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RESEARCH ARTICLE

Irrigated rice yield plateaus are caused by management factors in Argentina

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Abstract

Over the past 15 years, Argentina has experienced a consistent stagnation in rice grain yield, diverging from the substantial annual increases observed in other South American countries. It is important to understand the causes of this stagnation to take corrective measures to increase the productivity and competitiveness of Argentine rice farmers. This research incorporates data from ten growing seasons to explore rice yield improvements through enhanced management practices. Our study aims to determine the yield potential and yield gap and to identify key factors associated with yield losses in irrigated rice fields in Argentina. Yield and management practice data from farmers were collected via a survey that included 2470 site-year observations (2010–2020). The yield potential was simulated using the Oryza model. The yield gap was calculated as the difference between the yield potential and the average yield from the field. Our findings indicated that 22% of the current yield gap is due to the sowing date, 9% is associated with the adoption of rotation/succession, and 5% is associated with the early onset of irrigation up to the V3 stage. The implementation of these practices has demonstrated the potential to reduce the current yield gap from 48% to 33%. Additionally, previous work has shown that the amounts of N and K fertilizers influence the yield gap. Rice yield stagnation is limited by both low genetic progress and farmers' reluctance to adopt improved management practices. Hence, a 10-day shift toward early sowing in Argentina (high yield *versus* low yield) would result in a 510 kg ha^{-1} yield increase. Addressing these management issues illustrates the power of this approach for impact assessment to support policy and investment prioritization and for monitoring the impact of research and extension programs.

Keywords *Oryza sativa* L. · Yield potential · Yield gap · Crop management · Food security

1 Introduction

Argentina is the fifth-largest rice producer in the Americas, cultivating approximately 200 thousand hectares and producing 1.3 MMTs of rice annually (USDA 2020). Argentina holds a significant position in the global rice export market, ranking 13th worldwide and being the sixth-largest exporter outside of Asia (FAOSTAT 2022). Notably, rice production in Argentina is characterized by large-scale, mechanized operations and operates without government subsidies (Fig. 1). This substantial rice production is primarily concentrated in the northeast region of the country, spanning latitudes between 27°S and 34°S, where the climate is temperate to subtropical and humid (Fernandez et al. 2017).

Yield plateaus have been reported for several crops worldwide (Cassman and Grassini 2020; Peng et al. 2020). These plateaus in yield trends are particularly concerning

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Figure 1 Extensive and mechanized irrigated rice cropping system in Argentina. Photo credit: Cesar Eugenio Quintero.

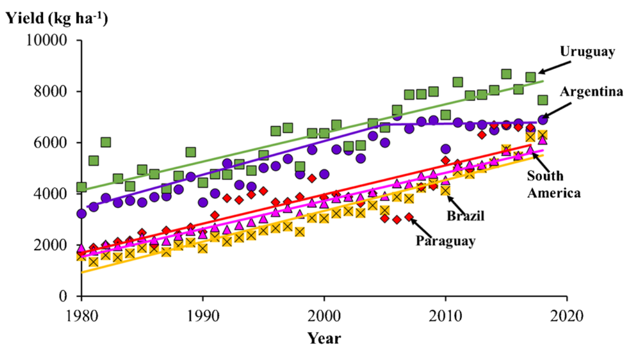

Figure 2 Overall yield trends of irrigated rice in Argentina, Brazil, Paraguay, Uruguay, and South America. Fitted linear regression models for Brazil (orange), Paraguay (red), Uruguay (green), and South America (pink) and quadratic plateaus for Argentina (purple) are shown. The data were visualized via GraphPad Prism (GraphPad Software, www.graphpad.com). Data source: FAOSTAT 2022.

in regions with the potential to become the future breadbaskets of the world, such as Argentina, owing to the ample availability of land, water, and solar radiation for agriculture (Bourne 2014; Cassman 1999). Although rice production in Argentina has plateaued over the past 15 years (see Fig. 2), rice yields in South America have increased by 1.5 Mg ha^{-1} during the same period (FAOSTAT 2022).

Investigating the yield gap in Argentina involves identifying key factors that limit yields and conducting a detailed analysis to pinpoint the specific elements contributing to the difference between potential (Yp) and actual (Ya) yields. Understanding these factors is crucial for devising targeted strategies to close the yield gap. Over the years, changes in crop yields in different parts of the world have been attributed to three main factors: genetic improvement, changes in management practices (such as fertilization and protection), and climate change (Grassini et al. 2015). The yield gap (Yg) is defined as the difference between the yield potential (Yp) and actual yield (Ya) (Lobell et al. 2009). Yp is determined by several factors, including solar radiation, temperature, genetics, and CO_2 concentration (van Ittersum et al. 2013). Yield gap analysis aims to meet future food demand with minimal environmental impact while maximizing profitability for farmers (Grassini et al. 2011; Heilmayr et al. 2020).

Yield gap studies in Argentina were initiated with sunflower crops (Hall et al. 2013) and expanded to include wheat, soybeans, and maize (Aramburu Merlos et al. 2015). For rice, the yield gap in Argentina is greater than 50%, and it has been shown that the gap could be reduced through better management practices (Meus et al. 2022). This information is particularly crucial for Argentina, which has experienced stagnant rice yields since 2005, whereas neighboring countries have seen increases in their rice production over that same period (see Fig. 1). Achieving yield potential in farmer fields is challenging, requiring extensive inputs and sophisticated management to eliminate yield-reducing factors, often leading to reduced profit and significant environmental impacts. Instead, reaching 75 to 85% of the simulated yield potential is considered a reasonable level of yield gap closure for farmers with adequate access to inputs, markets, and extension services (Lobell et al. 2009). The key question concerning the yield plateau is whether farmers have reached 75 to 85% of their yield potential (Lobell et al. 2009; Xavier et al. 2021) or whether deficiencies in farming practices limit yield increases, which helps identify constraints, inform decision-makers for improvement, and guide farmers in optimizing resource allocation. Understanding the proximity to the yield potential plateau enables the setting of realistic goals, the exploration of innovative technologies, and the fostering of continuous yield improvement. In this study, we used a large and robust farmer-reported dataset to identify factors related to the yield gap in flooded rice in

Corrientes Province, the main rice-producing area of Argentina. Furthermore, we used data over ten growing seasons to validate a rice simulation model using information that accurately reflects potential conditions.

The objectives of this study were to determine the yield potential and yield gap in flooded rice fields and to identify key factors associated with high-yield (HY) and low-yield (LY) fields in Argentina.

2 Material and methods

2.1 Identification of the causes of yield gaps

Yield and management practices data were collected during ten growing seasons (2010–2020) in flooded rice fields located in the lowlands of Corrientes Province in Argentina (where more than 50% of the rice in Argentina is grown) exclusively for the IRGA 424 RI variety (the most planted variety) (Fig. 2, Ribas et al. 2021), totaling 26 farmers and 2470 fields. The data collected over 10 years cover a total rice area of more than 130 thousand hectares, and each data point represents an average of 55 hectares. Digital surveys were completed, and the data included more than one field by farm, field location, average yield (13% grain moisture), crop management (e.g., sowing date, previous crop, pre-sowing weed control, etc.), and applied inputs (e.g., nutrient fertilizer, biocides, etc.) (Supplemental Table S1). Survey data were already input into a digital database, with subsequent removal of any spurious or incomplete entries. The long-term (10 yr) daily weather data required for simulating the irrigated yield potential via the Oryza (version 3) model (solar radiation and minimum and maximum temperature) were retrieved from two weather networks (INTA: https://siga.inta.gob.ar/, and SMN: https://www.smn.gob.ar/). A total of 14% of the meteorological data for running the Oryza model were missing, and these gaps were filled via data from NASA-POWER (http://power.larc.nasa.gov/).

We observed distinct weather variations between the coolest and warmest regions (Fig. 3 and 4). In the southern rice region (Gualeguaychú), the temperature is lower, and the radiation is greater compared with the northeast region (Posadas) (Fig. 4). The selection of rice production regions took into account climate differences to reflect current variability in rice yields via the methodology proposed by van Wart et al. (2013), a technique also applied in the Global Yield Gap Atlas Project. This classification focused on a specific climate factor crucial for flooded rice production:

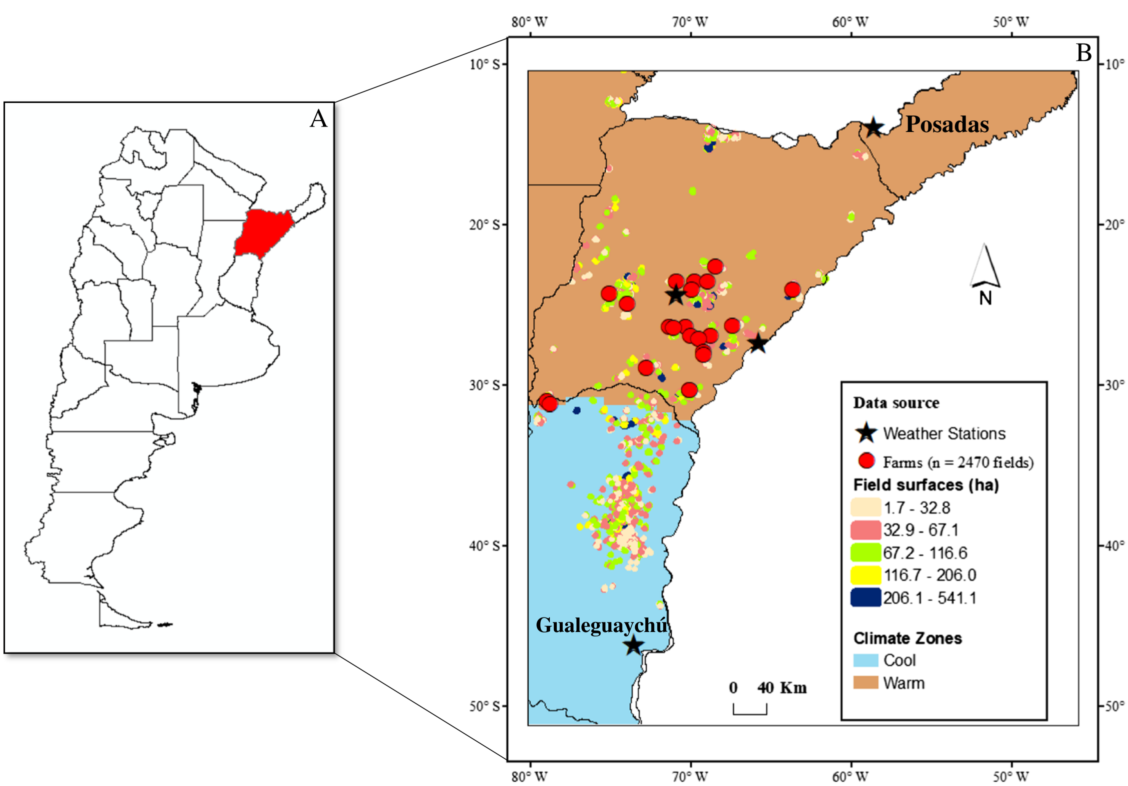

Figure 3 **A** Location of Corrientes Province in Argentina and (**B**) map of Corrientes Province in Argentina showing the locations of the 26-farm site-year observations (red solid circles). The stars indicate the locations of the weather stations used to simulate the rice yield potential. The rice surface area is shown in different colors (source: https://www.bolsacer.org.ar/Fuentes/siberd.php?Id=1509). This figure is based on the Global Yield Gap Atlas (GYGA, 2020 - https://www.yieldgap.org/argentina).

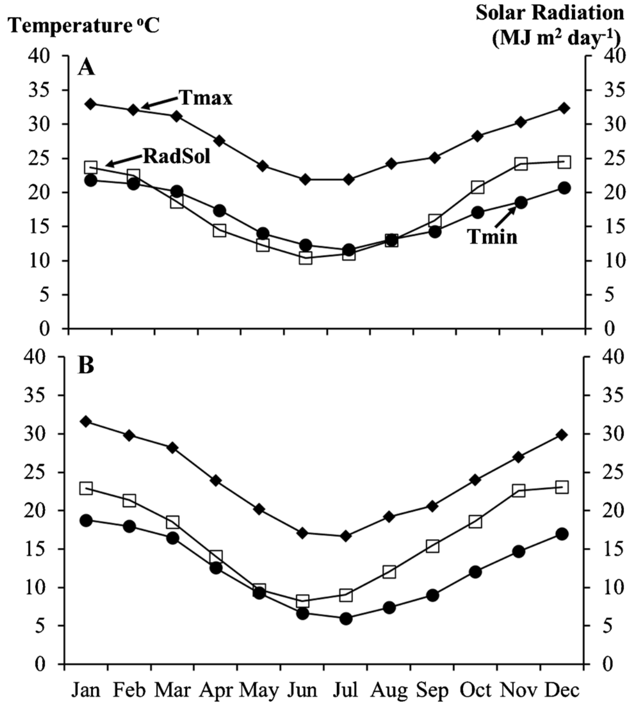

Figure 4 Monthly average incoming solar radiation (Radsol) and maximum (Tmax) and minimum temperatures (Tmin) for two locations representative of the (**A**) Posadas and (**B**) Gualeguaychú sites of the irrigated rice area in Argentina. Each data point represents the mean of the meteorological variables calculated from five years (Radsol) or 30 years (Tmax and Tmin) of measured weather data.

the accumulation of annual degree days (GDD). According to these criteria, rice-growing areas were classified into homogeneous climate zones (CZs) to analyze Yg, with no difference between CZs *versus* yield *versus* year (Fig. 3, van Wart et al. 2013). Figure 3 shows the geographical distribution of rice farms in Argentina and the two CZs. All of our field data (red circles) were collected within the warm climatic zone where more than 50% of Argentina's rice is produced.

2.2 Estimating yield potential and yield gap for each field plot of irrigated rice

The flooded rice Yp was simulated with the Oryza Version 3 model (Li et al. 2017). This process-based model simulates the development and growth of rice at a daily time step without constraints from abiotic factors, including water and nutrient availability, as well as biotic factors, such as insects, diseases, and weeds. The genetic coefficients in the Oryza model were previously calibrated via data derived from irrigated rice experiments conducted in Argentina (Meus et al. 2022). The yield potential for the rice variety IRGA 424 RI (https://www.argentina.gob.ar/sites/default/files/if_sisa_arroz_21-22.pdf) was simulated over ten growing seasons (2010–2020). This simulation considered measured daily weather data according to each field planting date, maturity group (intermediate, 135 days), and plant density of 200 plants m^{-2}. Further details on model calibration and simulations were published in the Global Yield Gap Atlas (GYGA, 2020; www.yieldgap.org/argentina) and in Meus et al. (2022). The yield gap (Yg) was determined by calculating the difference between the simulated yield potential (Yp) and the average yield achieved by farmers. To assess the variability in yield potential over the ten-year period (2010-2020), we estimated the interannual coefficient of variation (cv) for Yp.

The management yield gap was measured by investigating the interaction of environmental and management factors on the basis of the GYGA 10-year database (https://www.yieldgap.org/argentina), and the environmental gain was calculated to determine the environmental impact conditions on overall yield. A comparative assessment encompassing 16 years (from 2004/2005 to 2019/2020) of actual yield for Brazil, Uruguay, and Argentina was performed using data from the USDA, 2023 (https://apps.fas.usda.gov/psdonline/app/index.html#/app/advQuery) to highlight variations in yield gain among countries, offering insights into the regional dynamics of yield outcomes (Fig. 2). Additionally, we evaluated the genetic progress via data from reports that compared regional field trials conducted by INTA (https://ri.conicet.gov.ar/bitstream/handle/11336/166556/conicet_digital_nro.b972e7a1-398b-428e-9e61-7c6cf9c42011_v.pdf?sequence=5&isallowed=y) across locations and years in the Corrientes and Entre Ríos provinces. The genetic gain was estimated by leveraging data from these reports over four growing seasons (2013/2014, 2014/2015, 2017/2018, and 2018/2019) using cultivars released from 1984/1985 to 2018/2019 (Fig. 5), which contain information on the 10 most commonly grown cultivars in Argentina, including the IRGA 424 RI.

2.3 Statistical analysis

A regression tree analysis was used to determine the influence of previous crops *versus* other management practices on the rice yield gap via the "rpart" package in R (Ribas et al. 2021). Regression tree analysis was used because it renders a tree diagram output, with branches determined by splitting rules and a series of terminal nodes that contain the mean response (i.e., yield gap) and the number of observations that fall within each terminal node. The procedure initially grew maximal trees and then used a cross-validation technique (i.e., maxdepth) to prune the overfitted tree to an optimal size (Therneau and Atkinson 1997). A "caret" package in R was used to split the dataset into training (50%) and testing (50%) datasets. The training dataset was used to run the regression tree analysis, whereas the testing dataset was

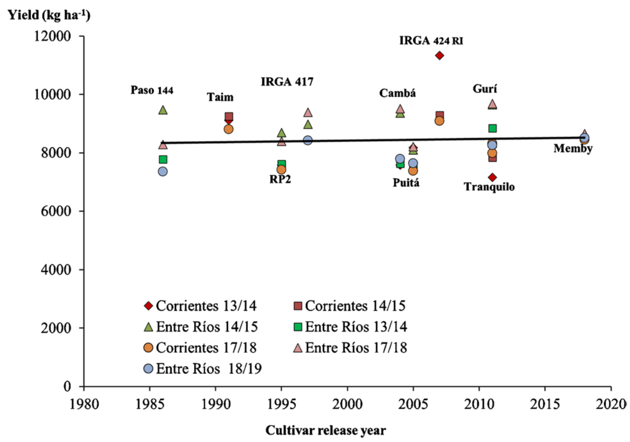

Figure 5 Genetic gain estimated by yield experiments and cultivar release year for irrigated rice in Argentina. The cultivars paso 144, TAIM, IRGA 417, RP2, Puitá, Cambá, Guri, Tranquilo, IRGA 424 RI, and Memby are positioned along the x-axis to indicate the year of their introduction/testing. The regression equation y = 5.620x - 2798.7 was derived from all the data points, revealing a significant average yield gain (genetic gain) of 5.62 kg ha^{-1} year^{-1} ($p < 0.05$). The cultivar standard errors throughout the release year ranged from 561 kg ha^{-1} (IRGA 424 RI) to 63 kg ha^{-1} (Memby).

used to estimate the mean square error (MSE) between the observed yield gap and the predicted yield gap. This methodology has advantages over other approaches in identifying the most important factors influencing yield gaps in crop management practices, determining nonlinear relationships, accommodating categorical variables, and offering easily interpretable results (Prasad et al. 2006; Tenorio et al. 2019), with practical application by enabling targeted interventions for maximizing crop yield and resource efficiency.

Rice fields were separated into high-yield (HY) (33% higher) and low-yield (LY) (33% lower) field classes each year (Grassini et al. 2015) based on their respective presence in the upper and lower terciles of the field yield distribution using Infostat Analysis software (Di Rienzo et al. 2011). Initial correlation analysis was conducted to identify relationships between actual field yield and reported variables (e.g., onset of irrigation, sowing date, weed treatment, previous crop, etc.). The difference between the HY and LY fields for each factor was assessed using t test. In cases where the distribution of observed values deviated from normality, the Wilcoxon test was used. The associations between the HY and LY field classes and other management variables, such as fertilizer inputs and fungicide application, were evaluated via the chi-square test. Fields with extremely low yields (< 3000 kg ha^{-1}) due to severe adversities such as hail or waterlogging were excluded from the analyses. One-way ANOVA was performed to examine the influence of soil preparation and in-season fungicide on rice yield. The GraphPad Prism statistical package (GraphPad software, Inc.) and Infostat software (Di Rienzo et al. 2011) were used for data analysis.

Quantile regression was applied to derive a boundary function for the relationship between farmer yield and sowing date delay based on the 90th percentile via the "quantreg" package in R (Tenorio et al. 2019; Ribas et al. 2021). Box plots generated via site−year observation fields, t tests, and factorial ANOVA were used to summarize yield variation in previous crops, pre-sowing weed control, soil preparation, and K_2O fertilizer.

3 Results and discussion

3.1 Rice yield increases with environment versus genetics versus management

Argentina, southern Brazil, and Uruguay share similar rice production systems, weather conditions and yield potentials. Additionally, the data indicate that Yp, which can be seen as an indicator of environmental factors, remained stable for those countries. From 2005 to 2020, the actual rice yield in Argentina did not increase or increased at a very low rate of 9 kg ha^{-1} year^{-1} (Fig. 2). In contrast, southern Brazil and Uruguay experienced more substantial growth, with yield rates of 76 and 80 kg ha^{-1} year^{-1}, respectively. To further elucidate this difference in growth rate, our data (Fig. 5) highlight a genetic gain in irrigated rice of 5.6 kg ha^{-1} year^{-1} in Argentina ($p < 0.05$), which would explain much of the increase in yield. Although we have not studied crop management practices for a specific cultivar through testing or modeling from both the past and present, the cultivars tested (Fig. 5) have shown similar yield potentials. However, management practices have not changed during recent years, suggesting that enhancing these practices is necessary to increase yields in fields. In addition, concerns have been raised in many rice-producing countries about the prospect of reaching a genetic yield ceiling, as highlighted by Cassman et al. (2003). In contrast, in the 1990s, Brazil achieved substantial yield increases, with a reported gain of 17 kg ha^{-1} (Soares et al. 2005). Over the past two decades, collaborative efforts among institutions such as the International Center for Tropical Agriculture (CIAT), the Instituto Rio-Grandense do Arroz (IRGA-Brazil), the Instituto de Investigaciones Agropecuarias (INIA-Uruguay), the Instituto Nacional de Tecnología Agropecuaria (INTA), the Fondo Latino americano para Arroz de Riego (FLAR), and the Latin America Hybrids Rice have enabled Argentina to register high-yield cultivars, contributing significantly to the genetic enhancement of rice production (Martínez et al. 2014). The question then is whether Brazil and Uruguay had greater genetic gains than Argentina did, which would explain their greater increases in yields. The studies revealed a genetic gain of 30-40 kg^{-1} ha^{-1} year^{-1} in Uruguay (www.ainfo.inia.uy/digital/bitstream/item/16493/1/st-262-p68-70.

pdf) and 70 kg^{-1} ha^{-1} year^{-1} in Brazil (https://ainfo.cnptia.embrapa.br/digital/bitstream/item/75312/1/moura.pdf). This information would explain a large part of the difference between Argentina and the other two countries. Specifically, the rice yield in Argentina is stagnant because of lower genetic gain, and improved management is available to farmers given that there is an important gap to explore.

3.2 Irrigated rice yield potential and yield gap in Argentina

The average Yp and Yg estimated for irrigated rice for our dataset in Argentina were approximately 14000 kg ha^{-1} and 44%, respectively. The variations in Yp and Yg across years are shown in Fig. 6. The yield potential was greater in 2012, reaching 15509 kg ha^{-1}, whereas it was relatively lower in 2019, at 12399 kg ha^{-1}. The Yp variability in Argentina is largely due to the El Niño−Southern Oscillation (ENOS), which causes variations in the solar radiation available during the growing season, especially during the reproductive and grain-filling phases. In our study, we found that the estimated yield potential (Yp) in Argentina is close to that in Uruguay (14000 kg ha^{-1}). Furthermore, the estimated yield potential exceeded values recorded in other temperate regions, including the United States (9400 kg ha^{-1}) and China (12400 kg ha^{-1}), as well as tropical regions such as Africa (9000 kg ha^{-1}) (Deng et al. 2019; Espe et al. 2016; Tseng et al. 2021; van Ittersum et al. 2016). However, our findings revealed that the Yp in Argentina is lower than that reported in Brazil (15100 kg ha^{-1}) (Ribas et al. 2021).

Although the estimated yield potential (Yp) for Argentina ranks among the highest globally, the actual yield is 56% of the Yp, and the yield gap (Yg) is 44%. Assuming reasonable access to resources, markets, and technical knowledge, an achievable goal to maximize profit is an actual yield of 80% of the Yp (Lobell et al. 2009). Therefore, our findings indicate that Argentina could close 36% of the yield gap through crop management improvements to maximize farmers' profit. These results contrast with those in the United States (27%Yg) (Deng et al. 2019; Espe et al. 2016), are similar to those in Uruguay (28% Yg) and Brazil (35% Yg), and are lower than those in Africa (60% Yg) (Tseng et al. 2021; van Ittersum et al. 2016).

The high coefficient of variation observed in Fig. 6 suggests significant opportunities for enhancing rice yields through management practices, especially during El Niño years such as the 2018/2019 season (CV = 28%). Interventions, such as adjusting the early sowing date, variety, and N inputs or introducing new crops into rice monocultures, can be explored to maximize yields in these fields (Ribas et al. 2021; Theisen et al. 2017).

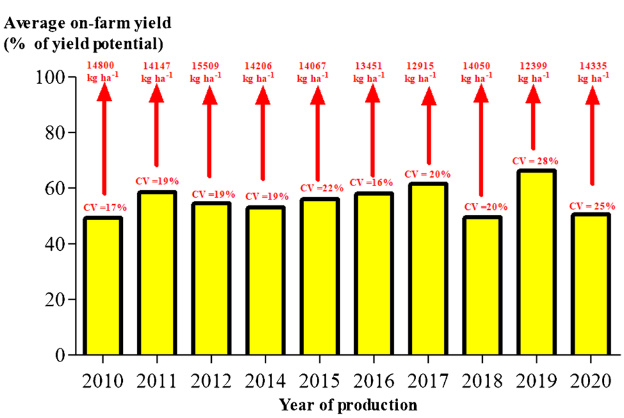

Figure 6 Rice yield potential (in red), actual yield (expressed in % of yield potential), and coefficient of variation in Corrientes province, a major rice production region of Argentina, over a 10-year period (2009/2010–2019/2020). Harvest data from 2012/2013 were not available. The coefficient of variation (CV) is shown for each year.

3.3 Understanding the factors affecting the yield gap in Argentina

The regression tree analysis provided valuable insights, explaining 35% of the rice yield gap. The most significant factor influencing this variability was the previous crop (Fig. 7). Additionally, the analysis revealed other key management factors contributing to the observed fluctuations in the rice yield gap, including pre-sowing weed control, potassium and nitrogen fertilizer application, and early sowing dates. When considering rice with crop rotation/succession, the yield gap was predominantly attributed to factors such as pre-sowing weed control, potassium and nitrogen fertilizer application, and sowing date. Overall, the lowest rice yield gap was achieved after crop rotation/succession in fields with pre-sowing weed control, in which nitrogen and potassium fertilizers were applied.

The average rice yield was 7% greater in rotation/succession than in rice sown on previous rice crops or monocultures (8326 and 7768 kg ha^{-1}, respectively) (Fig. 7). The rice yields in the rotation/ succession and rice monoculture systems represented 59% and 55% of the simulated Yp (14000 kg ha^{-1}), respectively. Considering the rice yield difference between the two sequences (560 kg ha^{-1}) and the current yield gapin continuous rice (6232 kg ha^{-1}), one could estimate that ca. 9% of the current yield gap is attributable to monoculture.

Closing the yield gap relies on improving multiple management practices simultaneously. In this study, we highlight some opportunities for decreasing the yield gap in irrigated rice in Argentina. A decrease in yield potential with delayed sowing in irrigated rice fields was reported by Ribas et al. (2021) for the subtropical region of Brazil. Our results revealed that the maximum yield plateau (11600 kg ha^{-1}) occurred before November 1st (Fig. 8A). The delay in the

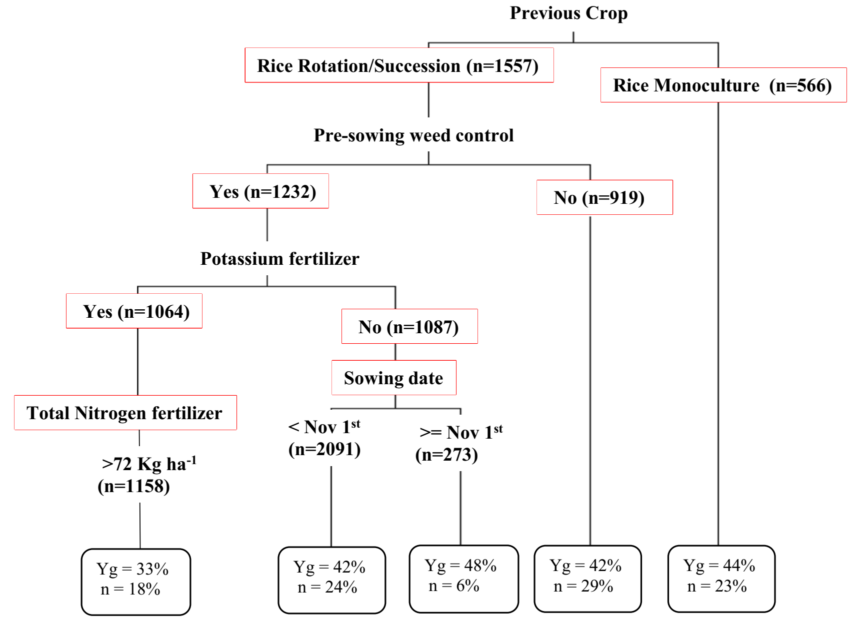

Figure 7 Regression tree model showing sources of variation in the grain yield of 2470 rice fields in Argentina over 10 years (2010-2020) due to management practices. The boxes are splitting nodes, with the bottom boxes representing terminal nodes. The values within each terminal node represent the average yield gap percentage (Yg), and n represents the percentage of observations at each terminal node.

sowing date after November 1st resulted in a yield loss of 99 kg ha^{-1} day^{-1}. Regarding the plateau in sowings before November 1st, it is hypothesized that farmers seek to obtain yields in fields to achieve maximum economic efficiency, which may depart actual yield from yield potential. The fields sown before and after November 1st represented 42% and 52%, respectively, of the simulated Yp (14000 kg ha^{-1}). Considering the rice yield difference between the two sowing dates (1400 kg ha^{-1}) and the current yield gap between the sowing dates (6050 kg ha^{-1}), we estimate that ca. 23% of the current yield gap is due to sowing before November 1st. However, more analyses are needed to quantify the climatic risk as a function of the climatic phenomena responsible for the annual variability in irrigated rice yield in Argentina, such as the El Nino−Southern Oscillation (ENSO) phenomenon (Meus et al. 2020). A cumulative yield probability function was performed for two sowing dates (before and after November 1st) (Fig. 8B). The probability of reaching yields below or above 7000 kg ha^{-1} (actual yield) is indicated by a vertical line (dashed yellow). The probability

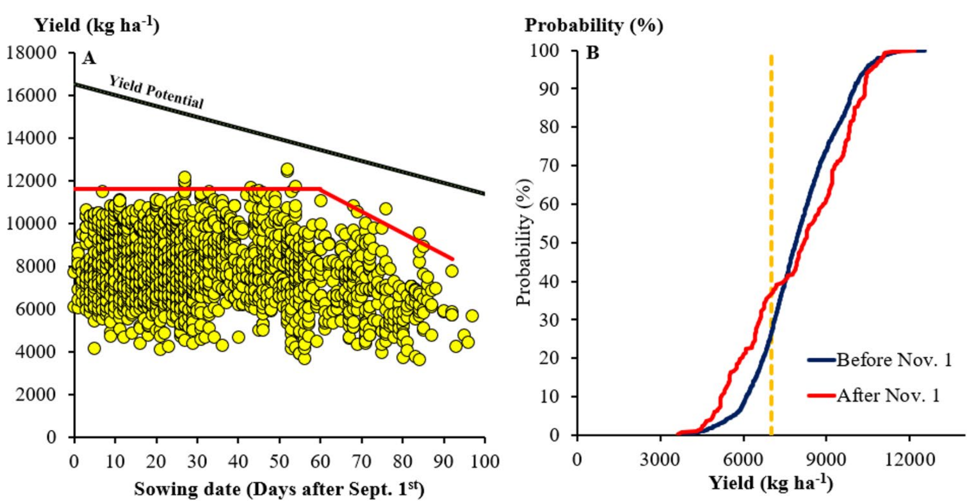

Figure 8 Rice yield as a function of sowing date across 2470 fields from 2009/2010 to 2020/2021 in Corrientes province, Argentina. (**A**) The black line represents the fitted trendline for yield potential by the Oryza model version 3 from September to December ($y = -51.497x + 16536$; coefficient of determination: $R^2 = 0.96$), and the red line corresponds to farmer yield data. The slope fitted in red was generated with data obtained after November 1st ($y = -99.236x+17472$; $R^2 = 0.86$). (**B**) A probability analysis is shown for a rice yield of 7000 kg ha^{-1} (dashed yellow line) as a function of sowing date.

analysis revealed a 40% chance of yields less than or equal to 7000 kg ha^{-1} in sowings after November 1st, whereas in sowings before November 1^{st,} the probability was 30%. Sowing dates after November 1st increased the Yg (Fig. 8A) due to a reduction in solar radiation during the grain-filling phase and an increase in disease pressure (Duarte Junior et al. 2021; Meus et al. 2020).

A comparison of high-yield and low-yield fields revealed a 53% greater yield for HY fields (Table 1). Clearly, reducing the yield gap requires improving combinations of various management practices in Argentina. The primary distinctions were associated with a range of management practices, including sowing date, weed control, onset of irrigation, nitrogen and potassium fertilizer, disease management, and soil conservation practices (involving soil preparation and the previous crop), as summarized in Table 1.

The average sowing dates for the HY and LY fields were September 27th and October 7th, respectively (Table 1). In HY fields sown 10 days earlier than LY fields, the cooler soil and air temperatures in early spring can slow the growth rate during the initial developmental stages, as the optimal temperature for emergence and vegetative development falls within the range of 20 °C to 35 °C (Fig. 4). This delay in growth and development also postpones the onset of irrigation (approximately 25 and 23 DAE), creating favorable conditions for weed emergence and competition. Weeds tend to germinate more readily at lower temperatures, underscoring the importance of effective weed control during the early stages of crop development (Yoshida 1981). The penalty may be related to the increase in weed competition, as reported by consultants in this study. This highlights an opportunity to increase yield by initiating irrigation early, when the plant is expected to have 2-3 leaves. This early irrigation strategy aims to mitigate the impact of delayed growth and optimize conditions for crop development, potentially improving overall yield (Table 1). According to Table 1, the onset of irrigation at 25 and 23 DAE represented 56% and 58%, respectively, of the Yp (14000 kg ha^{-1}). Considering the rice yield difference between the onset of irrigation (300 kg ha^{-1}) and the current yield gap (6044 kg ha^{-1}), we estimate that ca. 5% of the current yield gap is due to the onset of irrigation.

Table 1 Comparison of rice grain yield, management practices, and applied inputs between the highest terciles of field yields (HY) and lowest terciles (LY) of irrigated rice fields in Argentina. The values indicate the mean differences (HY–LY) between the upper and lower yield terciles (p<0.01***). DAE – Days after crop emergence. DOY – Days of the year. Cycle – Emergence to harvest.

Variables	Units	High-yield Fields (HY)	Low-yield Fields (LY)	HY-LY	
Grain yield	kg ha^{-1}	9579	6276	3303	***
Onset Irrigation	DAE	25	23	2	***
Sowing date	DOY	271	281	-10	***
Sowing density	kg ha^{-1}	96	103	-8	***
Crop cycle	days	142	132	10	***
Continuous rice	%	40	60	-20	***
Crop rotation	%	56	44	11	***
Fallow	%	64	36	29	***
Pasture	%	67	33	34	***
Conventional soil tillage	%	78	22	56	***
Minimum soil tillage	%	35	65	-30	***
Pre-sowing weed control	%	76	24	52	***
Foliar fungicide	%	80	20	60	***
Foliar Insecticide	%	78	22	56	***
K_2O fertilizer	kg ha^{-1}	93	71	22	***
Soil-N	kg ha^{-1}	70	45	25	***
Topdressing N fertilizer	kg ha^{-1}	76	86	-10	***
Total N (soil+topdressing)	kg ha^{-1}	146	132	14	***

Additionally, we observed that farmers are applying suboptimal doses of K fertilizer in their fields. Fields with relatively high yields use 22 kg ha^{-1} more K_2O. The total amount of nitrogen (N) was 14 kg ha^{-1} greater in HY fields. However, the amount applied as topdressing was 10 kg ha^{-1} lower in HY fields than in LY fields, indicating that nitrogen extraction from the soil may be occurring, as previously observed in soybean fields in Argentina (Koritschoner et al. 2023). We did not perform detailed analyses on N inputs and nitrogen use efficiency (NUE), but we hypothesize that farmers should first increase NUE with improved crop management practices, such as rotation with legume cover crops (Ogoshi et al. 2018), and then input N fertilizer according to sowing date, variety, field, and year (ENOS) (Duarte Junior et al. 2021).

The interaction effect between pre-sowing weed control and soil preparation × the previous crop was significant ($p < 0.05$). Despite the small yield differences between pre-sowing weed control and no pre-sowing weed control (2.6%, 8295 kg ha^{-1} vs 8076 kg ha^{-1}), the relationship between them was strong (p < 0.05) (Fig. 9A and B). Pre-sowing weed control plays a key role in mitigating weed competition for resources, ensuring that crops receive optimal sunlight, water, and nutrients.

The greatest yield difference was observed between the tillage fields and the minimum tillage or direct sowing fields (1261 kg ha^{-1}, Fig. 9B). Tillage preparation aids in the creation of an environment conducive to successful crop establishment by breaking up soil clumps, enhancing aeration, and facilitating effective herbicide application. Additionally, tillage for rice cultivation is often associated with extensive cattle grazing systems (Agostinetto et al. 2010). Pasture or

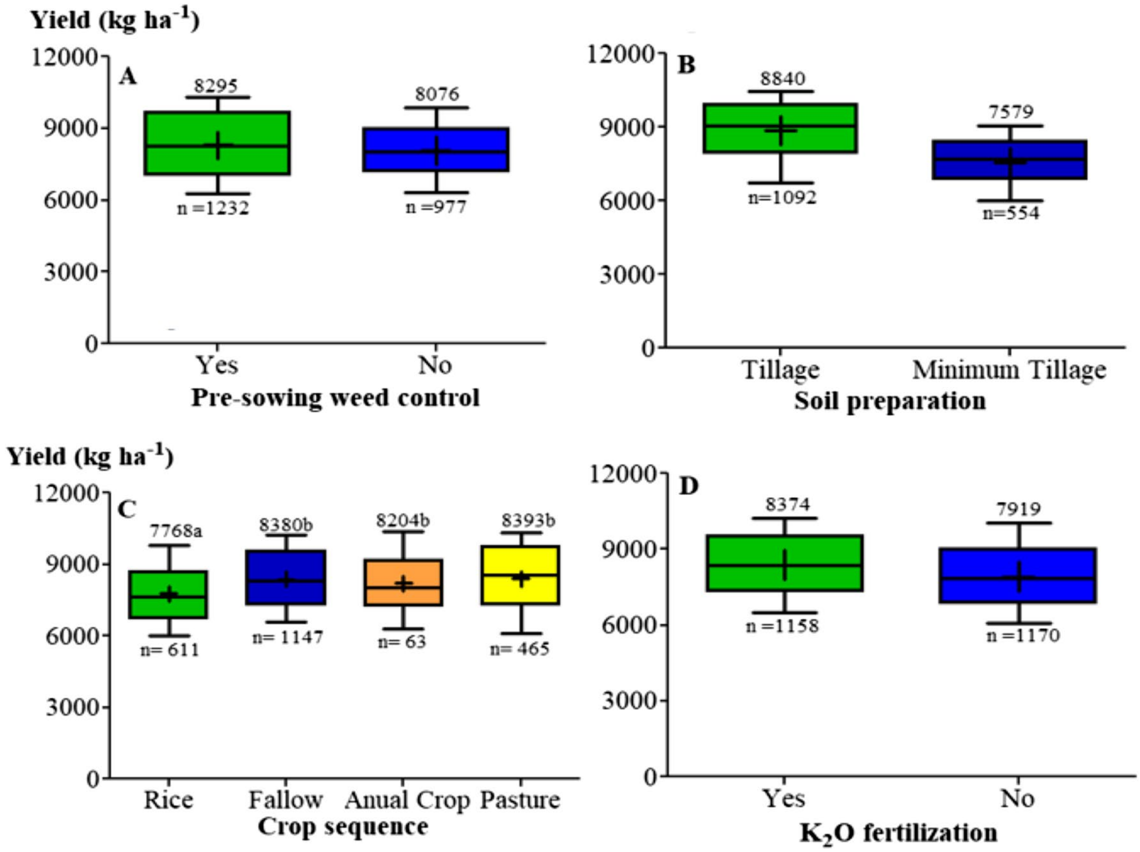

Figure 9 Box plots for (**A**) pre-sowing weed control (*difference* = 218 kg ha^{-1}, $p < 0.001$), (**B**) soil preparation (*difference* = 1261 kg ha^{-1}, $p < 0.001$), (**C**) crop sequence, and (**D**) topdressing K_2O fertilization (*difference* = 454 kg ha^{-1}, $p < 0.001$). Boxes delimit the 25th and 75th percentiles, whereas whiskers represent the 90th and 10th percentiles. The number of observations (n), median (horizontal line), and mean (+) are shown. The statistical significance of the difference in rice yield between crop sequences was evaluated via ANOVA, and t test results are shown.

fallow periods in fields not only help with weed management but also allow for soil regeneration and nutrient replacement. This period of rest provides a break in continuous cultivation, preventing the build-up of certain pests and diseases. The synergistic effect of these practices optimizes the seedbed for planting, minimizes weed interference, and promotes overall soil health (Chirinda et al. 2018). By combining pre-sowing weed control, tillage, and pasture or fallow practices, farmers can increase yield, foster sustainable land management, and achieve a balance between maximizing yields and preserving the long-term health of fields. As noted by Macedo et al. (2022) in Uruguay, the integration of rice and pastures with livestock achieves the best combination of stability across profitability and environmental performance, thus mitigating vulnerability to external stressors.

Although crop rotation is not widely employed in rice fields, it plays a crucial role, increasing rice yield by 5% compared with monocultures (8204 vs 7768 kg ha^{-1}) (Fig. 9C). Rice crop rotation, particularly when directly sown with minimum tillage, enables earlier sowing than monocultures do (Agostinetto et al. 2010; Goulart et al. 2020). This practice not only reduces the weed bank in the soil but also offers various benefits. However, despite these advantages, farmers are constrained in adopting crop rotation due to high interannual profit variation, risks associated with water deficit or excess water in lowland environments, and logistical challenges in altering current farm practices (Ribas et al. 2021).

In HY fields, there was an 80% greater use of fungicides than in LY fields. In summary, while the combination of rice cultivars with longer development cycles (142 d) at earlier sowing dates results in greater yield potential, the management of diseases, insects, and adverse conditions ultimately differentiates HY and LY rice fields in Argentina. The benefit of fungicides may only be expected in growing seasons with unfavorable weather conditions (Delmotte et al. 2011). The effect of fungicide is year dependent, as there was a difference in 3 out of 7 years (2010/2011, 2013/2014, 2018/2019; $p < 0.05$) between fields that did not receive any spraying and those that were sprayed with fungicides. This result may be associated with the sowing date (in the early season, there is low disease pressure), weed control (minimizing disease vectors), and weather conditions (El Niño or La Niña events affect rainfall and temperature patterns) (Ribas et al. 2021).

Indeed, closing the yield gap presents a challenge that hinges on the simultaneous improvement of multiple management practices. Some important factors of rice production, such as efficiency in weed control and irrigation, could not be assessed in our study. These problems frequently cause reduced yields in sectors where irrigation does not reach a permanent water table. Another relevant aspect that was not explored here is the use of higher rates of fertilizers. Nutrients are a factor in increasing yield, and higher doses of fertilizers surely reduce the yield gap (Andrade et al. 2017; Yuan et al. 2019).

A major contribution of this study was the identification of factors associated with the Yg in rice, which can provide Argentinean farmers with a framework for fine-tuning management practices with no or low cost increases. For example, our database shows that rice was sown, on average, 10 d earlier in HY fields than in LY fields. Given the overall yield penalty of 51 kg ha^{-1} per day delay in sowing reported for rice in Argentina (Fig. 8A), one could estimate a yield increase of 510 kg ha^{-1} as a result of earlier sowing in HY fields than in LY fields. This yield increase accounted for ca. 15% of the difference in average rice yield between the HY and LY fields (3303 kg ha^{-1}; Table 1). Hence, the rice Yg in Argentina can be decreased by adjusting one or more of the following management practices: (a) sowing date before November 1st (22% of the current yield gap is attributable to the sowing date), (b) adopting rotation/succession (accounting for an average rice yield increase of 9%), (c) early onset of irrigation up to V_3 stages (accounting for a 5% yield increase), (d) applying higher amounts of K fertilizer, and (e) enhancing NUE through improved crop management practices.

The identification of most factors related to the rice Yg illustrates the practical applications of this approach to guide Argentinean farmers and investment and policy decision-makers for monitoring the impact of research and extension programs. Future research should also explore the influence of limiting factors, particularly the efficiency of weed control, irrigation, and nutrients, on rice yields. It is crucial to expand upon the yield gap analysis presented here by conducting sustainability assessments that consider profitability, resource-use efficiency, and the interplay among these indicators in South America (Rizzo et al. 2021).

4 Conclusions

The main yield gap causes were determined in the flooded rice of Argentina. This research incorporates data from ten growing seasons to explore rice yield improvement through enhanced management practices. Our study revealed that rice yield has stagnated in Argentina during the last 15 years, which is due mainly to low genetic progress (5.6 kg^{-1} ha^{-1} y^{-1}) and factors related to management. Our database revealed a yield increase of 510 kg ha^{-1} as a result of sowing 10 days earlier in HY fields than in LY fields. Hence, to quickly break from the yield plateau, Argentinean farmers must adopt simple, low-cost management practices wherever possible, such as early sowing, avoiding monoculture, tilling the soil, incorporating potassium fertilizer, increasing nitrogen use efficiency, and using fungicides. These practices reduce the current yield gap from 48% to 33%.

The low input efficiency may be influenced by socioeconomic and political factors that impact the overall profitability of rice production in Argentina. However, further investigations are needed to explore these underlying factors. The insights gained from this study extend beyond Argentina and are relevant for rice farmers worldwide. These findings can serve as valuable guidance for setting research and extension program priorities at the local and regional levels. By addressing these management issues, we can work toward increasing rice yields, not only in Argentina but also worldwide, contributing to food security and sustainable agricultural practices on a global scale.

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Authors' contributions All the authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Lorenzo Dalcin Meus, Cesar Eugenio Quintero, Michel Rocha da Silva, Nereu Augusto Streck, Ivan Ricardo Carvalho, Maurício Fornalski Soares, and María de Los Angeles Zarmero. Giovana Ghisleni Ribas and Alencar Junior Zanon spearheaded the writing of the manuscript, actively contributing to its creation and development. All the authors commented on previous versions of the manuscript. All the authors read and approved the final manuscript.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Code availability Not applicable

Declarations

Ethics approval Not applicable

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication The authors affirm that the human research participants provided informed consent for publication of the images.

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References

Agostinetto D, Galon L, Silva JMBV, Tironi SP, Andres A (2010) Interferência e nível de dano econômico de capim-arroz sobre o arroz em função do arranjo de plantas da cultura. Plan Dan 28:993–1003. https://doi.org/10.1590/S0100-83582010000500007

Andrade JF, Poggio SL, Ermacora M, Satorre EH (2017) Land use intensification in the Rolling Pampa, Argentina: Diversifying crop sequences to increase yields and resource use. Eur J Agron 82:1–10. https://doi.org/10.1016/j.eja.2016.09.013

Aramburu Merlos F, Monzon JP, Mercau JL, Taboada M, Andrade FH, Hall AJ, Jobbagy E, Cassman KG, Grassini P (2015) Potential for crop production increase in Argentina through closure of existing yield gaps. Field Crops Res 184:145–154. https://doi.org/10.1016/j.fcr.2015.10.001

Bourne JK Jr (2014) The next breadbasket. Nat Geo 226:46–77 (ISSN 0027-9358)

Cassman KG (1999) Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. PNAS 96:5952–5959. https://doi.org/10.1073/pnas.96.11.5952

Cassman KG, Grassini P (2020) A global perspective on sustainable intensification research. Nat Sustain 3:262–268. https://doi.org/10.1038/s41893-020-0507-8

Cassman KG, Dobermann A, Walters DT, Yang H (2003) Meeting cereal demand while protecting natural resources and improving environmental quality. Annu Rev Environ Resour 28:315–358. https://doi.org/10.1146/annurev.energy.28.040202.122858

Chirinda N, Arenas L, Katto M, Loaiza S, Correa F, Isthitani M, Loboguerrero AM, Martinez-Baron D, Graterol E, Jaramillo S, Torres CF, Arango M, Guzman M, Avila I, Hube S, Kurtz DB, Zorrilla G, Terra J, Irisarri P, Tarlera S, LaHue G, Scivittaro WB, Noguera A, Bayer C (2018) Sustainable and low greenhouse gas emitting rice production in Latin America and the Caribbean: A review on the transition from ideality to reality. Sustain 10:671. https://doi.org/10.3390/su10030671

Delmotte S, Tittonell P, Mouret JC, Hammond R, LopezRidaura S (2011) On farm assessment of rice yield variability and productivity gaps between organic and conventional cropping systems under Mediterranean climate. Eur J Agron 35:223–236. https://doi.org/10.1016/j.eja.2011.06.006

Deng N, Grassini P, Yang H, Huang J, Cassman KG, Peng S (2019) Closing yield gaps for rice self-sufficiency in China. Nat Commun 10:1–9. https://doi.org/10.1038/s41467-019-09447-9

Di Rienzo JA, Casanoves F, Balzarini MG, González L, Tablada M, Robledo CW (2011) InfoStat versión 2011. Grupo InfoStat, FCA, Universidad Nacional de Córdoba, Argentina, vol 8, pp 195–199. http://www.infostat.com.ar

Duarte Junior A, Streck N, Zanon A, Ribas GG, Silva M, Cera J, Nascimento M, Pilecco I, Puntel S (2021) Rice yield potential as a function of sowing date in Southern Brazil. Agron J 113:1–12. https://doi.org/10.1002/agj2.20610

Espe MB, Cassman KG, Yang H, Guilpart N, Grassini P, Van Wart J, Andres M, Beighley D, Harell D, Liscombe S, Mckenze K, Mutters R, Wilson LT, Linquist BA (2016) Yield gap analysis of US rice production systems shows opportunities for improvement. Field Crops Res 196:276–283. https://doi.org/10.1016/j.fcr.2016.07.011

FAOSTAT (2022) Crops and livestock products. https://www.fao.org/faostat/en/#data/QCL. Accessed Oct 2022

Fernandez JPR, Franchito SH, Rao VB, Lopart M (2017) Changes in Koppen-Trewartha climate classification over South America from RegCM4 projections. Atmos Sci Lett 18:427–434. https://doi.org/10.1002/asl.785

Goulart RZ, Reichert JM, Rodrigues MF (2020) Cropping poorly-drained lowland soils: Alternatives to rice monoculture, their challenges and management strategies. Agric Syst 177:102715. https://doi.org/10.1016/j.agsy.2019.102715

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

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

Hall AJ, Feoli C, Ingaramo J, Balzarini M (2013) Gaps between farmer and attainable yields across rainfed sunflower growing regions of Argentina. Field Crops Res 143:119–129. https://doi.org/10.1016/j.fcr.2012.05.003

Heilmayr R, Rausch LL, Munger J (2020) Brazil's Amazon Soy Moratorium reduced deforestation. Nat Food 1:801–810. https://doi.org/10.1038/s43016-020-00194-5

Koritschoner JJ, Hulse JIW, Cuchietti A, Arrieta EM (2023) Spatial patterns of nutrients balance of major crops in Argentina. Sci Total Environ 858:159863. https://doi.org/10.1016/j.scitotenv.2022.159863

Li T, Angeles O, Marcaida M, Manalo E, Manalili MP, Radanielson A, Mohanty S (2017) From ORYZA2000 to ORYZA (v3) An improved simulation model for rice in drought and nitrogendeficient environments. Agr Forest Meteorol 237:246–256. https://doi.org/10.1016/j.agrformet.2017.02.025

Lobell DB, Cassman KG, Field CB (2009) Crop yield gaps: Their importance, magnitudes, and causes. Annu Rev Environ Resour 34:179–204. https://doi.org/10.1146/annurev.environ.041008.093740

Macedo I, Roel A, Velazco JI, Bordagorri A, Terra JA, Pittelkow CM (2022) Intensification of rice-pasture rotations with annual crops reduces the stability of sustainability across productivity, economic, and environmental indicators. Agric Syst 202:103488. https://doi.org/10.1016/j.agsy.2022.103488

Martínez CP, Torres EA, Chatel M, Mosquera G, Duitama J, Ishitani MM, Dedicova B, Tohme J, Grenier C, Lorieux M, Cruz M, Berrío L, Corredor E, De San Martin GZ, Breseghello F, Peixoto O, Colombari Filho JM, De Castro AP, Lopes SIG, Barbosa M, Funck GRD, Blanco P, De Vida FP, Molina F, Rosas J, Martínez S, Bonnecarrere V, Garaycochea S, Carracelas G, Marin A, Correa-Victoria F, Camargo I, Bruzzone CB (2014) Rice breeding in Latin America. Plant Breed Rev 38:187–278. https://doi.org/10.1002/9781118916865.ch05

Meus LD, Quintero CE, Ribas GG, Silva MR, Streck NA, Alberto CM, Angeles MAA, Zanon AJ (2022) Evaluating crop models to assess rice yield potential in Argentina. Crop Environ 1:182–188. https://doi.org/10.1016/j.crope.2022.08.002

Meus LD, Silva MR, Ribas GG, Zanon AJ, Rossato IG, Fogliato V, Pilecco IB, Ribeiro BSMR, Souza PM, Nascimento MF, Poersch AH, Duarte Junior AJ,Quintero CE, Garrido GC, Carmona LC, Streck NA (2020) Ecophysiology of Rice for Reaching High Yield Rio Grande do Sul Brazil 312

Ogoshi C, Carlos FS, Ulguim AR, Zanon AJ, Bittencourt CRC, Almeida RD (2018) Effectiveness of fungicides for rice blast control in lowland rice cropped in Brazil. TropSubtrop Agroecosyst 21:505–511 (ISSN 1870-0462)

Peng ZK, Wang LL, Xie JH, Li LL, Coulter JA, Zhang RZ, Luo ZZ, Cai LQ, Carberry P, Whitbread A (2020) Conservation tillage increases yield and precipitation use efficiency of wheat on the semi-arid Loess Plateau of China. Agric Water Manag 231:106024. https://doi.org/10.1016/j.agwat.2020.106024

Prasad AM, Iverson LR, Liaw A (2006) Newer classification and regression tree techniques: bagging and random forests for ecological prediction. Ecosyst 9:181–199. https://doi.org/10.1007/s10021-005-0054-1

Ribas GG, Zanon AJ, Streck NA, Pilecco IB, De SPM, Heinemann AB, Grassini P (2021) Assessing yield and economic impact of introducing soybean to the lowland rice system in southern Brazil. Agric Syst 188:103036. https://doi.org/10.1016/j.agsy.2020.103036

Rizzo G, Monzon JP, Ernst O (2021) Cropping system-imposed yield gap: Proof of concept on soybean cropping systems in Uruguay. Field Crops Res 260:107944. https://doi.org/10.1016/j.fcr.2020.107944

Soares PC, Melo PGS, Melo LC, Soares AA (2005) Genetic gain in an improvement program of irrigated rice in Minas Gerais. CBAB 5:142–148 (ISSN 1984-7033)

Tenorio FA, Eagle AJ, McLellan EL, Cassman KG, Howard R, Below FE, Clay DE, Coulter JA, Geyer AB, Joos DK, Lauer JG, Licht MA, Lindsey A, Maharjan B, Pittelkow CM, Thomison PR, Wortmann CS, Sadras VO, Grassini P (2019) Assessing variation in maize grain nitrogen concentration and its implications for estimating nitrogen balance in the US North Central region. Field Crops Res 240:185–193. https://doi.org/10.1016/j.fcr.2018.10.017

Theisen G, Silva JJC, Silva JS, Andres A, Anten NP, Bastiaans L (2017) The birth of a new cropping system: Towards sustainability in the sub-tropical lowland agriculture. Field Crops Res 212:82–94. https://doi.org/10.1016/j.fcr.2017.07.001

Therneau TM, Atkinson EJ (1997) An introduction to recursive partitioning using the RPART routines. Mayo Foundation-Technical Report 61:452. https://cran.r-project.org/web/packages/rpart/vignettes/longintro.pdf

Tseng MC, Roel A, Macedo I, Marella M, Terra JA, Zorrilla G, Pittelkow CM (2021) Field-level factors for closing yield gaps in high-yielding rice systems of Uruguay. Field Crops Res 264:108097. https://doi.org/10.1016/j.fcr.2021.108097

United States Department of Agriculture (USDA) (2020) Argentina: grain and feed annual 2020. USDA Foreign Agricultural Service. https://fas.usda.gov/data/argentina-grain-and-feedannual-10. Accessed 10 Mar 2024

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

Van Ittersum MK, van Bussel GJ, Wolf J, Grassini P, van Wart J, Guilpart N, Claessens L, Groot H, Wiebe K, Mason-DCroz D, Yang H, Boogaard H, van Oort PAJ, van Loon MP, Saito K, Adimo O, AdjeiNsiah S, Agali A, Bala A, Cassman KG (2016) Can sub-Saharan Africa feed itself? PNAS 113:14964–14969. https://doi.org/10.1073/pnas.1610359113

Van Wart J, Van Bussel LGJ, Wolf J, Licker R, Grassini P, Nelson A, Boogaard H, Gerber J, Mueller ND, Claessens L, Van Ittersum MK, Cassman KG (2013) Use of agro-climatic zones to upscale simulated crop yield potential. Field Crops Res 143:4–17. https://doi.org/10.1016/j.fcr.2012.11.023

Xavier AIS, Arbage AP, Da Silva MR, Ribas GG, Meus LD, Santos GA, Streck NA, Zanon AJ (2021) Economic and productive analysis of irrigated rice crops using a multicase study. PAB 56:e02037. https://doi.org/10.1590/S1678-3921.pab2020.v56.02037

Yoshida S (1981) Fundamentals of rice crop science. International Rice Research Institute, Los Baños, p 269

Yuan S, Cassman KG, Huang J, Peng S, Grassini P (2019) Can ratoon cropping improve resource use efficiencies and profitability of rice in central China? Field Crops Res 234:66–72. https://doi.org/10.1016/j.fcr.2019.02.004