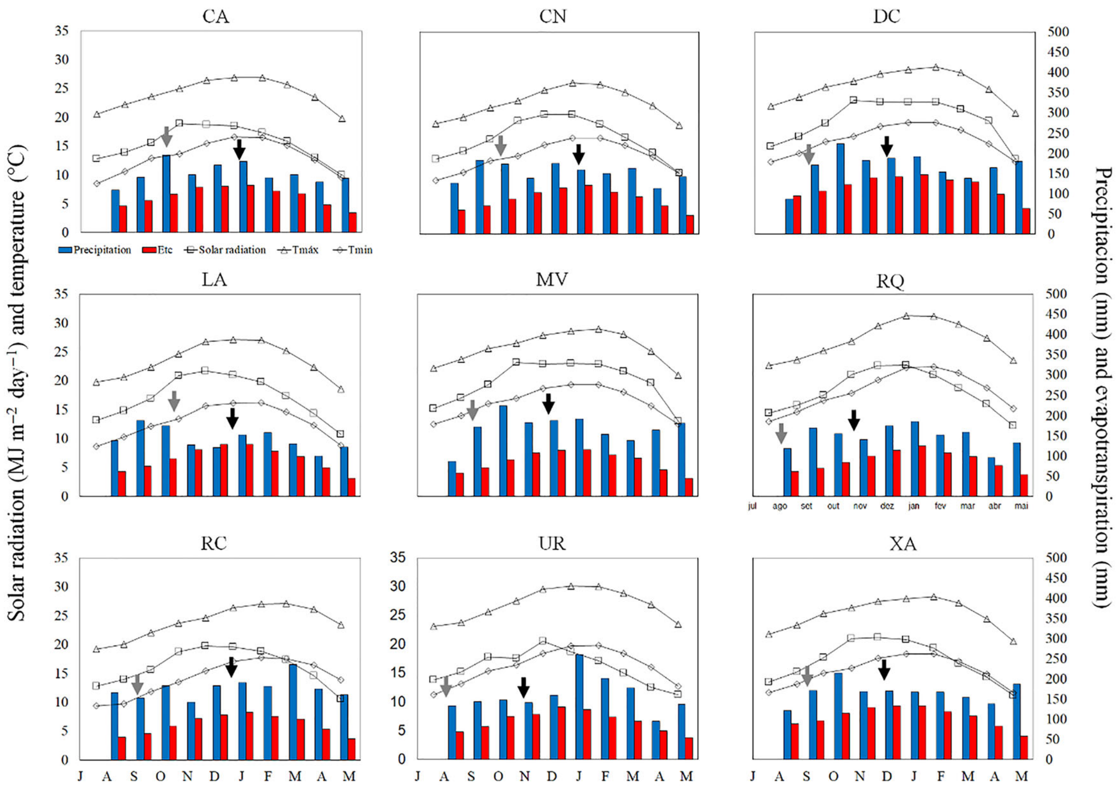

FIGURE 2 A 15-year average (from 2006 to 2020) of incident solar radiation, maximum temperature (Tmax), minimum temperature (Tmin), precipitation, and total evapotranspiration for the nine reference weather stations (RWSs) and buffer zones (BZs) selected in Santa Catarina state, Brazil. The gray arrow in each panel indicates the month of sowing, while the black arrow denotes the month of silking occurrence (R1). The acronyms on the panels represent the reference weather stations (RWSs): Caçador (CA), Campos Novos (CN), Dionísio Cerqueira (DC), Lages (LA), Major Vieira (MV), Rancho Queimado (RQ), Rio do Campo (RC), Urussanga (UR), and Xanxerê (XA).

BZ to achieve a more realistic estimation. The developmental cycle and sowing density representative of the crops in the region were employed, and the sowing time was determined to coincide with the point at which 50% of the maize area had been sown between the years 2017 and 2021. This information was obtained through meetings with agricultural engineers specializing in maize cultivation in each location, as well as through public statistics data released by EPAGRI/CEPA, accessible via the Agricultural Bulletins (for additional information, please see cepa.epagri.sc.gov.br/index.php/publicacoes/boletim-agropecuario/).

The meteorological data collected over a 15-year period (2006–2020) are sufficient for the accurate and reliable estimation of Yp and Yw simulations (Grassini et al., 2015). The dataset employed in the Hybrid-Maize model encompasses maximum and minimum temperatures, solar radiation, relative humidity, and wind speed and was procured from the EPAGRI/CIRAM RWSs (Epagri, 2020) (Figure 2). In instances where meteorological data were unavailable, data from one to three meteorological stations adjacent to each RWS were employed to supplement the dataset. To provide realistic estimations of yield gaps, it is of utmost importance to estimate Yw in a manner that reflects the actual conditions of the crops when all maize crops surveyed in Santa Catarina are grown under rainfed conditions. To this end, representative soil types for each BZ were selected in consultation with local experts in this production system. For each selected soil type, the necessary data to simulate Yw was obtained from the global soil information site ISRIC (additional information available at www.isric.org).

Following the estimation of Yp and Yw for each BZ, a weighted average was calculated using the harvest area represented by each BZ. This allowed for the estimation of the average Yp and Yw for Santa Catarina. Additional information utilized for the simulations is delineated for each BZ in Table 1. The actual farmer yield (Ya), used to estimate the yield gap, was obtained from a 5-year dataset (2017–2021) provided by the Brazilian Institute of Geography and Statistics (IBGE).

To achieve the greatest return on investment and optimal resource utilization, studies indicate that a reasonable goal is to attain a yield of between 70% and 80% of Yw in the field (Lobell et al., 2009; Monzon et al., 2021; Van Ittersum et al., 2013). The estimated attainable yield (Yat) of maize in Santa

TABLE 1 Characterization of biophysical and management variables employed to simulate yield potential for nine buffer zones in Santa Catarina State, Brazil. The acronyms represent the reference weather stations (RWSs): Caçador (CA), Campos Novos (CN), Dionísio Cerqueira (DC), Lages (LA), Major Vieira (MV), Rancho Queimado (RQ), Rio do Campo (RC), Urussanga (UR), and Xanxerê (XA).

BZ and RWS	Latitude	Longitude	Altitude (m)	Climate zone (CZ)	Sowing time	Maturity group (degree days)	Seeding density (a thousand plants ha^{-1})	Soil type	Soil bulk density (g cm^{-3})	Field slope (%)	Soil surfaces with residue coverage (%)
CA	26.8S	51.0W	944	5801	Oct 15	1711	70	Oxisols	1.0	30	75
CN	27.4S	51.2W	963	5901	Oct 15	1711	70	Oxisols	1.1	30	75
DC	26.3S	53.6W	807	6901	Sep 15	1634	80	Ultisols	1.0	30	75
LA	27.8S	50.3W	952	5801	Oct 30	1634	70	Inceptisols/oxisols	1.0	30	50
MV	26.4S	50.4W	799	6801	Sep 15	1711	75	Inceptisols	0.9	10	50
RQ	27.7S	49.1W	881	6901	Aug 15	1711	80	Inceptisols	1.0	15	50
RC	26.9S	50.2W	591	6801	Sep 15	1634	75	Inceptisols	1.0	15	50
UR	28.5S	49.3W	467	6801	Aug 15	1711	80	Inceptisols	1.1	10	50
XA	26.9S	52.4W	917	6901	Sep 15	1634	80	Ultisols	1.0	15	75

Catarina was found to be 75% of Yw. The practical applicability of this value as an exploitable yield was evaluated by comparing it with the actual yield obtained by the most productive producers monitored in each BZ and with the 95th percentile (P95) of the entire dataset (Monzon et al., 2021). The yield gaps were calculated by subtracting Yp, Yw, Yat, and Ya from one another. Thus, four levels of yield gaps were considered:

$$\text{Total yield gap (Ygt)} = \text{Yp} - \text{Ya} \quad (1)$$

$$\text{Water yield gap (Ygw)} = \text{Yp} - \text{Yw} \quad (2)$$

$$\text{Suboptimal management yield gap (Ygm)} = \text{Yw} - \text{Ya} \quad (3)$$

$$\text{Attainable yield gap (Ygat)} = \text{Yat} - \text{Ya} \quad (4)$$

2.4 | Identifying the causes of yield gaps

During the 2020/2021 and 2021/2022 growing seasons, a total of 293 maize fields in the state of Santa Catarina were monitored to provide edaphoclimatic and management data on the variability of the cropping area (Figure 1D). These data were used to identify the biophysical and management factors that cause maize yield gaps in Santa Catarina. The fields were selected to encompass a range of yield levels and to reflect the diverse circumstances of each municipality within the BZ. The management data were collected through personal surveys conducted by consultants from the Agricultural Research and Rural Extension Company of Santa Catarina (Epagri).

In addition to the farmer's yield, the impact of management practices employed before and throughout the growing season was assessed. This included an assessment of sowing date, crop rotation, weed, insect, and disease control, fertilization, and other practices. The dataset was divided into terciles based on the average yield, with the upper group classified as high-yield (HY) fields and the lower group classified as low-yield (LY) fields (Grassini et al., 2015). The difference between the means of HY and LY fields for each variable was assessed using the *t*-test or Wilcoxon (if the data were not normal), with significance levels of 1% and 5%. Categorical variables were assessed using the chi-squared test at a 5% significance level. The statistical analyses were conducted using InfoStat software (Di Rienzo et al., 2012).

The complete dataset was subjected to an evaluation utilizing the nonparametric regression tree test with the "caret" package in R. The dataset was divided into two distinct subsets: the first comprising 80% of the data for the calibration of the regression tree analysis, and the second comprising the remaining 20% for the evaluation of the analysis. The analysis

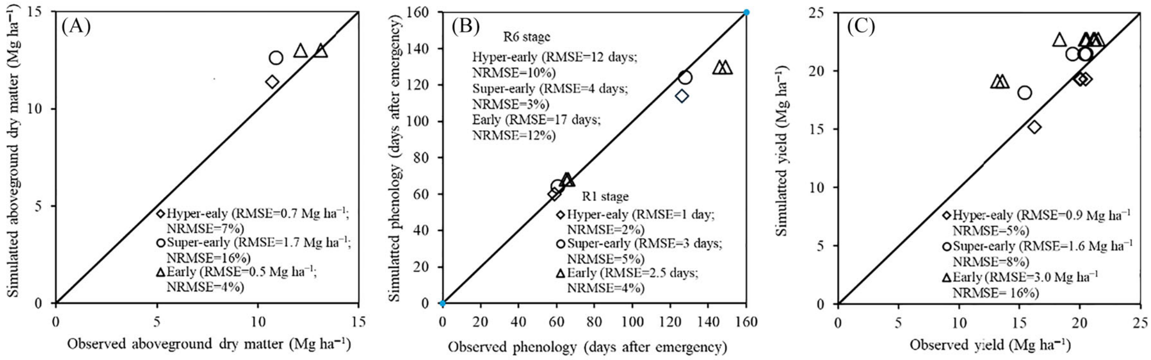

FIGURE 3 Comparison of simulated and observed maize aboveground dry matter (A); phenology until silking (R1) and black layer (R6) (B); and grain yield (C) for early, super-early, and hyper-early cycles. Points represent the meaning for each cycle across the 2020/2021 and 2021/2022 growing seasons. The solid black line represents $y = x$. NRMSE, normalized root mean squared error; RMSE, root mean squared error.

subdivides the data into smaller groups with binary divisions based on a single continuous predictor variable (Breiman et al., 1984). The output is a tree diagram, in which the branches are determined by the splitting rules, and the series of terminals includes the average response and the number of observations for each terminal node. The impact of each quantitative factor present in the nodes of the regression tree on yield was quantified in isolation using boundary function analysis (French & Schultz, 1984). This analysis enables the identification of the optimal value for the factor under consideration. The optimal value was defined as the point at which a one-unit increase in the factor resulted in less than a 0.05% increase in yield (Ribas et al., 2021; Winck et al., 2023).

3 | RESULTS

3.1 | Evaluation of the Hybrid-Maize model in simulating aboveground dry matter, phenology, and yield of maize

The Hybrid-Maize model tended to overestimate the aboveground dry matter at the end of the cycle (Figure 3A). Nevertheless, this overestimation was within an acceptable range, with an NRMSE below 16% for all maturity groups. A similar trend was observed for grain yield, with only one maturity group presenting an NRMSE of 16%, whereas the others exhibited considerably lower values, ranging from 5% to 8% (Figure 3C). Regarding phenological predictions, the model demonstrated remarkable accuracy in forecasting the onset of silking (R1) (Figure 3B). The estimation of physiological maturity (i.e., the date of black layer formation, R6) showed a larger error but remained within an acceptable range (Figure 3B).

3.2 | Yield potential, water-limited yield potential, and yield gaps of maize in Santa Catarina State

The yield potential (Yp) and water-limited yield potential (Yw) of maize in Santa Catarina are 17.4 and 14.7 Mg ha^{-1}, respectively. The actual yield (Ya) is 7.0 Mg ha^{-1}, representing 47.6% of Yw. This results in a Ygat, or difference between 75% of the Yw and Ya, of 4.0 Mg ha^{-1}.

Across the BZs, the Yp ranged from 14.7 to 19.6 Mg ha^{-1} (Figure 4A), while the Yw ranged from 10.4 to 16.9 Mg ha^{-1} (Figure 4B). The attainable yield in rainfed fields, defined as 75% of the Yw, ranged from 7.8 to 12.7 Mg ha^{-1} (Figure 4C). The actual farmer yield in the different BZs within this state ranged from 4.7 to 8.5 Mg ha^{-1} (Figure 4D).

The highest Yp was observed in BZ Campos Novos, while the highest Yw was recorded in BZ Major Vieira (MV). In contrast, the BZ Urussanga (UR) exhibited the lowest Yp and Yw. The elevated Yw in BZ MV can be attributed to the substantial accumulated and evenly distributed rainfall throughout the growing season (Figure 2), which exceeds the evapotranspiration. This suggests that the crop in this region is not experiencing a significant water deficit. Furthermore, this is supported by the assessment of the Ygw in this BZ, which began with a value of 1.0 Mg ha^{-1} (Table 2).

This was the second lowest among the selected BZs, surpassed only by BZ Rio do Campo, which exhibited a Ygw of 0.7 Mg ha^{-1} (Table 2). The results of this study indicate that the highest Ygw are in the BZs UR (4.3 Mg ha^{-1}) and Lages (3.9 Mg ha^{-1}). The suboptimal management yield gap (Ygm) ranged from 4.4 to 11.3 Mg ha^{-1}. Concerning Ygm, the BZ Rancho Queimado exhibits the most pronounced discrepancy (71% of Yw). The lowest Ygm was attributed to BZ UR at 42% of Yw.

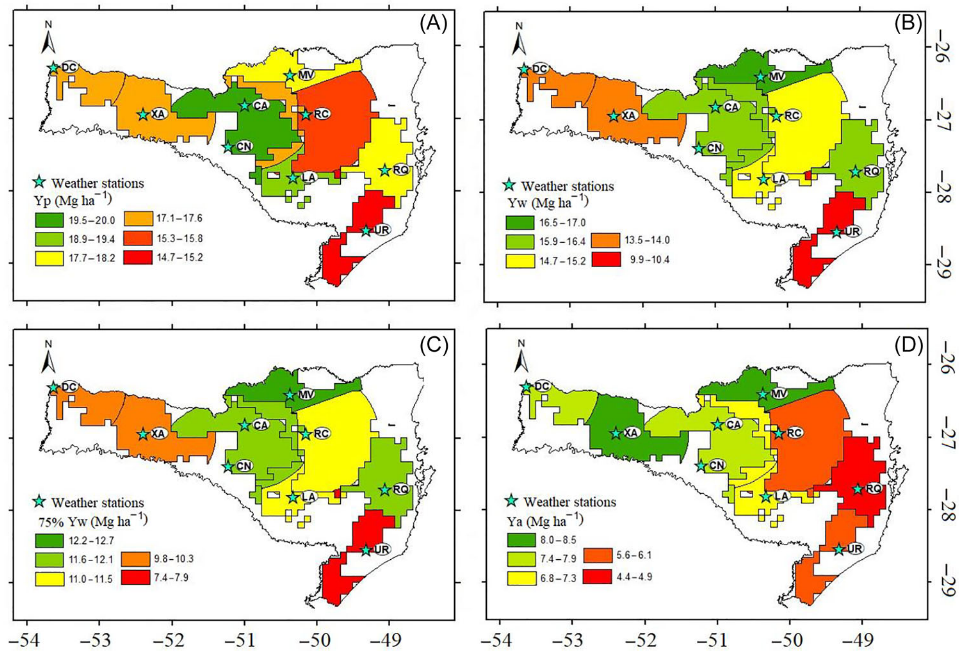

FIGURE 4 Maize yield potential (Yp) (A), water-limited yield potential (Yw) (B), attainable yield (75% of Yw) (C) for a 15-year period (2006–2020), and actual farmer yield (Ya) for a 5-year period (2016–2020) (D) in nine buffer zones (BZs) in the state of Santa Catarina, Brazil. The acronyms represent the reference weather stations (RWSs): Caçador (CA), Campos Novos (CN), Dionísio Cerqueira (DC), Lages (LA), Major Vieira (MV), Rancho Queimado (RQ), Rio do Campo (RC), Urussanga (UR), and Xanxerê (XA).

TABLE 2 Total yield gap (Ygt), water yield gap (Ygw), suboptimal management yield gap (Ygm), and attainable yield gap (Ygat) for maize during a 15-year period (from 2006 to 2020) in nine buffer zones in the state of Santa Catarina, Brazil. The acronyms represent the reference weather stations (RWSs): Caçador (CA), Campos Novos (CN), Dionísio Cerqueira (DC), Lages (LA), Major Vieira (MV), Rancho Queimado (RQ), Rio do Campo (RC), Urussanga (UR), and Xanxerê (XA).

	Ygt		Ygw		Ygm		Ygat	
Buffer zone	Mg ha^{-1}	% Yp	Mg ha^{-1}	%Yp	Mg ha^{-1}	% Yw	Mg ha^{-1}	% Yw
CA	10.2	58	1.6	9	8.6	54	4.6	29
CN	11.9	61	3.5	18	8.4	52	4.4	27
DC	9.5	55	3.5	20	6.0	44	2.6	19
LA	11.6	61	3.9	21	7.7	51	4.0	26
MV	9.4	53	1.0	6	8.4	50	4.2	25
RQ	13.1	74	1.8	10	11.3	71	7.3	46
RC	9.8	63	0.7	5	9.1	61	5.4	36
UR	8.7	59	4.3	29	4.4	42	1.8	17
XA	9.0	53	3.4	20	5.6	41	2.2	16

3.3 | Biophysical and management factors that cause yield gaps in maize fields

The mean yield of the 293 fields under consideration was 6.9 Mg ha^{-1}, representing an 8.7% increase relative to the average yield of Santa Catarina (6.3 Mg ha^{-1}) in the same growing season as reported by the Instituto Brasileiro de Geografia e Estatística (IBGE) (2024). The fields designated as HY field in Santa Catarina are yielding an average of 9.7 Mg ha^{-1}, which represents 65.1% of the Yw (Table 3). In contrast, fields classified as LY field are harvesting 4.1 Mg ha^{-1}, which means only 27.5% of the Yw (14.7 Mg ha^{-1}). In comparison, the yield of HY fields was 57.7% higher than that of LY fields.

A regression tree was constructed to hierarchically evaluate the influence of management factors on yield. The analysis identified that among the factors exhibiting a significant difference between HY and LY fields, the established plant population exerts the greatest influence on yield (Figure 5).

TABLE 3 Mean values of biophysical and management factors for high-yield (HY) and low-yield (LY) fields, with a mean yield of 9.7 and 4.1 Mg ha^{-1}, respectively. The difference between HY and LY (Δ) fields was evaluated using the *t*-test, Wilcoxon test (in cases where the distribution did not adhere to the normality assumption), and chi-squared test (for categorical variables).

Variables	Units	*n*	High-yield fields (HY)	Low-yield field (LY)	HY–LY	
Grain yield	Mg ha^{-1}	197	9.7	4.1	5.6	***
Sowing time	Date	197	Sep 20	Oct 04	−14.0	***
Established plants population	Thousand plants ha^{-1}	155	68.2	63.4	4.8	**
Time between lime application	Years	189	2.8	3.4	−0.6	***
N fertilizer rate	kg ha^{-1}	194	202.8	192.0	10.8	*
K_2O fertilizer rate	kg ha^{-1}	187	117.0	99.0	18.0	**
P_2O_5 fertilizer rate	kg ha^{-1}	174	83.2	61.5	21.8	**
pH	–	106	5.8	5.4	0.4	**
Herbicide	No. of applications	165	2.5	2.1	0.5	***
Insecticide	No. of applications	166	2.9	2.2	0.7	***
1° insecticide	No. of leaf	154	1.2	2.6	−1.4	***
Fungicide	No. of applications	92	1.0	0.4	0.6	***
1° fungicide	No. of leaf	51	8.4	7.1	1.3	NS
System						
No-tillage	% field	140	59.3	40.7	18.6	**
Conventional	% field	51	33.3	66.7	−33.3	**

Significance: *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$. NS, not significant.

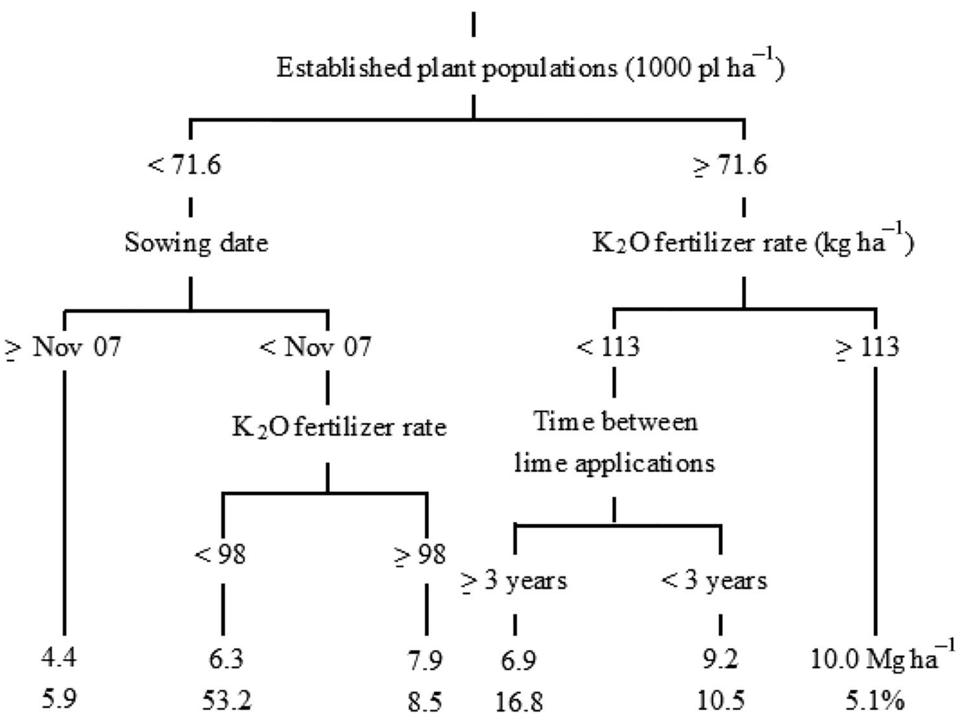

FIGURE 5 Regression tree showing a variation in maize grain yield in Santa Catarina, Brazil, due to crop management factors. Values within each terminal node indicate the average grain yield at a 13% moisture content basis (in Mg ha^{-1}) and the percentage of observations.

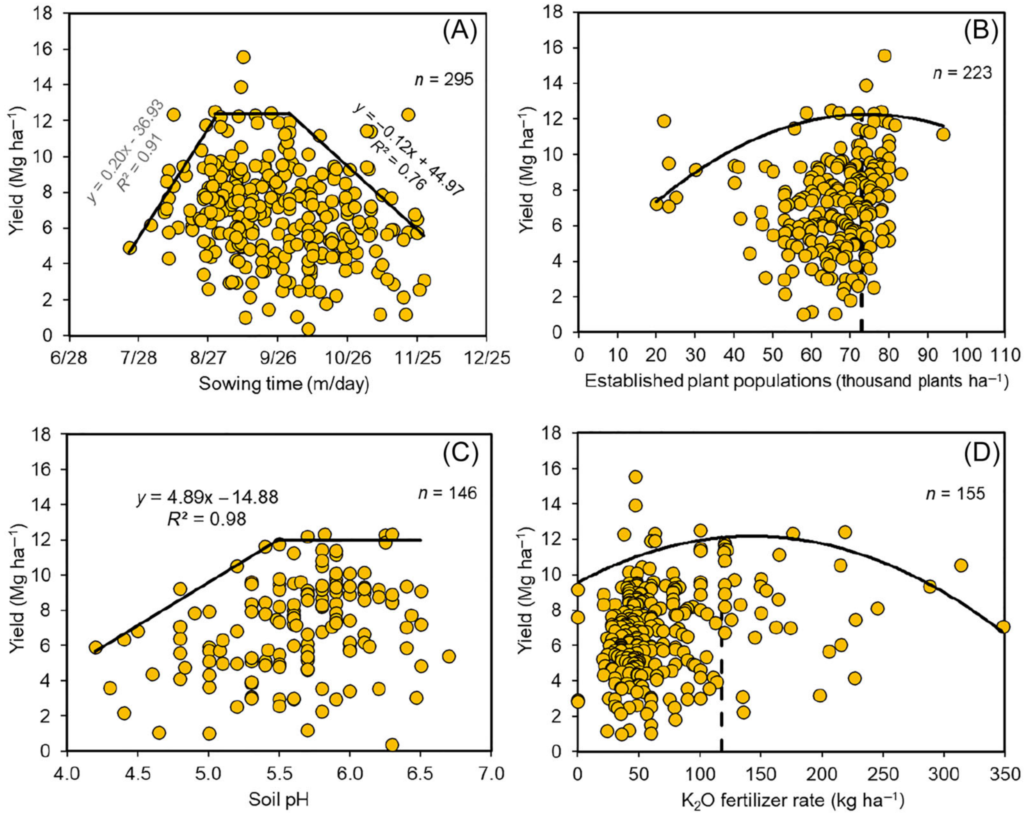

FIGURE 6 The relationship between biophysical and management factors on maize yield in Santa Catarina State, Brazil. The factors include sowing time (A), established plants population (B), soil pH (C), and K_2O fertilizer rate (D). The "*n*" denotes the number of fields that were monitored during the 2020/2021 and 2021/2022 crop seasons. The black line represents the boundary function. In panel A, the gray equation indicates the linear regression of yield loss per sowing day prior to August 31 and the black equation is the linear regression indicating yield loss per sowing day after October 2. In panels B and D, the dashed vertical black line indicates the maximum point of the boundary function. In panel C, the equation is the linear regression that indicates the loss of yield of fields with soil pH values below 5.5.

The subsequent yield level of crops with an established plant population of less than 71,600 plants per hectare is contingent upon the sowing time. The boundary function facilitated the identification of losses resulting from sowing that occurred either early or late (Figure 6A). The optimal period for maize sowing in the state of Santa Catarina is between August 31 and October 2. The results demonstrate that for each day preceding August 31, there was a notable decline in yield, amounting to an average reduction of 200 kg ha^{-1}. Conversely, for each day following October 2, the yield exhibited a more modest decline, with an average of 120 kg ha^{-1}. The established plant population, which enables the attainment of high yields (12 Mg ha^{-1}) in the maize fields of Santa Catarina, has a density of 73,000 plants per hectare (Figure 6B). A soil with a pH above 5.5 is conducive to high maize yield (12 Mg ha^{-1}) in the agricultural fields of Santa Catarina (Figure 6C).

Conversely, a negative linear relationship was observed at soil pH levels below 5.5, with a notable decline in maize yield. For every 0.1 pH unit below 5.5, there was a loss of 489 kg ha^{-1}. The highest maize yields were obtained with K_2O doses of 118 kg ha^{-1}. The mean soil potassium concentration was 153 mg dm^{-3}, with higher values observed in high-yielding fields (168 mg dm^{-3}) compared to low-yielding fields (139 mg dm^{-3}).

4 | DISCUSSION

The accuracy of models is classified as excellent, appropriate, middle, and poor, corresponding to NRMSE values less than 10%, 10%–20%, 20%–30%, and greater than 30%, respectively (Aghelpour & Varshavian, 2020). Moreover, in irrigated conditions, Sandhu and Irmak (2020) and Z. Liu et al. (2012) also observed an NRMSE of less than 22%, with simulated values exceeding observed values, which is in good agreement. The RMSE values for grain yield (Figure 3C) are consistent with those reported in Nebraska, where RMSE ranged from 1.2 to 2.0 Mg ha^{-1} (Sandhu & Irmak, 2020), except for the early maturity group. Nevertheless, for all cycles, the NRMSE was less than 16%, which is considered appropriate. In the US Corn Belt, the value identified for the NRMSE for grain yield was 18% (Morell et al., 2016). Therefore, the Hybrid-Maize model was deemed suitable for simulating the growth, development, and yield of maize in Santa Catarina, Brazil.

The Yp and Yw values simulated using the Hybrid-Maize model in the present study are consistent with those reported by Andrea et al. (2018), who conducted a study in a similar region using one weather station in Rio Grande do Sul and two in Paraná, near Santa Catarina. In that study, Yp ranged from 15.4 to 20.7 Mg ha^{-1}, while Yw ranged from 10.0 to 17.3 Mg ha^{-1}.

The elevated Ygm (41%–71% Yw) in Santa Catarina indicates the need for further research to enhance the technical efficiency of maize production, which has the potential to achieve yields approximately 75% of Yw through improved management practices. In Santa Catarina, 47% of row crops, including maize, are cultivated on fields averaging 17 ha in size (Instituto Brasileiro de Geografia e Estatística [IBGE], 2024). Farm size likely influences Ygm due to the technological levels present in these fields (B. Liu, Chen, et al., 2017). A correlation has been identified between the prevalence of large-scale agriculture and elevated levels of Ya and diminished levels of Yg in China (B. Liu, Chen, et al., 2017).

Among the surveyed fields, high-yield producers achieved yields ranging from 52% to 91% of the water-limited yield potential (Yw). The P95 yield of the dataset was 11.5 Mg ha^{-1}, which corresponds to 77% of the Yw for Santa Catarina (14.7 Mg ha^{-1}). This suggests that the yield gap attributable to suboptimal practices can be reduced, as the benchmark for attainable yield (Ygat, 75% of Yw) is already reached by some farmers.

HY fields yielded 57.7% more than LY fields. This trend is consistent with results from irrigated rice systems in Rio Grande do Sul State, Brazil, where HY fields produced 50% more than LY fields (Ribas et al., 2021). These findings highlight the potential of using HY fields as benchmarks to guide improvements in management practices on LY fields, thereby reducing the Ygm. If technical improvements were implemented and all fields reached 75% of Yw, maize production in Santa Catarina could increase by approximately 1.0 million Mg in the current rainfed growing area (246,000 ha). Furthermore, if all maize fields in the state received supplementary irrigation and achieved 75% of their irrigated yield potential, annual maize production could increase by 3.2 million Mg.

This demonstrates that intensification (higher yields per existing arable land) can be utilized as a means of satisfying a portion of the demand for grains while circumventing the deterioration of natural ecosystems and/or the necessity to import maize from external sources. However, a discrepancy exists between the global increase in average yield and the increase in yield among top producers in each region (Grassini et al., 2013). It is therefore imperative that producers, technicians, and decision-makers collaborate to facilitate the attainment of 75% of Yw across all fields. Achieving this requires not only understanding the specific characteristics of production environments but also gaining deeper insight into management practices across fields with varying technological levels. Based on this understanding, it becomes possible to identify the most effective strategies for fields with LYfield.

Survey data were used to identify factors limiting yield. Considering that the difference between average yields from surveyed fields and official IBGE data is only 8.7%, close to the 5% deviation observed in the correlation between survey and IBGE data for irrigated rice in southern Brazil (Ribas et al., 2021), it can be concluded that the survey data accurately represent the mean maize yield in Santa Catarina.

In the case of maize, the selection of an appropriate hybrid, the sowing date, plant density, and the management of fertilizer inputs are the primary factors influencing the attainment of higher yields (Chen et al., 2011). The management practices that differed between HY and LY fields were as follows: sowing date, established plant population, interval between lime applications, rate of fertilization, management of plant health, and practice of crop rotation (Table 3).

About plant health management, research on soybeans in the subtropical region of Brazil revealed that crops with higher yields were subjected to a greater number of fungicide applications (Winck et al., 2023). Our findings corroborate this result, as crops with high yields exhibited a greater frequency of applications for herbicides, insecticides, and fungicides. The timing of insecticide application is also an important factor. High-yielding crops that commence treatment when the plants have fewer leaves are associated with a higher incidence of corn leafhoppers in the 2020/2021 and 2021/2022 growing seasons.

The early stages of maize development are identified as the period when attacks by this pest have the greatest impact, thus necessitating control measures currently (Martins & Frizzas, 2021; Pozebon et al., 2022). However, no statistically significant difference was observed in the timing of the initial fungicide application. This is likely attributable to the findings of studies indicating that the period of greatest responsiveness to chemical disease control measures occurs at the tassel stage (Silva et al., 2021).

Regarding the cropping system, as has been demonstrated in the case of soybeans in Southern Brazil (Winck et al., 2023), our findings indicate that most crops that are cultivated using no-till methods (59.3%) are in the high-yield group. The use of no-till and cover crops has been shown to enhance soil characteristics, which can positively impact crop yield (Wulanningtyas et al., 2021).

The optimal sowing date is contingent upon the temperature, solar radiation, and water availability conditions to which the crop will be exposed during its development cycle (Lobell et al., 2009). The reduction in yield observed in fields sown before August 31 may be attributed to the potential impact of frost. In addition to the detrimental impact of low soil temperatures on crop emergence, which prolongs the exposure of seeds to pathogens and insects, thereby reducing the established plant population, the primary factor contributing to high yields in Santa Catarina is the optimal soil temperature range for seed germination.

Conversely, delayed sowing after October 2 results in the critical developmental stages (immediately preceding crop maturation) occurring during periods of unfavorable environmental conditions (Z. Liu et al., 2012; Pu et al., 2019; Zhao et al., 2015). In general, September sowing enables the crop to reach the R1 (silking) stage during December and January, when solar radiation availability peaks in southern Brazil. A comparable result was documented for soybeans in the subtropical region of Brazil, where the highest yields were attained when sowing occurred between September and November (Tagliapietra et al., 2021; Zanon et al., 2016).

Besides adjusting the critical periods to the months with the greatest availability of solar radiation, it is essential to ensure that leaf area is not a limiting factor to maximize the utilization of this resource (Tagliapietra et al., 2018). The enhanced yield potential of contemporary maize hybrids is linked to their capacity to withstand the deployment of elevated sowing densities (Assefa et al., 2018; Rizzo et al., 2022; Schwalbert et al., 2018). Plant density is a critical determinant of the leaf area index, which in turn influences the efficiency of solar radiation interception (G. Liu, Hou, et al., 2017). Moreover, the optimal plant density must be adapted to the specific production environment, hybrid, and management practices employed, as exceeding the optimal density for a given environment can result in a reduction in yield per plant and, subsequently, in field yield (Assefa et al., 2018; Friedrich et al., 2022).

Soil acidity represents a significant limiting factor for crop yields (Li et al., 2019). In the subtropical environment of southern Brazil, a loss of 151 kg ha^{-1} per 0.1 unit pH below 5.5 in soybean fields (Winck et al., 2023). Most soils in Santa Catarina exhibit acidic characteristics, with a pH value below 5.0 (Ernani et al., 2000). One of the principal strategies for achieving high crop yields in acidic soils is the application of lime. However, the interval between liming applications has been observed to influence soil pH. The results of Li et al. (2019) are in alignment with those of the present study, indicating that to effectively neutralize soil acidity, liming should be performed with a frequency of less than 3 years.

The decrease in field yield at pH levels below 5.5 is likely attributable to the correlation between soil pH and the accessibility of nutrients, and the presence of toxic elements, which can impede root growth (Li et al., 2019). One illustrative example is the availability of phosphorus (P). In acidic soils with high P content, as is the case in Santa Catarina, liming is an essential practice for ensuring the availability of this nutrient to plants (Antoniadis et al., 2015; Pavinato et al., 2020). Moreover, the presence of deeper roots is associated with an enhanced utilization of precipitation, which is crucial for rainfed crops, particularly during La Niña years in southern Brazil (Mulazzani et al., 2024).

A further factor about plant nutrition that emerged as a constraint on maize yield in Santa Catarina was potassium. While the mean soil K concentration (153 mg dm^{-3}) falls within the adequate range stipulated by regional guidelines, and the applied K_2O dose (118 kg ha^{-1}) appears to satisfy the potassium requirements for the current yield levels (which ranged from 4.7 to 8.5 Mg ha^{-1}), it is possible that this may not be sufficient to fully address the observed yield gap. Bender et al. (2013) reported that 202 kg ha^{-1} of K_2O is required to produce 12 Mg ha^{-1} of maize, suggesting that higher potassium inputs might be necessary in fields aiming to reach maximum yield potential. The attainable yield in rainfed fields ranged from 7.8 to 12.7 Mg ha^{-1}, suggesting that current fertilization practices may be insufficient to meet nutrient requirements in high-yielding conditions. It is imperative to underscore that this delineates a prevailing trend, and the adequacy of K fertilization ought to be appraised at the field level, considering both the soil K status and the regional yield potential. Consequently, the implementation of customized fertilization strategies may be imperative to facilitate additional increases in yield and to efficiently mitigate the yield gap.

An examination of Yp, Yw, and Yg is imperative for a comprehensive understanding of the factors that facilitate agricultural intensification and mitigate expansion into new areas. The findings of this study are of considerable value to the agricultural and livestock sectors of Santa Catarina, given the central role that maize plays in the production of livestock feed.

The selected monitored fields spanned major maize-producing regions of Santa Catarina, thereby representing spatial variability. A primary contribution of this study was the identification of factors associated with maize yield gaps, thus guiding future research, extension projects, and public policy. It is important to note that certain management strategies, which are intended to impose limitations, can result in minimal or no additional costs (e.g., sowing date) and can enhance resource use efficiency (e.g., plant population, potassium fertilization, and liming intervals). The findings indicate that the optimization of management practices can contribute to a sustainable augmentation in maize production, thereby addressing the escalating demand for cereals while concurrently ensuring the optimal utilization of existing agricultural land.

The Hybrid-Maize model demonstrated satisfactory performance in simulating maize growth, development, and yield under Santa Catarina conditions, as evidenced by observed data comparisons. However, as with all models, it relies on assumptions and simplifications that may not fully capture the field complexity and variability. To enhance the precision of the simulation, the most reliable soil and weather data available were utilized. These data were obtained from local researchers, extension agents, and an extensive weather station network.

A yield gap analysis was conducted at the BZ level, but yield variation factors were identified at the state level due to limited survey responses per BZ. The aggregation of data at the state level has the potential to obscure significant regional variations in management and production constraints. It is noteworthy that certain BZs incorporated within the simulations exhibited constrained survey coverage, a factor that may have occasioned a diminution in the representativeness of the findings about yield-limiting factors. It is recommended that future studies increase farmer survey data within each BZ, thereby enabling localized analyses and improving yield gap assessment precision. Despite its limitations, this study offers valuable preliminary insights into yield-limiting factors in Santa Catarina. The findings highlight key regional yield gaps and inform target management practices to enhance yield.

5 | CONCLUSIONS

The potential yield (Yp) and water-limited yield (Yw) of maize in Santa Catarina are 17.4 and 14.7 Mg ha^{-1}, respectively. The total yield gap (Yg) was estimated at 10.4 Mg ha^{-1}, with 2.7, 7.7, and 4.0 Mg ha^{-1} attributed to the water-limited yield gap, suboptimal management yield gap, and attainable yield gap, respectively. The findings indicate that most of the observed yield disparity is attributable to suboptimal management practices under rainfed conditions. The study identified the primary contributing factors as suboptimal plant population, inadequate potassium fertilization, delayed sowing, and protracted intervals between lime applications. The findings indicate the possibility of achieving a substantial increase in maize yields in Santa Catarina through the implementation of enhanced agronomic practices. This would help reduce yield disparities and promote more sustainable production systems.

AUTHOR CONTRIBUTIONS

Isabela Bulegon Pilecco: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; writing—original draft. **Leandro do Prado Ribeiro**: Data curation; funding acquisition; investigation; project administration; resources; writing—review and editing. **Matheus Cavalheiro Moreira de Camargo**: Data curation; writing—review and editing. **Cintia Piovesan Pegoraro**: Data curation; writing—review and editing. **Álvaro De Souza Carnellosso**: Data curation; writing—review and editing. **Nereu Augusto Streck**: Conceptualization; methodology; supervision; writing—review and editing. **Alencar Junior Zanon**: Conceptualization; formal analysis; investigation; methodology; project administration; resources; supervision; writing—review and editing.

ACKNOWLEDGMENTS

The authors thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for granting a scholarship to the first author. We also acknowledge the staff of EPAGRI/CEPAF for their support in conducting the field experiments. Finally, we thank the extension agents from the Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina (Epagri) and the members of the FieldCrops Team for their assistance in monitoring the maize fields through farmer surveys.

The Article Processing Charge for the publication of this research was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) (ROR identifier: 00x0ma614).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Isabela Bulegon Pilecco https://orcid.org/0000-0002-9089-8517

REFERENCES

Aghelpour, P., & Varshavian, V. (2020). Evaluation of stochastic and artificial intelligence models in modeling and predicting of river daily flow time series. *Stochastic Environmental Research and Risk Assessment*, *34*(1), 33–50. https://doi.org/10.1007/s00477-019-01761-4

Alvares, C. A., Stape, J. L., Sentelhas, P. C., De Moraes Gonçalves, J. L., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, *22*(6), 711–728. https://doi.org/10.1127/0941-2948/2013/0507

Antolin, L. A. S., Silva, E. H. F. M., Zanon, A. J., Ribeiro, B. S. M. R., & Marin, F. R. (2025). How much would irrigation increase maize production in Brazil? *Scientia Agricola*, *82*, 1–13. https://doi.org/10.1590/1678-992X-2024-0083

Antoniadis, V., Hatzis, F., Bachtsevanidis, D., & Koutroubas, S. D. (2015). Phosphorus availability in low-P and acidic soils as affected by liming and P addition. *Communications in Soil Science and Plant Analysis*, *46*(10), 1288–1298. https://doi.org/10.1080/00103624.2015.1033539

Assefa, Y., Carter, P., Hinds, M., Bhalla, G., Schon, R., Jeschke, M., Paszkiewicz, S., Smith, S., & Ciampitti, I. A. (2018). Analysis of long term study indicates both agronomic optimal plant density and increase maize yield per plant contributed to yield gain. *Scien-*

tific Reports, *8*(1), Article 4937. https://doi.org/10.1038/s41598-018-23362-x

Bender, R. R., Haegele, J. W., Ruffo, M. L., & Below, F. E. (2013). Nutrient uptake, partitioning, and remobilization in modern, transgenic insect-protected maize hybrids. *Agronomy Journal*, *105*(1), 161–170. https://doi.org/10.2134/agronj2012.0352

Breiman, L., Friedman, J. H., Olshen, R. A., & Stone, C. J. (1984). *Classification and regression trees*. Wadsworth.

Cassman, K. G., Dobermann, A., Walters, D. T., & Yang, H. (2003). Meeting cereal demand while protecting natural resources and improving environmental quality. *Annual Review of Environment and Resources*, *28*(1), 315–358. https://doi.org/10.1146/annurev.energy.28.040202.122858

Chen, X.-P., Cui, Z.-L., Vitousek, P. M., Cassman, K. G., Matson, P. A., Bai, J.-S., Meng, Q.-F., Hou, P., Yue, S.-C., Römheld, V., & Zhang, F.-S. (2011). Integrated soil–crop system management for food security. *Proceedings of the National Academy of Sciences of the USA*, *108*(16), 6399–6404. https://doi.org/10.1073/pnas.1101419108

Coelho, A. E., Sangoi, L., Balbinot, A. A., Kuneski, H. F., & Martins, M. C. (2022). Nitrogen use efficiency and grain yield of corn hybrids as affected by nitrogen rates and sowing dates in subtropical environment. *Revista Brasileira de Ciência do Solo*, *46*, e0210087. https://doi.org/10.36783/18069657rbcs20210087

Da S Andrea, M. C., Boote, K. J., Sentelhas, P. C., & Romanelli, T. L. (2018). Variability and limitations of maize production in Brazil: Potential yield, water-limited yield and yield gaps. *Agricultural Systems*, *165*, 264–273. https://doi.org/10.1016/j.agsy.2018.07.004

Di Rienzo, J. A., Casanoves, F., Balzarini, M. G., Gonzalez, L., Tablada, M., & Robledo, C. W. (2012). *InfoStat* (Versión 2012) [Computer software]. Universidad Nacioal de Córdoba. http://www.infostat.com.ar

EPAGRI (Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina). (2020). *Banco de dados de variáveis ambientais de Santa Catarina* (Documentos 310). Epagri.

Ernani, P. R., Nascimento, J. A. L., Campos, M. L., & Camillo, R. J. (2000). Influência da combinação de fósforo e calcário no rendimento de milho. *Revista Brasileira de Ciência do Solo*, *24*, 537–544. https://doi.org/10.1590/S0100-06832000000300007

French, R. J., & Schultz, J. E. (1984). Water use efficiency of wheat in a Mediterranean-type environment. I. The relation between yield, water use and climate. *Australian Journal of Agricultural Research*, *35*(6), 743–764. https://doi.org/10.1071/AR9840743

Friedrich, E. D., Ribeiro, B. S. M. R., Inklman, V. B., Pilecco, I. B., Streck, N. A., Bortoluzzi, M. P., Nied, A. H., & Zanon, A. J. (2022). Agronomic optimal plant density for corn in subtropical environments. *Pesquisa Agropecuária Brasileira*, *57*, e02963. https://doi.org/10.1590/S1678-3921.PAB2022.V57.02963

Ghisleni Ribas, G., Streck, N. A., Da Rosa Ulguim, A., Selau Carlos, F., Maus Alberto, C., Mazzuco De Souza, P., Bercellos, T., Puntel, S., & Zanon, A. J. (2021). Assessing factors related to yield gaps in flooded rice in southern Brazil. *Agronomy Journal*, *113*(4), 3341–3350. https://doi.org/10.1002/agj2.20754

Grassini, P., Eskridge, K. M., & Cassman, K. G. (2013). Distinguishing between yield advances and yield plateaus in historical crop production trends. *Nature Communications*, *4*(1), Article 2918. https://doi.org/10.1038/ncomms3918

Grassini, P., Thorburn, J., Burr, C., & Cassman, K. G. (2011). High-yield irrigated maize in the Western US Corn Belt: I. On-farm yield, yield potential, and impact of agronomic practices. *Field Crops Research*, *120*(1), 142–150. https://doi.org/10.1016/j.fcr.2010.09.012

Grassini, P., Van Bussel, L. G. J., Van Wart, J., Wolf, J., Claessens, L., Yang, H., Boogaard, H., De Groot, H., Van Ittersum, M. K., & Cassman, K. G. (2015). How good is good enough? Data requirements for reliable crop yield simulations and yield-gap analysis. *Field Crops Research*, *177*, 49–63. https://doi.org/10.1016/j.fcr.2015.03.004

Guimarães, A. G., Ceccon, G., Capristo, D. P., & Fachinelli, R. (2023). Dose of Azospirillum brasilense in single maize and intercropped with brachiaria in different soils. *Revista Brasileira de Ciências Agrárias*, *18*(2), e3097. https://doi.org/10.5039/agraria.v18i2a3097

Instituto Brasileiro de Geografia e Estatística (IBGE). (2024). *Sistema IBGE de Recuperação Automática—SIDRA*. http://www.sidra.ibge.gov.br/bda/pesquisas/pam/default.asp?o=18&i=P

Jacovides, C. P., & Kontoyiannis, H. (1995). Statistical procedures for the evaluation of evapotranspiration computing models. *Agricultural Water Management*, *27*(3–4), 365–371. https://doi.org/10.1016/0378-3774(95)01152-9

Li, Y., Cui, S., Chang, S. X., & Zhang, Q. (2019). Liming effects on soil pH and crop yield depend on lime material type, application method and rate, and crop species: A global meta-analysis. *Journal of Soils and Sediments*, *19*, 1393–1406. https://doi.org/10.1007/s11368-018-2120-2

Liu, B., Chen, X., Meng, Q., Yang, H., & van Wart, J. (2017a). Estimating maize yield potential and yield gap with agro-climatic zones in China—Distinguish irrigated and rainfed conditions. *Agricultural and Forest Meteorology*, *239*, 108–117. https://doi.org/10.1016/j.agrformet.2017.02.035

Liu, G., Hou, P., Xie, R., Ming, B., Wang, K., Xu, W., Liu, W., Yang, Y., & Li, S. (2017b). Canopy characteristics of high-yield maize with yield potential of 22.5 Mg ha− 1. *Field Crops Research*, *213*, 221–230. https://doi.org/10.1016/j.fcr.2017.08.011

Liu, Y., & Hwang, Y. (2015). Improving drought predictability in Arkansas using the ensemble PDSI forecast technique. *Stochastic Environmental Research and Risk Assessment*, *29*, 79–91. https://doi.org/10.1007/s00477-014-0930-3

Liu, Z., Yang, X., Hubbard, K. G., & Lin, X. (2012). Maize potential yields and yield gaps in the changing climate of northeast China. *Global Change Biology*, *18*(11), 3441–3454. https://doi.org/10.1111/j.1365-2486.2012.02774.x

Lobell, D. B., Cassman, K. G., & Field, C. B. (2009). Crop yield gaps: Their importance, magnitudes, and causes. *Annual Review of Environment and Resources*, *34*(1), 179–204. https://doi.org/10.1146/annurev.environ.041008.093740

Marcondes, T. (2023). *Síntese Anual da Agricultura de Santa Catarina 2022-2023*. Epagri/Cepa.

Marin, F., Zanon, A., Monzon, J. P., Andrade, J., Silva, E., Antolin, L., Martin, B. S., Ribas, G., Battisti, R., Heinemann, A., & Grassini, P. (2022). Agricultural intensification can help protect the Amazon Forest and reduce global warming. *Research Square*, https://doi.org/10.21203/rs.3.rs-1581982/v1

Martins, C., & Frizzas, M. R. (2021). Eight decades of *Dalbulus maidis* (DeLong & Wolcott) (Hemiptera, Cicadellidae) in Brazil: What we know and what we need to know. *Neotropical Entomology*, *51*(1), 1–17. https://doi.org/10.1007/s13744-021-00932-9

Minussi Winck, J. E., Tagliapietra, E. L., Schneider, R. A., Inklman, V. B., Nora, M. D., Savegnago, C., Paula, L. S., da Silva, M. R., Zanon, A. J., & Streck, N. A. (2023). Decomposition of yield gap of soybean in environment × genetics × management in Southern Brazil. *Euro-*

pean Journal of Agronomy, 145, 126795. https://doi.org/10.1016/j.eja.2023.126795

Monzon, J. P., Slingerland, M. A., Rahutomo, S., Agus, F., Oberthür, T., Andrade, J. F., Couëdel, A., Rattalino Edreira, J. I., Hekman, W., Van Den Beuken, R., Hidayat, F., Pradiko, I., Purwantomo, D. K. G., Donough, C. R., Sugianto, H., Lim, Y. L., Farrell, T., & Grassini, P. (2021). Fostering a climate-smart intensification for oil palm. *Nature Sustainability*, *4*(7), 595–601. https://doi.org/10.1038/s41893-021-00700-y

Morell, F. J., Yang, H. S., Cassman, K. G., Wart, J. V., Elmore, R. W., Licht, M., Coulter, J. A., Ciampitti, I. A., Pittelkow, C. M., Brouder, S. M., Thomison, P., Lauer, J., Graham, C., Massey, R., & Grassini, P. (2016). Can crop simulation models be used to predict local to regional maize yields and total production in the US Corn Belt? *Field Crops Research*, *192*, 1–12. https://doi.org/10.1016/j.fcr.2016.04.004

Mulazzani, R. P., Boeno, D., Ribeiro, B. S. M. R., Alves, A. F., Zanon, A. J., & Gubiani, P. I. (2024). Chemical constraints are the major limiting factor of root deepening in southern Brazil soils. *Geoderma Regional*, *38*, e00825. https://doi.org/10.1016/j.geodrs.2024.e00825

Pavinato, P. S., Cherubin, M. R., Soltangheisi, A., Rocha, G. C., Chadwick, D. R., & Jones, D. L. (2020). Revealing soil legacy phosphorus to promote sustainable agriculture in Brazil. *Scientific Reports*, *10*(1), Article 15615. https://doi.org/10.1038/s41598-020-72302-1

Pott, L. P., Amado, T. J. C., Schwalbert, R. A., Gebert, F. H., Reimche, G. B., Pes, L. Z., & Ciampitti, I. A. (2021). Effect of hairy vetch cover crop on maize nitrogen supply and productivity at varying yield environments in Southern Brazil. *Science of the Total Environment*, *759*, 144313. https://doi.org/10.1016/j.scitotenv.2020.144313

Pozebon, H., Stürmer, G. R., & Arnemann, J. A. (2022). Corn stunt pathosystem and its leafhopper vector in Brazil. *Journal of Economic Entomology*, *115*(6), 1817–1833. https://doi.org/10.1093/jee/toac147

Prado Ribeiro, L. D., Telles Amandio, D. T., Rakes, M., Belegante, F., Moresco, C., Nesi, C. N., Zanardi, A. M., Grützmacher, A. D., Bernardi, D., & Zanardi, O. Z. (2023). Insecticides for corn leafhopper management versus entomopathogenic fungal isolates: In vitro compatibility, physical-chemical interactions, and on-farm assessments. *Crop Protection*, *174*, 106417. https://doi.org/10.52945/rac.v34i2.1144

Pu, L., Zhang, S., Yang, J., Chang, L., & Bai, S. (2019). Spatio-temporal dynamics of maize potential yield and yield gaps in Northeast China from 1990 to 2015. *International Journal of Environmental Research and Public Health*, *16*(7), 1211. https://doi.org/10.3390/ijerph16071211

Ritchie, S. W., Hanway, J. J., & Benson, G. O. (1989). *How a corn plant develops*. Iowa State University of Science and Technology, Cooperative Extension Service.

Rizzo, G., Monzon, J. P., Tenorio, F. A., Howard, R., Cassman, K. G., & Grassini, P. (2022). Climate and agronomy, not genetics, underpin recent maize yield gains in favorable environments. *Proceedings of the National Academy of Sciences of the USA*, *119*(4), e2113629119. https://doi.org/10.1073/pnas.2113629119

Sandhu, R., & Irmak, S. (2020). Performance assessment of Hybrid-Maize model for rainfed, limited and full irrigation conditions. *Agricultural Water Management*, *242*, 106402. https://doi.org/10.1016/j.agwat.2020.106402

Schwalbert, R., Amado, T. J. C., Horbe, T. A. N., Stefanello, L. O., Assefa, Y., Prasad, P. V. V., Rice, C. W., & Ciampitti, I. A. (2018). Corn yield response to plant density and nitrogen: Spatial models and yield distribution. *Agronomy Journal*, *110*(3), 970–982. https://doi.org/10.2134/agronj2017.07.0425

Segatto, C., Souza, C. A., Fiori, M. A., Lajús, C. R., Silva, L. L., & Riella, H. G. (2023). Seed treatment with magnesium nanoparticles alters phenology and increases grain yield and mineral content in maize. *Australian Journal of Crop Science*, *17*(2), 165–178. https://doi.org/10.21475/ajcs.23.17.02.p3734

Silva, R. S., Campos, H. D., Ribeiro, L. M., Braz, G. B. P., Magalhães, W. B., & Bueno, J. N. (2021). Damage to the corn crop due to the reduction of leaf area by artificial defoliation and diseases. *Summa Phytopathologica*, *46*, 313–319. https://doi.org/10.1590/0100-5405/231093

Stuart, A. M., Pame, A. R. P., Silva, J. V., Dikitanan, R. C., Rutsaert, P., Malabayabas, A. J. B., Lampayan, R. M., Radanielson, A. M., & Singleton, G. R. (2016). Yield gaps in rice-based farming systems: Insights from local studies and prospects for future analysis. *Field Crops Research*, *194*, 43–56. https://doi.org/10.1016/j.fcr.2016.04.039

Tagliapietra, E. L., Streck, N. A., Da Rocha, T. S. M., Richter, G. L., Da Silva, M. R., Cera, J. C., Guedes, J. V. C., & Zanon, A. J. (2018). Optimum leaf area index to reach soybean yield potential in subtropical environment. *Agronomy Journal*, *110*(3), 932–938. https://doi.org/10.2134/agronj2017.09.0523

Tagliapietra, E. L., Zanon, A. J., Streck, N. A., Balest, D. S., Da Rosa, S. L., Bexaira, K. P., Richter, G. L., Ribas, G. G., & Da Silva, M. R. (2021). Biophysical and management factors causing yield gap in soybean in the subtropics of Brazil. *Agronomy Journal*, *113*(2), 1882–1894. https://doi.org/10.1002/agj2.20586

Van Ittersum, M. K., Cassman, K. G., Grassini, P., Wolf, J., Tittonell, P., & Hochman, Z. (2013). Yield gap analysis with local to global relevance—A review. *Field Crops Research*, *143*, 4–17. https://doi.org/10.1016/j.fcr.2012.09.009

Van Wart, J., Van Bussel, L. G. J., Wolf, J., Licker, R., Grassini, P., Nelson, A., Boogaard, H., Gerber, J., Mueller, N. D., Claessens, L., Van Ittersum, M. K., & Cassman, K. G. (2013). Use of agro-climatic zones to upscale simulated crop yield potential. *Field Crops Research*, *143*, 44–55. https://doi.org/10.1016/j.fcr.2012.11.023

Wulanningtyas, H. S., Gong, Y., Li, P., Sakagami, N., Nishiwaki, J., & Komatsuzaki, M. (2021). A cover crop and no-tillage system for enhancing soil health by increasing soil organic matter in soybean cultivation. *Soil and Tillage Research*, *205*, 104749. https://doi.org/10.1016/j.still.2020.104749

Yang, H., Grassini, P., Cassman, K. G., Aiken, R. M., & Coyne, P. I. (2017). Improvements to the hybrid-maize model for simulating maize yields in harsh rainfed environments. *Field Crops Research*, *204*, 180–190. https://doi.org/10.1016/j.fcr.2017.01.019

Yang, H. S., Dobermann, A., Lindquist, J. L., Walters, D. T., Arkebauer, T. J., & Cassman, K. G. (2004). Hybrid-maize—A maize simulation model that combines two crop modeling approaches. *Field Crops Research*, *87*(2–3), 131–154. https://doi.org/10.1016/j.fcr.2003.10.003

Zanon, A. J., Streck, N. A., & Grassini, P. (2016). Climate and management factors influence soybean yield potential in a subtropical environment. *Agronomy Journal*, *108*(4), 1447–1454. https://doi.org/10.2134/agronj2015.0535

Zebalho, C. S., Pilecco, I. B., Streck, N. A., Cardoso, P. D. S., Freitas, C. P. D. O. D., Vieira, E. A., Soares, M. F., Tagliapietra, B. L., Ferigolo, A. A., Swarowsky, A., Follmann, D. N., Souza, J. V. S. D., & Zanon, A. J. (2024). Assessing management factors limiting yield and starch content of cassava in the western Brazilian Cerrado. *Agronomy Journal*, https://doi.org/10.1002/agj2.21722

Zhao, Y., Chen, X., Cui, Z., & Lobell, D. B. (2015). Using satellite remote sensing to understand maize yield gaps in the North China Plain. *Field Crops Research*, *183*, 31–42. https://doi.org/10.1016/j.fcr.2015.07.004

How to cite this article: Pilecco, I. B., do Prado Ribeiro, L., Cavalheiro Moreira de Camargo, M., Piovesan Pegoraro, C., Carnellosso, Á. D. S., Streck, N. A., & Zanon, A. J. (2025). Identifying maize yield potential and farm yield gaps in Southern Brazil. *Agronomy Journal*, *117*, e70258. https://doi.org/10.1002/agj2.70258