UNIVERSIDADE FEDERAL DE SANTA MARIA
CENTRO DE CIÊNCIAS RURAIS
PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA AGRÍCOLA

Giovana Ghisleni Ribas

POTENCIAL E LACUNAS DE PRODUTIVIDADE EM ARROZ IRRIGADO NO RIO GRANDE DO SUL

Santa Maria, RS, Brasil
2020

Giovana Ghisleni Ribas

POTENCIAL E LACUNAS DE PRODUTIVIDADE EM ARROZ IRRIGADO NO RIO GRANDE DO SUL

Tese apresentada ao Curso de Doutorado do Programa de Pós-Graduação em Engenharia Agrícola da Universidade Federal de Santa Maria (UFSM), como requisito parcial para obtenção do título de **Doutora em Engenharia Agrícola**

Orientador: Prof. Ph.D. Nereu Augusto Streck

Santa Maria, RS, Brasil
2020

This study was financied in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) – Finance Code 001

Ghisleni Ribas, Giovana
POTENCIAL E LACUNAS DE PRODUTIVIDADE EM ARROZ IRRIGADO NO RIO GRANDE DO SUL / Giovana Ghisleni Ribas. 2020.
92 p.; 30 cm

Orientador: Nereu Augusto Streck
Coorientador: Alencar Junior Zanon
Tese (doutorado) - Universidade Federal de Santa Maria, Centro de Ciências Rurais, Programa de Pós Graduação em Engenharia Agrícola, RS, 2020

1. Oryza sativa 2. potencial de produtividade 3. lacuna de produtividade 4. lavouras 5. questionários I. Streck, Nereu Augusto II. Zanon, Alencar Junior III. Título.

Sistema de geração automática de ficha catalográfica da UFSM. Dados fornecidos pelo autor(a). Sob supervisão da Direção da Divisão de Processos Técnicos da Biblioteca Central. Bibliotecária responsável Paula Schoenfeldt Patta CRB 10/1728.

Giovana Ghisleni Ribas

POTENCIAL E LACUNAS DE PRODUTIVIDADE EM ARROZ IRRIGADO NO RIO GRANDE DO SUL

Tese apresentada ao Curso de Doutorado do Programa de Pós-Graduação em Engenharia Agrícola da Universidade Federal de Santa Maria (UFSM), como requisito parcial para obtenção do título de **Doutora em Engenharia Agrícola**

Aprovado em 19 de dezembro de 2019:

Nereu Augusto Streck, Ph.D.
(Presidente/Orientador)

Filipe Selau Carlos Dr.(UFPEL)

André da Rosa Ulguim Dr. (UFSM)

Alencar Junior Zanon, Dr. (UFSM)

Cleber Maus Alberto Dr. (UNIPAMPA)

AGRADECIMENTOS

A concretização deste trabalho ocorreu, principalmente, pelo auxílio, compreensão e dedicação de várias pessoas. Agradeço a todos que, de alguma forma, contribuíram para a conclusão deste estudo e, de uma maneira especial, agradeço:

- á Deus por me guiar e proteger
- o meu orientador Nereu Augusto Streck pela oportunidade concedida no Programa de Pós-Graduação em Engenharia Agrícola, pela confiança em mim depositada, e pela pessoa humana, incentivadora e dedicada, grata pela orientação;
- a meu coorientador Alencar Junior Zanon, pelo apoio e confiança, pelo emprenho dedicado à elaboração deste trabalho, pelas suas correções e incentivos;
- ao professor Patricio Grassini da University of Nebraska - EUA, pelo suporte no pouco tempo que lhe coube, pelas suas correções e incentivos;
- a minha mãe Vera Lúcia Ghisleni e minha avó Eni Angela Ghisleni por todo amor verdadeiro e apoio em todos os momentos, porque sempre acreditaram na minha capacidade e tudo que conquistei na minha vida foi graças a elas;
- aos meus amigos, que souberam entender minha ausência e que sempre me deram incentivo;
- aos colegas Nicolas Cafaro, Fatima Tenorio e Shen Yuan, que sempre estiveram à disposição para me atender na University of Nebraska, EUA;
- à Universidade pública, gratuita e de qualidade, pela oportunidade de desenvolver e concretizar este estudo;
- aos professores e funcionários do Programa de Pós-Graduação da Engenharia Agrícola por contribuírem de uma forma ou de outra pela conquista desse título;

Enfim a todos àqueles que fazem parte da minha vida e que são essenciais para eu ser, a cada dia nessa longa jornada, um ser humano melhor.

RESUMO

Potencial e lacunas de produtividade em arroz irrigado no Rio Grande do Sul

AUTOR: Giovana Ghisleni Ribas
ORIENTADOR: Nereu Augusto Streck

O Estado do Rio Grande do Sul é o principal produtor brasileiro de arroz (*Oryza sativa* L.). Apesar do contínuo aumento na produtividade média do arroz nos últimos anos, ainda há uma considerável diferença entre as produtividades medidas em experimentos de estações de pesquisa de arroz e da produtividade média atual de arroz no Rio Grande do Sul. O potencial de produtividade é a produtividade de uma cultivar que cresce sem limitações biótica e abiótica. Entre os objetivos deste projeto destacam-se (i) introduzir três cultivares convencionais de arroz atualmente, muito utilizadas no RS nos modelos SimulArroz e Oryza, (ii) estimar o potencial de produtividade e as lacunas de produtividade da culturas do arroz nas regiões de terras baixas do Estado do Rio Grande do Sul, (ii) identificar os fatores biofísicos e de manejo que potencialmente explicam a lacuna de produtividade nas lavouras de arroz nas regiões de terras baixas do Estado do Rio Grande do Sul. Levantamento de dados de manejo foram feitos por meio de 324 questionários aplicados em três anos agrícolas (2015/2016, 2016/2017 e 2017/2018). Os modelos mostraram bom desempemho, apresentando variação do NRMSE entre 0,8% à 34%. O potencial reportado no RS com o modelo Oryza v3 (14,8 t ha^{-1}). Sob ponto de vista das melhores lavouras de arroz no RS foi observado que estão produzindo 68% do potencial, enquanto que as demais lavouras estão produzindo 52% do potencial no RS. Estes resultados indicam o quanto, ainda, é possível melhorar o manejo de arroz no RS sendo época de semeadura, época de entrada de água na lavoura, controle de plantas daninhas, rotação de culturas e fertilizantes os fatores que potencialmente estão relacionados com a lacuna. O uso combinado entre agricultores e a estratégia de programas de pesquisa e extensão é uma ótima ferramenta para capturar variações regionais que podem ajudar a transferencia de informar.

Palavras-chave: *Oryza sativa*, potencial de produtividade, lacuna de produtividade, lavouras, questionários.

ABSTRACT

Yield potential and yield gap in irrigated rice in Rio Grande do Sul

AUTHOR: Giovana Ghisleni Ribas
ADVISOR: Nereu Augusto Streck

The Rio Grande do Sul state is the main Brazilian rice producer (Oryza sativa L.). Despite continue increase of average rice yield in the last years, there is still a huge difference between yield experiments from rice research centers and actual yield in irrigated rice in the Rio Grande do Sul. The yield potential is the yield from a cultivar that gown without biotic and abiotic limitation. Among the objectives of this study highlight (i) to introduce of three conventional rice cultivar actual widely used in RS by SimulArroz and Oryza models, (ii) to estimate yield potential and yield gap in lowland rice area in the Rio Grande do Sul state, (ii) to identify the biophysics and management factors that are potentially causing the yield gap in lowland area in the Rio Grande do Sul state. Management data were collected from 324 surveys applied in three growing seasons (2015/2016, 2016/2017 e 2017/2018). The models showed a great performance and the NRMSE varied from 0,8% to 34%. The yield potential reported in RS using Oryza v3 was 14.8 t ha^{-1}. From the point of view of best rice fields in RS was found that they are reaching 68% of yield potential, whereas the other fields are reaching 52% of yield potential in RS. This result indicates how much fields in RS still need to improve the management, where the most consistent factors to cause the gaps were sowing date, onset irrigation, pre-sowing weed control, soybean-rice rotation, and fertilizer. The combined use of farmers and strategize research and extension programs at is a great tool to capture regional variation which can help to inform.

Key-words: *Oryza sativa*, yield potential, yield gap, farmers, surveys.

SUMÁRIO

1. INTRODUÇÃO E JUSTIFICATIVA

O arroz (*Oryza sativa* L.) é o segundo cereal mais produzido no mundo, sendo fundamental para segurança alimentar do Planeta (FAO, 2018). Nos últimos dois anos (2014-2015), a área cultivada com arroz no mundo foi, aproximadamente, de 160 milhões de hectares, com uma produção de aproximadamente 478 milhões de toneladas, respectivamente. O Brasil é o nono maior produtor mundial de arroz, na média de cinco anos (2010-2014), a produção brasileira de arroz foi de 12 milhões de toneladas (USDA, 2018), sendo a região Sul (Paraná, Rio Grande do Sul e Santa Catarina) responsável por 82% da produção brasileira e o Estado do Rio Grande do Sul (RS) o maior produtor, com 73% da produção nacional (IRGA, 2018). Em termos de área, anualmente no RS são cultivados 1,1 milhão de hectares com arroz irrigado (CONAB, 2016), sendo que esta cultura tem grande participação no produto interno bruto gerado pelo setor agrícola neste Estado. Em ambiente de solo alagado é possível alcançar produtividades de 12 a 15 t ha^{-1}, devido à adaptação da planta a essa condição (MENEZES et al., 2013).

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 Insituto 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 dos níveis de adubação e antecipação da época de semeadura, o que resultou no incremento da produtividade média de 5,5 Mg ha^{-1} (1998-2002) para 7,5 Mg ha^{-1} (2010-2015) (MENEZES et al., 2013). Apesar do contínuo aumento no produtividade médio do arroz nos últimos anos no RS, ainda há uma considerável diferença entre os produtividades medidos em experimentos de estações de pesquisa de arroz (13 Mg ha^{-1}) e do produtividade médio atual de arroz (7,5 Mg ha^{-1}) no RS (BATTISTI et al., 2013; IRGA 2016). Esta lacuna é um incentivo para continuar os esforços científicos visando minimizá-la.

O potencial de produtividade (PR) (também referido como produtividade potencial por muitos autores) é o produtividade de uma cultivar que cresce sem limitações de nutrientes, estresses bióticos (plantas daninhas, insetos e doenças) e água, ou seja, a taxa de crescimento da planta ou da cultura é determinada pela radiação solar interceptada pelo dossel, temperatura, CO_2 atmosférico e características genéticas (EVANS, 1993; VAN ITTERSUM; RABBINGE, 1997). A lacuna de produtividade (LR), do inglês *yield gap*, é a diferença entre PR ou PR_A (para culturas de sequeiro) e os produtividades médios dos agricultores (R_M) (LOBELL et al., 2009).

O tema da proposta (lacunas de produtividade – *Yield Gap*) é um dos temas agronômicos mais estudados atualmente nos Estados Unidos. Nos países em desenvolvimento, como o Brasil, este tema ainda não é muito estudado, porém nestes países a lacuna é, teoricamente, muito maior que nos países desenvolvidos devido ao nível tecnológico das lavouras ser mais baixo em função do custo dos insumos de produção. Neste projeto foi usada a metodologia mais recomendada internacionalmente para determinar a lacuna de produtividade (modelos agrícolas baseados em processos e dados coletados diretamente em lavouras comerciais) da principal cultura agrícola do Rio Grande do Sul (arroz). Assim, em nível internacional, a contribuição científica foi de determinar a lacuna de produtividade e os fatores biofísicos que causam esta lacuna em uma região agrícola importante utilizando uma metodologia aceita na comunidade científica internacional. Os dados gerados neste projeto serão compartilhados com o projeto GYGA (www.yieldgap.org), um esforço global para mapear as lacunas de produtividade ao redor do Planeta.

1.1. OBJETIVOS

1.1.1 Objetivo Geral

Estimar o potencial de produtividade e a lacuna de produtividade dos modelos SimulArroz e Oryza como simuladores da cultura de arroz irrigado no Rio Grande do Sul.

1.1.2 Objetivos Específicos

- Introduzir três cultivares convencionais de arroz atualmente, muito utilizadas no RS nos modelos SimulArroz e Oryza.

- Estimar o potencial de produtividade de cultivares de arroz irrigado do Estado do Rio Grande do Sul.

- Estimar a lacuna de produtividade da cultura do arroz no Estado do Rio Grande do Sul.

- Identificar os fatores biofísicos e de manejo que potencialmente explicam a lacuna de produtividade nas lavouras de arroz irrigado por inundação do Estado do Rio Grande do Sul.

2. REFERENCIAL TEÓRICO

2.1 A CULTURA DO ARROZ

A maioria das pessoas associam o arroz à Ásia, no entanto o arroz também é de origem africana. Entre as muitas espécies do gênero *Oryza*, apenas duas foram domesticadas, uma na Ásia (*Oryza sativa*) e a outra na África Ocidental (*Oryza glaberrima*) (LU, 1999). Enquanto a Ásia tem sido conhecida como país sinônimo da cultura do arroz, a África não. Contudo, uma exceção notável ocorre em comunidades isoladas do nordeste da América do Sul, onde descendentes de escravos e quilombolas comemoram o arroz como parte de sua herança africana. Desde o povo Suriname até o Cayenne e do outro lado da Amazônia, aos estados brasileiros do Amapá, Pará e Maranhão, surgiu uma tradição que afirma que uma mulher africana introduziu arroz escondendo grãos em seus cabelos. As sementes preciosas escaparam à detecção e, como explicam, foi assim que o arroz foi plantado nas américas, mesmo o arroz plantado na Carolina do Sul colonial, sugere um relato semelhante. Em 1726, o correspondente suíço, Jean Watt, observou que "foi por uma mulher que o arroz foi transplantado em Carolina" (VAILLANT, 1948).

Este relato apresenta uma perspectiva contrastante sobre as transferências transoceânicas de sementes que ocorreram entre os séculos XVI e XVIII e substitui os relatos de dispersão de sementes por navegadores ocidentais (navegadores europeus, colonos e pesquisadores). Foi por uma mulher africana escravizada, cujo esforço deliberado de seqüestrar grãos de arroz em seus cabelos foi possível que seus descendentes sobrevivessem (CROSBY, 2003). Desta forma, a história vincula as transferências de sementes de arroz ao comércio transatlântico de escravos, à iniciativa africana e as preferências de subsistência dos escravizados. Essa visão da introdução do arroz é estabelecida em uma região ampla, onde três potências européias criaram economias de plantação e contrasta fortemente com os relatos escritos que dão créditos aos marinheiros europeus as sementes da Ásia (RIBEIRO, 1983), sendo a única perspectiva compartilhada entre as duas versões da história que o arroz foi introduzido nas Américas.

No Brasil, o cereal foi cultivado para subsistência um século antes de seu surgimento, logo após a fundação da colônia da Carolina em 1670. Atualmente, 77% do arroz cultivado no Brasil encontra-se no estado do Rio Grande do Sul, onde é cultivado sob irrigação por inundação. O arroz é do gênero *Oryza sativa*, uma planta megatérmica, aquática, de cultivo anual, porte ereto, com altura variando de 60 a 150 cm, pertencente a subfamília Oryzoideae (BOLDRINI et al., 2005), 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).

A evolução da produtividade de arroz nos Estados do Rio Grande do Sul se deve principalmente ao desenvolvimento de cultivares adaptadas as condições climáticas locais, que atendem as exigências do mercado e com maior tolerância aos estresses bióticos e abióticos, o que gerou cultivares de arroz denominadas "modernas", com alto teto produtivo (COMISSÃO DE AGRICULTURA PECUÁRIA E COOPERATIVISMO, 1999). Com cultivares mais responsivas ao manejo do solo e da cultura, o investimento financeiro e tecnológico se torna economicamente viável.

2.2 MODELAGEM NA AGRICULTURA

A produção de alimentos na agricultura tem se tornado cada vez mais complexa nas últimas décadas por instabilidades economicas, inflações, preços no exterior e regulamentação governamentais, junto com oferta de dinheiro e manipulaçoes de crédito. Para lidar com toda está complexidade na agricultura modelos agrícolas tem sido vistos como uma poderosa ferramenta para avaliar e selecionar estratégias políticas (KROPFF, 1994, SHIN et al., 2006).

Modelos podem ser usados para gerar previsões quantitativas e avaliar o efeito de alternativas de decisões ou estratégias sob controle direto na politica de mercado (KROPFF, 1994). Na essência, modelos podem oferecer uma estrutura para condução de experimentos em laboratorios sem influenciar diretamente na agricultura. Muitos modelos tem sido construidos com finalidade de fazer previsões climáticas e também da cultura, sendo o mais demandado, pois é utilizado na tomada de decisão na agricultura através de um sistema estocástico dinâmico (BOUMAN et al., 2000, AGGARWAL et al., 2006, ROSA et al., 2015, RIBAS et al., 2020).

Modelos matemáticos estão sendo cada vez mais utilizados na agricultura, pois são ferramentas de baixo custo operacional que permite descrever as complexas interações nos agroecossitemas (WALTER et al., 2012). Na área agrícola, para ser representativo e confiável, cada modelo matemático precisa ser adaptado e testado em diferentes ambientes. Após testados, com os modelos agrícolas pode-se prever o crescimento, o desenvolvimento e a produtividade da cultura em função das condições meteorológicas que ocorre em cada estação de crescimento, em diferentes locais (SHIN et al., 2006; SHIN et al., 2010).

Para a cultura do arroz existem modelos dinâmicos de simulação do produtividade de grãos mais complexos, como o CERES-rice (SINGH et al., 1993) e o ORYZA1 (KROPFF et al., 1994), e outros mais simplificados, como o InfoCrop (AGGARWAL et al., 2006), SimulArroz (STRECK et al., 2013; ROSA et al., 2015). Os modelos ORYZA e SimulArroz são modelos ecofisiológicos dinâmicos baseados em processos. Estes modelos utilizam a radiação solar como forçante ambiental principal para o cálculo diário do acúmulo de matéria seca, e a temperatura mínima e máxima como base do cálculo da taxa de desenvolvimento da fenologia (BOUMAN & VAN LAAR, 2006; WALTER et al., 2014; ROSA et al., 2015).

O modelo ORYZA é o modelo de simulação da cultura do arroz do Instituto Internacional de Pesquisa em Arroz (IRRI - *The International Rice Research Institute*), nas Filipinas, e o modelo para estimativa de PR em estudos de lacuna de produtividade em arroz no projeto GYGA. O SimulArroz (www.ufsm.br/simularroz), é um modelo mais simples que o ORYZA, mas ajustado para o cultivo de arroz no RS e de fácil uso.

2.3 ESTIMATIVA DO POTENCIAL DE PRODUTIVIDADE A PARTIR DE MODELOS AGRÍCOLAS ORYZA E SIMULARROZ

Os modelos matemáticos baseados em processos (*process-based models*) são as ferramentas mais indicadas para estimar o potencial de produtividade (PP) (LOBELL et al., 2009). O PP é a produtividade de uma cultivar que cresce sem limitações de nutrientes, estresses bióticos (plantas daninhas, insetos e doenças) e água, ou seja, a taxa de crescimento da planta ou da cultura é determinada pela radiação solar interceptada pelo dossel, temperatura, CO2 atmosférico e características genéticas (EVANS, 1993; VAN ITTERSUM & RABBINGE, 1997).

Os modelos ORYZA (BOUMAN et al., 2006) e SimulArroz (STRECK et al., 2013; ROSA et al., 2015) são modelos ecofisiológicos dinâmicos baseados em processos. Estes modelos utilizam a radiação solar como forçante ambiental principal para o cálculo diário do acúmulo de matéria seca, e a temperatura mínima e máxima como base do cálculo da taxa de desenvolvimento da fenologia (BOUMAN & VAN LAAR, 2006; WALTER et al., 2014; ROSA et al., 2015).

O modelo ORYZA é o modelo de simulação da cultura do arroz do Instituto Internacional de Pesquisa em Arroz (IRRI - *The International Rice Research Institute*), nas Filipinas, e o modelo para estimativa de PR em estudos de lacuna de rendimento em arroz no projeto GYGA. O ORYZA simula o crescimento e desenvolvimento de arroz irrigado em situações de potencial de produção, limitação de água e limitação de nitrogênio (BOUMAN & VAN LAAR, 2006), já foi calibrado para o cultivo de arroz em terras altas do Brasil (LORENÇONI et al., 2010; HEINEMANN et al., 2015), entretanto não se tem estudos da utilização deste modelo para o Rio Grande do Sul.

O SimulArroz (www.ufsm.br/simularroz), foi desenvolvido pela equipe FieldCrops da Universidade Federal de Santa Maria (UFSM), para simular o crescimento, desenvolvimento e produtividade de arroz irrigado no sistema por inundação para o estado do Rio Grande do Sul na condição potencial e em três níveis tecnológicos da lavoura (ALTO, INTERMEDIÁRIO e BAIXO). É um modelo mais simples que o ORYZA, mas ajustado para o cultivo de arroz no RS e de fácil uso. A atual versão do SimulArroz (versão 1.1) tem uma lista de vinte cultivares de arroz que podem ser selecionados pelo usuário. Atualmente, o SimulArroz foi selecionado para estimar o zoneamento agroclimático para a cultura do arroz irrigado no RS.

3. RESULTADOS

3.1 ARTIGO I: (PUBLICADO NA REVISTA PESQUISA AGROPECUÁRIA BRASILEIRA)

An update of new rice cultivars in the SimulArroz model

Giovana Ghisleni Ribas[(1)], Nereu Augusto Streck[(1)], Ary José Duarte Junior[(1)], Bruna Rolin San Martin Ribeiro[(1)], Isabela Bulegon Pilecco[(1)], Ioran Guedes Rossato[(1)], Gean Leonardo Richter[(1)], Kelin Pribs Beixaira[(1)], Vladison Fogliato Pereira[(1)] and Alencar Junior Zanon[(1)]

[(1)] Universidade Federal de Santa Maria/ Agrometeorology, Av. Roraima, 1000 – 97105-900 – Santa Maria, RS – Brazil. e-mails: giovana.ghisleni@hotmail.com, nstreck2@yahoo.com, aryduartee@gmail.com, brunasanmartinrolim@gmail.com, isabelabpilecco@gmail.com, ioranrossato@gmail.com, geanleonardorichter@gmail.com, kelin_bexaira@hotmail.com, vladisom_15@hotmail.com, alencarzanon@hotmail.com

Abstract - The objective of this study was to model the three rice cultivars currently most grown in the Rio Grande do Sul State in the SimulArroz model. The experiments to calibrated and validated SimulArroz model were conducted in Cachoeirinha, Santa Maria, Uruguaiana, Santa Vitória do Palmar e Cachoeira do Sul in Rio Grande do Sul, Brazil. There were evaluated the number of leaves, phenology, dry matter biomass aboveground and yield for the currently most grown cultivars in the State. The results showed a slightly overestimate of the R1, R4 and R9 stages, but overall, the model had good performance in simulating rice phenology for the three genotypes. Furthermore, the model had a reasonable accuracy in simulating aboveground dry matter and yield. The RMSE for dry matter aboveground ranged from 0.5 to 3.0 Mg ha^{-1} (leaves, stems, panicle and grain). For yield the RMSE ranged from 0.8 to 1.3 Mg ha^{-1}. The calibration of the SimulArroz model used is efficient in simulating the growth, development and grain yield for the most important irrigated rice cultivars in Southern Brazil and can be used to estimated harvest forecast, yield potential and yield gap studies.

Index terms: *Oryza sativa*, mathematical model, yield.

Uma atualização de novas cultivares de arroz no modelo SimulArroz

Resumo - O objetivo deste trabalho foi modelar três cultivares de arroz atualmente mais cultivadas no Estado do Rio Grande do Sul no modelo SimulArroz. Os experimentos para calibrar e validar o modelo SimulArroz foram conduzidos em Cachoeirinha, Santa Maria, Uruguaiana, Santa Vitória do Palmar e Cachoeira do Sul, no Rio Grande do Sul, Brasil. Foram avaliados o número de folhas, a fenologia, a biomassa da matéria seca aérea e a produtividade das cultivares atualmente mais cultivadas no Estado. Os resultados mostraram uma leve superestimativa dos estádios R1, R4 e R9, mas no geral, o modelo apresentou bom desempenho na simulação da fenologia do arroz para os três genótipos. Além disso, o modelo teve uma precisão razoável em simular matéria seca e produtividade. O RMSE para a matéria seca da parte aérea variou de 0,5 a 3,0 Mg ha^{-1} (folhas, caules, panículas e grãos). Para produtividade, o RMSE variou de 0,8 a 1,3 Mg ha^{-1}. A calibração do modelo SimulArroz utilizado é eficiente em simular o crescimento, desenvolvimento e produtividade de grãos das cultivares de arroz irrigado mais importantes do Sul do Brasil e pode ser utilizada para estimar a previsão de safra, potencial de produtividade e estudos de lacunas de produtividade.

Termos para indexação: *Oryza sativa*, modelo matemático, produtividade.

Introduction

Brazil is the first largest rice (*Oryza sativa* L.) producer in the world outside Asia (FAO, 2018; USDA, 2018) with an annual production of around 11 Mt. The Rio Grande do Sul (RS) State is the largest producer of rice in Brazil (1.1 million ha) with 70% of the national production and a yield of 7.4 Mg ha^{-1} (CONAB, 2019). Analyzing the time series of rice yield in RS, during the first decade of the 21st century, rice yield steady increased and reached 7.5 Mg ha^{-1} in 2011 as result of farmers adopting the Clearfield system (CL), and genetic breeding that developed cultivars with resistance to the imidazolinone herbicide, such as IRGA 424 RI, Guri INTA CL and Puitá INTA CL (Menezes et al., 2013). Since 2012, rice yields have been stable and these cultivars represented around 80% of the farmers in the last two growing seasons (2016/2017 and 2017/2018).

Simulation modelling is among the most used research techniques in recent years in Brazil, and its application in the rice area focused on the comparative assessment of different crop models in current and future weather scenarios (Walter et al., 2015; Castro et al., 2018; Ramirez-Villegas et al., 2018), the evaluation of alternative water management strategies (Heinemann, et al., 2002), and the assessment of the yield losses due weeds (Richter et al., 2019).

From a crop modeler perspective, the genotypic differences regulating the phenological development- e.g., the thermal requirements to reach flowering - the plant physiological traits - e.g., the specific leaf area - and its morphological features - e.g., the maximum plant height - are embedded into parameters, driving the response of process-level models, in turn leading to yield formation (Hossard et al., 2017). Model parameters can thus be considered as crop “genetic coefficients”, providing a mathematical representation of the gene effects under different environmental conditions (Boote et al., 2001). It follows that crop models could be successfully used to analyze the interactions between genotype, environment, and management (G×E×M) occurring at the yield level (Rattalino Edreira et al., 2017), estimating at the yield potential (Evans, 1993; Van Ittersum & Rabbinge, 1997), and quantifying the yield gap (difference between farm yield and yield potential, according to Van Ittersum et al., 2013).

In RS, irrigated rice modeling studies are provided by SimulArroz model (Rosa et al., 2015), which has already been calibrated for rice cultivars and technological farm levels, and it has been used for a variety of applications at a farm and regional levels, e.g. to evaluate, in "real-time" basis, the impact of current weather on irrigated rice yield potential (Rosa et al., 2015; Ribas et al., 2017). As a result, SimulArroz model was selected for updating the Agricultural Zoning for rice in the State (ZARC), which is the first time a process-based model will be used for agricultural zooning in Brazil. Therefore, this model has a potential use as a tool to improve on-farm management through estimative of yield potential and yield gap, according to the methodology proposed by Grassini et al. (2015). However, the latest version of the SimulArroz model (Ribas et al., 2017) does not include the currently most grown cultivars in the RS state (IRGA 424 RI, Puitá INTA CL and Guri INTA CL) which is crucial to make happening those estimates (Cassman et al., 2003; Lobell et al., 2009; Van Ittersum et al., 2013), providing information about the yield potential and yield gap for irrigated rice in southern Brazil.

The objective of this study was to model the three rice cultivars currently most grown in the Rio Grande do Sul State into the SimulArroz model.

Material and Methods

Field experiments were conducted during four growing seasons (2013/2014, 2014/2015, 2015/2016 and 2016/2017) in five locations (Table 1), which represent the range of environments where irrigated rice is grown in the Rio Grande do Sul State, Brazil. In these fields experiments with irrigated rice two cultivars of early maturation group (Puitá INTA-CL and Guri INTA CL) and one intermediate maturation group (IRGA 424 RI) were used. These cultivars represent around 80% of the rice area sown in Rio Grande do Sul, approximately 800 thousand hectares (IRGA, 2018). Sowing dates were on September, October, November and December, which are sowing dates within the period recommended by the rice agroclimatic zoning (Table 1). The experimental design was randomized blocks with four replicates. The sowing density was 0.1 Mg of seeds ha^{-1}, at a spacing of 0.17 m between rows and a seeding depth of 0.03 m. Each plot had 20 meters long and 13 meters wide.

Leaf appearance and phenology were weekly evaluated by the Haun (Haun, 1973) and the Counce (Counce et al., 2000) scales, respectively. Panicle differentiation (R1) was determined through a destructive sampling of 10 plants and the R1 date was considered when 50% of the plants were in this development stage. During the growing season in Cachoeirinha and Santa Maria, aboveground biomass was collected (clipped close to the soil), in an area of 1.36 m^2 per cultivar at the following developmental stages: V2 (before irrigation), between V3 and R1, R1, between R1 and R4, R4, between R4 and R9, R9. 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 in a precision scale (0.001 g). For the determination of grain yield (Mg ha^{-1}), an area of 20 m^2 was collected for each cultivar.

The genetic parameters calibrated in the SimulArroz model were: maximum rate of appearance of the first and second leaves ($LARmax_{1,2}$), cumulative number of leaves on the main stem (HS), development rates (DVR), total thermal time necessary to complete the Sowing-Emergence phase (TTEM), total thermal time necessary to complete the Emergence-Panicle Differentiation phase (TTVG), total thermal time necessary to complete the Panicle Differentiation-Anthesis phase (TTRP), total thermal time necessary to complete the Anthesis-maturation phase (TTEG), radiation use efficiency (RUE), dry matter biomass aboveground (DM), assimilate partitioning factors; leaf area index (LAI), Spike formation factor (SOCF), and maximum grain weight (Pmax). The calibration approach was the same as in Rosa et al. (2015) and Ribas et al. (2017).

The evaluation of the model in simulating leaf appearance, phenology, aboveground dry matter (leaves, stems, panicle and grain yield) was performed with data from the experiments described in Table 1. The model was run in the potential level mode for the experiments where dry matter was collected and in the high technology mode for the remaining experiments. The potential level in the model represents experiments without biotic and abiotic stress, while high technological level in the model represents the best farmers in state, which use to integrated management of weeds, insects and diseases, and high fertilization (Menezes et al., 2013). The weather data to run the model were from automatic weather stations located close to the experiments in each location as possible.

The performance of the SimulArroz model was evaluated using the statistics measuring the accuracy, precision, and trend metrics by root-mean-square error (RMSE) – equation 1 (Janssen e Heuberger, 1995), normalized-root-mean-square error (NRMSE) – equation 2 (Janssen e Heuberger, 1995), BIAS index – equation 3 (Gabriel, et al., 2014), agreement index (dw) – equation 4 (Gabriel, et al., 2014), adjusted coefficient of determination (R^2_a) – equation 5 (Srivastava et al., 1995), and Systematic Error (Es) – equation 6 (Streck et al., 2008)

1. ACCURACY METRICS :

$$RMSE=\left[\frac{\sum(S_i-O_i)^2}{n}\right]^{0.5} \quad (1)$$

$$NRMSE = 100 \text{ x } RMSE/\bar{O} \quad (2)$$

$$BIAS = \frac{\sum S_i - \sum O_i}{\sum O_i} \quad (3)$$

$$d_w=1-\frac{\sum(S_i-O_i)^2}{[(|S_i-\bar{O}|)+(|O_i-\bar{O}|)]^2} \quad (4)$$

2. METRICS FOR ACCURACY :

$$R2_a = \frac{\sum_{i-1}^{N}(Si-\bar{O})^2}{\sum_{i-1}^{N}(Oi-\bar{O})^2} \quad (5)$$

3. TREND METRICS:

$$Es = \sqrt{\frac{\sum_{i-1}^{N}(Oi - \bar{O})^2}{n}} \qquad (6)$$

Where, Si - simulated values; S - mean of simulated values; Oi - observed values; Ō - mean of observed values; and n - number of observations.

Results and Discussion

The maximum appearance rates of the first and second leaves ($LAR_{max1,2}$) were similar for Guri INTA CL, Puitá INTA CL and IRGA 424 RI cultivars (Table 2), indicating that leaf appearance is not different among these three genotypes. For the thermal time (TTEM), the duration of the Emergence-Panicle Differentiation and Panicle Differentiation-Anthesis phases are shorter in early than in intermediate maturity cultivars (Table 2), as verified in rice hybrids by Ribas et al. (2017). In addition, RUE and LAI for Puitá INTA CL and RUE for Guri INTA CL were higher than for IRGA 424 RI, indicating greater efficiency in converting light energy (solar radiation) into chemical energy (photosynthesis). However, Puitá INTA CL and Guri INTA CL had a lower SOCF and Pmax, which caused lower grain yield in Puitá INTA CL (10.2 Mg ha^{-1}) and Guri INTA CL (11.5 Mg ha^{-1}) compared to IRGA 424 RI (13.2 Mg ha^{-1}) (Table 2).

Despite a general slight underestimation, the SimulArroz model accurately simulated HS values (Figure 1a), with an RMSE equal to 1 leaf, which is close to values (0.6 to 1.48 leaves) found for rice by Streck et al. (2008) using Streck, Wang and Engel and phyllochron models . In all cases the other statistics indicate a good model performance for this variable. A slightly overestimate of the R1, R4 and R9 stages was observed, as verified by RMSE ranging from 3 to 8 days, and by NRMSE ranging from 6% to 26% (Figure 1b). These values are similar to the RMSE for rice varied from 3 to 7 days (RMSE) using the ORYZA2000 model (Van Oort et al., 2011). In Italy, Mongiano et al. (2019) reported RMSE and NRMSE values for rice of 5.5 (R1), 7.1 (R9) and 6.2% (R1) 22% (R9) using the WOFOST_GT model. Overall, the model had good performance in simulating rice phenology for the three genotypes (Figure 1b).

The cultivars (IRGA 424 RI, Guri INTA CL and Puitá INTA CL) allocated more photoassimilates into the leaves, translocating more than 50% until the development stage (DVS) of 0.43 (Table 3), compared to rice hybrids (40% into the leaves) (Ribas et al., 2017). Rice hybrids allocate more photoassimilates into the stems to sustain a bigger panicle (Ribas et al., 2017). In general, SimulArroz had a reasonable accuracy in simulating aboveground biomass accumulation (Figure 2a to 2d). The RMSE (Mg ha^{-1}) of simulation aboveground DM, leaves, stems and panicle IRGA 424 RI ranged from 1.0 to 3.0 Mg ha^{-1}. The values of the index BIAS, indicated an overestimation of the model for the Guri INTA CL and Puitá INTA CL cultivars in DM partitioning, with the exception of the total DM in Guri INTA CL cultivar, and an underestimate to the cultivar IRGA 424 RI, except for DM of leaves. In addition, the index dw indicated a good performance of the model, with values above 0.80 (Figure 2). As a result, the Es and R_a^2 ranging from 0.6% to 9.3% and from 0.52 to 0.97, respectively for dry matter. Tang et al. (2009) to apply the models RiceGrow and ORYZA2000 to describe the aboveground dry matter and grain yield they found RMSE values from 0.2 to 0.8 Mg ha^{-1} (Table 4). In turn, in study of Confalonieri et al. (2016) with rice, WARM model reported large values of RMSE, between 0.97 to 3.78 Mg ha^{-1} and NRMSE values between 8% to 36%, respectively to aboveground and panicle dry matter. For dry matter grain yield, the RMSE and NRQME of SimulArroz model varied from 0.6 to 1.0 Mg ha^{-1} and from 6.3 to 8.3% respectively (Figure 2e). As a result, Tang et al. (2009) and Artacho et al. (2011) achieved values of RMSE (from 0.6 to 1.6 Mg ha^{-1}) and NRMSE (19%) slightly higher in relation to the SimulArroz model of this study for grain yield.

In the validation of the model with the simulated grain yield a comparison was made with yield dataset of experiments with different sowing dates with the cultivars IRGA 424 RI, Guri INTA CL and Puitá INTA CL being RMSE and NRMSE ranging from 0.8 to 1.3 Mg ha^{-1} and from 10.5 to 11.2% respectively. In China, Boling et al. (2011) reported a RMSE of 0.6 Mg ha^{-1} and an NRMSE of 20.4 % for rice, showing that the errors of the present study are within the range reported by the authors mentioned. Same in Italy, where Mongiano, et al. (2019) reported RMSE and NRMSE of 0.81 Mg ha^{-1} and 13.2%, respectively, using the WOFOST_GT model. Also, the SimulArroz model simulated yields ranging from 4.1 to 15.0 Mg ha^{-1}, indirectly proving the robustness of the model approach (Figure 3). The relationship between the experimental data and data generated by the model confirmed the goodness of fit of the models to the yield with R_a^2 ranging from 0.59 to 0.78 and Es approximately of 8.9%, these results are in agreement with the literature.

Following the international literature, rice models have been used by researchers to estimate the yield impact across stacking resistance in rice fields by using CL variates (Dauer et al., 2017), rice hydration at different thermal conditions (Balbinoti et al., 2018a), estimates of rice yield potential and yield gap (Deng et al., 2019; Liu et al., 2019), and modeling the interactions of rice structure and level protein-ligand (Baicharoen et al., 2018) which could lead to an enhancement in rice quality, market price and increase the yielded without increase area. Furthermore, models with the same fits are mathematically identical and can be used by anyone to modeling plant behavior (Balbinoti, et al., 2018b; Dauer et al., 2017; Baicharoen et al., 2018). In this study, the analysis of the statistical parameters allowed concluding that the SimulArroz model may with the same degree of quality describe the growth and development for irrigated rice.

Therefore, the robustness and accuracy of SimulArroz combined with the low requirements in terms of inputs for reproducing biophysical processes strongly influencing the year-to-year yield variation, make the model suitable for grain yields of the most important CL cultivars of irrigated rice in RS. The model can be applied with confidence to explore potential yields in this State, also, this study confirmed the existence of a yield gap between potential and actual yields. The average simulated yields potential (13.5 Mg ha^{-1}) exceeded the actual yield to the cultivars IRGA 424 RI, Guri INTA CL and Puitá INTA CL in the same growing season (7.5 Mg ha^{-1}) (IRGA 2018).

Conclusions

1. The SimulArroz model tested in this study made possible to predict the reproduce growth, development and grain yield variability within years and locations for IRGA 424 RI, Puitá INTA CL and Guri INTA CL with NRMSE between 6% to 105%.

2. The evaluation of the parameter mean of RMSE (7 days to phenology; 1.4 Mg ha-1 to dry matter and grain yield), R_a^2 (0.77) and Es (13%) demonstrate that the SimulArroz model present good fitness to the experimental data (109 field experiments) in the major rice-producing area of the Brazil (Rio Grande do Sul) with a mean relative error of 28%, and due to its predictive ability, this model can support potential yield and yield gap studies.

References

AGGARWAL, P.K.; KALRA, N.; CHANDER, S.; PATHAK, H. InfoCrop: a dynamic simulation model for the assessment of crop yields, losses due to pests, and environmental impact of agro-ecosystems in tropical environments. **Agricultural Systems**, v.89, p.1-25, 2006. DOI: 10.1016/j.agsy.2005.08.001.

ARTACHO, P.; MEZA, F.; ALCALDE, J.A. Evaluation of the Oryza2000 rice growth model under nitrogen-limited conditions in an irrigated Mediterranean environment. **Chilean Journal of Agricultural Research**, v.71, p.23-33, 2011. DOI: 10.4067/S0718-58392011000100003.

BAICHAROEN, A., VIJAYAN, R.; PONGPRAYOON, P. Structural insights into betaine aldehyde dehydrogenase (BADH2) from Oryza sativa explored by modeling and simulations. **Scientific reports**, v.8, p.12892, 2018. DOI: 10.1038/s41598-018-31204-z.

BALBINOTI, T. C. V., DE MATOS JORGE, L. M.; JORGE, R. M. M. Mathematical modeling of paddy (Oryza sativa) hydration in different thermal conditions assisted by Raman spectroscopy. **Journal of cereal science**, v.79, p.390-398, 2018a. DOI: 10.1016/j.jcs.2017.11.019.

BALBINOTI, T. C. V., DE MATOS JORGE, L. M.; JORGE, R. M. M. Modeling the hydration step of the rice (Oryza sativa) parboiling process. **Journal of Food Engineering**, v.216, p.81-89, 2018b. DOI: 10.1016/j.jfoodeng.2017.07.020.

BOLING, A.A.; BOUMAN, B.A.M.; TUONG, T.P.; KONBOON, Y.; HARNPICHITVITAYA, D. Yield gap analysis and the effect of nitrogen and water on photoperiod-sensitive Jasmine rice in north-east Thailand. **Wageningen Journal of Life Science**, v.58, p.11-19, 2011. DOI: 10.1016/j.njas.2010.05.001.

BOOTE, K.J.; KROPFF, M.J.; BINDRABAN, P.S. Physiology and modelling of traits in crop plants: implications for genetic improvement. Agricultural System. v.70, p.395–420. 2001. DOI:10.1016/s0308-521x(01)00053-1.

BOUMAN, B.A.M.; KROPFF, M.J.; TUONG, T.P.; WOPEREIS, M.C.S.; TEN BERGE, H.F.M.; LAAR, H.H. VAN. **Oryza 2000: modeling lowland rice.** Manila, Philippines: International Rice Research Institute (IRRI), 2004. 245p.

CASSMAN, K.G.; DOBERMANN, A.; WALTERS, D.T.; YANG, H. Meeting cereal demand while protecting natural resources and improving environmental quality. **Annual Review Environment Resources**, v.28, p.315–358, 2003. DOI: 10.1146/annurev.energy.28.040202.122858.

CASTRO, J. R. D., CUADRA, S. V., PINTO, L. B., SOUZA, J. M. H. D., SANTOS, M. P. D.; HEINEMANN, A. B. Parametrization of Models and Use of Estimated Global Solar Radiation Data in the Irrigated Rice Yield Simulation. **Revista Brasileira de Meteorologia**, v.33, p.238-246, 2018. DOI: 10.1590/0102-7786332003.

CONAB. **Acompanhamento da safra brasileira de grãos.** Available at: < www.conab.gov.br >. Accessed on: May. 01 2018.

CONFALONIERI, R.; BREGAGLIO, S.; ACUTIS, M. Quantifying uncertainty in crop model predictions due to the uncertainty in the observations used for calibration. **Ecological modelling**, v.328, p.72-77, 2016. DOI: 10.1016/j.ecolmodel.2016.02.013

COUNCE, P.; KEISLING, T.C.; MITCHELL, A.J. A uniform, objective, and adaptative system for expressing rice development. **Crop Science**, v.40, p.436-443, 2000. DOI: 10.2135/cropsci2000.402436x.

DAUER, J., HULTING, A., CARLSON, D., MANKIN, L., HARDEN, J.; MALLORY-SMITH, C. Gene flow from single and stacked herbicide-resistant rice (Oryza sativa): modeling occurrence of multiple herbicide-resistant weedy rice. **Pest Management Science**, v.74, p.348-355, 2018. DOI: 10.1002/ps.4711.

DENG, N.; GRASSINI, P.; YANG, H.; HUANG, J.; CASSMAN, K. G.; PENG, S. Closing yield gaps for rice self-sufficiency in China. **Nature communications**, v.10, 1725, 2019. DOI: 10.1038/s41467-019-09447-9.

ESPE, M.B.; CASSMAN, K.G.; YANG, H.; GUILPART, N.; GRASSINI, P.; VAN WART, J.; ANDRES M.; BEIGHLEY D.; HARELL D.; LISCOMBE S.; MCKENZE K.; MUTTERS R.; WILSON L.T.; LINQUIST. B.A. Yield gap analysis of US rice production systems shows opportunities for improvement. **Field Crops Research**. v.196, p.276-283, 2016. DOI: 10.1016/j.fcr.2016.07.011.

EVANS, L. T. Crop evolution, adaptation and yield. Cambridge university press.1996.

FAO. **Database of the Food and Agricultural Organization of the United Nations**. Available at: <www.fao.org/faostat/en/#data/QC>. Accessed on: May. 01 2018.

GABRIEL, L.F.; STRECK, N.A.; ROBERTI, D.R.; CHIELLE, Z.G.; UHLMANN, L.O.; SILVA, M. R.DA.; SILVA, S.D. da. Simulating cassava growth and yield under potential conditions in Southern Brazil. **Agronomy Journal**, v.106, p.1119-1137, 2014. DOI: 10.2134/agronj2013.0187.

GRASSINI, P.; TORRION, J.A.; YANG, H.S.; REES, J.; ANDERSEN, D.; CASSMAN, K.G.; SPECHT, J.E. Soybean yield gaps and water productivity in the western U.S. Corn Belt. **Field Crops Research**, v.179, p.150-163, 2015. DOI: 10.1016/j.fcr.2015.04.015.

HAUN, J.R. Visual quantification of wheat development. **Agronomy Journal**, v.65, p.116-119, 1973. DOI: 10.2134/agronj1973.00021962006500010035x.

HEINEMANN, A. B.; HOOGENBOOM, G.; DE FARIA, R. T. Determination of spatial water requirements at county and regional levels using crop models and GIS: An example for the State of Parana, Brazil. **Agricultural Water Management**, v.52, p.177-196, 2002. DOI: 10.1016/S0378-3774(01)00137-8.

HOSSARD, L.; BREGAGLIO, S.; PHILIBERT, A.; RUGET, F.; RESMOND, R.; CAPPELLI, G.; DELMOTTE, S. A web application to facilitate crop model comparison in ensemble studies. Enviromental Model Software. v.97, p.259–270. 2017. DOI:10.1016/j.envsoft.2017.08.008.

IRGA. **Levantamento da área semeada com arroz irrigado no Rio Grande do Sul**. Available at: <http://www.irga.rs.gov.br>. Accessed on: Feb. 20 2018.

JANSSEN, P. H. M.; HEUBERGER, P. S. C. Calibration of process-oriented models. **Ecological Modelling**, v.83, p.55-56, 1995. DOI: 10.1016/0304-3800(95)00084-9.

LI, T.; ANGELES, O.; MARCAIDA M.; MANALO, E.; MANALILI, M. P.; RADANIELSON, A.; MOHANTY, S. From ORYZA2000 to ORYZA (v3): An improved simulation model for rice in drought and nitrogen-deficient environments. **Agricultural and forest meteorology**, v.237, p.246-256, 2017. DOI: 10.1016/j.agrformet.2017.02.025.

LIU, Y., LI, C., FANG, B., FANG, Y., CHEN, K., ZHANG, Y.; ZHANG, H. Potential for high yield with increased seedling density and decreased N fertilizer application under seedling-throwing rice cultivation. **Scientific reports,** v.9, p.731. 2019. DOI: 10.1038/s41598-018-36978-w.

LOBELL, D.B.; CASSMAN, K.G.; FIELD, C.B. Crop yield gaps: their importance, magnitudes, and causes. **Annual Review Environment Resources**, v.34, p.179–204, 2009. DOI: 10.1146/annurev.environ.041008.093740.

MENEZES, V. G.; ANGHINONI, I.; SILVA, P. R. F. DA; MACEDO, V. R. M.; PETRY, C.; GROHS, D. S.; FREITAS, T. F. S. DE; VALENTE, L. A. L. **Project 10 - Management strategies to increase yield and sustainability of irrigated rice in RS: advances and new challenges**. Cachoeirinha, Brazil: Instituto Rio Grandense do Arroz (IRGA), 2013. 96p.

MONGIANO, G.; TITONE, P.; TAMBORINI, L.; PILU, R.; BREGAGLIO, S. Advancing crop modelling capabilities through cultivar-specific parameters sets for the Italian rice germplasm. **Field Crops Research**, v.240, p.44-54. 2019. DOI: 10.1016/j.fcr.2019.05.012

RAMIREZ-VILLEGAS, J., HEINEMANN, A. B., PEREIRA DE CASTRO, A., BRESEGHELLO, F.; NAVARRO-RACINES, C., LI, T., REBOLLEDO, M.C.; CHALLINOR, A. J. Breeding implications of drought stress under future climate for upland rice in Brazil. **Global Change Biology**, v.24. p.2035-2050, 2018. DOI: 10.1111/gcb.14071.

RIBAS, G.G.; STRECK, N.A.; DUARTE JUNIOR, A.J.; NASCIMENTO, M.F.; ZANON, A.J.; SILVA, M.R. Number of leaves and phenology of rice hybrids simulated by the SimulArroz model. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v.21, p.221-226, 2017. DOI: 10.1590/1807-1929/agriambi.v21n4p221-226.

RICHTER, G. L.; STRECK, N. A.; ZANON, A. J.; ULGUIM, A. D. R.; KRUSE, N. D.; SANTOS, G. A. D. A. D.; CERA, J.C.; RIBAS, G.G.; DUARTE JUNIOR, A.J.; PILECCO, I. B. Introducing rice yield loss caused by weed competition into the SimulArroz model. Pesquisa Agropecuária Brasileira, v.54. 2019. DOI: 10.1590/s1678-3921.pab2019.v54.01418

ROSA, H.T.; WALTER, L.C.; STRECK, N.A.; CARLI, C.DE; RIBAS, G.G.; MARCHESAN, E. Simulação do crescimento e produtividade de arroz no Rio Grande do Sul pelo modelo SimulArroz. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v.19, p.1159-1165, 2015. DOI: 10.1590/1807-1929/agriambi.v19n12p1159-1165

SRIVASTAVA, A. K.; SRIVASTAVA, V. K.; ULLAH, A. The coefficient of determination and its adjusted version in linear regression models. Econometric Reviews, v.14. p. 229-240. 1995. DOI: 10.1080/02664760802553000

STÖCKLE C.O.; WILLIAMS J.R.; ROSENBERG C.A.; JONES C.A. A method for estimating direct and climatic effects of rising atmospheric carbon dioxide on crops growth and yield. **Agricultural Systems**, v.38, p.225–238, 1992. DOI: 10.1016/0308-521X(92)90067-X.

STRECK, N. A.; BOSCO, L. C.; LAGO, I. Simulating leaf appearance in rice. **Agronomy Journal**, v.100, p.490-501, 2008. DOI: 10.2134/agronj2007.0156.

TANG, L..; ZHU, Y.; HANNAWAY, D.; MENG, Y.; LIU, L.; CHEN, L.; CAO, W. RiceGrow: A rice growth and productivity model. **NJAS-Wageningen Journal of Life Sciences**, v.57, p.83-92, 2009. DOI: 10.1016/j.njas.2009.12.003.

USDA. **Production, Supply and Distribution**. Available at: <www.usda.gov/wps/portal/usda/usdahome?navid=DATA_STATISTICS> Accessed on: Feb. 20 2018.

VAN ITTERSUM, M. K., & RABBINGE, R. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crops Research, v.52. p. 197-208. 1997. DOI: 10.1016/s0378-4290(97)00037-3

VAN ITTERSUM, M.K.; CASSMAN, K.G.; GRASSINI, P.; WOLF, J.; TITTONELL, P.; HOCHMAND, Z. Yield gap analysis with local to global relevance—a review. **Field Crops Research**, v.143, p.4–17. 2013. DOI: 10.1016/j.fcr.2012.09.009

VAN OORT, P.A.J.; ZHANG, T.; DE VRIES, M.E.; HEINEMANN, A. B.; MEINKE, H. Correlation between temperature and phenology prediction error in rice (Oryza sativa L.). **Agricultural and Forest Meteorology**, v.151, p.1545-1555, 2011. DOI: 10.1016/j.agrformet.2011.06.012.

WALTER, L. C.; STRECK, N. A.; ROSA, H. T. Mecanismos de aclimatação das plantas à elevada concentração de CO2. Ciência Rural, v. 45, p. 1564-1571, 2015. DOI: 10.1590/0103-8478cr20140527

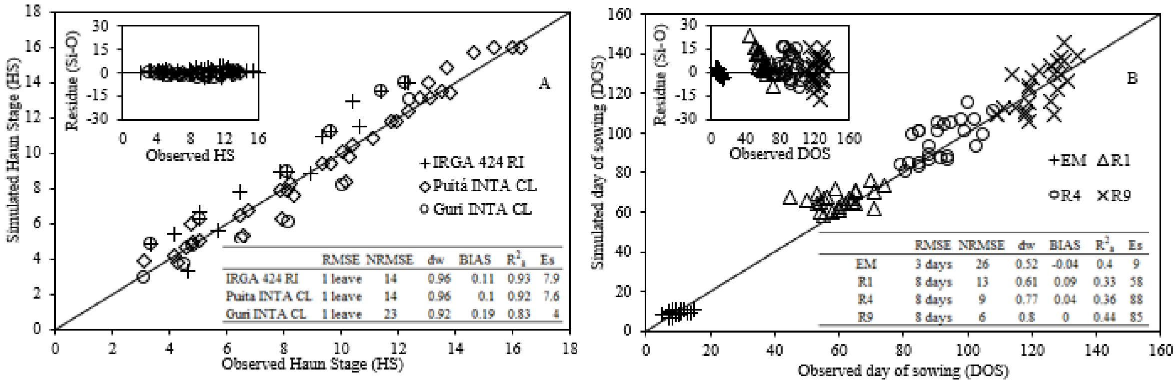

Figure 1. Evaluation of SimulArroz model in simulating the HS (A) and Days of Sowing (B), following the Counce Scale: Sowing-Emergence phase (EM), panicle differentiation (R1), anthesis (R4) and physiological maturity (R9). The model was run in potential-level mode, for three cultivars of irrigated rice and two seasons in Rio Grande do Sul (see Table 1). n is the number of observations, RMSE (leaves; days - units), NMRSE (%), BIAS, dw, R^2_a (%), Es (%).

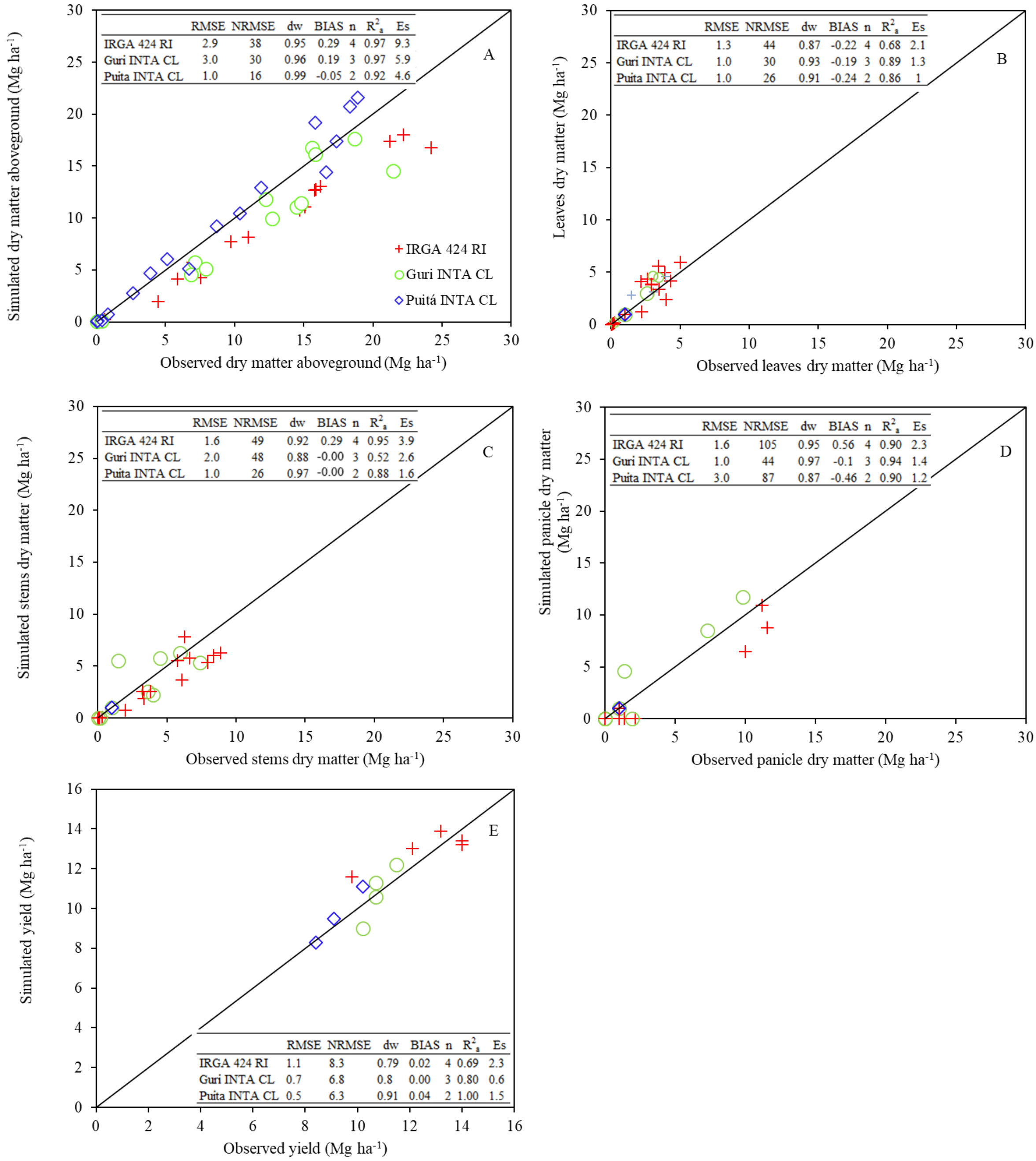

Figure 2. Evaluation of SimulArroz model to the total dry matter aboveground (DM) (A), leaves (B), stems (C), panicle (D) and grain yield at 13% moisture (E). The model was run in potential mode for three irrigated rice cultivars, in two growing season and two sites in Rio Grande do Sul (see Table 1). RMSE (Mg ha^{-1}), NMRSE (%)BIAS = index (BIAS), dw, R^2_a (%) and Es (%) and n is the number of observations.

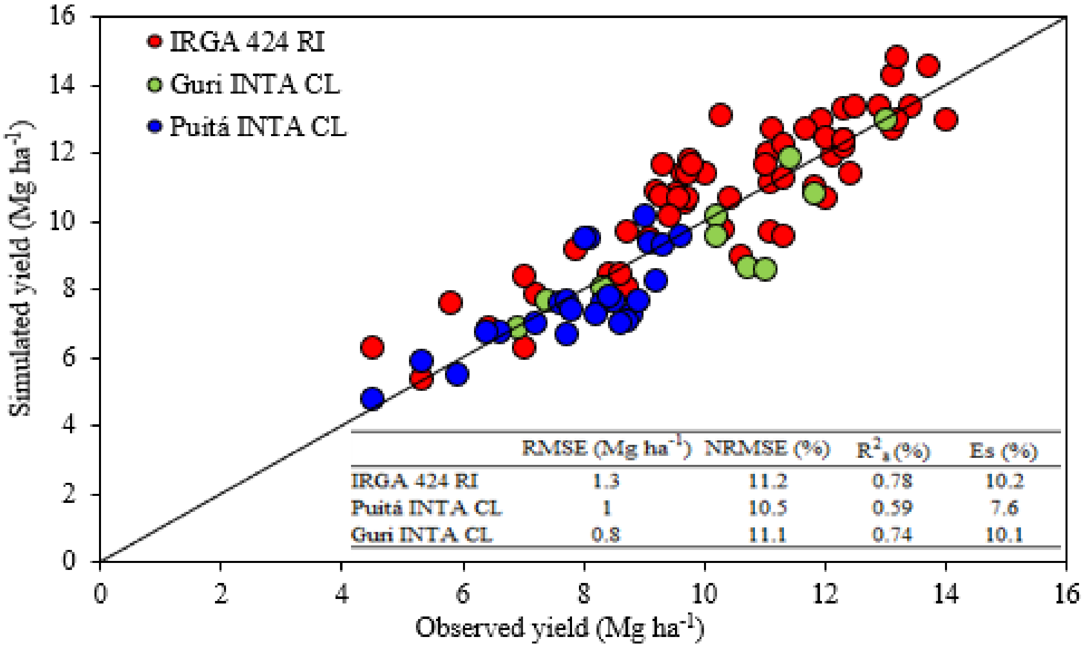

Figure 3. Evaluation of SimulArroz model for the observed grain yield at 13% moisture in the experiments with different sowing dates. The model was run in the high-level mode for three cultivars, in five sites and four growing seasons (see Table 1). Statistics analyses are showed.

Table 1. Experiments with flood-irrigated rice conducted during four growing seasons (2013/2014, 2014/2015, 2015/2016 and 2016/2017) at the five locations in the Rio Grande do Sul State, Brazil, used in the study to calibration and evaluation (independent data) of the submodels of leaf appearance, phenology, dry matter partitioning and yield in the SimulArroz model.

Data		Calibration		Evaluation	
Experiments (location)	Soil Type (Clay %)	n* Sowing date (range)	n** Cultivars (MG)	n* Sowing date (range)	n** Cultivars (MG)
Cachoeirinha (29° 95’ S, 51° 12’ W and 17 m)	Typic Albaqualf (6%)	2 (Oct 01 - Nov 09)	3 (early – intermediate cycle)	33 (Oct 18 - Dez 15)	3 (early – intermediate cycle)
Cachoeira do Sul (-30° 02’ S, -52°53’ W and 68 m)	Typic Albaqualf (6%)	-	-	20 (Set 01 - Dez 15)	3 (early – intermediate cycle)
Santa Vitória do Palmar (-33º 51’ S, -53º 35’ W and 24 m)	Typic Albaqualf (6%)	-	-	16 (Set 01 - Dez 15)	3 (early – intermediate cycle)
Santa Maria (-29º 72’S, -53º71’ W and 95 m),	Typic Hapludalf (43%)	-	-	15 (Oct 24 - Dez 03)	3 (early – intermediate cycle)
Uruguaiana (-29º 83’ S, -57º 08’ W and 74 m),	Lithic Udorthent (39%)	-	-	23 (Set 01 - Dez 15)	3 (early – intermediate cycle)

n*: number, n**: Guri INTA CL and Puitá INTA CL - Early cycle (106 to 120 days); IRGA 424 RI - Intermediate cycle (121 to 135 days).

Table 2. Parameters of the submodels of leaf production and phenology in the SimulArroz model calibrated for three rice cultivars.

Parameter*	Unit	Cultivars		
		IRGA 424 RI	Guri INTA CL	Puitá INTA CL
$LAR_{max\ 1,2}$	Leaves day^{-1}	0.272	0.276	0.276
TTEM	˚C day	80.0	80.0	80.0
TTVG	˚C day	659.2	581.6	591.4
TTRP	˚C day	168.4	134.6	156.85
TTEG	˚C day	108.7	95.9	89.81
RUE	g MJ^{-1}	2.87	2.65	2.77
LAI		8.3	8.3	6.5
SOCF	spikelets /g MS	70.0	90.0	90.0
Pmax	grams (g)	0.0232	0.0245	0.0245

* $LAR_{max\ 1,2}$ = the maximum appearance rate of the first and second leaves; TTEM = total thermal to complete the Sowing-Emergence phase; TTVG = total thermal time to complete the Emergence-Panicle Differentiation phase; TTRP = total thermal time to complete the Panicle Differentiation-Anthesis phase; TTEG = total thermal time to complete the Anthesis-maturation phase; RUE = radiation use efficiency; LAI = leaf area index; SOCF = Spike formation factor, Pmax = maximum grain weight.

Table 3. Parameters of the partitioning dry matter, development stage of irrigated rice (DVS), leaves (L), Stems (S) and panicle (P) of the SimulArroz model calibrated for three rice cultivars (IRGA 424 RI, Guri INTA CL, Puitá INTA CL) compared to rice hybrids that were already into the SimulArroz model. The model was run in the potential level mode.

		CULTIVARES											
DVS (1)	Dry matter aboveground	IRGA 424 RI			Guri INTA CL			Puitá INTA CL			Híbridos		
		L.	S.	P.	L.	S.	P.	L.	S.	P.	L.	S.	P.
0	0.5	0.73	0.27	0.0	0.7	0.30	0.0	0.75	0.25	0.0	0.4	0.6	0.0
0.43	0.75	0.5	0.5	0.0	0.6	0.4	0.0	0.48	0.52	0.0	0.4	0.6	0.0
0.75	0.75	0.3	0.7	0.0	0.2	0.8	0.0	0.19	0.81	0.0	0.3	0.7	0.0
1.0	1.0	0.0	0.9	0.1	0.0	0.8	0.2	0.0	0.90	0.1	0.1	0.3	0.6
1.2	1.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	0.0	1.0
1.6	1.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	0.0	1.0
2.0	1.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	0.0	1.0

(1) DVS = Developmental stages; 0 = emergency; 1.0 = anthesis or flowering; 2.0 = physiological maturity.

Table 4. Statistical analyses of both data described in the literature and SimulArroz model reported in this study. The comparison below was made between mathematical models calibrated and evaluated from field experimental data. The results found in the literature were similar to in this study.

Dry matter (DM)	RMSE	NRMSE	Model, contry, reference
DM aboveground	0.5	20	Oyza2000, Filipinas, Boling et al. (2011)
	2.2	19	Oyza2000, Chile, Artacho et al. (2011)
	0.8	12	InfoCrop, Índia, Aggarwal et al (2005)
	0.7	-	RiceGrow, China, Tang et al. (2009)
	0.8	-	Oryza2000, China, Tang et al. (2009)
	2.5	27	SimulArroz, Rio Grande do Sul, Brasil
DM of leaves	0.9	47	Oyza2000, Chile Artacho et al. (2011)
	0.2	-	RiceGrow, China, Tang et al. (2009)
	1.2	35	SimulArroz, Rio Grande do Sul, Brasil
DM os stems	2.2	37	Oyza2000, Chile Artacho et al. (2011)
	1.5	68	SimulArroz, Rio Grande do Sul, Brasil
DM of panicle	1.7	72	Oyza2000, Chile Artacho et al. (2011)
	2.5	75	SimulArroz, Rio Grande do Sul, Brasil
Grain yield	0.6	-	RiceGrow, China, Tang et al. (2009)
	1.6	19	Oyza2000, Chile Artacho et al. (2011)
	1.0	7	SimulArroz, Rio Grande do Sul, Brasil

3.2 ARTIGO II: (SUBMETIDO PARA AGRONOMY JOUNAL)

Assessing causes of yield gaps in irrigated rice areas in Southern Brazil

Assessing causes of yield gaps in flooded rice in Southern Brazil

Giovana Ghisleni Ribas a *, Alencar Junior Zanon a, Nereu Augusto Streck a, André da Rosa Ulguim a, Filipe Selau Carlos b, Cleber Maus Alberto c, Pablo Mazzuco de Souza d and Tuira Bercellos b

a Department of Plant Science - Hall 77, University Federal of Santa Maria, Santa Maria, RS 97105-900, BRA.

b Department of Soil Science, University Federal of Pelotas, Pelotas, RS 96010-610, BRA.

c Department of Agrometeorology, University Federal of Pampa, Itaqui, RS 97650-000, BRA.

d Rice extensionist at Rice Research Institute, Missões Avenue 342, Porto Alegre, RS 90230-100, BRA.

[*]Corresponding author e-mail address: giovana.ghisleni@hotmail.com

Abbreviations:

BRA, Brazil; CZ, Climate zones; GDD, annual growing-degree days; HY, High yield; LY, low yield; RS, Rio Grande do Sul; Yg, yield gap; Yp, yield potential

ABSTRACT

Identification of yield gap causes is key to understanding and adopting proactive measurements to improve management factors in some crops. This is need to identify Yp and key management factors explaining Yg in flooded rice in Rio Grande do Sul, Southern Brazil, which accounts for 73% of the national production. In the study, we evaluated Yp as benchmarks in relation to producer flooded rice yield fields, and identified key management factors explaining Yg in flooded rice in Southern Brazil. Survey data on yield and management were collected from 324 producer fields over three seasons (from 2015/2016 to 2017/2018) into two similar climate zones. Yp was estimated using Oryza v3 crop model. Yield gaps were calculated as the difference between yield potential and average producers yield. Explanatory factors for yield gaps were investigated by identifying management practices that were concordantly associated with high and low-yield fields. Flooded rice average Yp ranged from 13.2 to 15.7 Mg ha^{-1}. Highest producer yields were similar (±15%) to the estimated yield potential. Yield gap, calculated as percentage of yield potential, was higher in Center and Eastern RS BRA region (range: 50–51%Yp). Analysis of data base indicated that (i) rice producers in this region obtained yields 52% close to the estimated yield potential ceiling, and (ii) agronomic on-farm yield improvement might be achieved by current management practices, including earlier sowing date coupled with judiciously chosen tillage to achieve warmer soils in the springs plus suitably applied nutrient fertilizer application, seed density, weed control, and soybean-rice rotation.

INTRODUCTION

The rate of increase in average on-farm yields of agricultural crops worldwide has been relatively slow and average yields have remained well below yields obtained from well managed farms (Battisti et al., 2018). Likewise, there are increasing concerns about possible conversion of areas with grassland and rainforest into areas grown with grain crop (Franchini et al., 2009; Sentelhas et al., 2015). Brazil has a comparative advantage to help meet global food demand due to abundant land and water resources (FAO, 2018). Hence, it is crucial to determine the degree to which Brazil can increase crop production on existing cropland area through sustainable intensification of cropping systems, without increase production area.

Flooded rice (Oryza sativa L.) is of special importance for the nutrition of large parts of the population in Asia, Latin America, Caribbean and, Africa. Therefore, plays a key role for food security of over half the world population (Licker et al., 2010; Zorrilla et al., 2012; Agus et al., 2019; Deng et al., 2019; Van Loon et al., 2019). Brazil is the first largest rice producer in the world outside the Asian continent (USDA, 2020) with an annual production of 11 Mg (CONAB, 2020). The Southern region (Paraná, Rio Grande do Sul and Santa Catarina States) accounts for 82% of Brazilian production, with an average area of 1.1 Mha, and an average yield of 7.7 Mg ha-1 (CONAB, 2020). Rio Grande do Sul state is the largest producer of flooded rice in Brazil (1 million ha) with 73% of the national production and a yield of 7.8 Mg ha-1 (CONAB, 2020). Rice yield in Rio Grande do Sul, Southern Brazil has increased on average 2 Mg ha-1 over the past 10 years, due to genetic improvements (Clearfield® technology) and management practices changes (increased fertilization rates and early sowing date) (Menezes et al., 2013). However, there is still a considerable difference between the yields measured in flooded rice experiments (13 Mg ha-1) (Ribas et al., 2016; 2017) and the current mean yield of flooded rice (7.7 Mg ha-1) (CONAB, 2020). These differences is referred as yield gap (Yg).

Yield gap analysis has been a robust quantitative framework used to address not only the difference between actual yield and yield from well managed farms or experiments but also to identify the factors that cause the gap (Lobell et al. 2009; van Ittersum et al. 2013). Yield potential (Yp) is the yield of a crop grown in an environment to which it is adapted, with non-limiting water and nutrient supplies, and with pests, weeds, and diseases effectively controlled (Evans, 1993; Evans and Fisher, 1999; van Ittersum & Rabbinge, 1997). Under these optimal conditions, crop growth is determined by solar radiation, temperature, atmospheric CO_2 concentration, and management practices which influence crop cycle duration and light interception, such as sowing date, maturity group, and plant density. In irrigated systems, like flooded rice in Southern Brazil, yield potential is driven mainly by solar radiation and thermal time during crop growth. The Yp is very difficult to reach under field conditions, being more often estimated using process-based crop simulation models that properly crop describe the complex responses of crops to weather and crop management (Van Wart et al., 2015, Soltani et al., 2020). Desirable attributes of crop simulation models for Yg analysis were summarized by van Ittersum et al. (2013). Once Yp is known, then the yield gap (Yg) can be quantified and management practices to close the Yg can be identified, providing an opportunity to increase crop production on existing cropland (Cassman et al., 2003; van Ittersum et al., 2013).

In contrast to flooded rice systems in Asia, rice production in Southern Brazil is highly mechanized, with individual farmers managing large paddies (range: 150-750 ha). About half of the rice area is owned by the farmers, the rest is rented. All the rice area is direct-seeded with Indica cultivars, paddies are flooded from the V3-V4 stage by pumping water from streams or man-made reservoirs and kept flooded during the entire growing season and drained around physiological maturity to allow mechanical harvest. Sowing spans from September to December and harvest is in February and March.

A thorough assessment of Yg is lacking for major crops in Brazil which includes flooded rice (Sentelhas et al., 2015, Marin et al., 2016, Heinemann et al., 2019) and, to our knowledge, there are no reports of previous Yg studies for flooded rice in Brazil. The objectives of this study were identified Yp and key management factors explaining Yg in flooded rice in Southern Brazil.

MATERIALS AND METHODS

Database and descriptive data analyses

Data on flooded rice seed yield (reported on a 13% seed moisture basis), crop management (i.e., sowing date, seed density, maturity group, and tillage method), applied inputs (fertilizer and pesticides), and production-site adversities(i.e., incidence of insect pests, diseases, hail, waterlogging, or frost) were collected from 324 fields via mail survey forms completed and returned by producers and multiple personal interviews conducted by the co-authors with producers (Figure 1). Each producer was asked to report the yield range across his/her rice fields, for each year, and provide data for a number of fields that portray well the reported yield range. Data were collected during the 2016, 2017 and 2018 crop seasons.

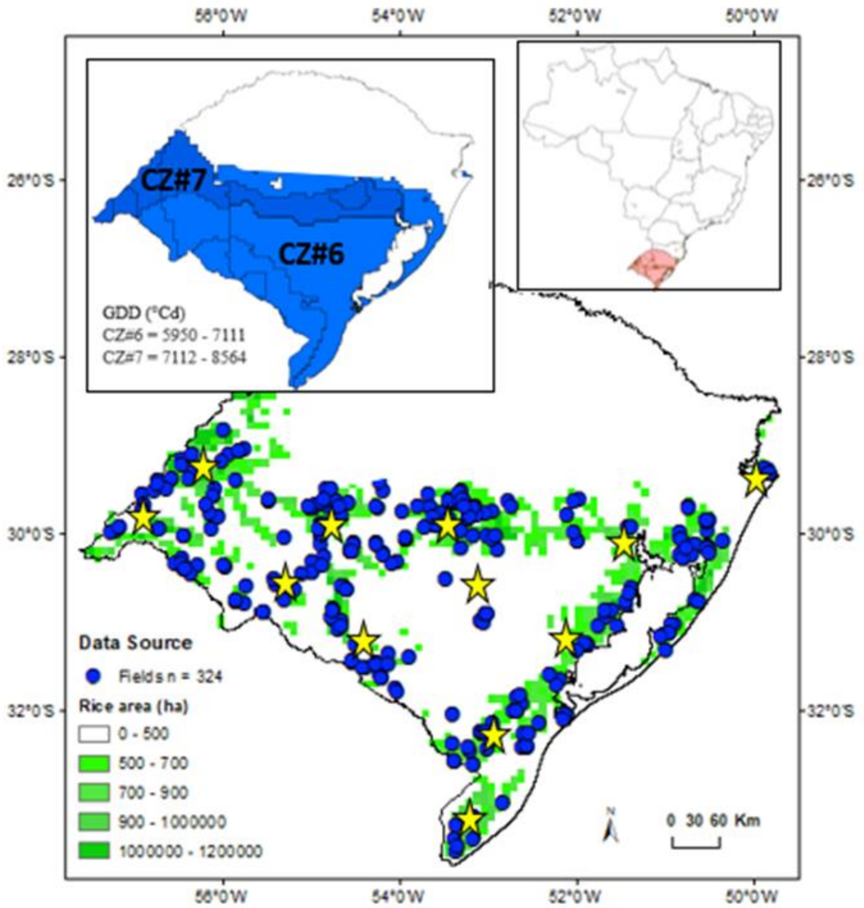

Figure 1. Map of Rio Grande do Sul State showing the harvested area in year 2010 (green area; CONAB, 2010) and location of the 324 surveyed flooded rice fields (blue dots). Meteorological stations are shown by yellow starts. Top left inset in blue color shows the annual growing-degree days according to the Global Yield Gap Atlas framework. A coding system (from CZ 6 to 7) is used to identify each CZ, Top right inset shows the location of Rio Grande do Sul (red color) State in Southern Brazil.

The 108 field-year data points naturally grouped into five regions: Central, Southern, Western, Eastern, Southwestern of RS (Figure 1). These five regions constitute the rice production area in Rio Grande do Sul (RS), Southern Brazil region. The regional means for the producer-reported yield data were slightly higher (i.e., 10%) than IRGA (Rice Research Institute) yields (https://irga.rs.gov.br/safras-2) for the corresponding regions. Likewise, management practices (e.g., sowing date) and applied inputs (e.g., pesticides, fertilizer) reported by producers were remarkably similar to most recent (year 2019) RS state average values reported for these variables for rice by IRGA (http://www.ers.usda.gov). Differences among the coolest and warmest regions relative to weather are readily apparent in Figure 2. Temperature and radiation are lower in the southern region of the state (Rio Grande) compared with the western region (Uruguaiana).

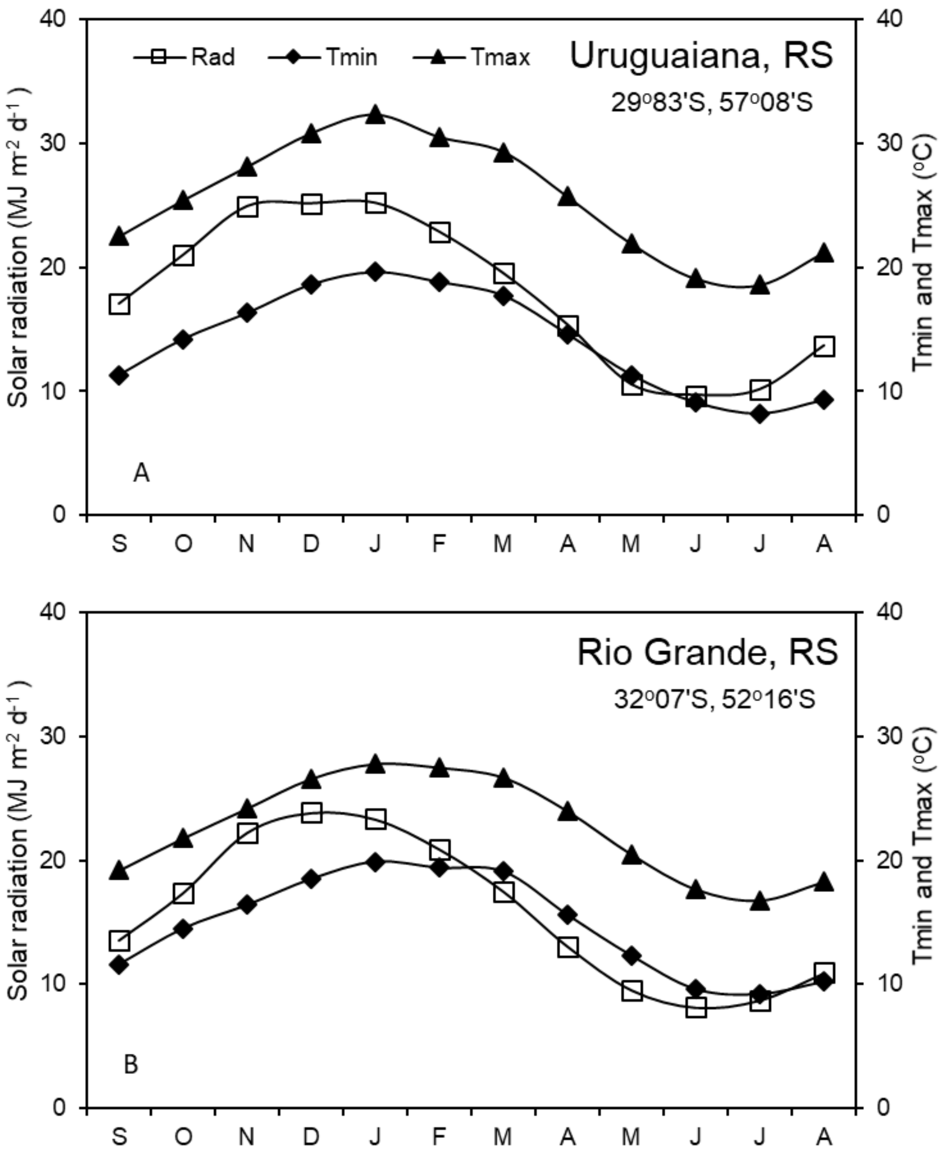

Figure 2. (A, B) Monthly average incident solar radiation and maximum (Tmax) and minimum temperature (Tmin) for two locations representative of the rice producing area in flooded area in Rio Grande do Sul (RS): Uruguaiana (western RS) and Rio Grande (southern RS). Each datapoint represent means of meteorological variables calculated based on five years (solar radiation) or 30 years (Tmax and Tmin) of measured weather data.

In this study, the rice-growing area of the Rio Grande do Sul State was classified in a single Climate Zone to analyze the the yield gap due to their similarity (Figure 1, top left inset), no difference between CZs x yield x year, according to the annual total growing degree-days biophisical criteria defined by the framework of the Global Yield Gap Atlas (GYGA, 2020; Van Wart et al., 2013).

Estimation yield gap and yield potential for flooded rice

In this study, Yp was simulated in order to portray the recommended management practices for high-yield flooded rice simulations using sowing window (from late September to early December), dominant cultivar name (IRGA 424 RI) and maturity (intermediate, 130 days), and optimal plant population density (200 pls m^{-2}) (Supplementary Table S1), reflecting a rice crop timely sown by end of February, which would efficiently capture most of the available solar radiation during the growing season (Menezes et al., 2013).

Daily weather data, including solar radiation, minimum and maximum temperature were retrieved from 2-3 stations in each region from Brazilian Institute of Meteorology (INMET) (Figure 1). In each region, daily weather data from 2-3 meteorological stations was used to run the model. Date of physiological maturity was estimated for using Oryza v3 model based on site-specific weather and management. Previous assessments on the variation of Yp indicates that the number of weather stations used in the present study was sufficient for a robust estimation (Van Wart et al., 2013). Likewise, our analysis indicated that there was a very little variation in simulated yield (Yp) among weather stations (coefficient of variation = 9%). Hence, our estimates of yield potential based on weather stations can be considered robust. Yp was used as benchmarks for calculating Yg for flooded rice. The Yg was calculated as the difference between Yp and average producer yield and expressed as percentage of Yp.

Identification of causes for yield gaps

In order to identify factors explaining Yg, high-yield (HY) and low-yield (LY) field classes were identified in the surveyed data by splitting the data into terciles. The data located in upper and lower terciles were assumed to the HY and LY farms, respectively. Differences in each management practice between the HY and LY fields were then tested for significance using

ANOVA and the t-test at 0.05% probability. Association between field classes and management variables (e.g., fertilizer, seed density, fungicide application) was evaluated using the Chi-square (χ2) test at 0.05%, 0.01% and 0.1% probability using the quantreg package in R (R Development Core Team, 2016).

Management variables identified as statistically significant on their influence on grain yield were further investigated. Quantile regression was used to derive a boundary function for the relationship between grain yield and sowing date and onset irrigation delay based on the best yield reported using the quantreg package in R (R Development Core Team, 2016). For management variables (e.g., fertilizer, seed density, pesticide application), average yields calculated for contrasting management categories were compared in the same classes using unpaired t-test and Wilcoxon test at 0.05%, 0.01% and 0.1% probability.

RESULTS AND DISCUSSION

Flooded rice yield potential and yield gap in the RS BRA region

Using simulation modeling, estimated Yp for flooded rice ranged from 13.2 to 15.7 Mg ha^{-1} across fields, year, and regions. Yp was higher in Southern (15.6 Mg ha^{-1}) and lower in Western (14.3 Mg ha^{-1}) (Figure 3). In RS, Yp is similar to the Yp reported in Uruguay (14 Mg ha^{-1}), and greater than reported in the United States (9,4 Mg ha^{-1}), China (12.4 Mg ha^{-1}) and Africa (9 Mg ha^{-1}) as reported by Espe et al. (2016), Van Ittersum et al. (2016), and Deng et al. (2019), respectively. The Yp difference can be explained by a greater availability of solar radiation and larger longer photoperiod during flowering and grain filling phases, provided by in the Brazilian subtropical climate conditions in comparison to the tropical climate of South and Southeast Asia. Besides that, subtropical rice production regions, near to the Latitude of 30°, presents higher Yp when compared to lower latitudes, as near to the tropics there is less solar radiation available during the growing season, and temperate regions presents higher risk of crop damage due to low temperatures.

In contrast, Yg, expressed as percentage of their respective simulated Yp, in RS was higher (47% Yp) than in USA (27%Yp) and China (33%Yp), similar to Uruguay (43%Yp) and lower than Africa (60%Yp) as reported by Espe et al. (2016), Van Ittersum et al. (2016), Carracelas et al. (2019) and Deng et al. (2019), respectively. The Yg in RS tended to be larger in Eastern, Center and Southern part (range: 51-50%Yp) than in Western and Southern (range: 44-47%Yp), which shows room to improve rice yields on fields in Brazil by changing management practices (Figure 3).

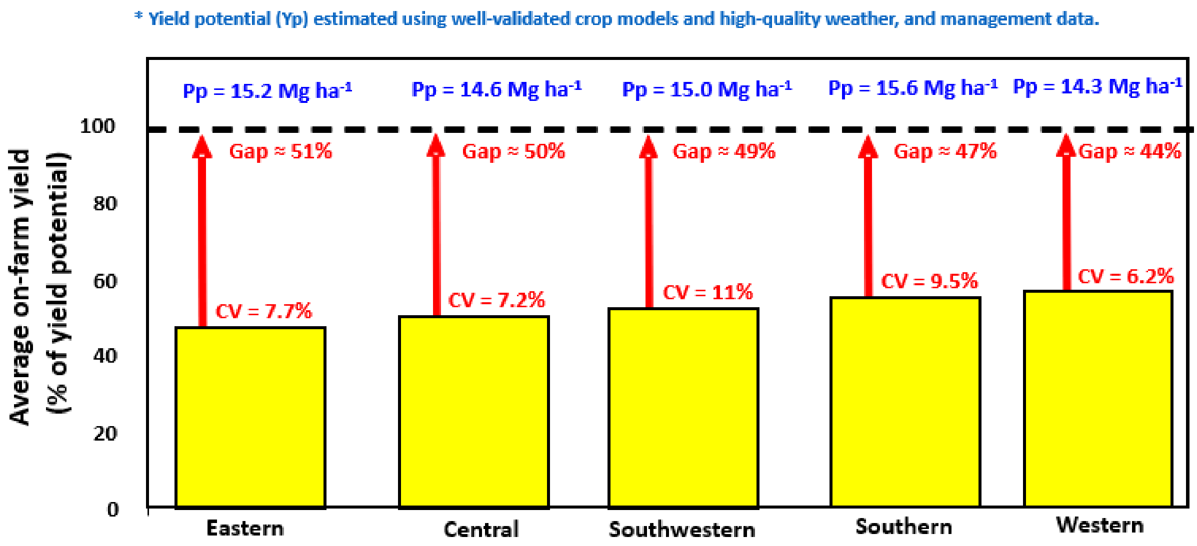

Figure 3. Simulated flooded rice yield potential and for yield gap in the East, Central, Southwest, South and West regions during three (2016–2018) crop seasons.

Underpinning causes for yield variation among fields and yield gap

Analysis of management practices allowed identification of candidate factors explaining Yg (Table 2). Differences in sowing date and onset irrigation between HY and LY fields were statistically significant ($p < 0.1$). Additionally, on average, we verified that 32% and 44% of total Yg are due to delay of sowing date (from September 20) and timing of irrigation (from

V3-stage). Sowing date and onset irrigation had the most consistent impact on flooded rice yield (Figures 4 and 5).

Table 2. Comparison of producer flooded rice yield, management practices and applied inputs between the highest terciles of field yields (HY) and the lowest terciles (LY) in the Southern Brazil region. Values indicate the mean differences (HY – LY) between the upper and lower yield terciles (p<0.01***, p<0.05**, p<0.1*).

Variables	Units	High-yield fields (HY)	Low-yield fields (LY)	HY- LY[2]
Yield	t ha^{-1}	10.3	6.9	3.4**
Sowing date	date	Oct 16	Nov 5	-20**
Seed density	kg ha^{-1}	87	93	-6**
Timing on flooding	V stage	3	4	-1*
Foliar insecticide	% fields	50	50	<1
Foliar fungicide	% fields	50	50	<1
N fertilizer amount	kg ha^{-1}	130	103	26**
P_2O_5 fertilizer amount	kg ha^{-1}	63	50	13**
K_2O fertilizer amount	kg ha^{-1}	75	65	9
Lime application	% fields	65	35	30**
Previous summer crop				
Rice	% fields	29	71	-42***
Soybean	% fields	64	36	28***
Pre-sowing herbicide application				
Disc + herbicide	% fields	30	70	-40***
Only herbicide	% fields	61	39	22***

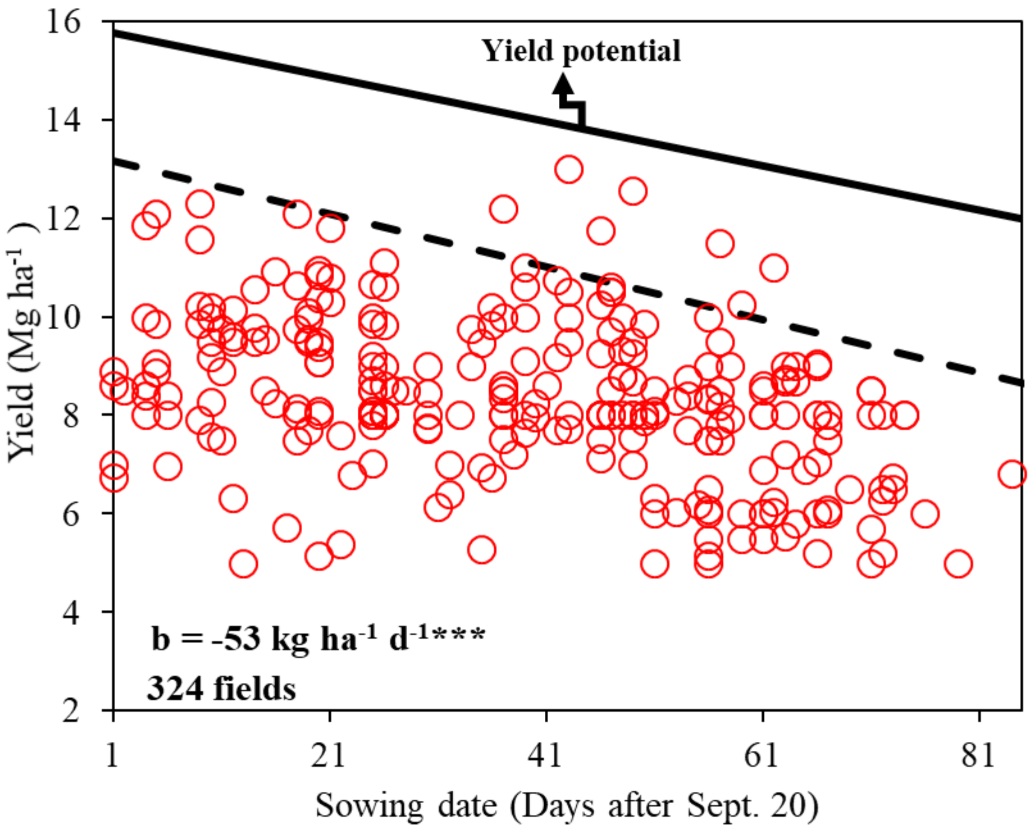

Figure 4. Flooded rice yield as a function of sowing date in Rio Grande do Sul. The solid line corresponds to the yield potential estimated by Oryza model v3 and the dash line corresponds to the fitted boundary function using quantile regression (percentile 90th). Slope of the fitted boundary function (b) is shown, with asterisks indicating significance at p< 0.01*** for the null hypothesis of b= 0.

Timing of sown and irrigation in HY fields were, on average, 20 and 7 days earlier than LY fields respectively (Table 2).The yield penalty over sowing dates was 53 kg ha^{-1} d^{-1} (Figure 4), explained by lower soil temperatures (16-19 ^{o}C) that is typical in this time of year at RS, weed competition and flood problems causing a smaller stand of plants established, whereas yield penalty by delay of irrigation from V_3-stage was 180 kg ha^{-1} d^{-1} (Figure 5), which can be related by weed competition. V3-Stage is also the crop moment to define the number of panicles per area in rice and N fertilizer cover applied in this moment was significative between HY and LY ($p < 0.05$).

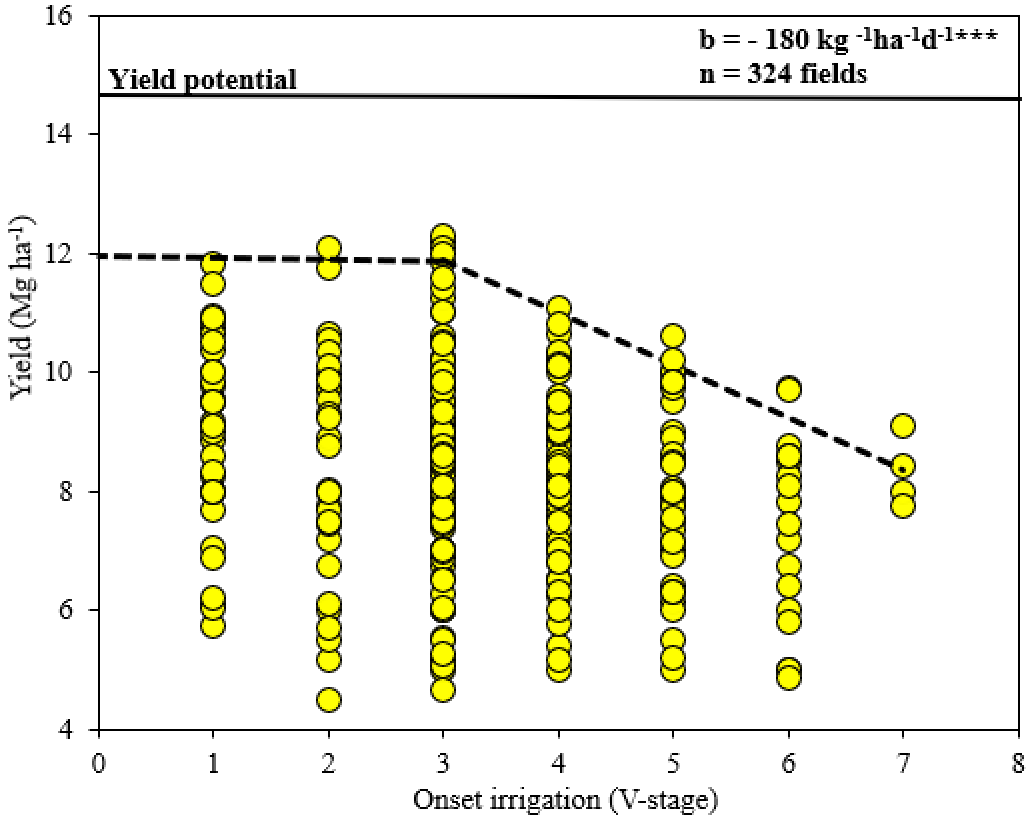

Figure 5. Comparison of onset irrigation versus yield in irrigated flooded rice on different V-stages in Rio Grande do Sul, Southern Brazil region the dash line shows the fitted boundary function using quantile regression (percentile 90th). Slope of the fitted boundary function (b) is shown, with asterisks indicating significance at $p < 0.01$***.

N fertilizer must be applied by producer, as a common management practice, on the fields in the same day that irrigation starts, reducing N losses mainly due to ammonia volatilization and giving more efficiency to the system. Our assumption is, the yield response to delay of irrigation exhibited much higher explanatory power by the time and amount of N application at this crop moment, which is consistent with reported by Fageria et al., 2001; Peng et al., 2010. N fertilizer amount explain, on average, 26% of Yg of flooded rice on Southern Brazil (Table 2), and it is related with the sowing date, genotype and weather forecast. In this study was identified HY fields applying on average 130 kg N fertilizer ha^{-1}. Likewise, in China, Yuan et al. (2019) reported higher rice yield by 150 kg N fertilizer ha^{-1} cover applied in rice fields. Therefore, the results of this study are consistent according has been reported in the literature. Similar to sowing date, onset irrigation and N fertilizer, other management practices also exhibited a significance (Table 2, Figure 6).

There were statistically impact of pre-sowing weed control ($p < 0.01$), previous summer crops ($p< 0.01$) seed density ($p< 0.01$) on rice seed yield, (Table 2, Figure 6). For example, the average yield of fields with only herbicides control was 0.7 Mg ha^{-1} higher in relation with disc+herbicide control fields. Likewise, soybean previous summer crop fields achieved statistically higher yields compared with fields with rice previous summer crop. Furthermore, 80 kg ha^{-1} of seed density fields achieved statistically higher yields compared with fields with 100 to 120 kg ha^{-1} of seed density. Still, lime, P_2O_5 fertilizer variables that seemed to be irrelevant for this study shows up the significance (Table 2). Our belief is lime and P_2O_5 application might influence previous summer crop yield in lowland fields due to soil acidity (soybean crop needs pH 6.0) associated with low levels of clay, organic matter, and deficient in phosphorus (Pollet et al., 2019). The 30% of soybean-rice lowland area cultivation (Zanon et al., 2016) needs almost twice amounts of P2O5 for soybean, highlighting the higher P_2O_5 soil availability (higher critical content) in soybean-rice system which make it a relevant factor to yield increase (Partey et al., 2016; Pollet et al., 2019).

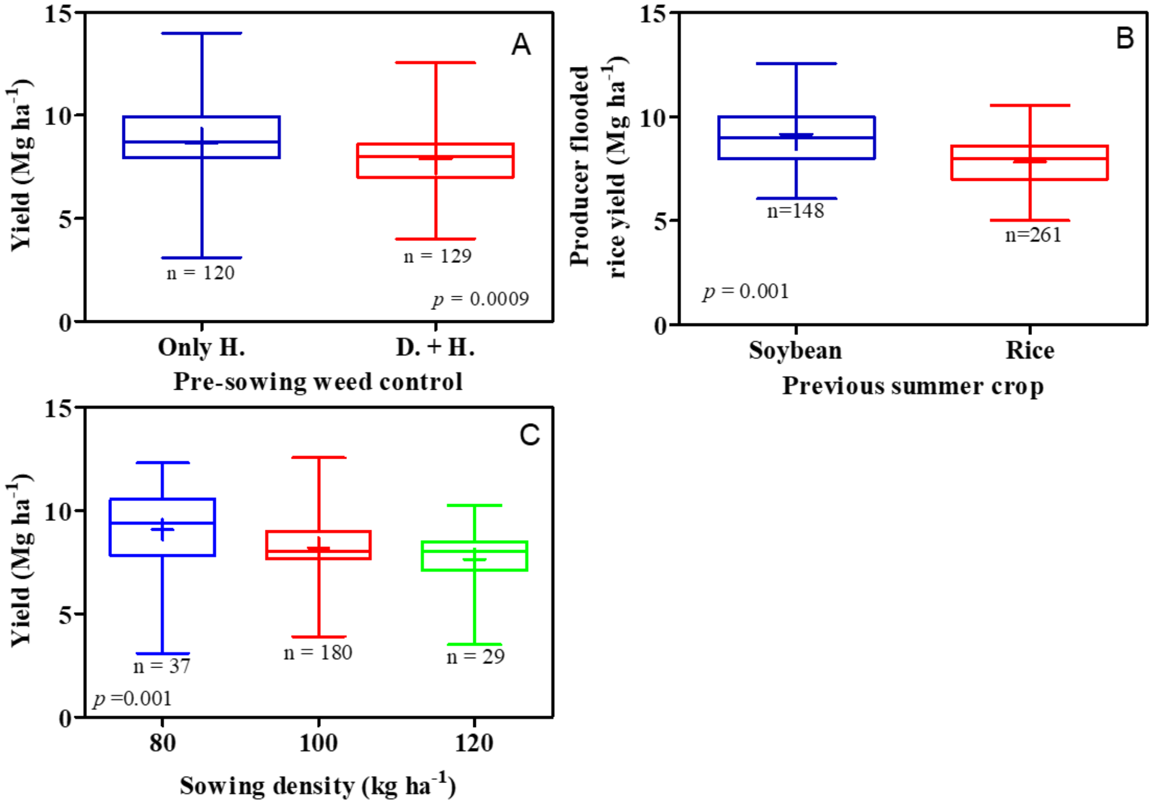

Figure 6. Comparison of pre-sowing weed control (A), previous summer crop (B) and sowing density (C) in flooded rice in the Southern Brazil region. The median (continue line), mean (+), t-test and ANOVA significance are shown.

However, there may be reasons for producers to adopt for example, disc+herbicide, rice after rice, and high seed density on the fields despite the observed yield penalty. For example, disc+herbicide can help soil drainage in lowland areas, whereas rice after rice fields can be only option for fields closer by rivers where flood problems happen often. Indeed, we found that, on average, soybean after rice turned rice fields 20% more productive than rice after rice fields ($p < 0.01$) by weed control resistance, diversifying herbicide mechanisms of herbicides action and cultural practices (Filizadeh et al., 2007; Angus et al., 2015; Theisen et al., 2017), whereas only herbicide control and less seed density (80 kg ha^{-1}) were 8% and 15% more yielded than disc+hebicide and higher seed density (100-120 Kg ha^{-1}), respectively (Figure 6).

Pre-sowing weed control aims to manage some annual winter weed species and prepare flooded rice seedbed, being rarely the weed survivors at this phase reducing crop yield. For this, the results observed in the present study seems more related to previous summer crop, once in crop rotation cases producers managing weeds on winter predominantly with only herbicides, while producers with flooded rice monoculture using to tillage to reduce the soil disturb caused to harvest on humidity conditions (Theisen et al., 2017). Whereas less seed density shows an increased yield in HY fields, our beliefs is this management practice plays as fine-tuning, which can give more net economic return by decreasing production costs using fewer seeds on the fields.

In contrast to the aforementioned variables, there were inconsistent (and generally small) differences between HY and LY fields in relation with fungicide e/or insecticide application, nutrient (K) fertilizer application (Table 2). Lack of statistically significant differences between management practices should be interpreted with caution. For example, some practices might influence yield depending upon the level of another management practice [e.g., K fertilizer in relation with previous summer crop (Peoples et al., 2009; Partey et al., 2016)]. Likewise, the benefit of other practices may only be realized in crop seasons with unfavorable weather, which was not the case in our study [e.g., fungicide e/or insecticide; Delmotte et al., 2011).

Similarly, yield impact of some practices may be masked by other field variables not accounted here. For example, lack of yield differences between fields that received higher amount of NPK fertilizer application versus those that receive lower amount fertilizer might reflect producer tendency to apply fertilizer only in fields where soil nutrient status is inadequate as evaluated using soil nutrient tests. It may also reflect many producers over-fertilizing the previous soybean crop, expecting the subsequent rice crop to benefit from the residual soil fertility.

Finally, there are management practices that exhibited a very narrow range (e.g., fungicide/insecticide, seed density) or inputs that were applied in amounts well above their optimums. For example, on-farm average rice seed density ranged from 70 to 140 Kg ha^{-1}. These densities are higher than the required plant density for maximum yields (80 kg ha^{-1}) (Ali et al., 2014); hence, our analysis does not fully capture the influence of these management factors on seed yield.

A contribution of the present study is to provide an assessment of the extra crop production, that would result from producer fine-tuning of a given management practice. For example, the potential extra production derived from earlier flooded rice sowing can be calculated based on the (i) the degree to which the current average sowing date differs from the optimal one, and (ii) flooded rice harvested area. Hence, a 2-week shift towards early sowing in Southern Brazil, from current average sowing on October 26 to a hypothetical, but realistic, October 11 sowing, would result in 0.75 Mg ha^{-1} yield increase and 705,000 Mg production increase, leading to a 10% increase. This example illustrates the power of this approach for impact assessment to support policy and investment prioritization and for monitoring the impact of research and extension programs.

CONCLUSIONS

The framework applied in this study explained the largest portion of the management practices across the RS BRA region. Flooded rice Yg in RS BRA was relatively high, averaging 48% of the estimated yield potential. Sowing date, onset irrigation and N fertilizer amount, pre-sowing weed control, previous summer crop and seed density were the most consistent factors explaining yield variation, with magnitude of yield response to sowing delay dependent upon degree of soil temperature, weed control, and flood problems. Variability in yields was also associated with the association between sowing date and onset irrigation, NPK fertilizer amount, lime, previous summer crop, pre-sowing weed control. The combined use of producers and strategize research and extension programs at is a great tool to capture regional variation which can help inform

ACKNOWLEDGMENTS

We would like to especially thank all colleagues from the Rice Research Institute (IRGA) in Brazil for helping to collect data used for this study.

SUPPLEMENTAL MATERIAL

Supplementary Table S1. Southern Brazil meteorological station, climate zones (CZs), and management data to run the model are shown.

Local	CZ	Sowing date	Cultivar (MG)	Plant density (pls m^{-2})
CachoeiradoSul	7	15-Oct	IRGA 424 RI (intermediate)	200
Camaqua-A838	6	15-Oct	IRGA 424 RI (intermediate)	200
SaoBorja-A830	7	15-Oct	IRGA 424 RI (intermediate)	200
Jaguarao-A836	6	15-Oct	IRGA 424 RI (intermediate)	200
Cangucu-A811	6	15-Oct	IRGA 424 RI (intermediate)	200
SantaMaria-A803	7	15-Oct	IRGA 424 RI (intermediate)	200
DomPedrito-A881	6	15-Oct	IRGA 424 RI (intermediate)	200
SantaVitoriadoPalmar-A899	6	15-Oct	IRGA 424 RI (intermediate)	200
Alegrete-A826	7	15-Oct	IRGA 424 RI (intermediate)	200
Uruguaiana-A809	7	15-Oct	IRGA 424 RI (intermediate)	200
SaoVicentedoSul-A889	7	15-Oct	IRGA 424 RI (intermediate)	200

REFERENCES

Agus, F., Andrade, J. F., Edreira, J. I. R., Deng, N., Purwantomo, D. K., Agustiani, N., ... and Makka, A. 2019. Yield gaps in intensive rice-maize cropping sequences in the humid tropics of Indonesia. Field Crops Research, 237, 12-22. https://doi.org/10.1016/j.fcr.2019.04.006

Ali, A., Erenstein, O., and Rahut, D.B. 2014. Impact of direct rice-sowing technology on rice producers' earnings: Empirical evidence from Pakistan. Development Studies Research. An Open Access Journal, 1(1), 244-254. https://doi.org/10.1080/21665095.2014.943777

Angus, J.F., Kirkegaard, J.A., Hunt, J. R., Ryan, M. H., Ohlander, L., and Peoples, M. B. 2015. Break crops and rotations for wheat. Crop and Pasture Science, 66(6), 523-552. http://dx.doi.org/10.1071/CP14252

Battisti, R., Sentelhas, P.C., Pascoalino, J.A.L., Sako, H., de Sá Dantas, J. P., and Moraes, M. F. 2018. Soybean yield gap in the areas of yield contest in Brazil. International Journal of Plant Production, 12, 3, 159-168. https://doi.org/10.1007/s42106-018-0016-0

Bouman, B.A.M., and Van Laar, H.H. 2006. Description and evaluation of the flooded rice growth model ORYZA2000 under nitrogen-limited conditions. Agricultural Systems, 87(3), 249-273. https://doi.org/10.1016/j.agsy.2004.09.011

Carmona, L. Projeto 10+ - Uma Nova Etapa na Transferência de Tecnologia da Lavoura Orizícola no RS. Instituto Rio Grandense do Arroz (IRGA) 2019. 56p.

Carracelas, G., Hornbuckle, J., Rosas, J., and Roel, A. 2019. Irrigation management strategies to increase water productivity in Oryza sativa (rice) in Uruguay. Agricultural water management, 222, 161-172. https://doi.org/10.1016/j.agwat.2019.05.049

Cassman, K. G. 1999. Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. Proceedings of the National Academy of Sciences USA 96, 5952–5959. https://doi.org/10.1073/pnas.96.11.5952

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

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

CONAB - Companhia Nacional de Abastecimento. Levantamentos de Safra. 2020 Available in: https://www.conab.gov.br/info-agro/safras/graos . GrosZjaneiroZcompletoZ2020.pdf (accessed 10 jan. 2020).

Counce, P.; Keisling, T.C.; Mitchell, A.J. 2000. A uniform, objective, and adaptative system for expressing rice development. Crop Science, v.40, p.436-443. DOI: https://doi.org/10.2135/cropsci2000.402436x.

Delmotte, S., Tittonell, P., Mouret, J.C., Hammond, R., and Lopez-Ridaura, S. 2011. On farm assessment of rice yield variability and productivity gaps between organic and conventional cropping systems under Mediterranean climate. European Journal of Agronomy, 35(4), 223-36. https://doi.org/10.1016/j.eja.2011.06.006

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

Edreira, J. I. R., Mourtzinis, S., Conley, S. P., Roth, A. C., Ciampitti, I. A., Licht, M. A. and Naeve, S. L. 2017. Assessing causes of yield gaps in agricultural areas with diversity in climate and soils. Agricultural and forest meteorology, 247, 170-180. https://doi.org/10.1016/j.agrformet.2017.07.010

Espe, M.B., Cassman, K.G., Yang, H., Guilpart, N., Grassini, P., Van Wart, J., Anders, M., Beighley, D., Harrell, D., Linscombe, S., McKenzie, K., Mutters, R., Wilson, L.T., Linquist, B.A. 2016. Yield gap analysis of US rice production systems shows opportunities for improvement. Field Crops Research, 196, 276-283. https://doi.org/10.1016/j.fcr.2016.07.011

Evans, L.T., 1993. Crop Evolution, Adaptation, and Yield. Cambridge University Press, Cambridge, UK.

Evans, L.T., Fisher, R.A., 1999. Yield potential: its definition, measurement, and significance. Crop science, 39(6), 1544-1551. https://doi.org/10.2135/cropsci1999.3961544x

Fageria, N.K., and Baligar, V.C. 2001. Lowland rice response to nitrogen fertilization. Communications in Soil Science and Plant Analysis, 32(9-10), 1405-1429. https://doi.org/10.1081/CSS-100104202

FAO - Food and Agriculture Organization of the United Nations. World production. 2018. Available at http://www.fao.org/economic/est/publications/flooded rice -publications/en/. (accessed 10 Sept. 2018).

Filizadeh, Y., Rezazadeh, A., Younessi, Z., 2007. Effects of crop rotation and tillage depth on weed competition and yield of flooded rice in the paddy fields of Northern Iran. Journal of Agricultural Science and Technology, 9, 99-105.

Fischer, R.A. 1985. Number of kernels in wheat crops and the influence of solar radiation and temperature. J. Agric. Sci. 105:447–461. https://doi.org/10.1017/S0021859600056495

Franchini, J.C., Debiasi, H., Sacoman, A., Nepomuceno, A.L. and Farias, J.R.B. 2009. Soil Management to Reduce Yield Gap by Drought. Documentos 314. Londrina: Embrapa Soja. (In Portuguese, with English abstract)

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

GYGA – GLOBAL YIELD GAP ATLAS. Brazil Irrigated rice yield potential. available in: http://www.yieldgap.org/brazil . (accessed 25 Jan. 2020).

Heinemann, A. B., Ramirez-Villegas, J., Rebolledo, M.C., Neto, G.M.F.C., and Castro, A.P. 2019. Upland rice breeding led to increased drought sensitivity in Brazil. Field Crops Research, 231, 57-67. https://doi.org/10.1016/j.fcr.2018.11.009

Licker, R., Johnston, M., Foley, J.A., Barford, C., Kucharik, C.J., Monfreda, C., and Ramankutty, N. 2010. Mind the gap: how do climate and agricultural management explain the ‘yield gap’of croplands around the world? Global ecology and biogeography, 19(6), 769-782. https://doi.org/10.1111/j.1466-8238.2010.00563.x

Lobell, D.B., Cassman, K.G., and Field, C.B. 2009. Crop yield gaps: their importance, magnitudes, and causes. Annual review of environment and resources, 34, 179-204. https://doi.org/10.1146/annurev.environ.041008.093740

Marin, F. R., Martha Jr, G. B., Cassman, K.G., and Grassini, P. 2016. Prospects for increasing sugarcane and bioethanol production on existing crop area in Brazil. BioScience, 66(4), 307-316. https://doi.org/10.1093/biosci/biw009

Menezes, V.G.; Anghinoni, I.; Silva, P.R.F. Da; Macedo, V.R.M.; Petry, C.; Grohs, D.S.; Freitas, T.F.S. De; Valente, L.A. De L. Projeto 10: management strategies to increase productivity and sustainability of irrigated rice fields growth in the state of Rio Grande do Sul, Brazil: developments and new challenges. Porto Alegre: IRGA, 2013. Available at: <http://oryzasoy.com/publicacoes/projeto-10-management-strategies-toincrease-

productivity-and-sustainability-of-irrigated-rice-fieldsgrowth-in-the-state-of-rio-grande-do-sul-brazil-developmentsand-new-challenges/>. Accessed on: Dec. 18 2019

Partey, S.T., Saito, K., Preziosi, R.F., and Robson, G.D. 2016. Biochar use in a legume–rice rotation system: effects on soil fertility and crop performance. Archives of Agronomy and Soil Science, 62(2), 199-215. https://doi.org/10.1080/03650340.2015.1040399

Peng, S., Buresh, R.J., Huang, J., Zhong, X., Zou, Y., Yang, J., Wang, G., Liu, Y., Hu, J., Tang, Q., Cui, K., Zhang, F., and Dobermann, A. 2010. Improving nitrogen fertilization in rice by sitespecific N management. A review. Agronomy for sustainable development, 30(3), 649-656. https://doi.org/10.1051/agro/2010002

Peoples, M. B., Brockwell, J., Herridge, D. F., Rochester, I. J., Alves, B. J. R., Urquiaga, S., Boddey, R.M., Dakora, F.D., Bhattarai, S., Maskey, S.L., Sampet, C., Rerkasem, B., Khans, D.F., Hauggaard-Nielsen, H.and Jensen, B.S. 2009. The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. Symbiosis, 48(1-3), 1-17. https://doi.org/10.1007/BF03179980

Pollet, C. S., Silva, L. S. D., Chaves, B., Rosa Neto, L., Dossin, M. F., Giacomini, S. J., and Cargnelutti Filho, A. 2019. Influence of summer crop residues on 15N present in organic matter fractions under two lowland soils. Ciência Rural, 49(4). http://dx.doi.org/10.1590/0103-8478cr20180747

R Development Core Team, 2016. R: A Language and Environment for Statistical. Computing. R Foundation for Statistical Computing, Vienna, Austria.

Ribas G.G.; Streck N.A.; Duarte Junior A.; Nascimento M.F.; , Zanon A.J.; Silva, M.R. 2017. Number of leaves and phenology of flooded rice hybrids simulated by the SimulArroz model. Pesquisa Agropecuária Brasileira 51: 1907-1917. http://dx.doi.org/10.1590/1807-1929/agriambi

Ribas G.G.; Streck N.A.; Lago I.; Zanon A.J.; Waldow D.A.G.; Duarte Junior A.J.; Nascimento M.F.; Fontana V. 2016. Accumulated dry matter and grain yield in flooded hybrid flooded rice simulated with the SimulArroz model. Pesquisa Agropecuária Brasileira 51: 1907-1917 (in Portuguese, with abstract in English). http://dx.doi.org/10.1590/s0100-204x2016001200001

Soltani, A., Alimagham, S. M., Nehbandani, A., Torabi, B., Zeinali, E., Zand, E., Vadez, M. P., van Loon, M. K. and van Ittersum, M. K. 2020. Future food self-sufficiency in Iran: A model-based analysis. Global Food Security, 24, 100351. https://doi.org/10.1016/j.gfs.2020.100351

Theisen, G., Silva, J. J. C., Silva, J. S., Andres, A., Anten, N. P., and Bastiaans, L. 2017. The birth of a new cropping system: towards sustainability in the sub-tropical lowland agriculture. Field Crops Research, 212, 82-94. http://dx.doi.org/10.1016/j.fcr.2017.07.001

USDA – United States Department of Agriculture. Production, Supply and Distribution Online. Disponível em Zorrilla, G., Martínez, C., Berrío Orozco, L. E., Corredor, E., Carmona, L., and Pulver, E. (2012). Improving rice production systems in Latin America and the Caribbean. Centro Internacional de Agricultura Tropical (CIAT). http://www.usda.gov/wps/portal/usda/usdahome?navid=DATA_STATISTICS. (accessed 10 Sept. 2019).

Van Ittersum A, M.K., Cassman, K.G., Grassini, P., Wolf J., Tittonell; P., Hochman, Z. 2013. Yield gap analysis with local to global relevance - A review. Field Crops Research, v.143, p.4–17.

Van Ittersum M.K. , Van Bussel, G.J., Wolf, J., Grassini, P., van Wart, J., Guilpart, N., Claessens, L., Groot, H., Wiebe, K., Mason-D'Croz, D., Yang, H., Boogaard, H., van Oort, P.A.J., van Loon, M.P., Saito, K., Adimo, O., Adjei-Nsiah, S., Agali, A., Bala, A., Chikowo, Kaizzi, R.K., Kouressy, M., Makoi, J.H.J.R., Ouattara, K., Tesfaye, K. and Cassman, K.G. 2016. Can sub-Saharan Africa feed itself?. Proceedings of the National Academy of Sciences, 113(52), 14964-14969. https://doi.org/10.1073/pnas.1610359113

Van Ittersum, M. K. and Rabbinge, R. 1997. Concepts in production ecology for analysis and qualification of agricultural input-output combinations. Field Crops Research 52, 197–208

Van Loon, M. P., Deng, N., Grassini, P., Edreira, J. I. R., Wolde-Meskel, E., Baijukya, F., and van Ittersum, M. K. 2018. Prospect for increasing grain legume crop production in East Africa. European Journal of Agronomy, 101, 140-148. https://doi.org/10.1016/j.eja.2018.09.004

Van Wart, J., van Bussel, L. G., Wolf, J., Licker, R., Grassini, P., Nelson, A., Boogaard, H., Gerber, J., Mueller, N.D., Claessens, C., van Ittersum, M.K., Cassman, K.G. 2013. Use of agro-climatic zones to upscale simulated crop yield potential. Field Crops Research. 143, 44–55. https://doi.org/10.1016/S0378-4290(97)00037-3

Van Wart, J., Grassini, P., Yang, H., Claessens, L., Jarvis, A., and Cassman, K.G. 2015. Creating long-term weather data from thin air for crop simulation modeling. Agricultural and Forest Meteorology, 209, 49-58. http://dx.doi.org/10.1016/j.agrformet.2015.02.020

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

Yuan, S., Cassman, K. G., Huang, J., Peng, S., and Grassini, P. 2019. Can ratoon cropping improve resource use efficiencies and profitability of rice in central China?. Field crops research, 234, 66-72. https://doi.org/10.1016/j.fcr.2019.02.004

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

Zorrilla, G., Martínez, C., Berrío Orozco, L. E., Corredor, E., Carmona, L., and Pulver, E. 2012. Improving rice production systems in Latin America and the Caribbean. Centro Internacional de Agricultura Tropical (CIAT).

3.3 ARTIGO III : (SERÁ SUBMETIDO PARA EUROPEAN JOURNAL OF AGRONOMY)

Rotation impact on on-farm rice yield and input-use efficiency in southern Brazil

Giovana Ghisleni Ribas, Alencar Junior Zanon, Isabela Bulegon Pilecco, Thiago Schmitz Marques Rocha, Patricio Grassini

[a] University Federal of Santa Maria, Plant Engineering Hall 77, Roraima Avenue 1000, Santa Maria-Rio Grande do Sul, Brazil.

[b] Department of Agronomy and Horticulture, University of Nebraska-Lincoln, Lincoln, NE, 68583-0915, USA

[*]Corresponding author e-mail address: pgrassini2@unl.edu

Abstract

Cereal–legume rotations grain yields tend to be higher than cereal monoculture. We investigated the benefits on rice grain yield and input-use efficiency of introducing soybean to the irrigate rice monoculture. We used 3-yr producer-reported data from southern Brazil, which is the largest rice producer country outside Asia. Commodity prices obtained from literature and official statistics were used to estimate economic profit for two groups in consecutive 2-yr continues rice *versus* soybean–rice or rice-soybean sequence Average rice grain yield in the soybean-rice rotation was 20% (1.8 Mg ha^{-1}) higher than rice monoculture persistently across the wide range of rice yield analyzed (6 to 12.5 Mg ha^{-1}). Nitrogen fertilizer rate in soybean-rice fields was 61% (91 kg N ha^{-1}) lower than in soybean-rice crop rotation. Moreover, the highest net return (US$ 904 ha^{-1}) was obtained in soybean-rice rotation fields, which net returns difference between soybean-rice and continue rice systems was 25% (US$ 294 ha^{-1}). Like net returns, the benefit-to-cost ratio in soybean-rice was higher (1.4) than rice monoculture (1.1). In the context of fallow and pasture areas being replaced by soybean, our analysis indicated that soybean-rice can be a viable option to achieve both high annual productivity and large positive energy balance and profit, while reducing the environmental impact.

Keywords: Crop rotation, on-farm data, lowland rice, lowland soybean

1. Introduction

Brazil is the largest rice producing country in the world outside Asia, with an annual production of ca. 11 million metric tons (MMT) (FAO, 2019; USDA, 2019). There are two dominant rice producing regions: one in the central Brazil, where rainfed upland rice is grown in ca. half million ha, and another in southern Brazil, mostly Rio Grande do Sul (RS) state, where lowland irrigated rice is grown in ca. 1 million ha. Productivity is generally higher and more stable in lowland irrigated rice compared with upland rainfed rice. While the area of upland rice has declined steadily during the past 20 years (from 4.1 to 0.6 million ha), the area of lowland irrigated rice in southern Brazil has remained relatively stable over time. As upland rainfed rice production keeps declining, Brazil will increasingly rely on lowland irrigated rice production from southern Brazil, in particular RS state, which accounts for 77% of national rice production (CONAB, 2019).

Until mid-2000s, lowland irrigated rice in southern Brazil was typically grown in monoculture, with one rice crop per year as a result of the relatively shorter growing season compared with other tropical and subtropical regions where rice is produced. However, as a result of increasing weed pressure, together with high production costs, producers have introduced soybean to the traditional continuous rice system. Despite claims to be a ‘new cropping system’ (c.f. Theisen et al., 2017), the rice-soybean sequence has been practiced in the Mississippi Valley (USA) over the past 50 years (Wolf, 1970; Frank et al., 1988; Mayse & Tugwell, 1980; Gill & Kamprath, 1990; Cass et al., 1994; Cox & Gerard 2010; Smartt et al., 2016; Tsiboe et al., 2018). Nowadays, about one third of the rice area in RS state follows a 2-year rice-soybean sequence (Figure 1). In this system, soybean is typically grown without irrigation. However, growing upland crops such a soybean in lowlands is not easy. Field preparation for rice aims to create a compared soil layer that has low percolation rate so that rice fields can maintain the water level during most of the growing season without too many water applications. As a result, growing the subsequent soybean crop is difficult as a result of water excess due to the poor drainage (Pollet et al., 2019; Mitchell et al., 2013; Chan et al., 2004). Other difficulties for soybean include low soil pH (which rice can tolerate better as a result of the shallow root system), water and nutrient limitation due to the relatively shallow soil profile, lack of adapted soybean cultivars to the lowland environments, and general lack of knowledge in relation with suitable practices to grown soybean in the lowlands (e.g., tillage, water management, nutrients, etc.).

Despite the difficulties to grow soybean in the lowlands, rice producers in RGS have increasingly adopted the rice-soybean sequence as shown in Figure 1. One of the reasons, together with the higher profit from the soybean cycle in the rotation, is the 'perception' that rice yield is higher after the soybean crop compared with rice grown continuously. Similarly, they perceive that weeds, insect pests, and disease pressure in rice have decreased when it is grown in rotation. Growing rice after soybean is also logistically convenient as it reduces the need for field leveling compared with rice after rice. Theisen et al. (2017) have documented some of these benefits using data from small-plot experiments conducted in a research station in RS state over nine years, where crops were managed following "recommended" or "best" farm management practices. It is not clear, however, how the management followed in this experiment compare with actual practices in producer fields, where the aim is to maximize net profit rather achieving maximum productivity. Similarly, despite the advantages highlighted by Theisen et al. (2017), the fast adoption of the rice-soybean sequence observed during the early 2010s was followed by a stabilization in the area following rotation (Fig. 1), suggesting that there may be constrains limiting adoption of the rice-soybean system. A comprehensive on-farm assessment of yield and profitability in continuous rice and rice-soybean systems would be useful for understanding the drivers for adoption of the rice-soybean sequence and its limitations.

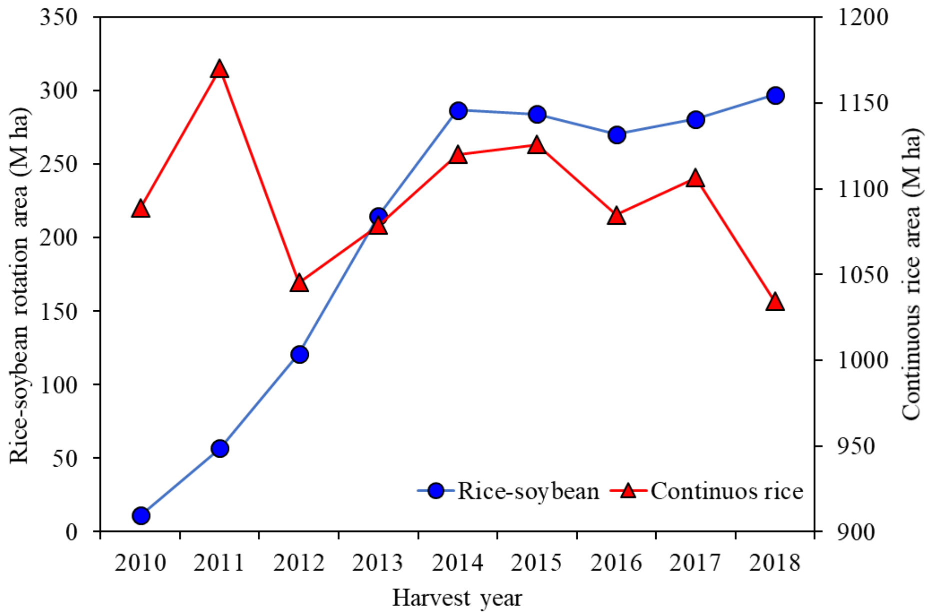

Figure 1 *– Trends in harvested area in continuous rice and rice-soybean rotation in the state of Rio Grande do Sul, Brazil. Source: Instituto Rio Grande do Arroz (https://irga.rs.gov.br/).*

To fill in the gap of knowledge in relation with the influence of crop sequence on the economic and productivity performance of rice-based systems in Southern Brazil, we used an original farmer database containing yield and management records collected from 350 farmer fields in Rio Grande do Sul (Brazil) over three years. The objective was to compare the continuous rice *versus* rice-soybean system in terms of profitability and discuss the advantages and trade-offs of the rice-soybean systems.

2. Material and Methods

2.1. Lowland irrigated rice production in southern Brazil

In contrast to lowland rice systems in Asia, rice production in southern Brazil is highly mechanized, with individual farmers managing large tracks of rice land (range: 150-750 ha). About half of the rice area is owned by the farmers, the rest is rented. All the rice area is direct-seeded with Indica cultivars; field are flooded ca. V3-V4 by pumping water from streams or reservoirs. Fields are kept flooded during the entire crop season and drained around physiological maturity to allow mechanical harvest. Direct seeding for rice and soybean starts in mid-Sept and continues until early Dec. Physiological maturity is reached in Feb-April, with harvest typically occurring two weeks after physiological maturity (Figure 2). Soybean water stress is more frequent and more intense in the southern and western regions of RS. Flowering and grain filling of early-sown crops coincide with the peak in solar radiation; in contrast, late-sown crops are exposed to lower solar radiation during reproductive stages and have lower yield potential. Temperature and radiation are lower in the southern region of the state (Rio Grande) compared with the western region (Uruguaiana).

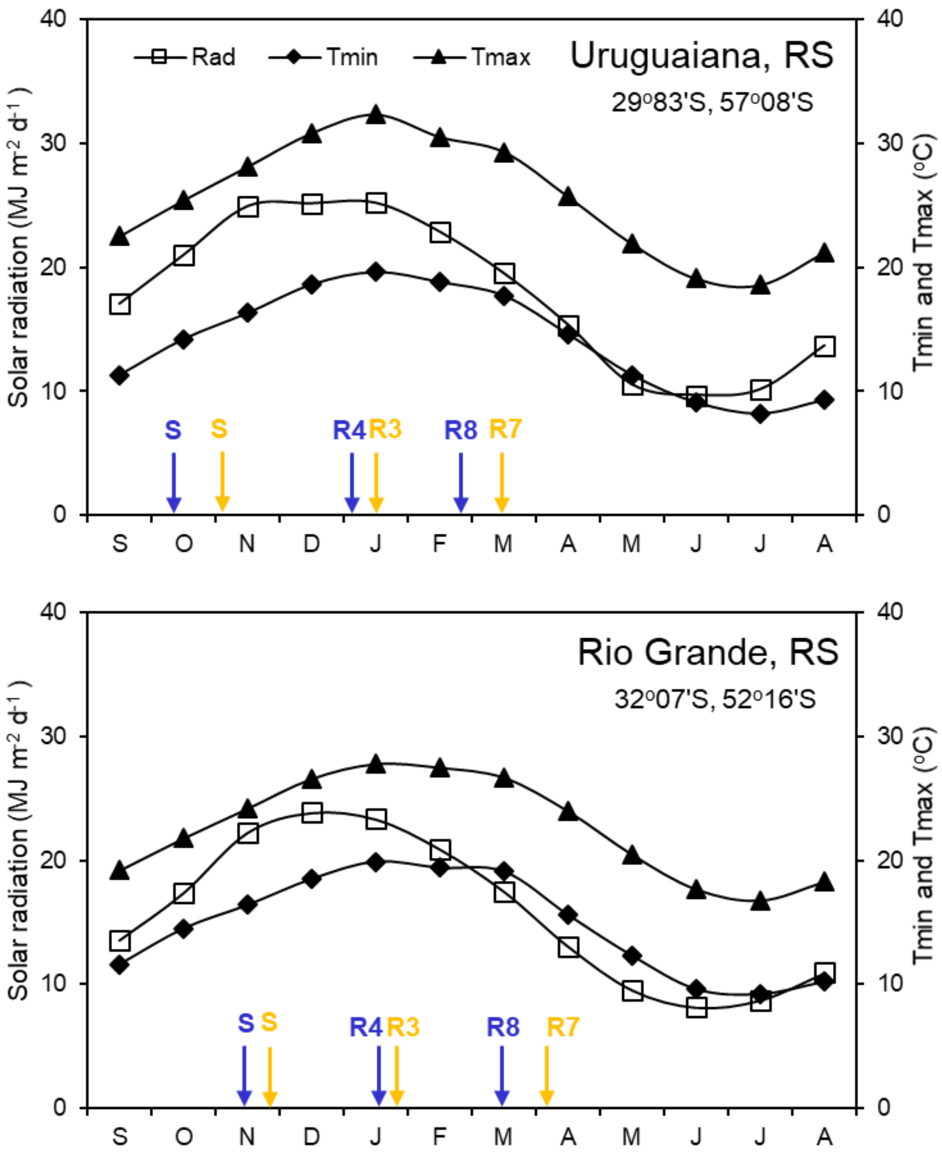

Figure 2. *(A, B) Monthly average incident solar radiation and maximum (Tmax) and minimum temperature (Tmin) for two locations representative of the rice and soybean producing area in lowland area in Rio Grande do Sul (RS): Uruguaiana (western RS) and Rio Grande (southern RS). Figure 3 shows location of meteorological stations. Each datapoint represent means of meteorological variables calculated based on five years (solar radiation) or 30 years (Tmax and Tmin) of measured weather data. Soild arrows inside panels indicate average dates of sowing (S), flowering (R1), and physiological maturity (R8) for irrigated rice. Dashed arrows \indicate average dates of sowing (S), beginning of pod setting (R3) and physiological maturity (R7) for rainfed soybean.*

2.2 On-farm database

Data on rice yield and management practices were collected over three years (2016, 2017, and 2018) from fields sown with continues rice and soybean-rice rotation in RS state (Figure 3). All surveyed fields were located in lowlands where continuous rice fields were cultivated with irrigation and received irrigation, while soybean fields were cultivated in rainfed conditions. Rice producers provided data *via* surveys distributed by local crop consultants, extensionists of the Instituto Rio Grandense do Arroz (IRGA) and by personal interviews. Briefly, producers were asked to report the average field yield across the fields sown with rice and soybean-rice rotation in each year and to provide data for a number of fields that portray well that yield range. Requested data also included field location, average field yield (at 13% seed moisture content for rice and soybean), crop management (e.g., sowing date, previous crop, pre-sowing weed control, etc.), applied inputs (e.g., nutrient fertilizer, biocides, etc.), and incidence of biotic and abiotic adversities (e.g., insect pests, diseases, weeds, waterlogging, frost, etc.). Survey data were inputted into a digital database and screened to remove erroneous or incomplete data entries. Around 324 fields over three years, over the total of fields 177 corresponding to continues rice and 147 correspond to rice fields with soybean rotations.

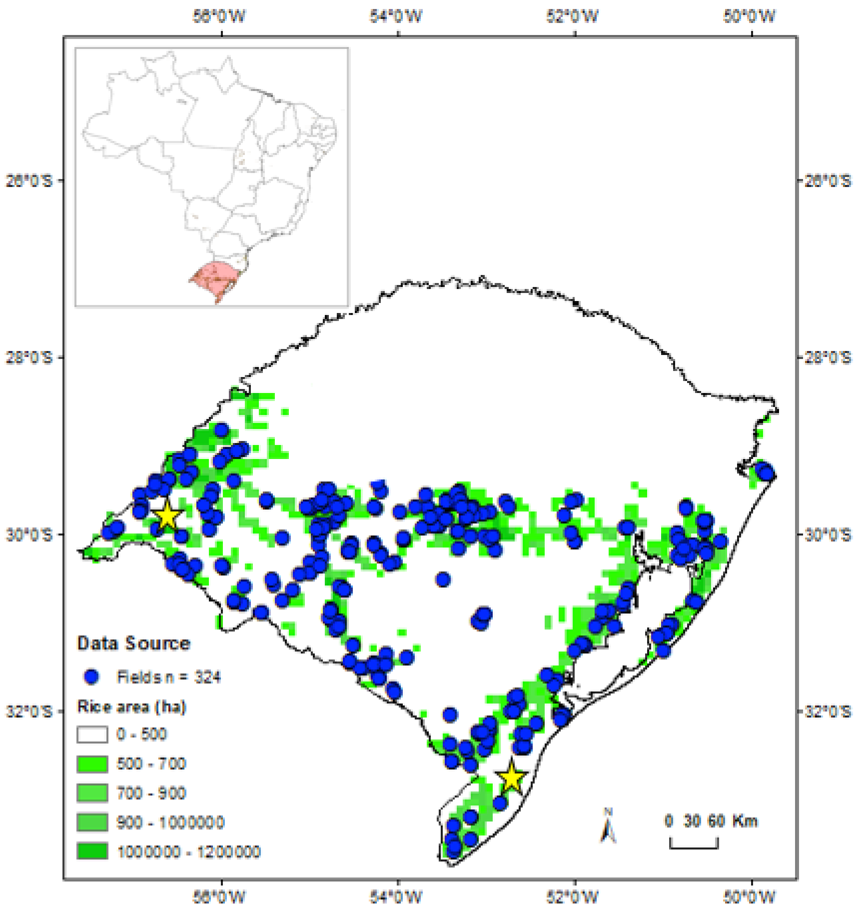

Figure 3. *Map of the state of Rio Grande do Sul (RS) state showing location of the 324 surveyed fields (solid circles). Green indicate the rice producing area within the state Inset shows the location of RS within Brazil. Stars indicate the location of the two meteorological stations used to illustrate weather patterns in Figure 2.*

2.3 Data analysis

At question is the degree to which crop sequence influences rice yield compared with other management practices (e.g., fertilizer, seeding rate, fungicide application, etc.). Here we used regression tree analysis to determine the influence of previous summer crop *versus* other management practices on rice yield using the “rpart” package in R (Hothorn et al., 2006). Regression tree analysis is a non-parametric method which recursively partitions the data into successively smaller groups with binary splits based on a single continuous predictor variable

(Breiman et al., 1984; Clark and Pregibon, 1992). Regression tree analysis produces a tree-diagram output, with branches determined by splitting rules and a series of terminal nodes that contain the mean response (*i.e.*, yield) and the number of observations that fall within each terminal node. The procedure initially grew maximal trees and then used of cross-validation technique to prune the over-fitted tree to an optimal size (Therneau and Atkinson, 1997). A “caret" package in R was used to split the dataset into training (80%) and testing (20%) datasets. The training dataset was used to run the regression tree analysis, while the testing dataset was utilized to estimate the mean square error (MSE) between observed and predicted yield. The regression tree analysis handled missing values in the explanatory factors (*na.rpart* function), excluding cases only if the response variable (i.e., yield) or all explanatory factors were missing. When missing values were encountered in considering a split, they were ignored and predictions are calculated from the non-missing values of that factor (Venables and Ripley, 2002).

Previous studies have used a similar approach to determine the influence of management practices on crop yields based on farmer or experimental data (Mourtzinis et al 2017; Tenorio et al., 2019).

Following other studies (e.g. Yuan et al., 2019), we calculated a number of parameters to assess the productivity and economic performance in consecutive 2-yr sequence between continues rice (total of 88 fields) and rice-soybean or soybean-rice (total of 26 fields) field groups. These parameters include: yield, inputs (and their share of total variable costs), labor, incidence of biotic stresses (weeds, insect pests, and diseases), variable costs, net profit (based on gross income and variable costs), net income-to-cost ratio, and the net profit-to-labor ratio. For each field, costs were calculated based on reported annual input amounts and associated market prices (in US$) around year 2018. Labor, land, and machinery costs were estimated based on expert opinion from local agronomists and researchers. Similarly, we calculated partial productivity factors for N fertilizer rate as the ratio between yield and N fertilizer input

(Cassman et al., 2002). Box plots were used to illustrate the range of values for these parameters in each crop sequence. Energy output was calculated based on farmer-reported yield and rice and soybean grain energy content (Amthor et al., 1994; Koester et al., 2014; Guilpart et al., 2017). Yield potential was calculated using Oryza2000 v3 (Bouman et al., 2004) using coefficients calibrated for the most dominant varieties in southern Brazil (www.yieldgap.org). To compare the two cropping sequence we use 2-year sums.

3. Results

3.2. Input use in continuous rice *versus* rice-soybean crop rotation

In both crop sequences, fossil fuel, labor, and biocides (herbicide, insecticide, and fungicide) accounted for more than 80% of total energy use (Table 1). Soybean-rice fields require substantially less resources than rice-rice (Table 1). Hence, soybean-rice had higher energy output and gross income, than rice-rice because of less requirement of machinery resource with soil preparation. Finally, field-to-field variation in NER, and benefit-cost-to ratio was relatively lower (< 74 % and 28%) in soybean-rice than rice-rice.

Table 2. *Sum of applied inputs, total fossil-fuel energy inputs (and average percentage of total production cost, based on farmer-reported data over two consecutive years cropping systems for soybean-rice and rice-rice.*

Inputs (per ha)	Sum over two years cropping system fields	
	soybean-rice	rice-rice
N fertilizer, kg N	147 (6)	238 (9)
P fertilizer, kg P	96 (4)	53 (1)
K fertilizer, kg K	120 (3)	135 (3)
Lime, kg	2500 (9)	0
Seed, kg ha^{-1}	148 (10)	197 (10)
Labor, h	80 (21)	110 (32)
Herbicide, kg a.i.	10 (5)	8 (4)
Insecticide, kg a.i	2 (4)	2 (3)
Fungicide, kg a.i.	2 (10)	2 (3)
Diesel, l	185 (20)	247 (21)
Eletricity, KWh	78 (8)	156 (14)

3.3. Productivity and economic performance of two crop sequences

Soybean-rice crop rotation attained the highest grain yield with a strong relationship between net economic return, energy output and benefit-to-cost ratio (r^2 = 0.66, P<0.01). In continues rice, the difference between the highest and lowest costs were US\$ 146 ha^{-1} whereas in soybean-rice system the production cost was almost the same US\$ 74 ha^{-1}, which means that there were a better resource-use efficiency and labor inputs for soybean-rice system making it more profitable than continues rice. The highest net return (US\$ 904 $ha^{–1}$) from the systems were obtained with soybean-rice rotation fields. The difference in average? net return in soybean-rice fields versus continue rice was US\$ 281 $ha^{–1}$. Like net returns, the benefit-to-cost ratio was the highest in soybean-rice fields (1.8), and these finding were consistent with difference between soybean-rice fields and continue-rice (0.2), indicating that soybean-rice fields attained larger economic benefit per unit of production cost compared with the continue rice system.

The PFP_N rice average was 75 kg kg^{-1} N for rice after soybean (safe 1y fertilizer but increase NUE)-rice fields and 137 kg kg^{-1} N in continue rice fields. Difference in PFP_N was unrelated with residual soil from prior crop and the PFP_N between soybean-rice and continue rice fields were not significant. In RS, there is a tremendous variation fertilizer N total applied in rice among soybean-rice (147 kg ha^{-1}) and continue rice systems (238 kg ha^{-1}). However, soybean-rice fields require less amount of N than continue rice, therefore rice farmers are not applying fertilizer N total to account for the wide range in soil N supply resulting imbalance contributes to low N-use efficiency. In this sense, there is no study in Brazil about the N-use efficiency in soybean-rice *versus* continues rice fields, in order to turn the soybean-rice system much more profitable.

Annual grain energy output explaining the variation among cropping systems as well as field-to-field variation within cropping systems (Figure 4B). The difference in grain yield among the two cropping systems was mainly attributable to differences in previous summer crop, fertilizers, biocides and sowing date (Figure 4A). Therefore, the soybean-rice rotation has shown the most promising summer cropping system for lowland area in RS where the most important benefit was to increase the rice grain yield by 20%. Crop rotation fields have shown an increase of 7% of rice yield by pre-sowing weed control using only herbicide instant of disc plus herbicide. Furthermore, rice producers appply 1% less N fertilizer input when the previous summer crop is soybean. However, the yield gap still 49% of yield potential (14.8 Mg ha^{-1}), because rice farmers still have on fields management problems, such as weed control, N fertilizer input, delayed sowing date.

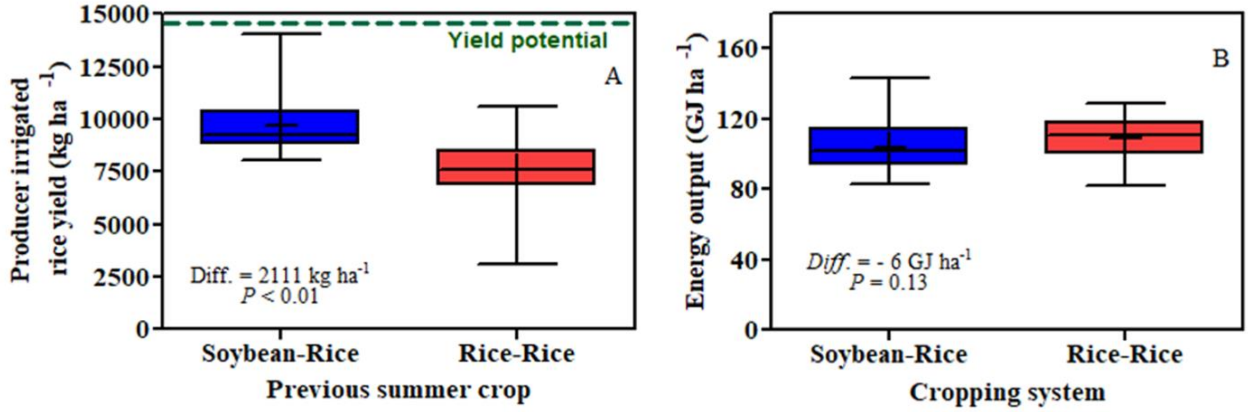

Figure 4 *– Comparison of average producer irrigated rice yield between groups of fields with different management. Letters indicate significance of the impact on rice yield with respect to the previous summer crop as evaluated using t test at p< 0.01. Comparison of irrigated rice yield in Soybean-Rice rotation versus Rice-Rice against sowing date in the Rio Grande do Sul Brazil region. The yield potential calculated with Oryza model, median (continue line) and mean (+) are shown.*

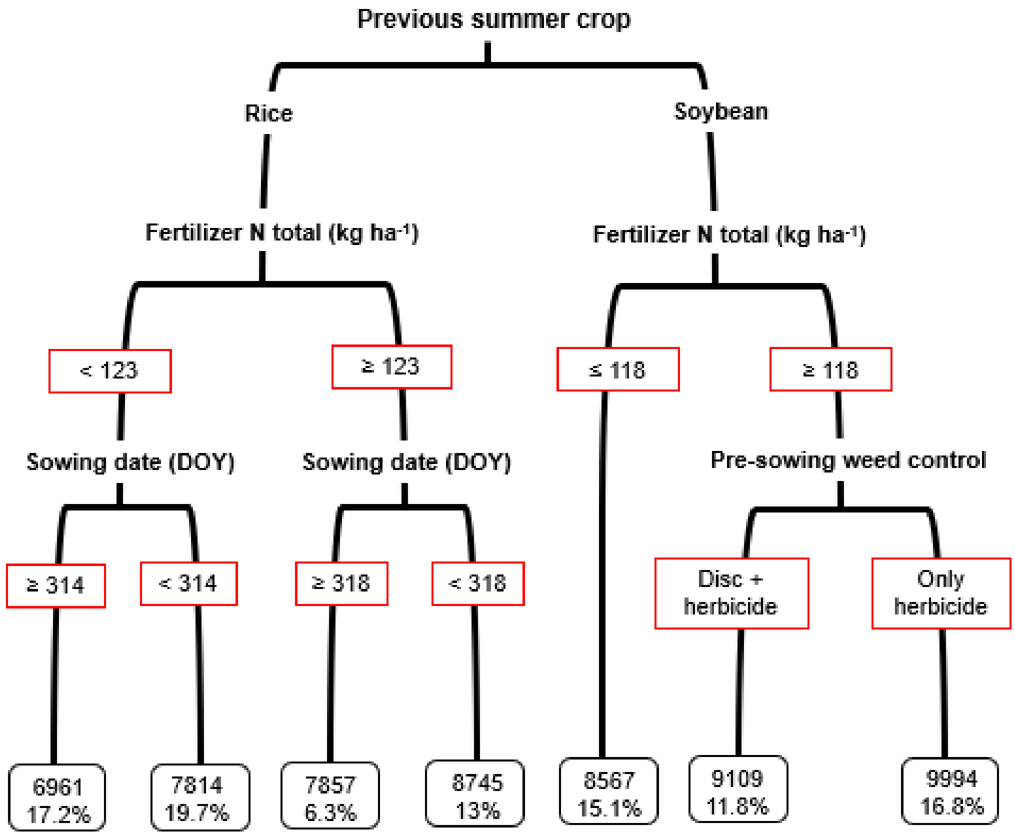

Figure 3*. Regression tree model showing sources of variation in grain yield due to previous summer crop (overall* R^2 *= 44%). Boxes are splitting nodes, with bottom boxes representing*

terminal nodes. Values within each terminal node indicate average of grain yield (in kg ha^{-1}) at a 13% moisture content basis and the percentage of observations in each terminal node.

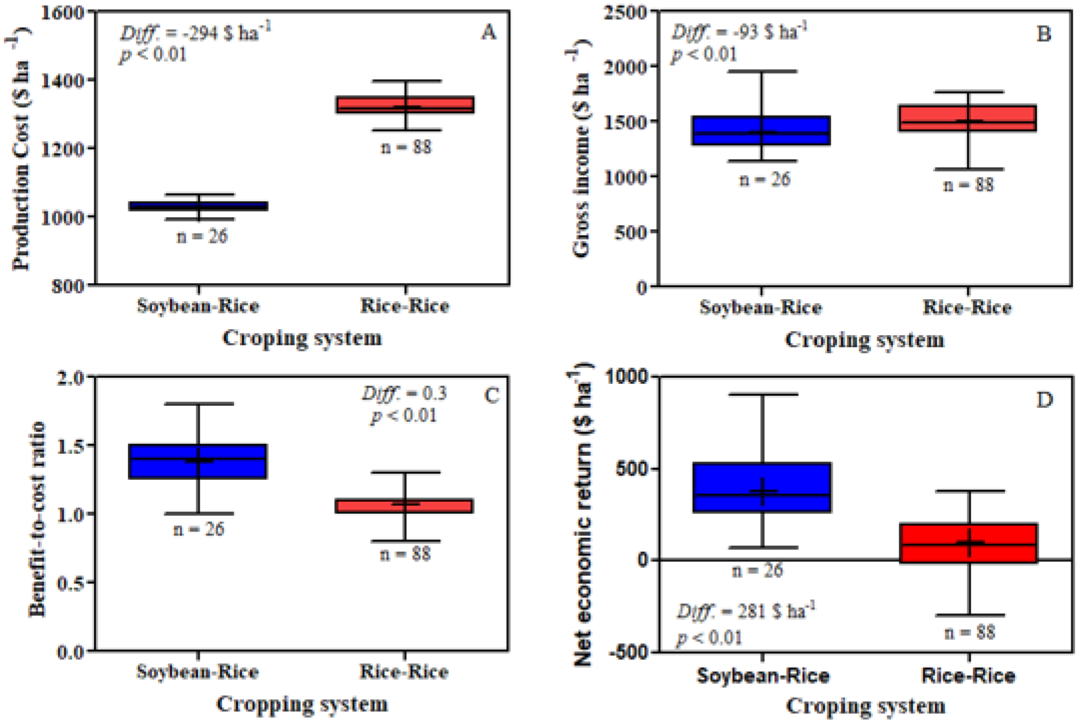

Figure 7. *Boxplots show the comparison of net economic return (A) a benefit-to-cost ratio (B) in irrigated rice in two systems with different previous summer crop in the Rio Grande do Sul - Brazil. Letters (a, b) indicate statistically significant differences (Anova and Contrast, p< 0.01). The median (continue line) and mean (+) are shown.*

3.1. Influence of crop sequence on rice yield

The regression tree explained 44% of variation in rice yield using four variables, included previous summer crop rotation, fertilizer nitrogen total, sowing date and pre-sowing control weed (Figure 3). Previous summer crop was the most important variable associated with grain yield, with crops under soybean-rice crop rotation reaching higher grain yield in relation with continuous rice. The influence of soybean-rice rotation in grain yield was amplified in fields that were also exposed higher fertilizer nitrogen total (≥ 118 kg ha^{-1}) and pre-sowing weed control by only herbicide, while fields with lowest grain yield were associated with small N fertilizer inputs (< 118 kg ha^{-1}) and pre-sowing weed control by disc plus herbicide. In contrast, the most important factors influencing grain yield in continuous rice were N fertilizer rate and sowing date: higher yield were associated with large N fertilizer input (≥123 kg ha^{-1}) and early sowing dates (DOY< 318).

4. Discussion

The yield benefit when cereal crops are rotated with legumes has been well documented for wheat and maize (Grassini et al., 2011; Fischer et al., 2002, Farmaha et al 2014 and references cited therein). For rice, t few studies including a side-by-side comparison of rice grown in rotation *versus* rice grown continuously showed a consistent rice yield advantage with rotation, ranging from +7% to +25% in relation with the continuous rice system (Anders et al., 2002; Olk et al., 2009; Smartt et al. 2016; Theisen et al., 2017). Studies have been showed continues rice has 19% average less grain yield than soybean-rice (Anders et al., 2004, 2007). Furthermore, there are situations where legume sources have provided a significant proportion (20-33%) of the next crop's N requirements (Peoples et al., 2009) by increasing nitrogen availability in the soil due to symbiotic N_2-fixation (Olk et al., 2009), increasing weed pre-sowing control by diversifying herbicide mechanisms of action of the herbicides and cultural practices (Filizadeh et al., 2007; Angus et al., 2015; Theisen et al., 2017) (Table 2). In this study we have provided information about the yield increasing soybean-rice crop rotation system by improving management practices and quantifying the production costs of systems. Soybean-rice rotation started to be adopted by farmers to control weed resistance, such as weedy rice (*Oryza sativa*), and barnyard grass (*Echinochloa crusgalli*) by rotating herbicides, and improving net returns. Legume N plays a key role in contributing to the soil organic matter (Schwenker et al., 2002) and may be the source of between 30-75% of the total mineral N accumulating after legumes (Evans et al., 2003). Furthermore, soybean-rice crop rotation is a stable tool allowing farmers to reduce production costs by using less machinery hours, biocides and labors inputs. Therefore, the soybean price selling grain (\$ 18.0 ha^{-1} at the industry is higher than rice (\$ 10.0 ha^{-1}) (IBGE, 2019) which makes the soybean-rice system more profitable than rice-rice as well.

Location-specific cropping-system data used in the analysis illustrated the shifts in southern Brazil rice production systems, where the total harvested irrigated rice area has decreased by 65% since 2010 (CONAB, 2019). Farmers are focusing resources on increasing yields by using the soybean-rice rotation to reduce the sizable yield gaps in monoculture fields offering the greatest potential to ensure southern continues growing enough rice for its population. The good news is RS has substantial flexibility to maintain self-sufficiency without increasing the cropland dedicated to rice production (Clapp, 2019). Economic reasons for adoption of soybean-rice system are the best returns from the soybean crop is the greater prices of grain and high price stability (Clapp, 2019), saving labor, time, water and energy costs. Furthermore, the net returns and benefit to cost ratio from continuous rice are less reliable than from a diversified cropping sequence in lowland environments.

Even though soybean-rice rotation has been elected the most promisor system in lowland areas in Brazil, this system cannot be implemented by all rice farmers. Still there are problems to crop soybean in fields close to the rivers, poor drainage condition fields. Another problem is the investment with equipment that rice producer should do to crop soybean in lowland rice fields. Farmers that have been adopted the soybean in lowland areas have to face risks with water surplus mostly in El Niño years, especially during germination and emergence period, which may turn soybean-rice system less profitable than continue rice sometimes. However, strategies can be adopted by farmers to minimize water surplus risks in lowland areas, as changing soybean sowing date to after November 1, decreasing the water surplus risk by less than 60% (Bortoluzzi et al., 2017).

Nowadays, the total cropping lowland area in RS is 3 M ha where 39% had been used by continue rice, 9% by soybean-rice rotation, 52% by fallow/pasture and continue soybean (IBGE, 2019). Our belief is, if part of the fallow/pasture and continue soybean current lowland area shift into the soybean-rice system, it can potentially increase the total rice production following the principle of high quality, efficiency, yielding, low cost and minimum impacts on the environment. Moreover, even the Brazilian production being smaller than Asian continent, the potential to increase rice production in Brazil is larger (66%) than Asia, which makes Brazil a potential rice exporter, and, Brazil, that already is a major global food supplier (Marin et al., 2016), will become more prominent in the global food security and it will be able to supply the estimated demand for rice in other countries, such as China (Nanyan et al., 2019), which guarantee the world food security and define public policies regarding the commercialization of rice.

5. Conclusions

Key insights from this study focusing on high-yield irrigated rice in the RS Brazil. Rice yield are: (i) rice grown with soybean has yield advantage (20%) than continue rice, (ii) soybean-rice may receive less N fertilizer than continue rice increasing the N-efficiency turn it more profitable, (iii) analysis of the data reported lower variation and higher average values in NER, and benefit-cost-to ratio in soybean-rice system than rice-rice system which makes soybean-rice system be more stable and profitable.

References

AGGARWAL, P.K.; KALRA, N.; CHANDER, S.; PATHAK, H. InfoCrop: a dynamic simulation model for the assessment of crop yields, losses due to pests, and environmental impact of agro-ecosystems in tropical environments. Agricultural Systems, v.89, p.1-25, 2006. DOI: 10.1016/j.agsy.2005.08.001.

ARTACHO, P.; MEZA, F.; ALCALDE, J.A. Evaluation of the Oryza2000 rice growth model under nitrogen-limited conditions in an irrigated Mediterranean environment. Chilean Journal of Agricultural Research, v.71, p.23-33, 2011. DOI: 10.4067/S0718-58392011000100003.

BAICHAROEN, A., VIJAYAN, R.; PONGPRAYOON, P. Structural insights into betaine aldehyde dehydrogenase (BADH2) from Oryza sativa explored by modeling and simulations. Scientific reports, v.8, p.12892, 2018. DOI: 10.1038/s41598-018-31204-z.

BALBINOTI, T. C. V., DE MATOS JORGE, L. M.; JORGE, R. M. M. Mathematical modeling of paddy (Oryza sativa) hydration in different thermal conditions assisted by Raman spectroscopy. Journal of cereal science, v.79, p.390-398, 2018. DOI: 10.1016/j.jcs.2017.11.019.

BALBINOTI, T. C. V., DE MATOS JORGE, L. M.; JORGE, R. M. M. Modeling the hydration step of the rice (Oryza sativa) parboiling process. Journal of Food Engineering, v.216, p.81-89, 2018. DOI: 10.1016/j.jfoodeng.2017.07.020.

BOLING, A.A.; BOUMAN, B.A.M.; TUONG, T.P.; KONBOON, Y.; HARNPICHITVITAYA, D. Yield gap analysis and the effect of nitrogen and water on photoperiod-sensitive Jasmine rice in north-east Thailand. Wageningen Journal of Life Science, v.58, p.11-19, 2011. DOI: 10.1016/j.njas.2010.05.001.

BOUMAN, B.A.M.; KROPFF, M.J.; TUONG, T.P.; WOPEREIS, M.C.S.; TEN BERGE, H.F.M.; LAAR, H.H. VAN. Oryza 2000: modeling lowland rice. Manila, Philippines: International Rice Research Institute (IRRI), 2004. 245p.

CASSMAN, K.G.; DOBERMANN, A.; WALTERS, D.T.; YANG, H. Meeting cereal demand while protecting natural resources and improving environmental quality. Annual Review Environment Resources, v.28, p.315–358, 2003. DOI:10.1146/annurev.energy.28.040202.122858.

CASTRO, J. R. D., CUADRA, S. V., PINTO, L. B., SOUZA, J. M. H. D., SANTOS, M. P. D.; HEINEMANN, A. B. Parametrization of Models and Use of Estimated Global Solar Radiation Data in the Irrigated Rice Yield Simulation. Revista Brasileira de Meteorologia, v.33, p.238-246, 2018. DOI: 10.1590/0102-7786332003.

CHAN, P., BASNAYAKE, J., NGOY, K., FUKAI, S., SAROM, M.E., 2004. The effect of water availability on rice-based double cropping in rainfed lowlands in Cambodia. In: SENG, V., CRASWELL, E., FUKAI, S., FISCHER, K. (Eds.), Water in Agriculture. ACIAR Proceedings Nº. 116, Australian Centre for International Agricultural Research, Canberra, Australia, pp. 72–85.

CONAB. Acompanhamento da safra brasileira de grãos. Available at: < www.conab.gov.br >. Accessed on: May. 01 2018.

CONFALONIERI, R.; BREGAGLIO, S.; ACUTIS, M. Quantifying uncertainty in crop model predictions due to the uncertainty in the observations used for calibration. Ecological modelling, v.328, p.72-77, 2016. DOI: 10.1016/j.ecolmodel.2016.02.013

COUNCE, P.; KEISLING, T.C.; MITCHELL, A.J. A uniform, objective, and adaptative system for expressing rice development. Crop Science, v.40, p.436-443, 2000. DOI: 10.2135/cropsci2000.402436x.

DAUER, J., HULTING, A., CARLSON, D., MANKIN, L., HARDEN, J.; MALLORY-SMITH, C. Gene flow from single and stacked herbicide-resistant rice (Oryza sativa): modeling occurrence of multiple herbicide-resistant weedy rice. Pest Management Science, v.74, p.348-355, 2018. DOI: 10.1002/ps.4711.

DENG, N.; GRASSINI, P.; YANG, H.; HUANG, J.; CASSMAN, K. G.; PENG, S. Closing yield gaps for rice self-sufficiency in China. Nature communications, v.10, 1725, 2019. DOI: 10.1038/s41467-019-09447-9.

ESPE, M.B.; CASSMAN, K.G.; YANG, H.; GUILPART, N.; GRASSINI, P.; VAN WART, J.; ANDRES M.; BEIGHLEY D.; HARELL D.; LISCOMBE S.; MCKENZE K.; MUTTERS R.; WILSON L.T.; LINQUIST. B.A. Yield gap analysis of US rice production systems shows opportunities for improvement. Field Crops Research. v.196, p.276-283, 2016. DOI: 10.1016/j.fcr.2016.07.011.

FAO. Database of the Food and Agricultural Organization of the United Nations. Available at: <www.fao.org/faostat/en/#data/QC>. Accessed on: May. 01 2018.

GABRIEL, L.F.; STRECK, N.A.; ROBERTI, D.R.; CHIELLE, Z.G.; UHLMANN, L.O.; SILVA, M. R.DA.; SILVA, S.D. da. Simulating cassava growth and yield under potential conditions in Southern Brazil. Agronomy Journal, v.106, p.1119-1137, 2014. DOI: 10.2134/agronj2013.0187.

GRASSINI, P.; TORRION, J.A.; YANG, H.S.; REES, J.; ANDERSEN, D.; CASSMAN, K.G.; SPECHT, J.E. Soybean yield gaps and water productivity in the western U.S. Corn Belt. Field Crops Research, v.179, p.150-163, 2015. DOI: 10.1016/j.fcr.2015.04.015.

HAUN, J.R. Visual quantification of wheat development. Agronomy Journal, v.65, p.116-119, 1973. DOI: 10.2134/agronj1973.00021962006500010035x.

HEINEMANN, A. B.; HOOGENBOOM, G.; DE FARIA, R. T. Determination of spatial water requirements at county and regional levels using crop models and GIS: An example for the State of Parana, Brazil. Agricultural Water Management, v.52, p.177-196, 2002. DOI: 10.1016/S0378-3774(01)00137-8.

IRGA. Levantamento da área semeada com arroz irrigado no Rio Grande do Sul. Available at: <http://www.irga.rs.gov.br>. Accessed on: Feb. 20 2018.

JANSSEN, P. H. M.; HEUBERGER, P. S. C. Calibration of process-oriented models. Ecological Modelling, v.83, p.55-56, 1995. DOI: 10.1016/0304-3800(95)00084-9.

LI, T.; ANGELES, O.; MARCAIDA M.; MANALO, E.; MANALILI, M. P.; RADANIELSON, A.; MOHANTY, S. From ORYZA2000 to ORYZA (v3): An improved simulation model for rice in drought and nitrogen-deficient environments. Agricultural and forest meteorology, v.237, p.246-256, 2017. DOI: 10.1016/j.agrformet.2017.02.025.

LIU, Y., LI, C., FANG, B., FANG, Y., CHEN, K., ZHANG, Y.; ZHANG, H. Potential for high yield with increased seedling density and decreased N fertilizer application under seedling-throwing rice cultivation. Scientific reports, v.9, p.731. 2019. DOI: 10.1038/s41598-018-36978-w.

LOBELL, D.B.; CASSMAN, K.G.; FIELD, C.B. Crop yield gaps: their importance, magnitudes, and causes. Annual Review Environment Resources, v.34, p.179–204, 2009. DOI: 10.1146/annurev.environ.041008.093740.

MENEZES, V. G.; ANGHINONI, I.; SILVA, P. R. F. DA; MACEDO, V. R. M.; PETRY, C.; GROHS, D. S.; FREITAS, T. F. S. DE; VALENTE, L. A. L. Project 10 - Management strategies to increase yield and sustainability of irrigated rice in RS: advances and new challenges. Cachoeirinha, Brazil: Instituto Rio Grandense do Arroz (IRGA), 2013. 96p.

MITCHELL, J., CHETH, K., SENG, V., LOR, B., OUK, M., FUKAI, S. Wet cultivation in lowland rice causing excess water problems for the subsequent non-rice crops in the Mekong region. Field Crops Research, v.152, p.57-64, 2013.

MONGIANO, G.; TITONE, P.; TAMBORINI, L.; PILU, R.; BREGAGLIO, S. Advancing crop modelling capabilities through cultivar-specific parameters sets for the Italian rice germplasm. Field Crops Research, v.240, p.44-54. 2019. DOI: 10.1016/j.fcr.2019.05.012

RAMIREZ-VILLEGAS, J., HEINEMANN, A. B., PEREIRA DE CASTRO, A., BRESEGHELLO, F.; NAVARRO-RACINES, C., LI, T., REBOLLEDO, M.C.; CHALLINOR, A. J. Breeding implications of drought stress under future climate for upland rice in Brazil. Global Change Biology, v.24. p.2035-2050, 2018. DOI: 10.1111/gcb.14071.

RIBAS, G.G.; STRECK, N.A.; DUARTE JUNIOR, A.J.; NASCIMENTO, M.F.; ZANON, A.J.; SILVA, M.R. Number of leaves and phenology of rice hybrids simulated by the SimulArroz model. Revista Brasileira de Engenharia Agrícola e Ambiental, v.21, p.221-226, 2017. DOI: 10.1590/1807-1929/agriambi.v21n4p221-226.

ROSA, H.T.; WALTER, L.C.; STRECK, N.A.; CARLI, C.DE; RIBAS, G.G.; MARCHESAN, E. Simulação do crescimento e produtividade de arroz no Rio Grande do Sul pelo modelo SimulArroz. Revista Brasileira de Engenharia Agrícola e Ambiental, v.19, p.1159-1165, 2015. DOI: 10.1590/1807-1929/agriambi.v19n12p1159-1165

STÖCKLE C.O.; WILLIAMS J.R.; ROSENBERG C.A.; JONES C.A. A method for estimating direct and climatic effects of rising atmospheric carbon dioxide on crops growth and yield. Agricultural Systems, v.38, p.225–238, 1992. DOI: 10.1016/0308-521X(92)90067-X.

STRECK, N. A.; BOSCO, L. C.; LAGO, I. Simulating leaf appearance in rice. Agronomy Journal, v.100, p.490-501, 2008. DOI: 10.2134/agronj2007.0156.

TANG, L..; ZHU, Y.; HANNAWAY, D.; MENG, Y.; LIU, L.; CHEN, L.; CAO, W. RiceGrow: A rice growth and productivity model. NJAS-Wageningen Journal of Life Sciences, v.57, p.83-92, 2009. DOI: 10.1016/j.njas.2009.12.003.

USDA. Production, Supply and Distribution. Available at: <www.usda.gov/wps/portal/usda/usdahome?navid=DATA_STATISTICS> Accessed on: Feb. 20 2018.

VAN ITTERSUM, M.K.; CASSMAN, K.G.; GRASSINI, P.; WOLF, J.; TITTONELL, P.; HOCHMAND, Z. Yield gap analysis with local to global relevance—a review. Field Crops Research, v.143, p.4–17. 2013. DOI:10.1016/j.fcr.2012.09.009

VAN OORT, P.A.J., ZHANG, T., DE VRIES, M.E., HEINEMANN, A. B., MEINKE, H. Correlation between temperature and phenology prediction error in rice (Oryza sativa L.).

Agricultural and Forest Meteorology, v.151, p.1545-1555, 2011. DOI: 10.1016/j.agrformet.2011.06.012.

4 DISCUSSÃO

Neste estudo de tese, calibramos e avaliamos modelos agrícolas para a determinação do potencial produtivo através da condução de experimentos de campo. Os modelos mostraram bom desempemho, apresentando variação do NRMSE entre 0,8% à 34% (Figura 1 - Apêndice, Tabelas 1, 2 e 3 - Artigo I). Além disso, o modelo SimulArroz foi testado para níveis tecnológicos baixo, médio e alto no RS e, mostrou que consegue capturar a variação de ambiente, época de semeadura, anos e nivel tecnológico (Figura 3 - Artigo I). Em estudos na China, BOLING et al. (2011) reportaram variação do NRMSE entre 20,4% à 35% com o modelo Oryza v3. Com este trabalho de tese foi possível identificar similaridade nos erros encontrados neste trabalho em relação à literatura, sendo possível afirmar que os dois modelos estão capturando a variação de ambiente.

As informações aqui relatadas podem ser usadas para ajustar o manejo atual das lavouras de arroz irrigado no sul do RS. Com a caracterização adequada da fenologia das cultivares de arroz atualmente utilizadas pelos agricultores, a medição da semeadura e o auxílio de modelos de simulação de culturas (BOUMAN & VAN LAAR, 2006), seria possível desenvolver ferramentas de auxílio à decisão para recomendar a data de semeadura e grupo de maturação da cultivar para combinar os estágios de enchimento de grãos (estágio que apresentou maior significância do coeficiente fototérmico) com o período de máxima disponibilidade de radiação solar (dezembro e janeiro) para maximizar as chances de atingir o potencial de produtividade.

O potencial reportado no RS com o modelo Oryza v3 (14,8 t ha^{-1}) (Figura 2 - Apêndice) foi similar ao reportado no Uruguai (14 t ha^{-1}), e maior aos reportados nos Estados Unidos (9,4 t ha^{-1}), China (12.4 t ha^{-1}) e África (9 t ha^{-1}). Já quando analisamos a lacuna de produtividade no RS (7,1 t ha^{-1} ou 49%) observamos que foi maior em relação aos EUA (27%) e China (33%), similar ao Uruguai (43%) e menor que a África (60%) (LICKER et al., 2010; ZORRILLA et al., 2012; AGUS et al., 2019; DENG et al., 2019; VAN LOON et al., 2019).

Sob ponto de vista das melhores lavouras de arroz no RS foi observado que estão produzindo 68% do potencial, enquanto que as demais lavouras estão produzindo 52% do potencial no RS. Estes resultados, estão de acordo com os reportados na California e no Texas, Estados Unidos por Espe et al. (2016) onde a variação foi de 61 à 76% do potencial produtivo para a cultura do arroz.

Nesse sentido, este estudo mostrou que as produtividades médias das lavouras nas diferentes regiões orizícolas do estado do RS não alcançaram 100% da produtividade atingível (80% Pp, VAN ISTTURSEM et al., 2013), sendo a Lp menor na Fronteira Oeste (44%) e a maior Lp nas Planícies Costeiras Internas e Externas (51%) (Figura 3 - Apêndice). Indicando o quanto, ainda, é possível melhorar o manejo de arroz no RS (Figura 2 -Apêndice), sendo época de semeadura, época de entrada de água na lavoura, controle de plantas daninhas, rotação de culturas e fertilizantes os fatores que potencialmente estão relacionados com a lacuna, sendo fundamental a transferência de informação das práticas de manejo através de roteiros técnicos ou palestras por técnicos, pesquisadores e/ou extensionistas para diminuir a Lp.

5 CONCLUSÃO

Os modelos agrícolas estão testados para o uso em simulações do potencial de produtividade no RS. Os resultados obtidos por esse estudo revelam que o potencial produtivo e a lacuna de produtividade variam com o ambiente, sendo o valor médio para o Pp de 14,8 t ha^{-1} e Lp 7.1 t ha^{-1}. Com relação aos fatores de manejo, época de semeadura, época de entrada de água na lavoura, plantas daninhas, fertilizantes e rotação de culturas são os fatores que estão afetando o desempenho de produtividade de arroz no RS.

REFERÊNCIAS BIBLIOGRÁFICAS

AGGARWAL, P. K. et al. **InfoCrop**: A dynamic simulation model for the assessment of crop yields, losses due to pests, and environmental impact of agro-ecosystems in tropical environments. I. Model description. Agricultural Systems, Netherlands, v. 89, 2006. p. 1-25.

AGUS, F., Andrade, J. F., Edreira, J. I. R., Deng, N., Purwantomo, D. K., Agustiani, N., ... and Makka, A. 2019. Yield gaps in intensive rice-maize cropping sequences in the humid tropics of Indonesia. **Field Crops Research**, 237, 12-22. https://doi.org/10.1016/j.fcr.2019.04.006 .

BATTISTI, R. et al. Climatic efficiency for soybean and wheat crops in the state of Rio Grande do Sul, Brazil, in different sowing date. (In Portuguese, with English abstract.) **Ciência Rural**, v. 43, p. 390-396, 2013. https://doi.org/10.1007/s42106-018-0016-0

BOLDRINI, I. I.; LONGHI-WAGNER, H. M.; BOECHAT, S. C. **Morfologia e taxonomia de gramíneas sul rio-grandenses.** Porto Alegre: UFRGS, 2005. 96 p.

BOLING, A.A.; BOUMAN, B.A.M.; TUONG, T.P.; KONBOON, Y.; HARNPICHITVITAYA, D. Yield gap analysis and the effect of nitrogen and water on photoperiod-sensitive Jasmine rice in north-east Thailand. **Wageningen Journal of Life Science**, v.58, p.11-19, 2011. https://doi.org/10.1016/j.njas.2010.05.001

BOUMAN, B. A. M. et al**. ORYZA 2000**: modeling lowland rice. Version 2.12, November, 2001. In: Cereal Knowledge Bank, International Rice Research Institute. 2000. 235p.

BOUMAN, B.A.M.; VAN LAAR, H.H. Description and evaluation of rice growth model ORYZA2000 under nitrogen-limited conditions. **Agricultural Systems**, v.87, p.249-273, 2006. https://doi.org/10.1016/j.agsy.2004.09.011

CASTRO, P. R. C.; FERREIRA, S. O.; YAMADA, T. **Ecofisiologia da produção agrícola. Piracicaba**: Associação Brasileira para Pesquisa da Potassa e do Fosfato, 1987. 249 p.

COMISSÃO DE AGRICULTURA PECUÁRIA E COOPERATIVISMO. **Série Culturas: Arroz. Estado do Rio Grande do Sul - Assembléia Legislativa**. Disponível em: <http://www.al.rs.gov.br/Download/CAPC/serie_culturas_arroz.pdf> Acesso em 14 de Maio de 2014. 1999.

CONAB - Companhia Nacional de Abastecimento. **Séries históricas**. Disponível em: http://www.conab.gov.br/conteudos.php?a=1252&. Acesso em 18 de janeiro de 2016.

CROSBY, A. W. **The Columbian exchange: biological and cultural consequences of 1492** (Vol. 2). Greenwood Publishing Group. 2003.

DENG, N. et al. Closing yield gaps for rice self-sufficiency in China. **Nature communications**. 10. 1-9. 2019. https://doi.org/10.1038/s41467-019-09447-9

ESPE, M.B. et al. Yield gap analysis of US rice production systems shows opportunities for improvement, Field Crops Research, p.1-8, 2016. https://doi.org/10.1016/j.fcr.2016.07.011

EVANS, L.T. Crop Evolution, Adaptation, and Yield. **Cambridge University Press**, Cambridge, UK, 1993.

FAO - Food and Agriculture Organization of the United Nations. **World production**. 2018. Available at http://www.fao.org/economic/est/publications/flooded rice -publications/en/. (accessed 10 Sept. 2018).

HEINEMANN, A.B. et al. Variation and impact of drought-stress patterns across upland rice target population of environments in Brazil. **Journal of Experimental Botany**, v. 11, p. 1-14, 2015. https://doi.org/10.1093/jxb/erv126

IRGA – INSTITUTO RIOGRANDENSE DO ARROZ**. Série Histórica de Produção e Produtividade - RS x BR**. Disponível em: http://www.irga.rs.gov.br/upload/20150720134318producao_rs_e_brasil.pdf. Acesso em 25 jan. 2016.

IRGA – INSTITUTO RIOGRANDENSE DO ARROZ. **Série Histórica de Produção e Produtividade - RS x BR**. Disponível em: http://www.irga.rs.gov.br/upload/20180713143631produtividade_municipios_safra_17_18_final.pdf. Acesso em 25 Set. 2019.

KROPFF, M. J.; VAN LAAR, H. H.; MATTHEWS, R. B. ORYZA1: **an ecophysiological model for irrigated rice production**. In: SARP Research Proceedings. Los Banos, Philippines: International Rice Research Institute - IRRI, 1994. 110 p.

LICKER, R. et al. Mind the gap: how do climate and agricultural management explain the 'yield gap'of croplands around the world? **Global ecology and biogeography**, 19(6), 769-782. 2010. https://doi.org/10.1111/j.1466-8238.2010.00563.x

LOBELL, D.B., Cassman, K.G., and Field, C.B. 2009. Crop yield gaps: their importance, magnitudes, and causes. Annual review of environment and resources, 34, 179-204. https://doi.org/10.1146/annurev.environ.041008.093740

LOBELL, D.B.; CASSMAN, K.G.; FIELD C.B. Crop yield gaps: their importance, magnitudes and causes. **Review of Environment and Resources**, v. 34, p. 179-204, 2009. https://doi.org/10.1146/annurev.environ.041008.093740

LORENÇONI, R.; DOURADO NETO, D.; HEINEMANN, A. B. Calibração e avaliação do modelo ORYZA-APSIM para o arroz de terras altas no Brasil. **Revista Ciência Agronômica** (UFC. Online), v. 41, p. 605-613, 2010. https://doi.org/10.1590/S1806-66902010000400013

LU, B. R. Et al. Preliminary studies on taxonomy and biosystematics of the AA genome Oryza species (Poaceae). **Grasses: systematics and evolution**. p.51-58.2000.

MENEZES, V. G. et al. **Projeto 10** - Estratégias de manejo para aumento da produtividade e da sustentabilidade da lavoura de arroz irrigado do RS: avanços e novos desafios. Instituto Rio Grandense do Arroz (IRGA), Cachoeirinha. 2013. 104p.

RIBAS,G.G. et al. An update of new rice cultivars in the SimulArroz model. **Revista Pesquisa Agropecuaria Brasileira.** V.55. p.1-10. 2020. http://doi.org/10.1590/S1678-3921.pab2020.v55.00865

RIBEIRO, O. A colonização de Angola e o seu fracasso. Lisboa: **Imprensa Nacional–Casa da Moeda.** 1981.

ROSA, H.T. et al. Simulação do crescimento e produtividade de arroz no Rio Grande do Sul pelo modelo SimulArroz. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v.19, p.1159–1165, 2015. https://doi.org/10.1590/1807-1929/agriambi.v19n12p1159-1165

SHIN, D. W. et al. Assessing maize and peanut yield simulations with various seasonal climate data in the Southeastern United States. **Journal of Applied Meteorology and Climatology**, v. 49, p. 592-603, 2010. https://doi.org/10.1175/2009JAMC2293.1

SHIN, D. W. et al. The role of an advanced land model in seasonal dynamical downscaling for crop model application. **Journal of Applied Meteorology and Climatology**, v.45, p.686-701, 2006. https://doi.org/10.1175/JAM2366.1

STRECK, N. A. et al. SimulArroz: um aplicativo para estimar a produtividade de arroz no Rio Grande do Sul. In: CONGRESSO BRASILEIRO DE ARROZ IRRIGADO, 8., 2013, Santa Maria. **Anais**... Santa Maria/RS: SOSBAI, 2013. p.1618‑1627.

USDA – United States Department of Agriculture. Production, **Supply and Distribution** Online. Disponível em http://www.usda.gov/wps/portal/usda/usdahome?navid=DATA_STATISTICS. (accessed 10 Sept. 2019).

VAILLANT, A. Milieu cultural et classification des variétés de riz des Guyanes française et hollandaise. **Journal d'agriculture traditionnelle et de botanique appliquée**, v.28, p.520-529. 1948.

VAN ITTERSUM, M.K. et al. Yield gap analysis with local to global relevance - A review. **Field Crops Research**, v.143, p.4–17, 2013. https://doi.org/10.1016/j.fcr.2012.09.009

VAN ITTERSUM, M.K.; RABBINGE, R. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. **Field Crops Research**, v. 52, p. 197–208, 1997. https://doi.org/10.1016/S0378-4290(97)00037-3

VAN LOON, M. P. et al. Prospect for increasing grain legume crop production in East Africa. **European Journal of Agronomy**, 101, 140-148. 2018. https://doi.org/10.1016/j.eja.2018.09.004.

WALTER, L. C. et al. Adaptação e avaliação do modelo infocrop para simulação do produtividade de grãos da cultura do arroz irrigado. **Engenharia Agrícola**, Jaboticabal, v.32, n.3, 2012. https://doi.org/10.1590/S0100-69162012000300010

WALTER, L. C. et al. Mudanças climáticas e seus efeitos no produtividade de arroz irrigado no Rio Grande do Sul. **Pesquisa Agropecuária Brasileira**, v. 49, p. 915-924, 2014. https://doi.org/10.1590/S0100-204X2014001200001

ZORRILLA, G. et al. **Improving rice production systems in Latin America and the Caribbean**. Centro Internacional de Agricultura Tropical (CIAT). 2012.

APÊNDICE

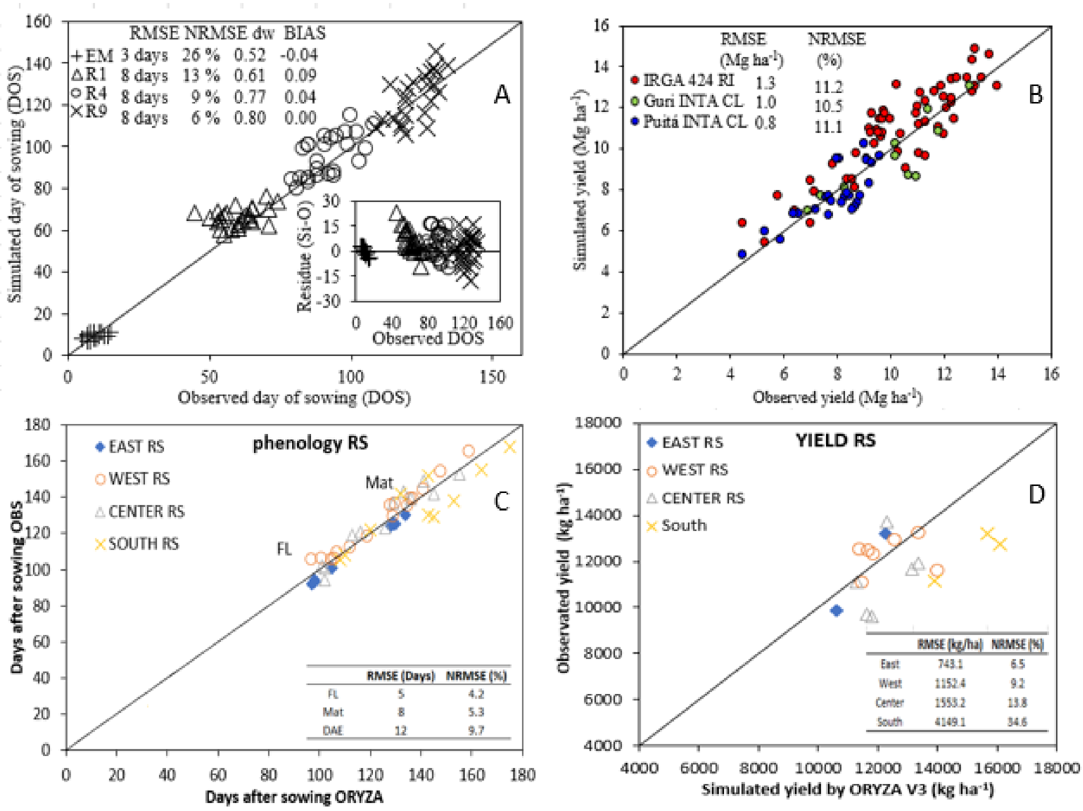

Figura 1. Validação dos modelos SimulArroz (A, B) com as cultivares IRGA 424 RI, Puitá INTA CL, Guri INTA CL, e Oryza v3 (C, D) com a cultivar IRGA 424 RI, para a cultura do arroz irrigado no Rio Grande do Sul.

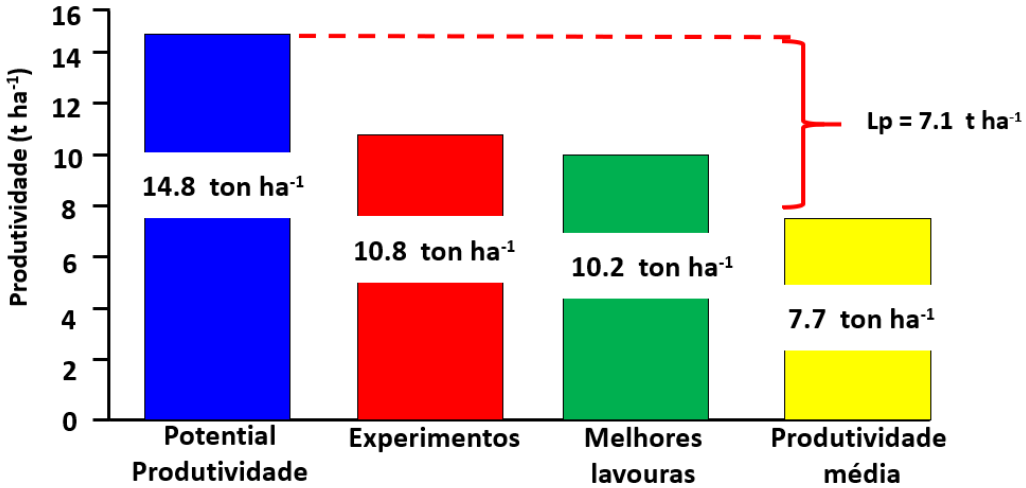

Figura 2. Potenciais de produtividade de grãos estimado pelo modelo oryza (barra em azul), experimentos, melhores lavouras e produtividades médias de grãos. A Lp foi medida entre Pp-Pm.

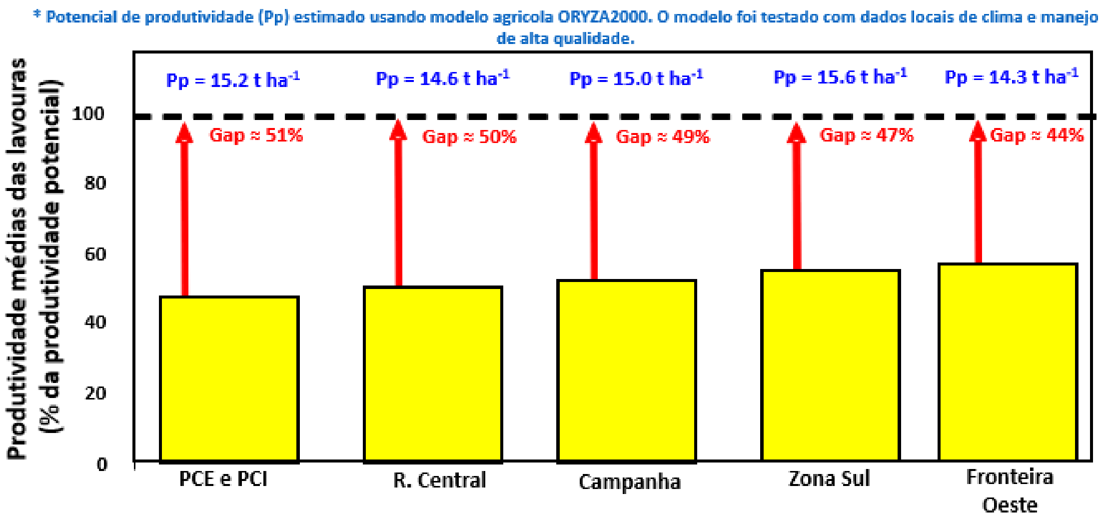

Figura 3. Estimativa dos potenciais de produtividade de grãos e as lacunas de produtividade relativa nas seis regiões do estado. O potencial foi estimado pelo modelo Oryza v3 (média de 10 anos).

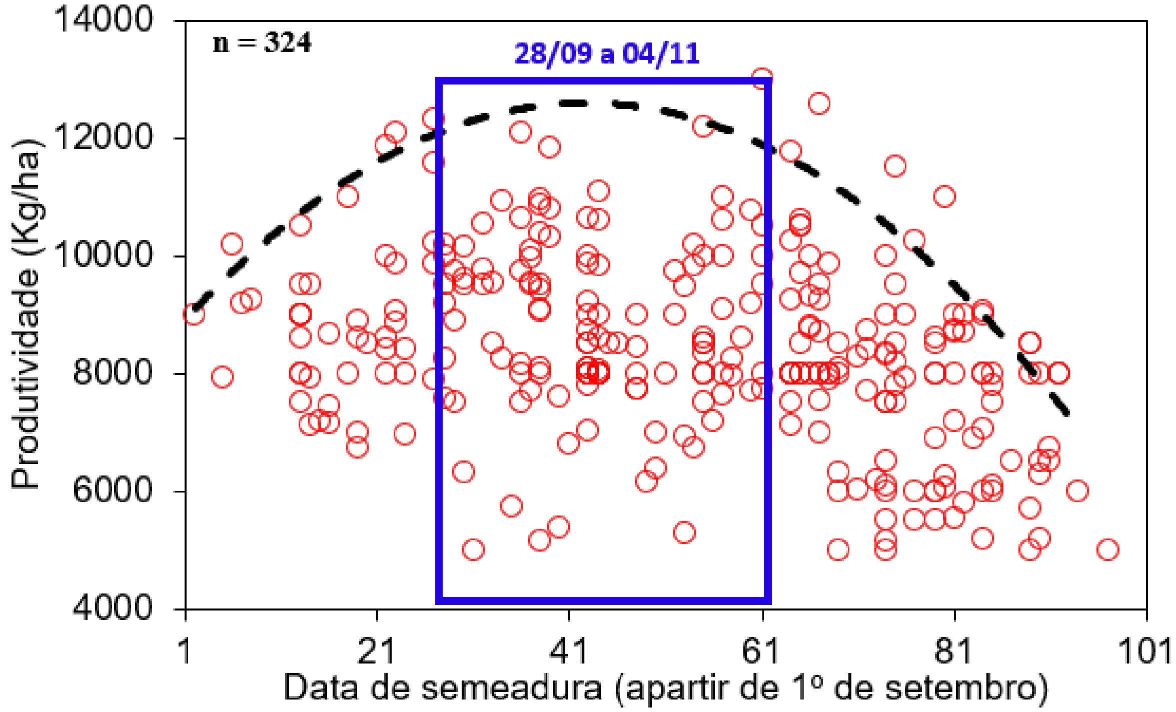

Figura 4. Época de semeadura entre as lavouras de arroz irrigado no Estado do Rio Grande do Sul. Os dados foram coletados nas seis regiões orizícolas pelos extensionistas do IRGA e estudantes de graduação em agronomia da UFSM e UNIPAMPA em 2015 à 2018 em 324 lavouras.

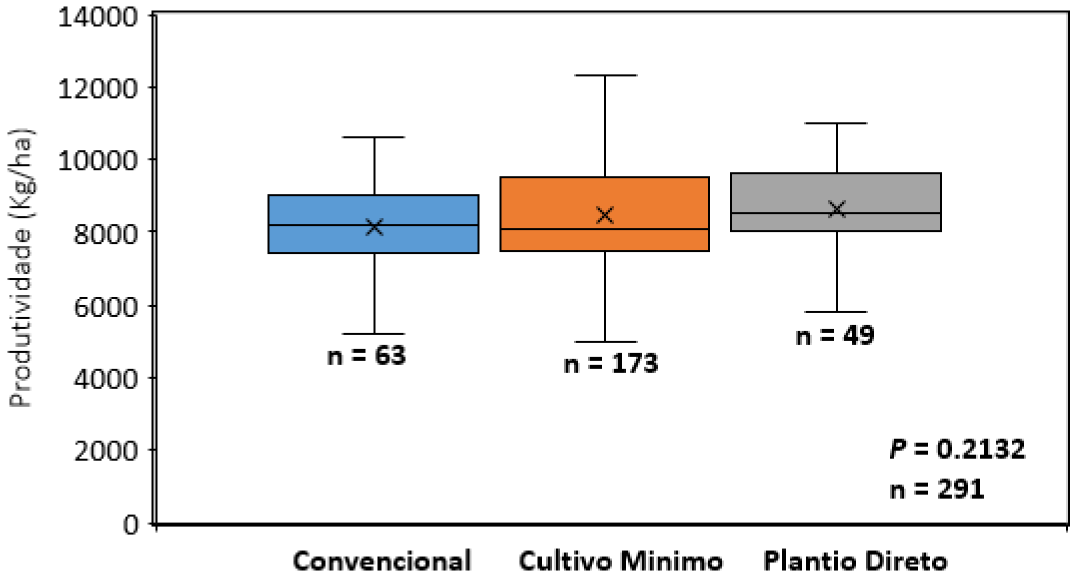

Figura 5. Sistemas de preparo do solo em as lavouras de arroz irrigado no Estado do Rio Grande do Sul. Os dados foram coletados nas seis regiões orizícolas pelos extensionistas do IRGA e estudantes de graduação em agronomia da UFSM e UNIPAMPA em 2015 à 2018 em 324 lavouras.

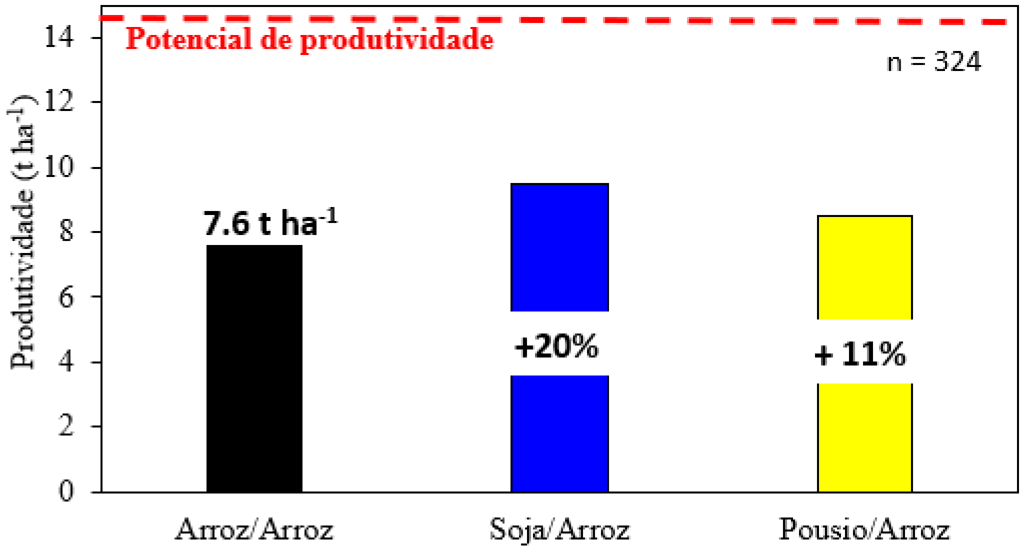

Figura 6. Sistema de produção de verão das lavouras de arroz irrigado no Estado do Rio Grande do Sul. Os dados foram coletados nas seis regiões orizícolas pelos extensionistas do IRGA e estudantes de graduação em agronomia da UFSM e UNIPAMPA em 2015 à 2018 em 324 lavouras.

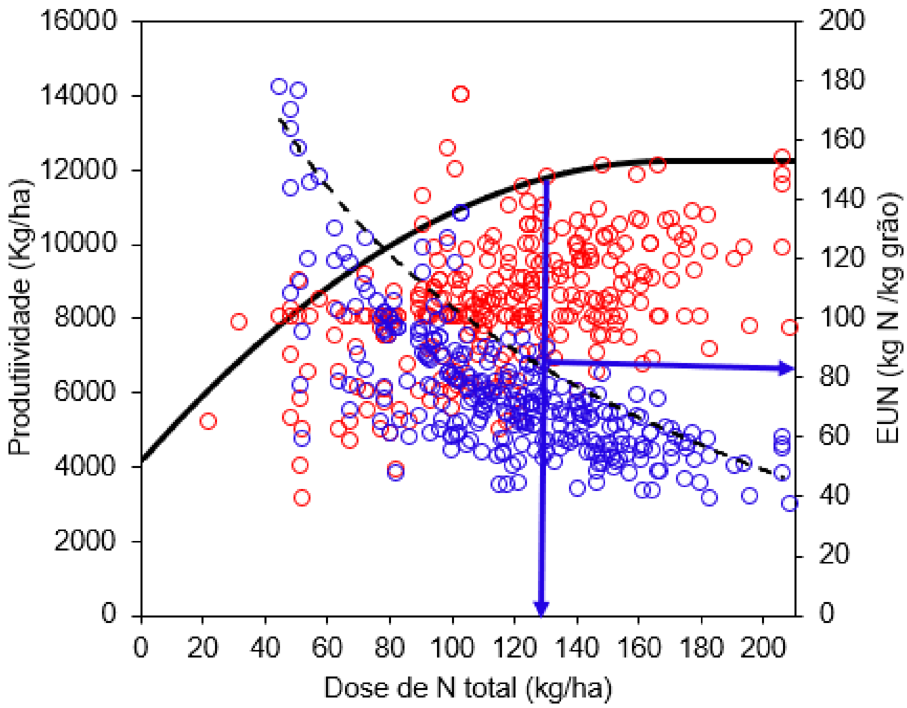

Figura 7. Dose de nitrogênio aplicada em cobertura e eficiência do uso de N das lavouras de arroz irrigado no Estado do Rio Grande do Sul. Os dados foram coletados nas seis regiões orizícolas pelos extensionistas do IRGA e estudantes de graduação em agronomia da UFSM e UNIPAMPA em 2015 à 2018 em 324 lavouras.

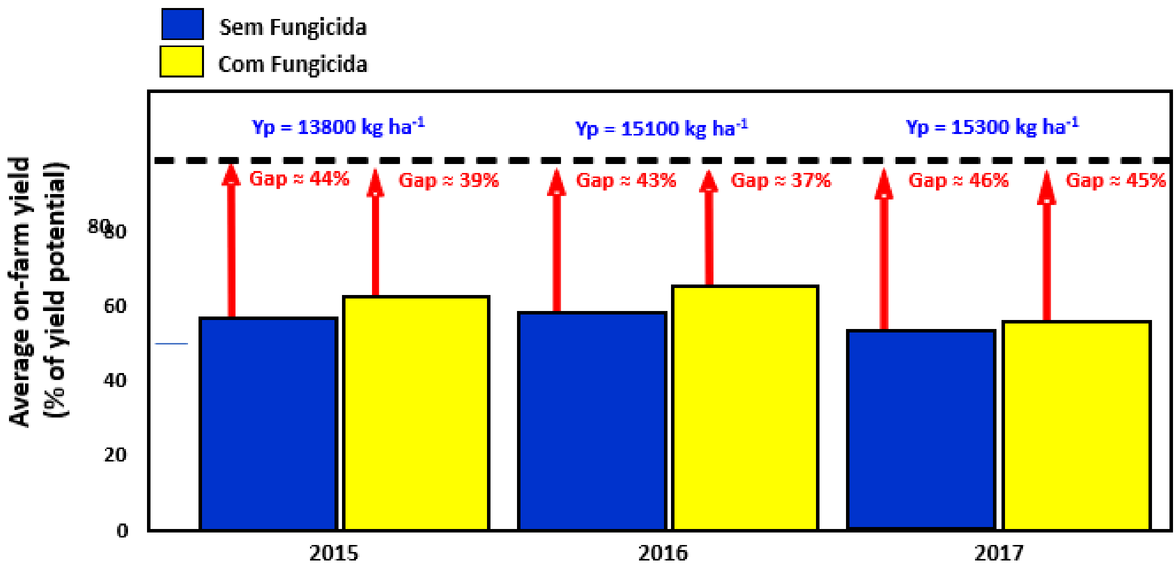

Figura 8. Comparação da produtividade entre as lavouras de arroz irrigado com e sem aplicação de fungicida no Estado do Rio Grande do Sul. Os dados foram coletados nas seis regiões orizícolas pelos extensionistas do IRGA e estudantes de graduação em agronomia da UFSM e UNIPAMPA em 2015 à 2019 em 412 lavouras.