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Ary Jose Duarte Junior

DECOMPOSIÇÃO DA LACUNA DE PRODUTIVIDADE DE ARROZ IRRIGADO NO RIO GRANDE DO SUL

Santa Maria, RS
2021

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Dissertação de mestrado apresentada ao Programa de Pós-Graduação em Agronomia (PPGAGRO), da Universidade Federal de Santa Maria (UFSM), como requisito parcial para obtenção do título de **Mestre em Agronomia.**

Orientador: Prof. PhD. Nereu Augusto Streck

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Aprovado em 24 de agosto de 2021:

Nereu Augusto Streck

Nereu Augusto Streck, PhD. (UFSM)
(Presidente/Orientador)

Vasco

João Vasco Silva, Dr. (CIMMYT/WUR)

Alexandre Bryan Heinemann

Alexandre Bryan Heinemann, Dr. (Embrapa)

Santa Maria, RS
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RESUMO

DECOMPOSIÇÃO DA LACUNA DE PRODUTIVIDADE DE ARROZ IRRIGADO NO RIO GRANDE DO SUL

AUTOR: Ary Jose Duarte Junior
ORIENTADOR: Nereu Augusto Streck

Como o maior produtor de arroz fora do continente Asiático, o Brasil pode contribuir potencialmente para a demanda futura por arroz, através da intensificação dos sistemas de produção. Uma das estratégias para alcançar esse objetivo é por meio da redução da lacuna de produtividade existente na área atual. Entretanto, a produtividade é definida por fatores limitantes, como genética, ambiente e manejo, que precisam ser estudados individualmente como afetam a lacuna de produtividade. Utilizando modelos de simulação de culturas, aplicação de questionários e análises de regressão, foi possível estimar o potencial de produtividade de arroz no Rio Grande do Sul (<6 a >14 t ha^{-1}), e estimar a perda de produtividade causada pelo atraso na semeadura (0.03 t ha dia^{-1} de 01/set a 13/out, 0.08 t ha dia^{-1} de 14/out a 21/dez e 0.29 t ha dia^{-1} após 21/dez). Além disso determinou-se que a lacuna de produtividade de arroz no Rio Grande do Sul é de 7,6 t ha^{-1} (48%) em relação ao potencial de produtividade, sendo 10% devido a fatores genéticos (escolha da cultivar), 20% por data de semeadura, e 70% é causada por fatores de manejo. Além disso, foram identificadas práticas de manejo que contribuem para mitigar a lacuna de produtividade, como rotação de culturas com soja, semeadura direta e redução da densidade de semeadura.

Palavras-chave: *Oryza sativa* L. Potencial de produtividade. SimulArroz. Modelagem de culturas.

ABSTRACT

DECOMPOSING RICE YIELD GAPS IN RIO GRANDE DO SUL

AUTHOR: Ary Jose Duarte Junior
ADVISOR: Nereu Augusto Streck

As the largest rice producer country outside the Asian continent, Brazil can potentially contribute for future global rice supply, by sustainable intensifying cropping systems. One of the strategies to achieve this goal is by narrowing the existing yield gap (Yg) in the current farming area. However, crop yield is determined by biological limitations of the genotype, crop management practices, environmental conditions and it is necessary to understand how each one of these factors affect the yield gap. By using crop simulation models, combined with surveys and regression analysis, the rice yield potential for Rio Grande do Sul (from < 6 t ha^{-1} to >14 t ha^{-1}), and the yield losses caused by the delay of the sowing date (0.03 t ha day^{-1} from 01-sept a 13-oct, 0.08 t ha day^{-1} from 14-oct to 21-dec and 0.29 t ha day^{-1} after 21-dec) were estimated. Also, the yield gap in Rio Grande do Sul was estimated, resulting in 7.6 t ha^{-1} (48%) of the yield potential, where 10% of the yield gap is caused by genetics (variety choice), 20% is caused by the environment (sowing date) and 70% is caused by management factors. Managements practices that can contribute for the yield gap reduction were also identified, such as crop rotation with soybeans, no-till planting system and use of lower sowing density.

Key-words: *Oryza sativa* L. Yield potential. SimulArroz. Crop modelling.

LISTA DE FIGURAS

ARTIGO 1

ARTIGO 2

LISTA DE TABELAS

ARTIGO 1

ARTIGO 2

LISTA DE ABREVIATURAS E SIGLAS

CA	Campaign
CE	Central
DM	Dry matter
ECP	External Coastal Plain
ICP	Internal Coastal Plain
IRGA	Instituto Rio Grandense do Arroz
LAI	Leaf area index
$LAR_{max\ 1,2}$	Maximum appearance rate of the first and second leaves
LN	Leaf number
LP	Lacuna de produtividade
LP	Lacuna de produtividade
Meff	Model efficiency
OLS	Ordinary least square
PA	Produtividade atual
PAR	Photosynthetically active radiation
Pmax	Maximum grain weight
PP	Produtividade potencial
PPA	Potencial de produtividade limitado por água
R^2	Coefficient of determination
RMSE	Root mean square error
RMSEn	Normalized-root mean square error
RS	Rio Grande do Sul
RUE	Radiation use efficiency
S	South
SOCF	Spikelet formation factor
Tb	Lower cardinal temperature
TB	Upper cardinal temperature
Topt	Optimum cardinal temperature
TTEG	Thermal time to complete the anthesis-maturation phase
TTEM	Thermal time to complete the sowing-emergence phase
TTRP	Thermal time to complete the panicle differentiation-anthesis phase
TTVG	Thermal time to complete the emergence-panicle differentiation phase
USDA	United States Department of Agriculture
WB	West Border
Ya	Actual farmers yield
Yg	Yield gap
Yg_e	Environmental yield gap
Yg_g	Genetic yield gap
Yg_m	Management yield gap
Yp	Yield potential
Yp_a	Yield potential for the highest yielding variety and optimum sowing date
Yp_b	Yield potential for the highest yielding variety and actual sowing date
Yp_c	Yield potential for the actual variety and actual sowing date

SUMÁRIO

1 INTRODUÇÃO

A população mundial vem crescendo anualmente, com uma projeção de alcançar 9 bilhões de pessoas no ano 2050 (ALEXANDRATOS; BRUINSMA, 2012). Junto com o aumento populacional vem o aumento da demanda por alimentos, principalmente nos países menos desenvolvidos da Ásia, África e América Latina, aonde as projeções de segurança alimentar são preocupantes (ALEXANDRATOS; BRUINSMA, 2012; GODFRAY et al., 2010;). Tendo o arroz (*Oryza sativa* L.) como principal cultura da base alimentar de mais da metade da população mundial (PANDEY et al., 2010), e a necessidade de suprir a demanda futura de alimento no mundo, estudos são necessários para identificar como e quanto a produção de alimentos pode ser incrementada de forma sustentável.

O arroz desempenha um papel estratégico na economia brasileira, sendo o maior produtor mundial do grão fora do continente asiático (USDA, 2018). O Rio Grande do Sul (RS) é o principal estado produtor do grão no Brasil, responsável por cerca de 70% de toda a produção nacional, cultivado em aproximadamente 1,1 milhão de hectares (CONAB, 2018). Diante deste cenário de incertezas futuras quanto à soberania alimentar global, o RS pode desempenhar um papel estratégico na segurança alimentar nacional e mundial, pois há uma grande lacuna de produtividade (LP) de arroz no RS a ser explorada entre a produtividade atual (7-8 t ha^{-1}) e a produtividade potencial (15 t ha^{-1}), de acordo com o Global Yield Gap Atlas (GYGA, 2019).

A produtividade potencial (PP) das culturas agrícolas pode ser definida como a produtividade de uma variedade adaptada, que cresce e desenvolve sob condições ideais de cultivo, sem qualquer estresse ou limitações causadas pela água, nutrientes, plantas daninhas, doenças e pragas (EVANS, 1993). Sob essas condições, a taxa de crescimento da cultura e sua produtividade são determinadas pela temperatura (ar e solo), radiação solar, concentração de CO_2 atmosférico e componente genético (EVANS, 1993; VAN ITTERSUM et al., 1997). A diferença entre a produtividade potencial (PP) e a produtividade atual (PA) dos produtores, é conhecida como a lacuna de produtividade (LP) (LOBELL et al., 2009).

Para aumentar sustentavelmente a produtividade é preciso entender as características climáticas, agronômicas e socioeconômicas de cada região. A compreensão das particularidades da produção de arroz no RS pode direcionar os rumos que os produtores de arroz do estado devem seguir, de forma que aqueles com menor acesso à tecnologia e insumos, devem aumentar a produção utilizando mais recursos (priorizar produtividade), enquanto outros produtores devem aumentar a eficiência dos recursos já utilizados (priorizar sustentabilidade), pois estes podem estar alocando os recursos de forma inadequada (SILVA et al., 2021).

A proposta de estudo lacunas de produtividade, do inglês “Yield Gap”, é um dos temas agronômicos mais estudados atualmente. Esses estudos ainda são incipientes em países em desenvolvimento, apesar de a lacuna ser, teoricamente, muito maior que nos países desenvolvidos. No Brasil este tema vem sendo estudado nos últimos anos pela Equipe FieldCrops da Universidade Federal de Santa Maria (UFSM), para as culturas de arroz, soja e milho, através do projeto *Global Yield Gap Atlas* (GYGA). Entretanto, os resultados disponibilizados na plataforma GYGA apenas informam o quanto é a lacuna de produtividade, porém muitas vezes não pode ser feita a identificação dos fatores determinantes. Para facilitar a identificação dos principais influenciadores da LP, é necessário decompô-la através de utilização de modelos de simulação de culturas, que conseguem isolar vários fatores não controláveis em lavouras comerciais ou experimentos de campo, e quantificar, por exemplo, o quanto cada variável (e.g. ambiente, genética ou manejo) está influenciando a LP.

1.1 OBJETIVOS

1.1.1 Objetivo geral

Quantificar e decompor a lacuna de produtividade de arroz irrigado no Rio Grande do Sul, utilizando o modelo SimulArroz.

1.1.2 Objetivo específico

Quantificar e decompor os principais componentes da lacuna de produtividade de arroz irrigado no estado do Rio Grande do Sul, principal região produtora do grão no país, e identificar os principais fatores de manejo que estão limitando a produtividade das lavouras.

2 REVISÃO BIBLIOGRÁFICA

2.1 A CULTURA DO ARROZ IRRIGADO

O arroz (*Oryza sativa* L.) é uma planta aquática, de cultivo anual, porte ereto, com altura variando de 60 a 150 cm, pertencente a subfamília Oryzoideae (BOLDRINI et al., 2005). É uma cultura agrícola adaptada a latitudes que variam de 50ºN (Checoslováquia) a 35ºS (Uruguai), ao nível do mar, e em elevadas altitudes (2000 m de altitude no Nepal) (CASTRO et al., 1987).

De origem asiática, a cultura do arroz foi introduzida no Brasil em meados do Século XVI, na Capitania de Ilhéus, onde atualmente localiza-se o estado da Bahia, e cultivava-se um arroz de pericarpo vermelho, conhecido como *arroz vermelho*, *arroz da terra* ou *arroz de Veneza* (PEREIRA e GUIMARÃES, 2010). Entretanto, o cultivo do arroz branco no Rio Grande do Sul só teve início em 1904, onde em uma lavoura no município de Pelotas semeou-se a primeira lavoura de arroz, e um ano depois, na Granja Progresso em Gravataí (onde hoje localiza-se a Estação Experimental do Arroz do IRGA), semearam-se 100 ha de arroz irrigado (PEREIRA; GUIMARÃES, 2010). Na metade do Século XX, o RS assumiu posição de destaque na produção nacional do grão, e hoje responde por cerca de 70% da produção brasileira (CONAB, 2018).

No final do século XX a produtividade de arroz nos Estados do Rio Grande do Sul e de Santa Catarina passou de 4 t ha^{-1} no início da década de 80, para quase 8 t ha^{-1} a partir de 2011 (SOSBAI, 2018). Esta evolução (a produtividade dobrou em quatro décadas) se deve principalmente ao desenvolvimento de cultivares semi-anãs adaptadas as condições climáticas locais, que atendem as exigências do mercado e com maior tolerância aos estresses bióticos e abióticos e a melhoria e ajuste nas práticas de manejo durante a estação de cultivo e na entressafra (PEREIRA; GUIMARÃES, 2010).

Durante a primeira década do século XXI, ocorreram mudanças nas lavouras de arroz no Sul do Brasil. No arroz, a mudança iniciou em 2003 com o denominado “Projeto 10” do Instituto Rio Grandense do Arroz (IRGA), que teve como objetivo aumentar a produtividade média da cultura no Rio Grande do Sul, através do manejo integrado de plantas daninhas, insetos e doenças, aumento nos níveis de adubação e antecipação da época de semeadura, o que resultou no incremento da produtividade média de 5,5 t ha^{-1} (1998-2002) para 7,5 t ha^{-1} (2012-2017) (IRGA, 2018; MENEZES et al., 2013). Apesar do contínuo aumento na produtividade média do arroz nos últimos anos no RS, ainda há uma considerável diferença entre as produtividades medidas em experimentos de estações de pesquisa de arroz (12-14 t ha^{-1}) e da produtividade média atual de arroz (7-8 t ha^{-1}) no RS (IRGA, 2018; RIBAS et al., 2017).

2.2 POTENCIAL DE PRODUTIVIDADE DAS CULTURAS AGRÍCOLAS

A produtividade potencial (ou potencial de produtividade, PP) das culturas agrícolas pode ser definida como a produtividade de uma variedade adaptada que cresce e desenvolve sob condições ideais de cultivo, sem qualquer estresse ou limitações causadas pela água, nutrientes, plantas daninhas, doenças e pragas (EVANS, 1993). Sob essas condições, a taxa de crescimento da cultura e sua produtividade são determinadas apenas pelas condições de temperatura, radiação solar, concentração de CO_2 atmosférico e componente genético (EVANS, 1993; VAN ITTERSUM et al., 1997).

Em culturas de sequeiro, a taxa de crescimento pode ser limitada por água e, neste caso, o conceito de potencial de produtividade limitado por água (PPA) é usado em substituição ao PP, e no qual a produtividade é influenciada pela quantidade e distribuição das chuvas, tipo de solo (capacidade de armazenamento de água e profundidade de enraizamento) e topografia do terreno, que limitam o fornecimento de água para o crescimento da cultura (VAN ITTERSUM et al., 2013; GRASSINI et al., 2015a).

A condução de experimentos de campo para determinar o potencial de rendimento de culturas, muitas vezes é inviável devido à dificuldade de conduzir experimentos que não sejam afetados pelos estresses bióticos ou abióticos, além da necessidade de repetições dos experimentos ao longo dos anos e em diferentes locais, para obter uma robusta estimativa do potencial. Por isso, os modelos matemáticos baseados em processos para simulação de culturas são as melhores ferramentas para a determinação do potencial de produtividade das culturas, pois utilizam como dados de entrada séries meteorológicas de longa data e permitem ao usuário isolar os efeitos bióticos e abióticos dos experimentos de campo, retratando melhor os impactos das variações de temperatura e radiação solar ao longo do tempo (VAN ITTERSUM et al., 2013).

2.3 MODELOS DE SIMULAÇÃO DE CULTURAS

Modelos de simulação de culturas são representações matemáticas que nos permitem entender processos biofísicos que acontecem nas lavouras (i.e., fenologia, assimilação de carbono, partição de fotoassimilados) e a resposta das culturas a fatores ambientais (e.g. temperatura, radiação solar, fotoperíodo, etc.) (VAN ITTERSUM et al., 2013). Modelos matemáticos mecanísticos baseados em processos biológicos estão sendo cada vez mais utilizados na agricultura, pois são ferramentas de baixo custo que permitem descrever as complexas interações nos agroecossitemas (WALTER et al., 2012).

Ao longo dos últimos anos, modelos de simulação de culturas foram desenvolvidos, como por exemplo, Hybrid-maize (YANG et al., 2004) para a cultura do milho, CSM-CROPGRO-Soybean (BOOTE et al., 1996) para a cultura da soja, Simanihot para a cultura da mandioca (TIRONI et al., 2017) e PhenoGlad para a cultura do gladíolo (UHLMANN et al., 2017). Para a cultura do arroz existem alguns modelos calibrados e testados para condições de cultivo asiático, em que alguns são mais complexos como o CERES-Rice (TIMSINA; HUMPHREYS, 2006), ORYZA 2000 (BOUMAN et al., 2001), e o SimulArroz (JUNIOR et al., 2021). No Brasil, o modelo SimulArroz foi desenvolvido pelo Grupo de Agrometeorologia da Universidade Federal de Santa Maria, para simular o crescimento, desenvolvimento e produtividade da cultura do arroz irrigado no RS. O modelo SimulArroz tem sido amplamente utilizado no RS e Brasil, e vem sendo atualizado e testado para as principais cultivares de arroz utilizadas no RS (RIBAS et al., 2016; RIBAS et al., 2017; ROSA et al., 2015; SILVA, M. R. et al., 2016; STRECK et al., 2013). Além disso, o modelo SimulArroz foi utilizado pela Empresa Brasileira de Pesquisa Agropecuária (Embrapa), de forma pioneira no Brasil, como ferramenta para determinar o Zoneamento Agrícola de Risco Climático do Arroz Irrigado no Rio Grande do Sul (ZARC Arroz Irrigado/RS) (EMBRAPA, 2018). Em sua versão atual (SimulArroz 1.1), o modelo simula o crescimento, desenvolvimento e produtividade de arroz irrigado no sistema de inundação para o RS, na condição de cultivo potencial e níveis tecnológicos de lavoura (baixo, médio e alto), e conta com 14 cultivares e 3 híbridos calibrados.

2.4 DECOMPOSIÇÃO DA LACUNA DE PRODUTIVIDADE

A produtividade atual das lavouras (PA) é a produtividade anual média obtida pelos produtores para uma determinada cultura e região (GRASSINI et al., 2015b). A PA pode ser obtida através de dados disponibilizados por instituições governamentais ou de pesquisa, ou através da coleta de dados por meio de questionários, à uma determinada amostra de produtores que represente a realidade da região em estudo (GRASSINI et al., 2015b). A diferença entre a produtividade atual (PA) dos produtores e a produtividade potencial (PP), é conhecida como a lacuna de produtividade (LP) (LOBELL et al., 2009). Estudos sobre lacuna de produtividade vêm aumentando nos últimos anos, motivados pela crescente demanda mundial de alimentos e de energia para atender ao aumento populacional e de renda em muitos países (FERMONT et al., 2009; GRASSINI et al., 2015a). Esta pressão por aumento na produção de alimentos e de energia está levando a repensar a agricultura para um novo patamar, o da "intensificação sustentável" (MUELLER et al., 2012), que é mais um fator a considerar para a consolidação da Segunda Revolução Verde (LYNCH, 2007). Os estudos de lacunas de produtividade permitem identificar os principais fatores biofísicos e de manejo que limitam o aumento da produtividade dos agricultores e direcionar novas linhas de pesquisa, além de aprimorar as atuais práticas de manejo (VAN ITTERSUM et al., 2013).

Diversos estudos relacionados à lacuna de produtividade de arroz vêm sendo desenvolvidos ao longo dos últimos anos ao redor do mundo. Em estudos anteriores, Laborte et al. (2012), Neumann et al. (2010), e Stuart et al. (2016), estimaram a LP em diversos sistemas de produção de arroz, e identificaram os principais fatores que afetam a lacuna. Silva, J. V. et al. (2016), van Dijk et al. (2017) e Villano et al. (2015), decompuseram e explicaram a lacuna de produtividade usando técnicas de análise de fronteira estocástica e modelagem de culturas, que resultaram em estimativas da LP ligada à tecnologia, eficiência do uso de recursos e fatores econômicos. Entretanto, estudos que utilizam apenas a modelagem de culturas para estimar e decompor a lacuna de produtividade individualmente são incipientes, principalmente no Brasil, visto que análises de fronteira estocástica tem um viés de modelagem econômica (KUMBHAKAR; LOVELL, 2003).

3 ARTIGO 1 – RICE YIELD POTENTIAL AS A FUNCTION OF SOWING DATE IN SOUTHERN BRAZIL

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Rice yield potential as a function of sowing date in Southern Brazil

Ary Jose Duarte Junior[1*], Nereu Augusto Streck[1], Alencar Junior Zanon[1], Giovana Ghisleni Ribas[1], Michel Rocha da Silva[1], Jossana Ceolin Cera[2], Moises de Freitas do Nascimento[1], Isabela Bulegon Pilecco[1], and Simone Puntel[1].

Core ideas:

- SimulArroz and ORYZA have similar performance in simulating rice phenology and yield;
- Yield potential ranges from 6 t ha^{-1} to 14 t ha^{-1};
- The yield potential decreases with sowing dates delayed;
- Brazilian subtropics have higher yield potential when compared to the tropics.

[1]Universidade Federal de Santa Maria (UFSM), Santa Maria, RS, Brazil.

[2]Instituto Rio Grandense do Arroz (IRGA), Cachoeirinha, RS, Brazil.

*Corresponding author: Ary Jose Duarte Junior, Universidade Federal de Santa Maria (UFSM), Av. Roraima 1000, Camobi, Santa Maria, RS, 97105-900, Brazil. E-mail: ary.duartee@gmail.com.

ABSTRACT

Most studies about yield potential (Yp) of modern rice varieties have been grown under tropical conditions of Asia, and little is known about the rice yield potential in the subtropics of Brazil, the biggest rice producer outside Asia. Playing a key role in the global rice production, it is necessary to estimate the amount of rice that Brazil can potentially produce. The objective of this study is to provide estimations of yield potential in southern Brazil by using the SimulArroz v1.1 and ORYZA v3 models. Models were calibrated and evaluated with data collected from five growing seasons across Rio Grande do Sul state in Brazil, where the cultivar IRGA 424 RI was sown from Sept to Dec. Both models presented similar performance in simulating phenology, with root mean square error (RMSE) of 9 days for ORYZA and 11 days for SimulArroz. For grain yield, the RMSE was 1.0 t ha^{-1} and 0.9 t ha^{-1} for ORYZA and SimulArroz, respectively. Using the SimulArroz model, yield potential maps were drawn, which ranged from lower than 6 t ha^{-1} to greater than 14 t ha^{-1}, according to the region and sowing date. The penalty in yield potential caused by the delay in sowing date is 0.03 t ha day^{-1} from 01 Sept to 13 Oct, 0.08 t ha day^{-1} from 14 Oct to 21 Dec, and 0.29 t ha day^{-1} after 21 Dec. SimulArroz model is a suitable model for studies on rice yield potential in the Brazilian subtropics.

INTRODUCTION

Rice (*Oryza sativa* L.) plays a strategic role in Brazilian economy and society, as the country is the largest world rice producer outside Asia (United States Department of Agriculture, 2018). About 70% of the Brazilian rice is produced in the Subtropics of the Rio Grande do Sul (RS) State (Companhia Nacional de Abastecimento, 2019), as flooded rice in 1.1 million hectares of lowlands (Figure 1A-B). Previous studies suggest that this region could become a future world rice breadbasket where the irrigated rice area receives abundant solar radiation (Figure 1C) (Bourne, 2014; Cassman, 1999; Mueller et al., 2012).

Yield potential (Yp) of any crop is defined as the yield of an adapted variety that grows in excellent conditions, without any stress or limitation caused by water, nutrients, weeds, pests and diseases (Evans, 1993). Under these conditions, the growth rate and yield are defined only by the intercepted solar radiation, temperature, atmospheric CO_2 and genetics (Evans, 1993; van Ittersum & Rabbinge, 1997). The 12-14 t ha^{-1} rice yield reported in well conducted experiments (Ribas et al., 2017) may be below Yp, as in field experiments it is difficult to keep the crop free of the biotic or abiotic stresses. On the other hand, Yp can be achieved by using crop simulation models (van Ittersum et al., 2013). The SimulArroz model is a process-based model developed for simulating rice growth and yield and it has been calibrated and evaluated for many rice varieties in the subtropics of Brazil (Ribas et al., 2017; Rosa et al., 2015; Walter, Rosa, Streck, & Ferraz, 2012). However, the SimulArroz model was not compared so far to a comprehensive and widely used process-based model such as ORYZA, and such a comparison is important to evaluate the predictive capacity of any new model (van Ittersum et al., 2013).

Previous studies that estimated the yield potential of rice were mainly focused in tropical environments of Asia, and with varieties not adapted to the Brazilian subtropical environment, where the potential was only estimated for a specific growing season (Agustiani et al., 2018; Heinemann, Ramirez-Villegas, Rebolledo, Costa Neto, & Castro, 2019; Kropff, Cassman, van Laar, & Peng, 1993; Laborte et al., 2012; Silva, Reidsma, Laborte, & van Ittersum, 2016; Stuart, et al., 2016). While local farmers and agronomists understand the effect of sowing date on rice yield, their knowledge is based upon field experience or on field trials that do not extend the effect of the whole range of sowing dates in different regions of the subtropical lowland rice production area in Brazil. In order to fulfill the lack of information and to quantify the variability of yield potential in the Brazilian subtropical lowland environment, the objective of this study was to estimate the yield potential of rice on a high-resolution grid for different sowing dates in the Brazilian subtropics.

MATERIALS AND METHODS

Study Region

This study was performed for the Rio Grande do Sul (RS) State, Southern Brazil (Figure 1A-B). Since 90% of all rice produced in Brazil is cultivated in irrigated lowlands, and the RS is responsible for 70% of the national production (Companhia Nacional de Abastecimento, 2019), this study comprised the majority of the Brazilian production area. According to van Wart et al. (2013), a coverage of 50% of the production area is enough to obtain a robust estimate of the yield potential on a national scale. The ‘’Instituto Rio Grandense do Arroz’’ (IRGA), an institute responsible for research, extension and policies of rice production in Brazil, divided the lowland area in six rice production regions, classified according to soil and climate characteristics: West Border (WB), Campaign (CA), South (S), Internal Coastal Plain (ICP), External Coastal Plain (ECP) and Central (CE) (Figure 1B). For practical application, these regions were used in this study.

The state average yield in the 2014-2018 period was 7.5 t ha^{-1} and farmers in the WB and S regions reported higher yields compared with farmers from the eastern regions from the state (Instituto Rio Grandense do Arroz, 2019). This difference can be explained by the climatic conditions, as temperature and solar radiation differ between the rice growing regions. Solar radiation (Figure 1C) and maximum temperature (Figure 1E) increase westwards, whereas minimum temperature decreases southwards (Figure 1D).

The SimulArroz model

SimulArroz is a process-based model that calculates phenology, dry matter (DM) production and yield potential for irrigated rice on a daily time step. Phenology is calculated with the thermal time approach (°C day^{-1}), using the lower and upper basal (temperatures below and above which plant growth is negligible, respectively) and optimum temperature (at which the development rate is maximum) (Streck et al., 2011). Four development stages are considered in the model (Table 1).

The vegetative phase is the period that rice is sensible to photoperiod induction (Aggarwal, Kalra, Chander, & Pathak, 2006). The SimulArroz model does not consider the photoperiod effect, since the cultivars used in Subtropical rice production areas in Latin America (South Brazil, Argentina and Uruguay) either do not respond to photoperiod or their response is negligible. SimulArroz differs from other existing rice models in its capacity to calculate the accumulated number of leaves on the main stem (LN) and the main stem final leaf number. The LN is based on Haun Stage (Haun, 1973) and is calculated using the Wang & Engel model modified for rice (Streck, Bosco, & Lago, 2008). This result is important information for rice management, since V3 is the onset of tillering - a key stage for the start of flood irrigation, nitrogen dressing, and weed control.

The dry matter production in the SimulArroz model is calculated through the radiation use efficiency (RUE) and the leaf area index (LAI), a classic and robust approach in ecophysiology (Connor, Loomis, & Cassman, 2011). The RUE is described as a function based on four cardinal air temperatures: between 22°C and 32°C the RUE is maximum; below 22°C and above 32°C the RUE decreases linearly and below 9°C and above 45°C the RUE is zero (Soltani, Zeinali, Galeshi, & Niari, 2001). The photosynthetically active radiation (PAR) is assumed as 50% of the incoming solar radiation, and the leaf light extinction coefficient is 0.4 from emergence to anthesis (R4) and 0.6 after R4 until physiological maturity. The daily dry matter production is partitioned among roots, leaves, stems and panicles, and LAI is calculated using daily leaves dry matter (g m^{-2} day^{-1}) and specific leaf area (m^2 g^{-1}) according to the developmental phase and cultivar. Grain yield and yield components are calculated by equations described in the InfoCrop (Aggarwal et al., 2006) and ORYZA2000 (Bouman et al., 2001) models, and with specific calibrations for the most used cultivars in flooded rice systems in Southern Brazil.

To run the SimulArroz model, users need to input daily weather data of maximum and minimum temperature (ºC), and solar radiation (MJ m^{-2} day^{-1}), and crop parameters, such as cultivar or maturity group, sowing or emergence date, plant density (pl m^{-2}), number of simulated years, technological level and atmospheric CO_2 concentration. Version 1.1 of the SimulArroz model, available for free download at www.ufsm.br/simularroz, was used in this study.

The ORYZA model

ORYZA version 3 model (Li et al., 2017) is an improved version of the ORYZA2000 (Bouman et al., 2001), which simulates growth, development and yield of flooded and non-flooded rice, on a daily basis. ORYZA has been widely used in research to simulate Yp across different environments (Agustiani et al., 2018; Espe et al., 2016; Heinemann et al., 2019; Stuart et al., 2016). It requires calibration of genetic parameters, such as developmental rates, photoperiod sensitivity, panicle development and dry matter partitioning. ORYZA is a more sophisticated and comprehensive model than SimulArroz, and is able to simulate not just Yp, but also limitations caused by water and nitrogen. This complexity of the model requires a great number of input data to simulate the dynamics of water, carbon and nitrogen in the soil, such as nitrogen and water management, soil texture, organic carbon, nitrogen and mineral nitrogen of the soil, and weather data.

Model calibration

In order to calibrate the SimulArroz and ORYZA models, field experiments were conducted in Cachoeirinha, RS. The cultivar IRGA 424 RI was directly sown in 2015, using a plant density of 100 kg ha^{-1} of seeds, spaced at 0.17 m between rows and seed depth of 3 cm. The experimental design was randomized blocks with four replications. The agronomic practices were managed according to rice phenology (Table 2) as follows: fertilizers were applied at sowing (30 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1} and 80 kg K_2O ha^{-1}) and nitrogen was side dressed at V3 (90 kg N ha^{-1}) and R0 (30 kg N ha^{-1}) according to soil tests for maximum yields. Flood irrigation started at V3. Weeds, insects and diseases were prophylactically controlled as follows: Herbicide management was composed by glyphosate applied 20 days before sowing, glyphosate plus clomazone was applied the day after sowing, and imazapyr plus imazapic plus quinclorac was applied before flooding at V3. Fungicide was applied at V7 (strobilurin plus triazole), and fungicide plus insecticide were applied at R2 (thiamethoxam and benzothiazole) and R4 (etophenproxy plus chlorantraniliprole and benzothiazole). The experiments were sown on 01 Oct 2015, 09 Nov 2015 and 03 Dec 2015 (Table 3). We selected these three best managed experiments and run a cross-validation calibration approach (Heinemann et al., 2019). As a result of this cross-validation, the experiment sown on 01 Oct 2015 was selected to calibrate SimulArroz and the experiments sown on 09 Nov 2015 and 03 Dec 2015 were selected to calibrate ORYZA (Table 3). Because of the nature of each model, which have their own parameters, it is expected that different combination of data sets can be more efficient to calibrate different models. The SimulArroz model is already in use by the Brazilian government for zoning rice in Southern Brazil and we have demonstrated elsewhere (Rosa et al., 2015; Ribas et al., 2017) that SimulArroz describes very well the complex on farm differences in rice production systems in Rio Grande do Sul State, where 70% of the Brazilian rice is produced, with much less parameters to be calibrated compared to ORYZA. However, a comparison of the two models is still needed in order to test if SimulArroz is suitable for estimating rice yield potential.

Leaf appearance and phenology were weekly evaluated using the Haun (Haun, 1973) and the Counce (Counce, Keisling, & Mitchell, 2000) scales, respectively (Table 2). Panicle differentiation (R1) was determined through a destructive sampling of 10 plants and the R1 date was considered when 50% of the plants were at this developmental stage. During the growing season, aboveground biomass was collected (clipped close to the soil) in an area of 1.36 m^2 at V3, R1, R4, R9 developmental stages. Aboveground biomass was separated into stems, panicles, and green leaf blade (>50% green area). Subsequently, the samples were oven dried at 60°C until constant weight, and then weighted. For the determination of grain yield (t ha^{-1}), yield components (number of spikelets and grain weight) were randomly collected in 15 panicles, and an area of 5 m^2 was manually harvested, threshed and dried to 13% moisture in each replicate.

The calibration approach used in SimulArroz was the same as in Rosa et al. (2015) and Ribas et al. (2017) (Table 4). For ORYZA, the auto-calibration tool (Li et al., 2017) was used to calibrate the model for potential conditions (no water or nitrogen limitations).

Model evaluation

The evaluation of the models was performed in two steps. Firstly, the performances of ORYZA and SimulArroz were compared in simulating phenology and grain yield using field experiments conducted under potential conditions in Cachoeira do Sul, Cachoeirinha and Santa Maria (Figure 1B and Table 3), which are independent data. The second step in the evaluation of the SimulArroz model was performed using data from well managed field experiments and from farmers' fields trials during four years (2013-2016). The cultivar was IRGA 424 RI sown from September to

December in eight sites (Figure 1B and Table 3). The technological levels in the SimulArroz model are divided into four levels: Potential technological level is a rice field without any biotic or abiotic stress; High technological level is a rice field with 82% of yield potential, representing a very well managed field, were weeds, pests and diseases cause minor reduction on rice yield; Medium technological level is a rice field with 72% of yield potential, with nitrogen supply below the required by the plant, and weeds, pests and diseases causing minor reduction on rice yield; Low technological level is a rice field with 60% of yield potential, with nitrogen supply below the recommendation and poor weeds, pests and diseases control. This is a simple approach used to simulate biotic or abiotic stresses using a correction factor over the radiation use efficiency (RUE) (Aggarwal et al., 2006). The second step of the evaluation was not performed for ORYZA because the model requires soil data to simulate nitrogen balance, which was not available in our field data.

The weather data to run the model for each site were obtained from the nearest automatic weather station (within 50 km distance) from the National Meteorology Institute (INMET). The statistics used for model evaluation were: coefficient of determination (R^2) – Equation 1, root-mean-square error (RMSE) – Equation 2, normalized-root-mean-square error (RMSEn) – Equation 3, and model efficiency (Meff) – Equation 4:

$$R^2 = \left(\frac{n(\sum OS) - (\sum O)(\sum S)}{[n\sum O^2 - (\sum O)^2][n\sum S^2 - (\sum S)^2]^{1\backslash 2}} \right)^2 \tag{1}$$

$$\text{RMSE} = \left[\frac{\sum (S - O)^2}{n} \right]^{0.5} \tag{2}$$

$$\text{RMSEn} = \frac{100 \text{ x RMSE}}{\bar{O}} \tag{3}$$

$$M_{eff} = 1.0 - \frac{\sum (O - S)^2}{\sum (O - \bar{O})^2} \tag{4}$$

where S are the simulated values, O are the observed values, n is the number of paired values, and $\bar{O}$ is the mean of observed values. Small RMSE and RMSEn, and high R^2 indicate good agreement between simulated and observed values. Meff indicates how well the plot of observed *versus* simulated data fits the 1:1 line.

Yield potential maps

Estimating crop yield potential from crop models requires using a robust long-term weather database to represent the impacts of temperature and solar radiation variability among years (Grassini et al., 2015; van Ittersum et al., 2013). Unfortunately, the density of weather stations with reliable and long-term data is low in several parts of the world, including Brazil. To overcome this problem, one acceptable approach is the use of reliable high-resolution grids of daily weather data, that allows the use of crop models to estimate the yield potential for locations without weather stations (Cedrez & Hijmans, 2018; Xavier, King, & Scanlon, 2016). In order to have a robust estimate of the yield potential that captures the spatial and time variability in Southern Brazil, we used daily weather data (solar radiation, minimum and maximum temperature) of a 0.25° x 0.25° grid during the period from 1980 to 2013 from the *Daily gridded meteorological variables in Brazil (1980-2013)* (see Xavier et al., 2016 for more information and evaluation of the weather data grid compared to observed data) (Figure 1B).

The cultivar IRGA 424 RI was used to simulate the Yp across the state, which is the highest yielding and most sown cultivar in South Brazil. The sowing dates were set on the 1st and 15th day of the month, from September to January, aiming to capture the entire range of the commonly used sowing dates. The plant density was set at 200 pl m^{-2} and the atmospheric CO_2 concentration was 400 ppm (Rosa et al., 2015). The technological level was set to potential, meaning that simulated yield potential was only a function of solar radiation and temperature (Lobell, Cassman, & Field, 2009). The model was run at 10 sowing dates, 33 years and 257 grid points, totaling 84810 runs.

The software QGIS v. 2.8.9 was used to interpolate the yield potential on the data grid using the Inverse Distance Weighting (IDW) method, and to draw maps for each sowing date.

RESULTS AND DISCUSSION

Model calibration and evaluation

Calibrated parameters in SimulArroz for the cultivar IRGA 424 RI are shown in Table 4. These parameters were estimated using an experiment very well managed that was likely under potential conditions. When calibrating the SimulArroz model for hybrid rice cultivars, Ribas et al. (2017) found similar values of thermal times for the cultivar QM 1010 CL, a hybrid with cycle duration similar to the IRGA 424 RI cultivar.

The first step in model evaluation tested the performance of SimulArroz and ORYZA models in simulating rice phenology and yield for the IRGA 424 RI cultivar under potential conditions. Figure 2 shows a comparison between independent observed phenology (Figure 2A) and yield (Figure 2B) against simulated values using ORYZA and SimulArroz models. For phenology, both models presented a reasonably good agreement between observed and simulated values ($R^2 > 0.88$, RMSEn < 11%, Meff > 0.86), with most of the points within the +/- 10 days variation envelope. Small differences in simulating phenology between the models can be explained by different approaches of calculating thermal time in the models. SimulArroz uses different cardinal temperatures for each developmental phase (Table 1) whereas ORYZA assumes a single set of cardinal temperatures for development throughout the entire developmental cycle (Tb = 8°C, TB = 42°C and Topt = 30°C) (Bouman et al., 2001). Heinemann et al. (2019) when calibrating

ORYZA v3 for Central Brazil, found an RMSE of 2.86 days and 2.45 days for flowering and maturity, respectively.

For simulating grain yield, both models also presented a reasonably good agreement for RMSEn (< 8%), and coefficient of determination ($R^2 < 0.59$). The Meff for grain yield was better in SimulArroz (Meff = 0.37) than in ORYZA (Meff = 0.25). Despite the differences in observed *versus* simulated yield, 100% of SimulArroz and 80% of ORYZA simulations were within the +/- 15% variation range, and 100% of both models' simulations were within the +/- 30% range.

In Thailand, Boling, Boumann, Tuong, Konboon, & Harnpichitvitaya (2011) reported a RMSE of 0.6 t ha^{-1} and RMSEn of 20% for rice yield. Li et al. (2017), when evaluating the performance of ORYZA v3 in Asia, reported RMSEn of 15% and a Meff of 0.92 for grain yield. Heinemann et al. (2019) reported an RMSE of 0.4 t ha^{-1} for rice yield in Central Brazil. The RMSEn reported by the mentioned authors, indicate that the errors of the first evaluation stage are in the range for rice models, while RMSE and Meff indicates that the errors for rice models are above in this study. The largest RMSE in Figure 2 compared to the RMSE reported in Boling et al. (2011) and in Heinemann et al. (2019) is due to the higher yields in the former (<10.0 t ha^{-1}) compared to lower yields in the latter (>6.0 t ha^{-1}). Despite the Meff of the models being low, in general, both models simulated Yp higher than the observed yield in potential experiments, which is expected as even with very good management practices, field experiments have their constraints to achieve Yp without any stress, which is attainable with crop models.

From results in Figure 2A and 2B we conclude that the SimulArroz model is as good as the ORYZA model in simulating irrigated rice phenology and yield in Southern Brazil. Because SimulArroz has less parameters to calibrate while presenting similar performances at ORYZA, we used SimulArroz in the second step of model evaluation and for the rest of the study.

The second step of model evaluation consisted in a comparison between the observed yield from field trials and farm fields *versus* the yield simulated by SimulArroz model in different technological levels (Figure 3). The performance of SimulArroz in simulating yield was better in the second step than in the first step, with $R^2 = 0.79$, RMSEn = 11% and Meff = 0.71. There was a large variation in observed simulated yields, ranging from 4.6 to 13.7 t ha^{-1} and from 5.4 to 14.6 t ha^{-1}, respectively. Despite the differences in observed *versus* simulated yields, 79% of the simulations with SimulArroz were within the +/- 15% variation range, and 96% were within the +/- 30% range.

Yield potential

The average rice yield potential (Yp) for Rio Grande do Sul (RS), estimated by the SimulArroz model, ranged from less than 6 t ha^{-1} to more than 14 t ha^{-1} depending on the regions and sowing dates (Figure 4 and Figure 5). With the exception of the sowing dates in January, the WB always presented the highest yield potential values, and the northern part of ECP the region with the lowest yield potential. The differences on yield potential between WB and ECP regions can be explained in Figure 1, as the WB region has climatic conditions more favorable to rice growth and development (temperature and solar radiation) when compared to northern ECP. According to Huang, Shan, Cao, & Zou (2016) biomass production is positively related to intercepted solar radiation, and yield is positively related to biomass production. In other words, the higher the intercepted solar radiation, the higher yields can be achieved, and the lower yield potential estimated in eastern RS might be related to lower solar radiation (Figure 1C). Furthermore, low temperatures can also reduce rice yield in sowing dates near the boundaries of the sowing window (Sept and Dec-Jan), which occur more frequently in CA and S regions (Figure 1D).

The Yp of rice found for Brazil is superior to the Yp of Bangladesh (11.7 t ha^{-1}), Indonesia (9.1 t ha^{-1}) and Philippines (6.1-8.7 t ha^{-1}), as reported by Timsina et al. (2016), Agustiani et al. (2018) and Silva et al. (2016), respectively. This difference can be explained by higher solar radiation during flowering and grain filling phases in the Brazilian subtropical climate compared to the tropical climate of South and Southeast Asia. Espe et al. (2016) estimated similar yield potential (8.2-14.5 t ha^{-1}) for temperate conditions of Southern United States, highlighting that environments outside tropical conditions have greater rice yield potential, but also pose higher risks of production losses due to cold damage. Sheehy and Mitchell (2015) estimated as 20.1 t ha^{-1} the theoretical rice maximum yield for semi-dwarf varieties in subtropical conditions. However, Sheehy and Mitchel (2015) estimate of yield potential are based on longer duration varieties than the majority of those used in Rio Grande do Sul (RS) state, and also on the three laws of maximum yield (see Sheehy and Mitchell, 2013), a simpler model that describes the relationship between crop photosynthesis and yield. Besides the different methods of Yp estimates, subtropical rice production regions, near to the Latitude of 30°, presents higher Yp when compared to lower latitudes, as near the tropics there is less solar radiation available during the growing season, and temperate regions present higher risk of crop damage due to low temperatures.

Influence of the sowing date

The response of yield potential estimated by the SimulArroz model according to the sowing dates (Figure 5) indicates that the yield potential decreases as the sowing date is delayed. A three-stage linear model that maximized R^2 decreased yield potential by 0.03 t ha day^{-1} from 01 Sept to 13 Nov, 0.08 t ha day^{-1} from 14 Nov to 21 Dec, and sowing dates after this date decrease yield potential at a rate of 0.29 t ha day^{-1}. As the best environmental conditions (i.e. solar radiation and temperature) for rice fields in the subtropics of the southern hemisphere subtropics occur during the summer season (Dec-Jan-Feb), the sowing dates before 14 Nov correspond to the critical stages of rice development (i.e. reproductive and grain filling stages) with the period with greatest availability of solar radiation, which is directly linked to rice yield and prevents yield losses caused by extreme temperatures during flowering (Huang et al., 2016; Stansel, 1975; Wrege et al., 2012). The Standard deviation of yield potential across the different sowing dates ranged from 9% on 01 Nov to over 126% on 15 Jan (Figure 5). The lower standard deviation in the sowing between 01 Oct and 01 Dec means that the yield potential is more stable.

Figure 5 also shows the observed yield data used for model evaluation (Table 3) as a function of the sowing date. Except for early sowing dates, the same trend on the yield ceiling is observed across the sowing window, as the observed data are located under the fitted trendline for yield potential, corroborating the results of the sowing date influence obtained by the SimulArroz model on yield potential.

According to Köppen's climate classification, Rio Grande do Sul (RS) rice production area has a humid subtropical climate without a dry season and hot summer climate (Cfa) (Alvares, Stape, Sentelhas, Gonçalves, & Sparovek, 2013). Under these conditions, RS has four well-defined seasons, with cold periods in Winter (Jun-Jul-Aug), hot periods in Summer (Dec-Jan-Feb) and intermediate periods in Spring and Autumn (Sept-Oct-Nov and Mar-Apr-May, respectively). As the optimum temperature for germination ranges from 20°C to 35°C, lower soil temperatures in early spring can lead to a slower growth rate at early developmental stages, favoring the emergence of weeds, as they can usually germinate under lower temperatures, requiring better weed control in early crop developmental stages (Kwon, Kim, & Park, 1996; Yoshida, 1981). Therefore, the differences between observed yield ceiling and simulated yield potential in early sowing dates can be explained by the fact that SimulArroz does not capture the soil temperature or excess of soil moisture effects during crop establishment. On the other hand, greater differences between yield potential and observed yields in earlier sowing dates indicate that management factors are still to be improved by famers.

This study presented the first estimates of rice yield potential for the Brazilian subtropical environment. The use of crop simulation models are effective tools to analyze the effect of different sowing dates and climatic conditions between regions and years on the yield potential, because in field experiments it is difficult to control unexpected biotic or abiotic effects. The SimulArroz model has been calibrated and evaluated in the last 6 years in Brazil (Ribas et al., 2017; Rosa et al., 2015; Walter et al., 2012), and its performance is similar to ORYZA, a rice model widely used in different places of the world. Therefore, it is safe to assume that the results obtained in this study are robust and represent the rice yield potential across the sowing dates under farming conditions in Southern Brazil.

Considering the range of yield potential obtained in this study, from less than 6 t ha^{-1} to over 14 t ha^{-1} across the different sowing dates and regions, and the average actual farmers' yield reported by the Instituto Rio Grandense do Arroz (IRGA) in the last five growing seasons (7.5 t ha^{-1}) we suggest that the sowing date might be one of the major causes of the rice yield gap in Brazil, and future studies should be performed to analyze the actual sowing dates of the farmers and its effect on the yield gap. If Rio Grande do Sul (RS) is able to achieve its yield potential (14 t ha^{-1}) on 100% of the rice farming area, approximately 90% more rice could be produced, being achieved with best management practices and cultivars with high yield potential, such as IRGA 424 RI. However, it is not clear from this analysis whether all regions will be able to undergo changes to their management practices, sowing in the best window and access high-yielding varieties, in order to reach the yield potential. In addition, it is not clear yet whether achieving such gains in yields will be possible without significantly damaging other ecosystem goods and services that society is dependent on.

The results obtained in this study represent the yield potential that can currently be achieved for rice in different sowing dates for each region of the RS State, given today's technology, management practices and variety that has already been adopted by the farmers. It is possible that higher yields might be found in experimental research plots or new varieties. We focus on those yields that have already been shown to be attainable by farmers with methods and tools that have already been found to be adoptable. These results illustrate where we can potentially increase yields today, by adopting agricultural practices that are already used in other regions. Our results can also be used in future studies about rice yield gaps in Brazil, as the Country's average yield is far from the yield potential. With higher yield potential than tropical environments, Brazil can contribute to future rice demand and contribute to the world's food security.

This study provides estimates of yield potential for the Brazilian subtropical irrigated rice in different sowing dates, based on a multi-year high resolution weather data. The yield potential is near 14 t ha^{-1} in early sowing dates and slightly decreases from 01 Sept to 13 Nov, intensify from 14 Nov to 21 Dec and significantly decreases after 21 Dec. The results fill the lack of information about subtropical rice yield potential in Brazil, which are higher than those found for tropical conditions. Our study provided local information that can be used by farmers and consultants when planning management decisions based on the yield potential for a given sowing date and region. On a national and global scale, this study provided information for future food security studies, as it suggests that there are still room to increase rice production by closing the yield gap, although a specific yield gap study should be performed to quantify how much the sowing date affects the yield gap in Brazil.

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FIGURES

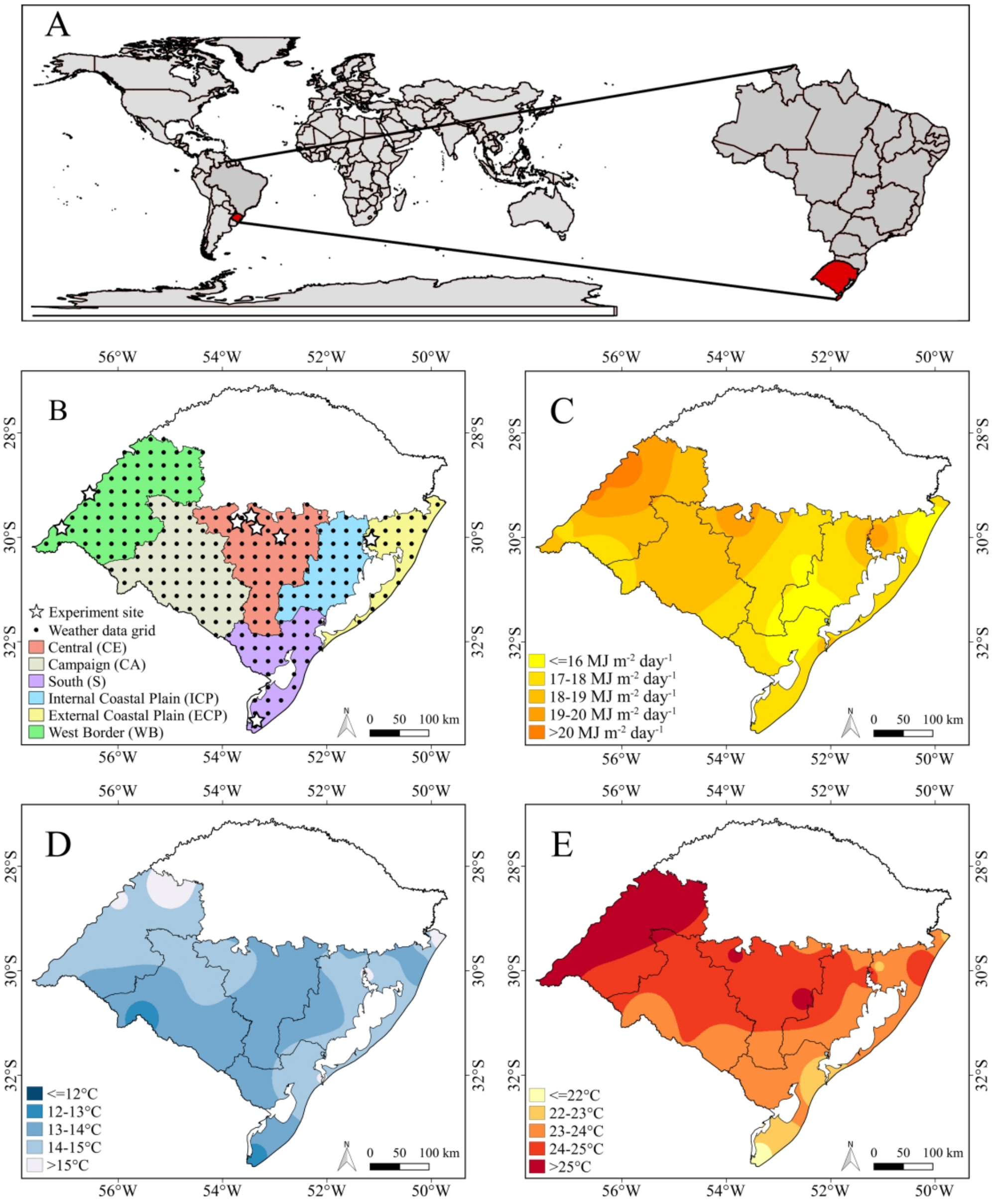

Figure 1. (A) Geographical location of the study area; (B) Regions of the Rio Grande do Sul state where rice is produced (1.1 million hectares of lowlands), field experiment sites and the weather data grid; (C) Daily average solar radiation for the Dec-Apr term (Wrege, Steinmetz, Reisser Junior, & Almeida, 2012); (D) Average annual minimum temperature (Wrege et al., 2012); (E) Average annual maximum temperature (Wrege et al., 2012).

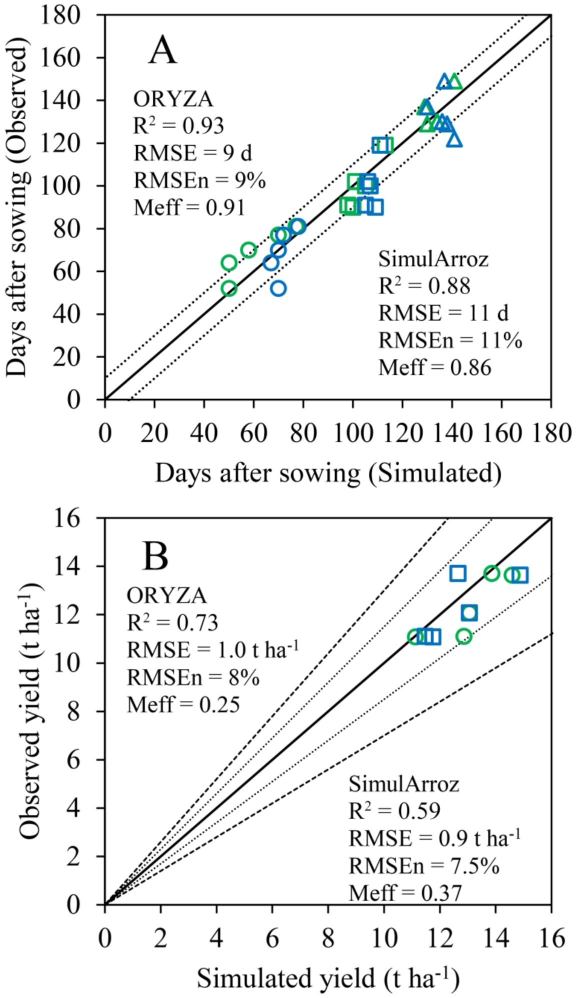

Figure 2. (A) Comparison between the phenology of rice observed (Counce et al., 2000 scale) in experiments under potential conditions compared to the phenology simulated by ORYZA and SimulArroz models. Circles represent the R1 stage (panicle differentiation), squares represent the R4 stage (flowering), and triangles represent the R9 stage (maturity). The solid diagonal is the 1:1 line. Dotted diagonal lines represent the variation envelope of +/- 10 days; (B) Comparison between the yield potential observed in the experiments versus the yield potential simulated by ORYZA and SimulArroz models. The solid diagonal is the 1:1 line. Dotted diagonal lines represent 15% and 30% of the range of yield variation, respectively. In both panels, green symbols are simulated with the ORYZA model, and blue symbols are simulated with the SimulArroz model.

The coefficient of determination (R^2), root mean square error (RMSE), normalized root mean square error (RMSEn) and Model efficiency (Meff) are shown in each panel. The observed data were obtained from three sites in Rio Grande do Sul (RS) during three growing seasons (2015, 2016 and 2017) (Table 3).

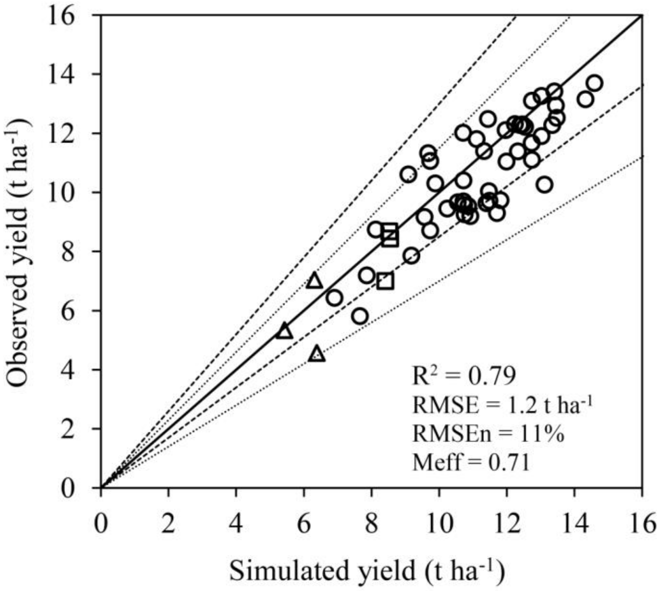

Figure 3. Comparison between observed versus simulated rice yield with SimulArroz. Circles represent experiments and farm fields at high technological level. Squares represent farm fields at medium technological level. Triangles represent farm fields with low technological level. Solid diagonal is the 1:1 line. The diagonal dashed lines represent 15% and 30% yield variation range. Coefficient of determination (R^2), root mean square error (RMSE), normalized root mean square error (RMSEn) and model efficiency (Meff) are shown in the figure. Observed data were obtained from eight sites in Rio Grande do Sul (RS) during four growing seasons (2013, 2014, 2015, and 2016) (Table 3).

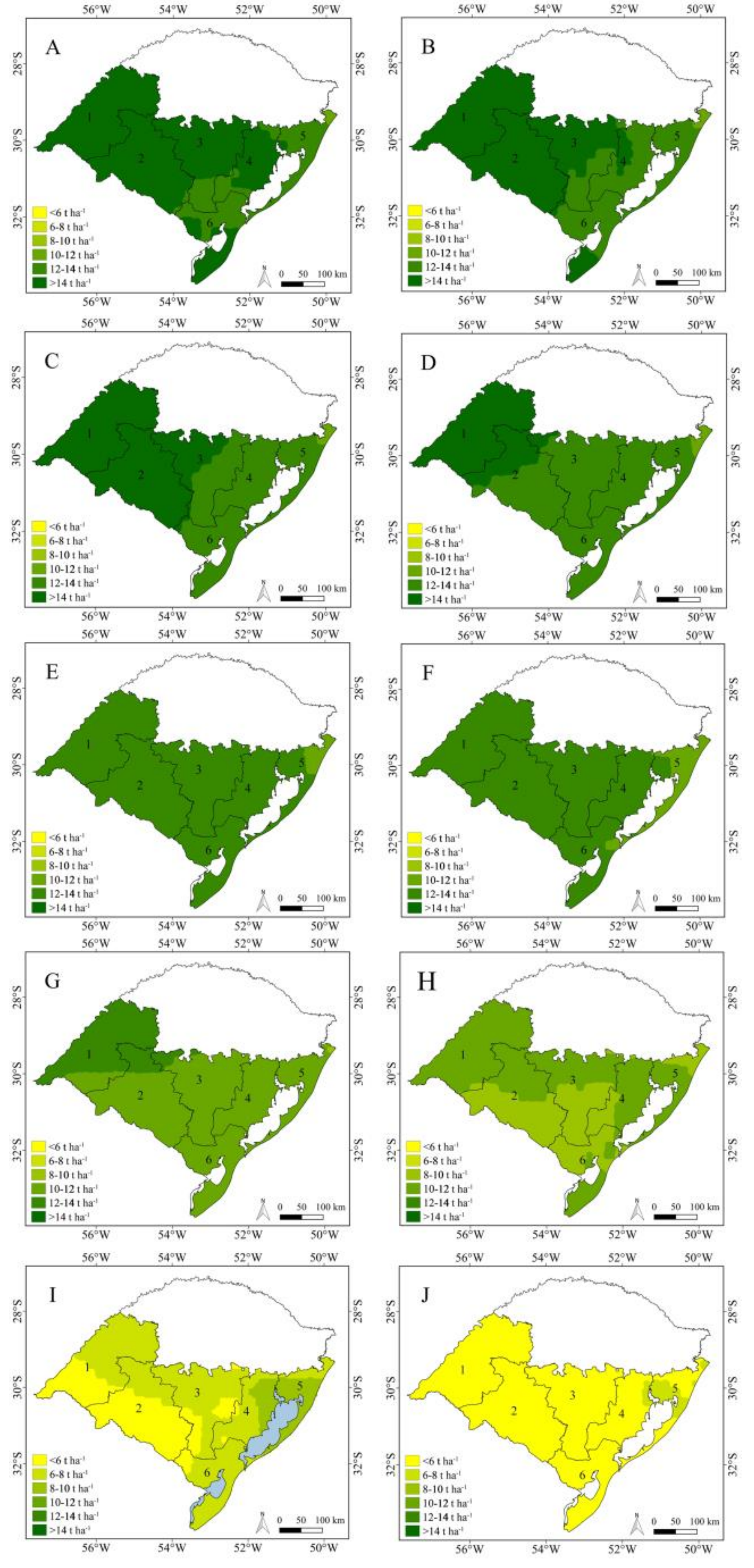
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Figure 4. Yield potential of rice on different sowing dates in lowlands of Rio Grande do Sul State, Brazil, with sowing dates on (A) 01 Sept; (B) 15 Sept; (C) 01 Oct; (D) 15 Oct; (E) 01 Nov; (F) 15 Nov; (G) 01 Dec; (H) 15 Dec; (I) 01 Jan; (J) 15 Jan. 1 West Border (WB); 2 Campaign (CA); 3 Central (CE); 4 Internal Coastal Plain (ICP); 5 External Coastal Plain (ECP); 6 South (S).

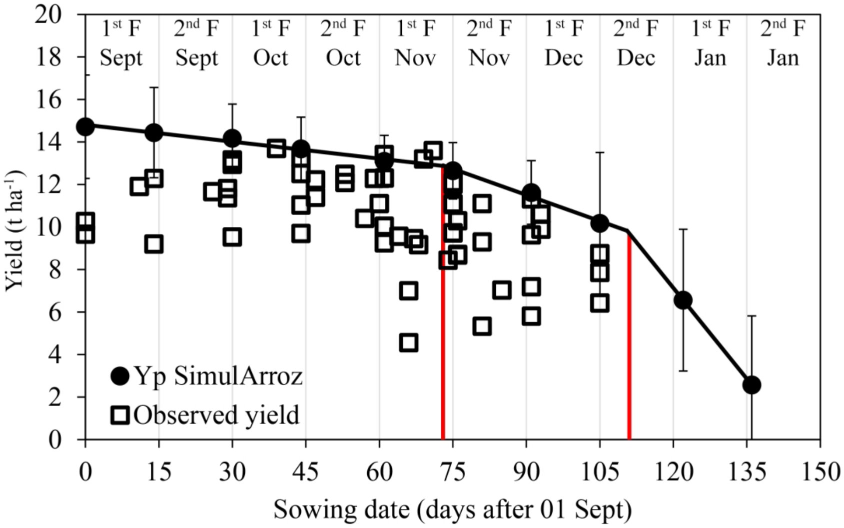

Figure 5. Rice yield as a function of sowing date (expressed as days after 01 Sept) in Brazilian subtropical lowlands. Solid circles represent the average yield potential simulated with the SimulArroz model for all grid data (n = 84810). Squares represent the observed yields on field experiments and farm fields used in the first and second steps of evaluation (Table 3) (n = 60). The black line represents the fitted trendline for yield potential from 01 Sept to 13 Nov ($y = -0.03x + 14.81$; $R^2 = 0.97$), 14 Nov to 21 Dec ($y = -0.08x + 12.90$; $R^2 = 0.98$) and after 21 Dec ($y = -0.29x + 9.70$; $R^2 = 1.00$). The red vertical lines represent the intersection of the sowing dates fitted trendlines. Bars indicate the standard deviation for yield potential.

TABLES

Table 1. Developmental phase (DVS) and their lower (Tb), upper (TB) and optimum (TOpt) cardinal temperatures used for calculating thermal time in the SimulArroz model.

Developmental phase (DVS)	T_b (°C)	T_B (°C)	T_{Opt} (°C)
Emergence (-1.0 to 0)	11	40	30
Vegetative (0 to 0.65)	11	40	30
Reproductive (0.65 to 1.0)	15	35	25
Grain filling (1.0 to 2.0)	15	35	23

Table 2. Rice developmental stages and morphological markers for management practices and phenology evaluation. Adapted from Counce, Keisling, & Mitchell, 2000.

Developmental Stages	Morphological Marker
V3	Collar formation in Leaf 3 on main stem
V7	Collar formation in Leaf 7 on main stem
R1	Panicle branches have formed
R2	Flag leaf collar formation
R4	One or more florets on the main stem panicle has reached anthesis
R9	All grains which have reached R6 have brown hulls

Table 3. Experimental sites used to calibrate and evaluate SimulArroz and ORYZA models.

Site	Coordinates	Technological Level***	Year	Sowing date range	Yield range (t ha^{-1})
Model calibration – SimulArroz					
Cachoeirinha*	30°03’S 51°10’W	Potential	2015 (1)	01 Oct	12.2
Model calibration – ORYZA					
Cachoeirinha*	30°03’S 51°10’W	Potential	2015 (2)	09 Nov - 03 Dec	9.9 - 13.2
1st step evaluation (phenology and yield) – SimulArroz and ORYZA					
Cachoeira do Sul*	30°00'S 52°55'W	Potential	2016 (2)	10 Oct - 31 Oct	11.1 - 13.7
Cachoeirinha*	30°03’S 51°10’W	Potential	2016 (2)	24 Oct - 21 Nov	11.1 - 12.1
Santa Maria*	29°43'S 53°43'W	Potential	2017 (1)	11 Nov	13.6

2nd step evaluation (yield) – SimulArroz					
Cachoeira do Sul*	30°00'S 52°55'W	High	2015 (6)	01 Sept - 15 Nov	10.3 - 13.1
			2016 (6)	12 Sept - 15 Dec	7.9 - 13.7
Cachoeirinha*	30°03'S 51°10'W	High	2015 (7)	30 Sept - 15 Dec	8.7 - 12.5
			2016 (5)	30 Sept - 21 Nov	9.3 - 12.5
Itaqui*	29°09'S 56°33'W	High	2016 (1)	07 Nov	9.5
Restinga Seca**	29°49'S 53°22'W	High	2016 (1)	16 Nov	10.3
Santa Maria*	29°43'S 53°43'W	High	2013 (1)	03 Dec	10.6
			2014 (1)	28 Oct	10.4
Santa Vitoria do Palmar*	33°32’S 53°21’W	High	2015 (8)	01 Sept - 15 Dec	5.8 - 11.1
			2016 (3)	04 Nov - 01 Dec	7.2 - 9.6
São João do Polesine**	29°36'S 53°26'W	High	2016 (1)	08 Nov	9.2
		Medium	2016 (3)	06 Nov - 16 Nov	7.0 - 8.7
		Low	2016 (3)	06 Nov - 25 Nov	4.6 - 7.0
Uruguaiana*	29°50'S, 57°04'W	High	2014 (2)	01 Nov - 15 Nov	11.1 - 13.4
			2015 (2)	01 Oct - 15 Oct	12.5 - 12.9
			2016 (3)	01 Oct - 01 Nov	12.3 - 13.3

*Yield data obtained from field experiments; **Yield data obtained from farmers’ fields; The value in parenthesis represent the number of experiments available during the season; ***Potential technological level: a rice field without any biotic or abiotic stress; High technological level: a rice field with 82% of yield potential, representing a very well managed field, were weeds, pests and diseases cause minor reduction on rice yield; Medium technological level: a rice field with 72% of yield potential, with nitrogen supply below the required by the plant, and weeds, pests and diseases causing minor reduction on rice yield; Low technological level: a rice field with 60% of yield potential, with nitrogen supply below the recommendation and poor weeds, pests and diseases control.

Table 4. Parameters of leaf development, growth and phenology calibrated for the rice cultivar IRGA 424 RI in the SimulArroz model.

Parameter	Unit	Value
$LAR_{max\ 1,2}$	Leaves day^{-1}	0.272
TTEM	˚C day	80.0
TTVG	˚C day	659.2
TTRP	˚C day	168.4
TTEG	˚C day	108.7
RUE	g MJ^{-1}	2.87
LAI		8.3
SOCF	Spikelets g^{-1} of DM	70.0
Pmax	grams (g)	0.0232

$LAR_{max\ 1,2}$ = maximum appearance rate of the first and second leaves; TTEM = thermal time to complete the sowing-emergence phase; TTVG = thermal time to complete the emergence-panicle differentiation phase; TTRP = thermal time to complete the panicle differentiation-anthesis phase; TTEG = thermal time to complete the anthesis- maturation phase; RUE = radiation use efficiency; LAI = leaf area index; SOCF = spikelet formation factor; Pmax = maximum grain weight; DM = dry matter.

4 ARTIGO 2 – DECOMPOSING RICE YIELD GAPS IN SOUTHERN BRAZIL

(Artigo a ser submetido em Agronomy Journal)

Decomposing rice yield gaps in Southern Brazil

Core ideas:

- The yield potential for southern Brazil is 16 t ha^{-1};
- The yield gap for southern Brazil is 48% of the yield potential;
- Management practices affect more the yield gap than the environment and genetics;
- The use of better farming practices such as crop rotation and direct seeding can reduce the yield gap;

ABSTRACT

As the largest rice producer country outside the Asian continent, Brazil can potentially contribute for future global rice demand, by sustainable intensifying cropping systems. One of the strategies to achieve this goal is by narrowing the existing yield gap (Yg) of the current farming area. However, crop yield is determined by biological limitations of the genotype, crop management practices, environmental conditions and it is necessary to understand how each one of these factors affect the yield gap. By using crop simulation models, combined to surveys and regression analysis, we estimated the relative contribution of the environment, genetics and management practices on the yield gap in Southern Brazil. The average yield gap for the region is 48% (7.6 t ha^{-1}) relative to the yield potential (16.0 t ha^{-1}), where the sowing date is responsible for 20% (1.5 t ha^{-1}), the genetics 10% (0.8 t ha^{-1}) and the management 70% (5.3 t ha^{-1}) of the total yield gap. Farming practices such as crop rotation with soybeans, no-till planting system and adequate sowing density should be considered to narrow the management yield gap.

INTRODUCTION

According to future projections, the global population is going to increase from 7.7 billion people in 2019 to 9.7 billion in 2050, with the majority of this increase occurring in low-income countries in Sub-Saharan Africa (52%), and Central and Southern Asia (25%) (UN, 2019). Tied to the global population increase is food demand, which will increase mainly on these countries where rice (*Oryza sativa* L.) is the main staple food (Pandey et al., 2010). To meet the future global food demand, rice production must increase sustainably on existing farmland as the availability of arable land, water and labor are limited, leading to an increase in crop yields through better use of resources and narrowing the existing yield gap (Stuart et al., 2016).

Responsible for producing c. 11.6 million t in 2020/2021 season, Brazil is the largest rice producer country outside Asia (CONAB, 2021; USDA, 2021). About 70% of the Brazilian rice is produced in the Subtropics of the Rio Grande do Sul (RS) State as flooded rice in 0.9 million hectares of lowlands (CONAB, 2021). The potential for RS to be another major global breadbasket is because most of the existing irrigated rice fields in RS receive abundant solar radiation during the reproductive phase, which is equal to or greater than all existing breadbaskets (Bourne, 2014; Cassman, 1999; Junior et al., 2021; Mueller et al., 2012).

One of the strategies to sustainably intensify cropping systems is by narrowing the existing yield gap (Yg). Yield gap studies are used to quantify the difference between the yield potential (Yp), which is the yield of an adapted variety that grow without any stress or limitation, and the actual farmers yield (Ya) (Evans, 1993; van Ittersum and Rabbinge, 1997; van Ittersum et al., 2013). Yield gap analysis have been widely studied across different crops and locations. In Brazil, Ribas et al. (2021) provided the first estimates about the rice Yp and Yg for the country (c. 15 t ha^{-1} and 48%, respectively), and identified the major management practices that drive the Yg.

However, crop yield is determined by biological limitations of the genotype, crop management practices and environmental conditions, i.e., the genetic x management x environment interaction (Hatfield and Walthal, 2015; van Ittersum and Rabbinge, 1997). To understand and quantify the contributions of these factors to Yg, it is useful to disentangle yield gaps into different components for a well-defined temporal and spatial scale (Silva et al., 2017; Silva et al., 2021; van Dijk et al., 2017).

Previous studies that unraveled yield gaps have used econometric analysis in combination with crop modelling to decompose yield gaps into efficiency, resource and technology yield gaps (Assefa et al, 2020; Silva et al., 2017; van Dijk et al., 2017). In this study, our framework to estimate and explain rice yield gaps builds on Silva et al. (2021), in which crop modelling approaches are used to quantify the contribution of genetic, environmental and management factors to rice yield gaps, and regression analysis are used to identify the key management practices that drives the yield gap.

MATERIAL AND METHODS

Study region and surveys

The Rio Grande do Sul State (RS) account for c.70% of the Brazilian rice production, with an annual production of 8.2 million t, cultivated in 0.9 million hectares of irrigated lowlands, with an average yield of 8.7 t ha^{-1} in the 2020/2021 season (CONAB, 2021) (Figure 1). The rice growing area of RS is located in the lowlands of the southern portion of the State, comprehended between the latitudes 29°S and 34°S, which provide subtropical climate conditions to the region, with four different seasons. Under these climate conditions, farmers grow rice during the summer season (Oct-Mar) and through winter time, the lower temperatures do not allow farmers to have a second rice season (Junior et al., 2021).

The rice farming characteristics of Rio Grande do Sul differ from those seen in other locations, as in Southeast Asia for example. The average farm size is over 100 ha, highly mechanized, with intense use of pesticides to control weeds, pests and diseases. In the majority of the farming area, rice is directly dry sown after soil preparation, which can be: conventional, with intense soil cultivation before seeding, without cover crop in winter; minimum-till, where the soil is cultivated after harvest and minimally prepared before seeding; no-till, where there is no soil cultivation with direct dry seeding, usually with cover crops in winter; and pre-germinated, where the soil is cultivated as in conventional system, but the seed is pre-germinated for direct seeding with flooded fields. Except for the pre-germinated system, the water layer is usually stablished at V3 – V6 stages (Counce et al., 2000). Nitrogen fertilizer is usually applied at a high rate (c. 150 kg ha^{-1}) with 2 splits.

Figure 1

Farmers were randomly surveyed during the 2015/2016, 2016/2017, 2017/2018, 2018/2019 and 2019/2020 seasons (Figure 1b), The extensionists from the Instituto Rio Grandense do Arroz (IRGA), Emater/RS, and agronomy students from the partner universities, randomly selected farmers to apply the survey, during and after harvest of the current farming season. Using a structured survey, the management practices, input quantities, area, yield, etc., for a selected parcel of land was collected. The information’s were self-reported by the farmers. The descriptive of the data collected are presented in Table 1.

Table 1

Crop modelling to estimate Yp

The SimulArroz crop model (Junior et al., 2021) was used to estimate the yield potential (Yp) for each location and season surveyed. SimulArroz is a process-based model that calculates phenology, dry matter (DM) production and yield potential for irrigated rice on a daily time step, and has been widely used, calibrated and evaluated for many rice varieties grown in RS rice systems (Junior et al., 2021; Ribas et al., 2017; Rosa et al., 2015; Walter et al., 2012). Further description of the model is available at Junior et al. (2021).

To run the model, users need to input daily weather data of maximum and minimum temperature (ºC), and solar radiation (MJ m^{-2} day^{-1}), and crop parameters, such as cultivar or maturity group, sowing or emergence date, plant density (pl m^{-2}), technological level and atmospheric CO_2 concentration. In this study, for each parcel surveyed, the crop parameters plant density, technological level and CO_2 concentration were standardized to 200 pl m^{-2}, potential level and 400 ppm, respectively, for all simulations. Cultivar or maturity group, and sowing date were collected individually from each farmers' field surveyed. The weather data were obtained from the nearest automatic weather station from the National Meteorology Institute (INMET) (Figure 1b).

The varieties reported by the farmers and its correspondent simulated varieties are described in Table 2. The varieties were calibrated in previous studies, where the crop parameters such as thermal time for each phenology phase, radiation use efficiency, leaf appearance rate, leaf area index and spikelet formation factor, are described in Junior et al. (2021), Ribas et al. (2017), Rosa et al. (2015), Streck et al. (2008), Streck et al. (2011) and Walter et al. (2012). If the variety reported by the farmer was not available among the calibrated varieties, the correspondent maturity group was used to simulate Yp. The sowing date was individually set for each field, as reported by the farmers.

Table 2

In order to decompose the Yg based on crop modelling, following Silva et al. (2021) approach, three variations of Yp were simulated using SimulArroz for each field (Figure 2). Yp_a is defined as the yield potential for the optimum sowing date and highest yielding variety for each location and season. The optimum sowing date was defined as the date with the highest simulated yield potential for each season within the optimum sowing window (1 September to 13 November), according to Junior et al. (2021). Among the simulated varieties (Table 2), the highest yielding variety was defined as IRGA 424 RI, as it presents the highest yield potential and it is the most sown variety in southern Brazi. Yp_b is defined as the yield potential for the highest yielding variety and actual sowing date collected for each field. Yp_c is defined as the simulated yield potential for each field, based on variety and sowing date reported by the farmers. Yp_b and Yp_c does not consider the genetic x sowing date interactions, which are known to influence resource use efficiencies (Evans & Fischer, 1999; Guilpart et al., 2017).

Figure 2

According to Lobell et al. (2009) the yield gap is defined as the difference between the yield potential and actual yield. To quantify and explain the participation of each yield component (environment, genetics and management) on the Yg, three intermediate gaps were identified (Figure 2) (Silva et al., 2021). The environmental yield gap (Yg_e) was estimated based on the yield difference between Yp_a and Yp_b for each individual field, as it considers the influence of the sowing date affected by the environmental conditions (i.e., temperature and solar radiation). The genetic yield gap (Yg_g) was estimated based on the yield difference between Yp_b and Yp_c for each individual field, as it considers the influence of low performance varieties (i.e., genetics) based on a yield potential perspective. The management yield gap (Yg_m) was defined as the difference between Yp_c and Ya for each field, as the remaining Yg cannot be explained by the SimulArroz model, and comprehend the management practices adopted by farmers.

Management yield gap drivers

To identify the management yield gap (Yg_m) drivers, regression methods were used based on Silva et al., (2021). The estimation method consisted of using ordinary least squares (OLS) regressions models, where the determinants of the Yg_m were examined through a set of agronomic practices (Equation 1). The agronomic practices considered included the previous summer crop, previous winter crop, planting system, sowing density, irrigation timing, pre-sowing weed control, presence of insects and diseases, use of herbicide, insecticide and fungicide, and quantity of nitrogen, phosphorous and potassium. A detailed description of the management practices from surveys is provided on Table 1. Relevant factors and agronomic practices with more than two possible values were assumed as dummies control factors (e.g., Campaign for region, rice for previous summer crop, conventional for planting system and 2015 for season). The regressions ran separately for each season and combined to capture year interactions. The continuous variables (i.e., Yg_m and fertilizer rate) were transformed to logarithmic, and robust standard errors were used. Binaries variables that were too skewed for one answer (>90%) were removed from the analysis. The estimation approach of OLS regression is specified below:

$$y_{it} = x_{it}'\beta + u_{it}, \qquad u_{it} \sim i.i.d.N(0, \sigma_u^2) \tag{1}$$

$$i = 1, 2, \dots\dots, N \qquad t = 1, 2$$

where, y_{it} is the scalar management yield gap of farmer i in season t, and x_{it}' is a vector of agronomic practices used by the farmer i in season t; β is the parameter to be estimated; N represents the sample size. The error term u_{it} is assumed to be independently and normally distributed ($i.i.d.$) with mean zero and constant variance σ_u^2.

RESULTS AND DISCUSSION

Decomposition of yield gaps

Throughout all the seasons, the combined results for Yp_a in Rio Grande do Sul was on average 16.0 t ha^{-1} and the Ya was on average 8.4 t ha^{-1}, resulting on an Yg of 7.6 t ha^{-1}, which correspond to 48% of the Yp. For seasons 2015, 2016, 2017, 2018 and 2019 Yp_a was 15.2 t ha^{-1} and the Ya was 8.0 t ha^{-1}, resulting on an Yg of 7.2 t ha^{-1} (47%).. In 2016 the Yp_a was 15.4 t ha^{-1} and the Ya was 8.5 t ha^{-1}, resulting on an Yg of 6.9 t ha^{-1} (45%). In 2017 the Yp_a was 16.5 t ha^{-1} and the Ya was 8.5 t ha^{-1}, resulting on an Yg of 8.0 t ha^{-1} (48%). In 2018 the Yp_a was 14.7 t ha^{-1} and the Ya was 8.2 t ha^{-1}, resulting on the smallest Yg of the studied seasons (6.5 t ha^{-1} or 44%). In 2019 the Yp_a was 17.4 t ha^{-1} and the Ya was 8.7 t ha^{-1}, resulting on the largest Yg of the studied seasons (8.7 t ha^{-1} or 50%) (Figure 3; Table 3).

Figure 3

Table 3

The results of Yp are similar to those found by Junior et al. (2021), Ribas et al. (2021) and Carracelas et al. (2017) of 14 t ha^{-1}, 15 t ha^{-1} and 14 t ha^{-1} respectively, for southern Brazil and Uruguay, and higher when compared to the Yp of Bangladesh (11.7 t ha^{-1}), Indonesia (9.1 t ha^{-1}) and Philippines (6.1-8.7 t ha^{-1}), as reported by Timsina et al. (2016), Agustiani et al. (2018) and Silva et al. (2016), respectively. The results of Yg are similar to those found for Southern

Brazil (48%) and Uruguay (43%) (Carracelas et al., 2017; Ribas et al., 2021), higher than the Yg for USA (27%) and China (33%) (Espe et al., 2016; Deng et al., 2019), and lower than sub-Saharan Africa (Dossou-Yovo et al., 2020).

The genetic yield gap (Yg_g) contributed with 10% of the Yg, which in general was the factor that less affected the Yg in RS, regarding that 59% of the surveyed farmers sown the highest yielding variety (IRGA 424 RI) (Table 2). The environmental yield gap (Yg_e) is the second most important factor affecting Yg, responsible for 20% of yield losses. Although the majority of the farmers (c. 70%) sown their fields inside the optimum sowing window (01 Sept to 13 Nov) (Figure 4), the sowing date is one of the yield gap causes in Southern Brazil. For all seasons, the yield gap can be mainly explained by the management yield gap (Yg_m) which represents 70% of the total Yg, thus the Yg was mostly explained by sub-optimal management practices, meaning that improving crop management practices should be prioritized for yield gaps to be narrowed. (Figure 3; Table 3).

Figure 4

In four rice bowls in Southeast Asia, Silva et al. (2021) found lower values for Yp, Ya and Yg, where the Yp for the optimum sowing date and highest yielding variety ranged from 8.6 to 11.8 t ha^{-1}, the Ya ranged from 2.5 to 7.9 t ha^{-1}, and the Yg ranged from 3.9 to 8.1 t ha^{-1} (33 to 75%, respectively). In the same study, Silva et al. (2021) found similar results for rice yield gap decomposition, where the management yield gap was the main cause of yield gap, followed by the environmental yield gap and genetic yield gap.

Management yield gap drivers

The regression analysis revealed management practices that can increase or decrease the management yield gap (Yg_m) in Southern Brazil (Table 4;Figure 5). Farmers that practiced crop rotation with soybeans in the previous summer, used no-till planting system, used fungicide or insecticide, tended to decrease the Yg_m. Whereas, farmers that practiced fallow in the previous summer, increased the sowing density, used only herbicide to control weeds before sowing or applied higher phosphorous rate tended to increase the Yg_m. However, the increasing factors should be interpreted with caution, as except for sowing density, they only appeared isolated in one season each, and not in the combined analysis, which can lead to misinterpretation due the lower number of samples in the seasonal analysis.

Figure 5

Table 4

The rice yield can benefit from various factors related to the soybean crop rotation, as it allows farmers to sown their fields under no-tillage system, which also contributes for reducing the Yg_m, allow early sowing under the optimum sowing window, reduce weed problems and increase soil quality (Ribas et al., 2021; Theisen et al., 2017). The use of no-till planting system permits a high amount of biomass to be produced during winter, facilitate crop rotation, and increase K soil levels, contributing for a more conservative agriculture (Theisen et al., 2017).

Although the use of fungicide presented a decreasing effect on Yg_m only for the 2017 season, the benefit of fungicide and/or insecticide is related to unfavorable weather conditions and diseases and/or pest incidence (Delmotte et al., 2011). Ribas et al. (2021) presented similar results for fungicide use where the effect of fungicide was year-dependent, as in two out of three years there was no difference between fields that did not receive any spraying and those that had spraying fungicide. However, the use of insecticide in our regression model presented significant results in reducing the management yield gap for the combined seasons.

The use of higher sowing density (>100 kg ha^{-1}) was significant for increasing the Yg_m. For Ribas et al. (2021), lower seeding rates also presented benefit for reducing the yield gap, and also Meus et al. (2021) found 93 kg ha^{-1} as an ideal sowing density to reach maximum yield. The crop rotation with fallow, use of only herbicide as pre-sowing weed control and higher phosphorous rate, cannot be affirmed by the authors as factors that contribute for increasing the Yg_m, as these variables presented significant results only when regressed for a single season.

Regarding the fertilizer input, our study was not able to supply information about the effect of the fertilizer in closing the yield gap, as the phosphorous input rate only appeared to be increasingly significant only in 2015 season, which was not sufficient to provide robust evidences of its effect. Nitrogen was expected to be a significant factor, as in previous studies related nitrogen as relevant factor affecting yields (Dossou-Yovo et al., 2020; Ribas et al., 2021; Senthilkumar et al., 2020; Silva et al., 2017).

The regional and seasonal factors also affected the management yield gap (Yg_m) (Table 1; Supplemental Figure S1; Supplemental Figure S2). Except for the Internal Coastal Plain, the regions located on the Central and Eastern portion of Rio Grande do Sul tended to present a decrease in Yg_m, whereas the West region tended to increase the Yg_m. In the 2016 and 2018 seasons there was also a tendency to decrease the Yg_m, and to increase in the 2019 season.

CONCLUSION

Our study provided the first estimates for yield gap decomposition, assessing the contribution of environment, genetic and management factors to rice yield gap in Southern Brazil. Our results show that the yield gap is on average 48% of the yield potential, with the environment being responsible for 20%, the genetics responsible for 10% and the management responsible for 70% of the total yield gap. Although farmers might experience delay on the sowing date related to weather conditions, lack of labor or equipment for bigger farms, the rice sowing before 13 Nov can contribute to reduce the yield gap. The use of better management practices such as crop rotation, direct seeding and adequate sowing density can reduce the management yield gap and consequently reduce the total yield gap. However, a large part of the management yield gap remains unexplained, which was not captured by our study and might be related to other farming practices such as seed origin, seed treatment with fungicide and insecticide, adequate fertilizer input, biotic or abiotic factors and other possible interactions between the management practices, environment and variety.

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FIGURES

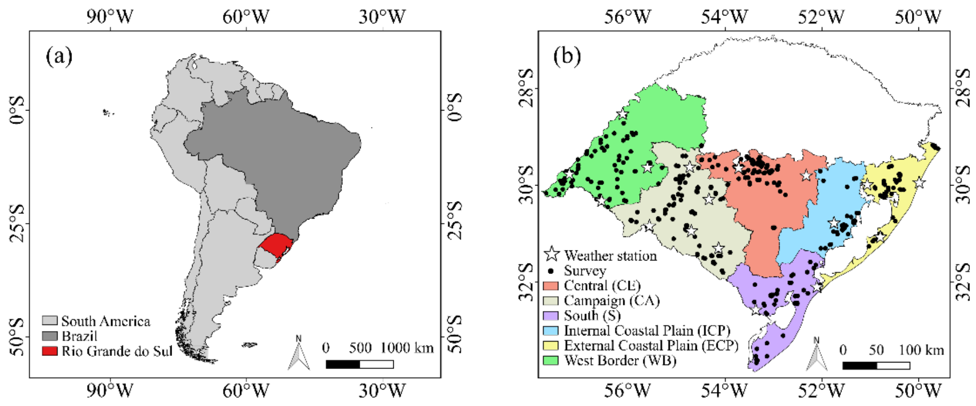


Figure 6. (a) Geographical location of the study area; (b) Regions of the Rio Grande do Sul state where rice is produced, weather stations and surveys collected.

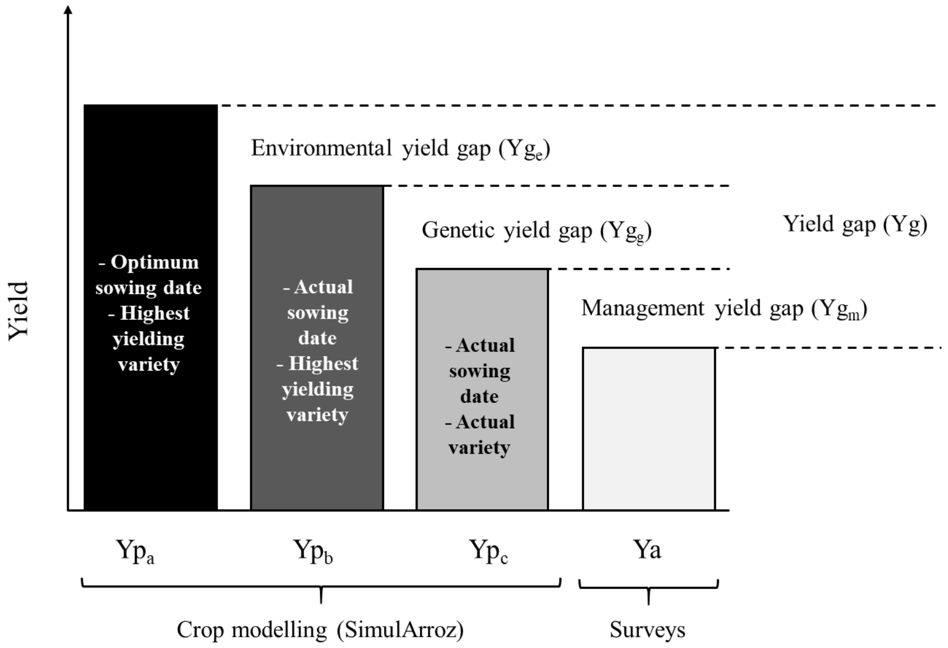


Figure 7. Concepts used to disentangle rice yield gaps in Southern Brazil (adapted from Silva et al., 2021). Yp_a = simulated yield potential for optimum sowing date and the highest yielding variety; Yp_b = simulated yield potential for actual farmers' sowing dates and highest yielding variety; Yp_c = simulated yield potential for actual farmers' sowing dates and variety used.

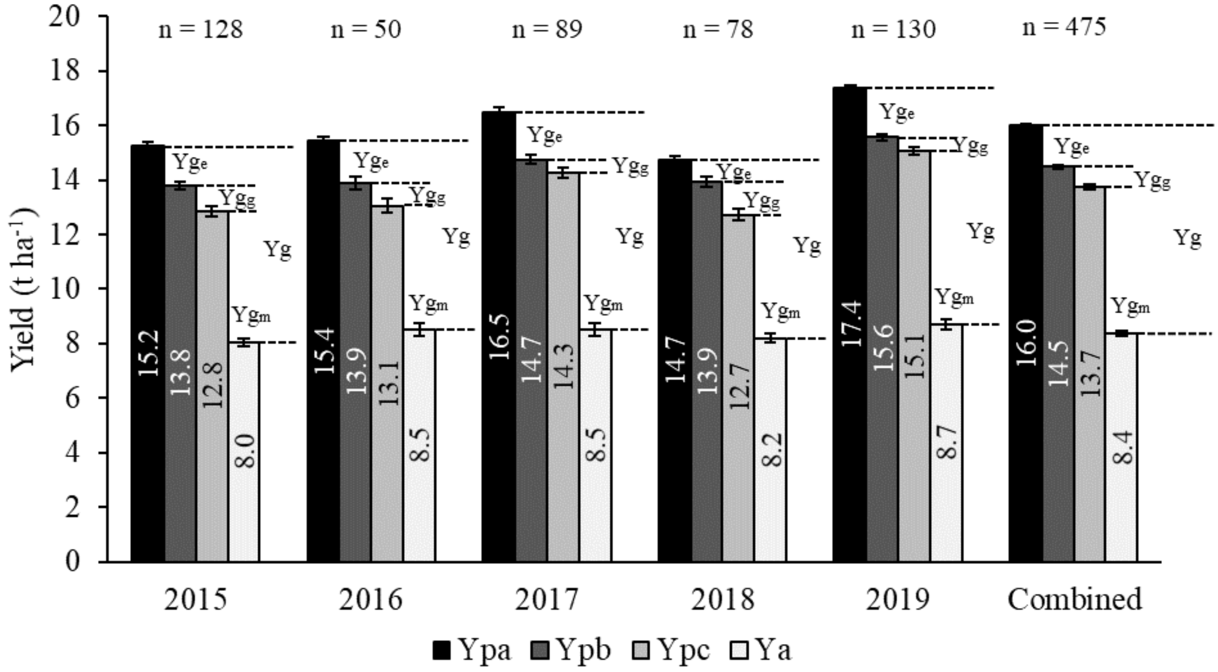


Figure 8. Decomposition of rice yield gaps across five seasons and combined seasons in Southern Brazil. Yg = yield gap; Yg_e = environmental yield gap; Yg_g = genetic yield gap; Yg_m = management yield gap; Yp_a = simulated yield potential for optimum sowing date and the highest yielding variety; Yp_b = simulated yield potential for actual farmers' sowing dates and highest yielding variety; Yp_c = simulated yield potential for actual farmers' sowing dates and variety used; Ya = actual farmers' yield.

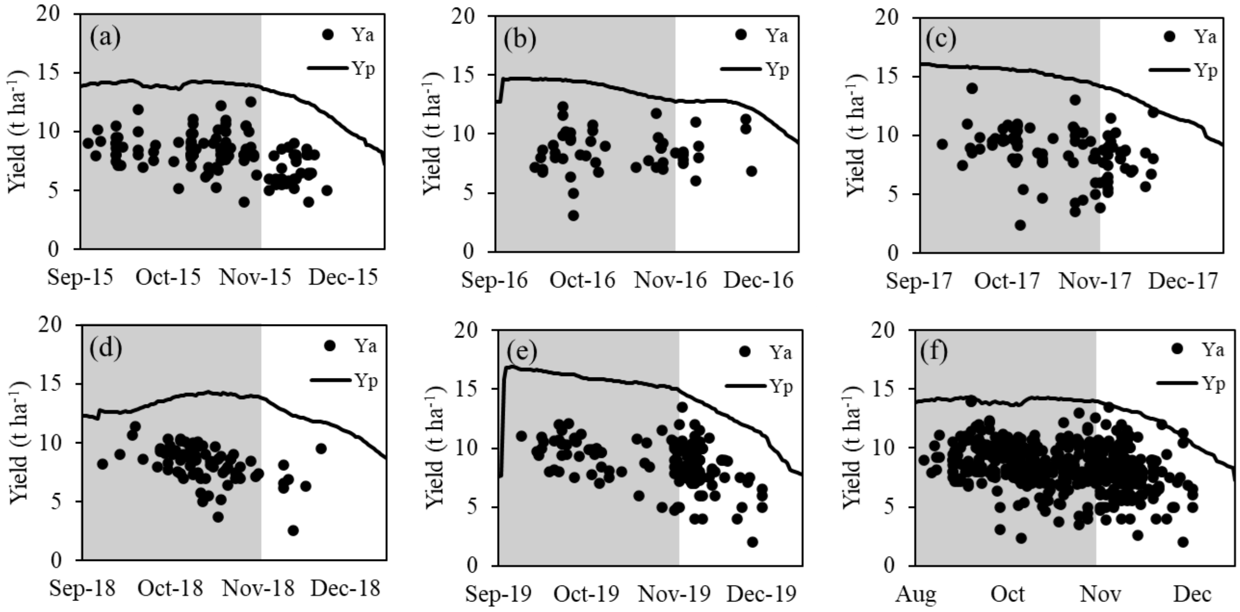


Figure 9. Distribution of farmers' actual yields (Ya) across different sowing dates in comparison with the average yield potential (Yp) for the highest yielding variety (IRGA 424 RI) in Southern Brazil. The shaded region represents the optimum sowing window (01 Sept to 13 Nov). (a) 2015 Season; (b) 2016 Season; (c) 2017 Season; (d) 2018 Season; (e) 2019 Season; (f) Combined seasons.

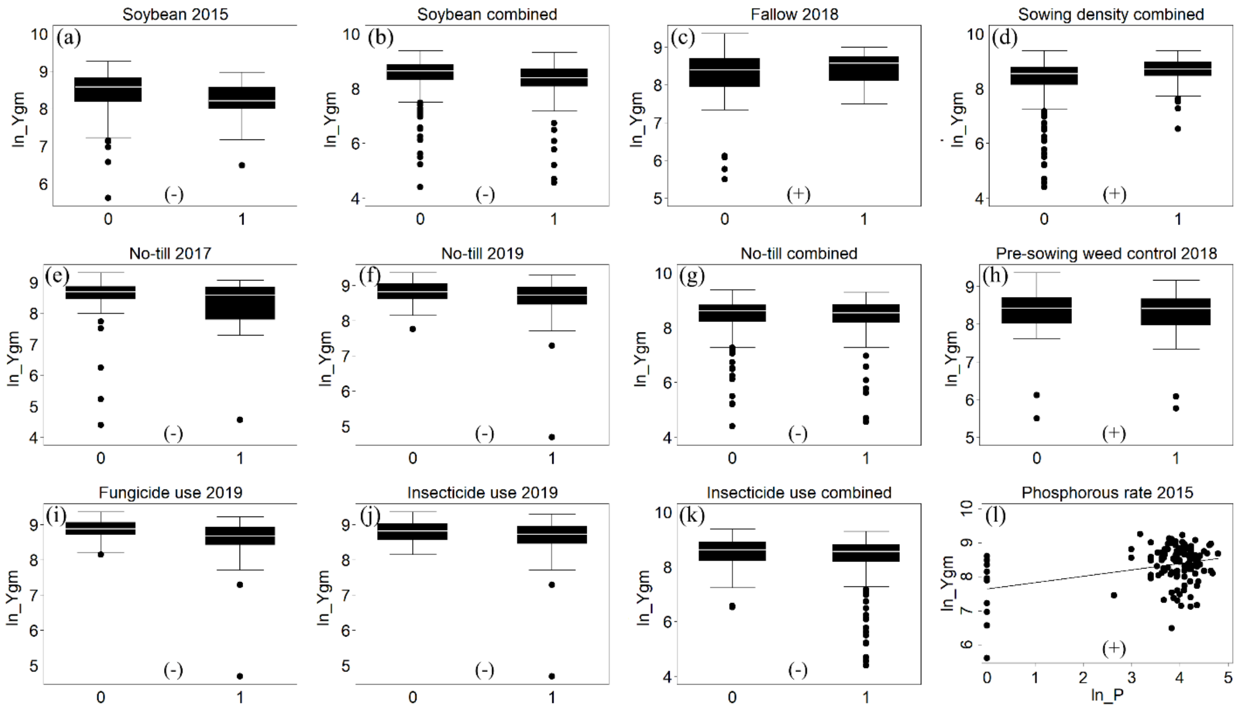
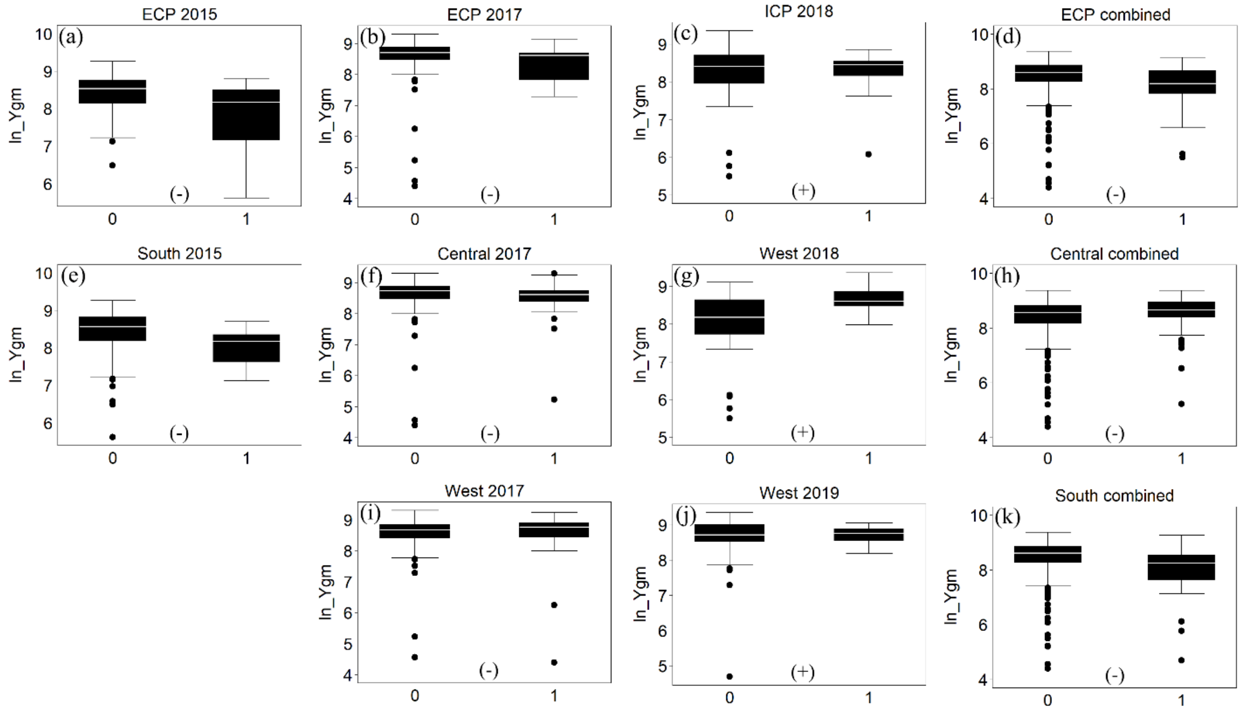
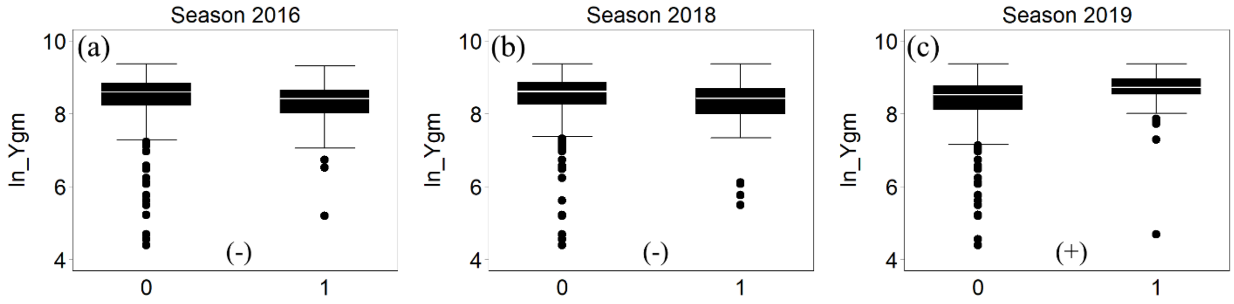


Figure 10. Significant management practices determinants of management yield gap (Yg_m) in Southern Brazil. (-) = decreasing effect on Yg_m; (+) increasing effect on Yg_m; (a) Use of soybeans as previous summer crop in 2015 season (0 = no; 1 = yes); (b) Use of soybeans as previous summer crop in combined seasons (0 = no; 1 = yes); (c) Use of fallow as previous summer crop in 2018 season (0 = no; 1 = yes); (d) Sowing density in combined seasons (0: <= 100 kg ha^{-1}; 1: > 100 kg ha^{-1}); (e) Use of no-till planting system in 2017 season (0 = no; 1 = yes); (f) Use of no-till planting system in 2019 season (0 = no; 1 = yes); (g) Use of no-till planting system in combined seasons (0 = no; 1 = yes); (h) Pre-sowing weed control in 2018 season (0 = Disc + herbicide; 1 = Only herbicide); (i) Fungicide use in 2019 season (0 = no; 1 = yes); (j) Insecticide use in 2019 season (0 = no; 1 = yes); (k) Insecticide use in combined seasons (0 = no; 1 = yes); (l) Phosphorous rate applied in 2015 season.



Supplemental Figure S1**.** Significant regional factors determinants of management yield gap (Ygm) in Southern Brazil. 0 = no; 1 = yes; (-) = decreasing effect on Ygm; (+) increasing effect on Ygm; (a) External Coastal Plain region farmers in 2015 season; (b) External Coastal Plain region farmers in 2017 season; (c) Internal Coastal Plain region farmers in 2018 season; (d) External Coastal Plain region farmers in combined seasons; (e) South region farmers in 2015 season; (f) Central region farmers in 2017 season; (g) West region farmers in 2018 season; (h) Central region farmers in combined seasons; (i) West region farmers in 2017 season; (j) West region farmers in 2019 season; (k) South region farmers in combined seasons.



Supplemental Figure S2. Significant seasonal factors determinants of management yield gap (Ygm) in Southern Brazil. 0 = no; 1 = yes; (-) = decreasing effect on Ygm; (+) increasing effect on Ygm; (a) Season 2016; (b) Season 2018; (c) Season 2019;

TABLES

Table 5. Descriptive of the survey data collected.

Collected data	Description
Region	Field region
Previous summer crop	Soybean (26%); Rice (56%); Fallow (13%); Pasture (5%)
Previous winter crop	Winter grass = 0 (38%); Fallow = 1 (62%)
Variety	Rice variety
Sowing date	Sowing date
Cropping system	Conventional (23%); Minimum tillage (41%); No-tillage (36%)
Sowing density	<=100 kg ha^{-1} = 0 (73%); >100 kg ha^{-1} = 1 (27%)
Irrigation group	<=3 leaves = 0 (57%); >3 leaves = 1 (43%)
Pre-sowing weed control	Disc + herbicide = 0 (44%); Only herbicide = 1 (56%)
Fungicide use	No = 0 (24%); Yes = 1 (76%)
Insecticide use	No = 0 (24%); Yes = 1 (76%)
Herbicide use	No = 0 (1%); Yes = 1 (99%)
Nitrogen fertilizer rate (kg/ha)	N fertilizer input (kg/ha)
Phosphorous fertilizer rate (kg/ha) P_2O_5	P_2O_5 fertilizer input (kg/ha)
Potassium fertilizer rate (kg/ha) K_2O	K_2O fertilizer input (kg/ha)
Yield	Yield (kg/ha)
Total number of observations	475
2015/2016 number of observations	128
2016/2017 number of observations	50
2017/2018 number of observations	89
2018/2019 number of observations	78
2019/2020 number of observations	130

The number in parenthesis is the representativeness of each sample;

Table 6. Actual varieties and its simulated correspondents.

Actual variety	Simulated Variety	n
GURI INTA CL	GURI INTA CL	74
IRGA 424; IRGA 424 RI	IRGA 424 RI	282
PUITA INTA CL	PUITA INTA CL	50
BRS Pampa; Inov CL; IRGA 417; IRGA 421; IRGA 431 CL	Short maturity group	30
BR/IRGA 409; BRS Pampeira; IRGA 426; IRGA 428 CL; IRGA 429; Lexus CL; Primoriso CL	Medium maturity group	21
El Paso 144; Epagri 108; Epagri 109; L3000; Olimar; SCS116 Satoru; SCS121 CL; SCS122 Miura	Late maturity group	18

n, number of simulated varieties;

Table 7. Decomposition of the yield gap (Yg)for five seasons and combined seasons in Southern Brazil.

Season	n	Yp_a	Yp_b	Yp_c	Ya	Yg	Yg_e	Yg_g	Yg_m	%Yg	$\%Yg_e$	$\%Yg_g$	$\%Yg_m$
2015	128	15.2	13.8	12.8	8.0	7.2	1.4	1.0	4.8	47%	20%	13%	67%
		(0.2)	(0.1)	(0.2)	(0.1)	(0.2)	(0.1)	(0.1)	(0.2)				
2016	50	15.4	13.9	13.1	8.5	6.9	1.5	0.8	4.6	45%	22%	12%	66%
		(0.2)	(0.2)	(0.2)	(0.2)	(0.3)	(0.2)	(0.1)	(0.3)				
2017	89	16.5	14.7	14.3	8.5	8.0	1.8	0.5	5.7	48%	22%	6%	72%
		(0.2)	(0.2)	(0.2)	(0.2)	(0.3)	(0.2)	(0.1)	(0.3)				
2018	78	14.7	13.9	12.7	8.2	6.5	0.8	1.2	4.5	44%	12%	18%	69%
		(0.1)	(0.2)	(0.2)	(0.2)	(0.2)	(0.1)	(0.2)	(0.3)				
2019	130	17.4	15.6	15.1	8.7	8.7	1.8	0.5	6.4	50%	21%	6%	73%
		(0.1)	(0.1)	(0.1)	(0.2)	(0.2)	(0.1)	(0.1)	(0.2)				
Combined	475	16.0	14.5	13.7	8.4	7.6	1.5	0.8	5.3	48%	20%	10%	70%
		(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)				

n, number of observations; Yp_a = simulated yield potential for optimum sowing date and the highest yielding variety; Yp_b = simulated yield potential for actual farmers' sowing dates and highest yielding variety; Yp_c = simulated yield potential for actual farmers' sowing dates and variety used; Ya = actual farmers' yield; Yg = yield gap; Yg_e = environmental yield gap; Yg_g = genetic yield gap; Yg_m = management yield gap; %Yg = Yg relative to Yp_a – Ya; $\%Yg_e$ = Yg_e relative to Yg; $\%Yg_g$ = Yg_g relative to Yg; $\%Yg_m$ = Yg_m relative to Yg

Table 8. Determinants of management yield gap (Yg_m) in Southern Brazil.

Variables	2015	2016	2017	2018	2019	Combined
Campaign Region[1]						
Central Region	-0.0004	-0.55	-0.674**		0.194	-0.226**
	(-0.139)	(-0.396)	(-0.283)		(-0.128)	(-0.0874)
ECP Region	-0.518**		-0.676***	0.481		-0.464***
	(-0.206)		(-0.252)	(-0.319)		(-0.125)
ICP Region				0.571*		-0.121
				(-0.338)		(-0.115)
South Region	-0.359***		-0.0524			-0.504***
	(-0.131)		(-0.251)			(-0.13)
West Region	0.0123	0.367	-0.564*	1.030***	0.348*	0.0743
	(-0.113)	(-0.257)	(-0.337)	(-0.273)	(-0.193)	(-0.0882)
Previous summer crop rice[1]						
Previous summer crop soybean	-0.305***	-0.268	-0.0876	0.199	-0.192	-0.187**
	(-0.108)	(-0.259)	(-0.23)	(-0.255)	(-0.203)	(-0.0732)
Previous summer crop fallow		-0.167	-0.373	0.287*	0.0578	-0.0715
		(-0.248)	(-0.289)	(-0.165)	(-0.0947)	(-0.1)
Previous summer crop pasture					-0.236	
					(-0.188)	
Previous winter crop fallow	-0.0503	0.151	0.131	-0.119	-0.033	0.0702
	(-0.0955)	(-0.198)	(-0.166)	(-0.201)	(-0.0805)	(-0.0578)
Conventional planting system[1]						
Minimum till planting system	0.0894	-0.251	-0.222	0.101		-0.0203
	(-0.133)	(-0.261)	(-0.151)	(-0.227)		(-0.0725)
No-till planting system	-0.0659		-0.807***	-0.278	-0.140*	-0.208**
	(-0.141)		(-0.261)	(-0.264)	(-0.0753)	(-0.0829)
Sowing density		-0.0754	0.201	0.391	0.199	0.189***
		(-0.264)	(-0.166)	(-0.35)	(-0.125)	(-0.0729)
Irrigation timing	0.0383	0.233	-0.574	0.315	0.107	0.0458
	(-0.0891)	(-0.217)	(-0.38)	(-0.318)	(-0.0869)	(-0.0711)
Pre-sowing weed control	0.141	0.0693	-0.162	0.377*		0.0419
	(-0.0968)	(-0.176)	(-0.168)	(-0.217)		(-0.0654)
Fungicide use		-0.0046	-0.043	-0.025	-0.117*	0.0025
		(-0.252)	(-0.279)	(-0.237)	(-0.0664)	(-0.081)
Insecticide use	0.0169	-0.286	-0.146	-0.394	-0.168*	-0.173**
	(-0.107)	(-0.345)	(-0.236)	(-0.256)	(-0.093)	(-0.0698)
Nitrogen rate	-0.168	-0.0448	0.216	-0.0528	-0.0674	0.0153
	(-0.114)	(-0.35)	(-0.281)	(-0.516)	(-0.1)	(-0.0855)
Phosporous rate	0.207***	-0.147	0.0725	-0.167	0.0361	0.0556
	(-0.0612)	(-0.125)	(-0.133)	(-0.31)	(-0.0453)	(-0.0552)
Potassium rate	-0.0429	0.0178	-0.0018	-0.0079	0.00201	-0.0041
	(-0.0362)	(-0.141)	(-0.0571)	(-0.244)	(-0.0411)	(-0.0339)

2015 season[1]						
2016 season						-0.376***
						(-0.119)
2017 season						0.0728
						(-0.124)
2018 season						-0.229**
						(-0.111)
2019 season						0.197*
						(-0.106)
Constant	8.668***	9.171***	8.063***	8.583***	8.867***	8.458***
	(-0.585)	(-1.579)	(-1.278)	(-1.828)	(-0.463)	(-0.376)
Observations	128	50	89	78	130	475
R-squared	0.376	0.386	0.219	0.316	0.195	0.194

Robust standard errors in parenthesis; *** p<0.01, ** p<0.05, * p<0.1; [1] Reference for region; [2] Reference for previous summer crop; [3] Reference for planting system; [4] Reference for season.

5 DISCUSSÃO

Estudos relacionados às lacunas de produtividade (LP) das culturas agrícolas vem sendo desenvolvidos no mundo todo para as mais diversas culturas, e a definição do potencial e lacuna de produtividade de arroz irrigado no Rio Grande do Sul (RS) nos permite mensurar como o Brasil pode futuramente contribuir com a soberania alimentar mundial, explorando sustentavelmente nossos recursos através da redução da lacuna de produtividade.

O potencial de produtividade (PP) de arroz irrigado para o sul do Brasil (>14 t ha^{-1}) está acima dos observados nas demais regiões agrícolas do mundo. Isso ressalta a importância que as regiões próximas à latitude 30° tem em relação à agricultura, onde há maior disponibilidade de radiação solar para as culturas de verão em relação aos trópicos, e menor risco de danos causados por baixas temperaturas, como nas regiões temperadas.

Além disso, devido às características locais do RS, há uma grande variação do PP de acordo com a região do estado ou da época de semeadura. A região Oeste do estado apresenta um maior PP em relação à região Leste, devido à maior disponibilidade de radiação solar durante o ciclo de cultivo de arroz, que influencia diretamente a produtividade de grãos. A época de semeadura também tem grande importância na definição do PP, onde as semeaduras realizadas nos primeiros 45 dias da janela de plantio de arroz no estado, permitem alcançar os maiores potenciais.

Entretanto, apesar do alto potencial produtivo, o Rio Grande do Sul apresenta uma grande lacuna de produtividade de arroz, próxima a 48% ou 7,6 t ha^{-1}. Os resultados obtidos nessa dissertação, destacam-se a influência dos fatores ambientais, genéticos e de manejo na LP. Quanto aos fatores ambientais, destaca-se a influência da época de semeadura, responsável por 20% da LP, onde a cada dia de atraso na data de semeadura, entre 01/setembro e 13/novembro leva a uma perda de 0.03 t ha dia^{-1}, entre 14/novembro e 21/dezembro 0.08 t ha dia^{-1}, e após 21/dezembro a perda intensifica-se em 0.29 t ha dia^{-1}.

Os fatores genéticos, ou seja, escolha da cultivar a ser semeada, pode levar a uma redução de 10% na LP, caso todos os produtores optarem pela cultivar de maior potencial produtivo. Entretanto, a nível de campo, isso seria muito difícil de ocorrer, visto que a diversidade genética das cultivares e híbridos de arroz são importantes para ajustar às necessidades de cada lavoura.

Responsável por 70% da LP, o manejo ineficiente da lavoura de arroz é o principal redutor de produtividade no RS. A adoção de práticas de manejo mais sustentáveis e que levam a maiores produtividades, podem ser mais eficientes em reduzir a LP em curto e médio prazo. Isto constata-se visto que a implementação de rotação de culturas com a soja em terras baixas, a adoção do sistema plantio direto, e menor densidade de semeadura foram destacados neste trabalho como as principais práticas de manejo com potencial de reduzir a LP.

6 CONCLUSÃO

Os resultados obtidos nesta dissertação fornecem estimativas em relação ao potencial de produtividade de arroz irrigado no Rio Grande do Sul, lacuna de produtividade, e importância dos fatores ambientais genéticos e de manejo.

O potencial de produtividade é próximo a 14 t ha^{-1} nas semeaduras realizadas no início da janela de plantio, e decresce suavemente de 01/setembro a 13/novembro, intensifica de 14/novembro a 21/dezembro, e decresce abruptamente após 21/dezembro.

A lacuna de produtividade de arroz irrigado no Rio Grande do Sul é em média 48% da produtividade potencial, onde o ambiente é responsável por 20%, os fatores genéticos 10% e o manejo responsável por 70% desta lacuna.

Apesar das dificuldades de alguns produtores realizarem a semeadura mais cedo, a semeadura de arroz realizada antes de 13 de novembro pode contribuir para a redução da lacuna de produtividade. Além disso, a utilização de melhores práticas de manejo, como a adoção de rotação de culturas, sistema plantio-direto e densidade de semeadura adequada também podem reduzir a lacuna.

Entretanto, grande parte da lacuna de produtividade causada pelo manejo continua sem explicação, que não foi possível capturar neste estudo, e podem estar relacionadas a outras práticas de manejo não coletadas com os questionários, ou pela interação entre as práticas de manejo, genética e embiente.

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