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

Lorenzo Dalcin Meus

POTENCIAL E LACUNA DE PRODUTIVIDADE EM ARROZ IRRIGADO NA ARGENTINA E FATORES DE MANEJO QUE AFETAM A PRODUTIVIDADE

Santa Maria, RS

2021

Lorenzo Dalcin Meus

POTENCIAL E LACUNA DE PRODUTIVIDADE EM ARROZ IRRIGADO NA ARGENTINA E FATORES DE MANEJO QUE AFETAM A PRODUTIVIDADE

Dissertação apresentada ao Curso de Pós-Graduação em Engenharia Agrícola, Área de Concentração em Engenharia de Água e Solo da Universidade Federal de Santa Maria (UFSM, RS), como requisito parcial para obtenção do título de **Mestre em Engenharia Agrícola.**

Orientador: Prof. Dr. Nereu Augusto Streck

Santa Maria, RS

2021

Ficha catalográfica

Meus, Lorenzo Dalcin
POTENCIAL E LACUNA DE PRODUTIVIDADE EM ARROZ IRRIGADO NA ARGENTINA E FATORES DE MANEJO QUE AFETAM A PRODUTIVIDADE / Lorenzo Dalcin Meus.- 2021.
75 p.; 30 cm

Orientador: Nereu Augusto Streck
Coorientador: Cesar Eugenio Quintero
Dissertação (mestrado) - Universidade Federal de Santa Maria, Centro de Ciências Rurais, Programa de Pós Graduação em Engenharia Agrícola, RS, 2021

1. Oryza sativa L. 2. potencial de produção 3. lacuna explorável 4. fatores de manejo 5. crescimento sustentável I. Streck, Nereu Augusto II. Quintero, Cesar Eugenio 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.

Lorenzo Dalcin Meus

POTENCIAL E LACUNA DE PRODUTIVIDADE EM ARROZ IRRIGADO NA ARGENTINA E FATORES DE MANEJO QUE AFETAM A PRODUTIVIDADE

Dissertação apresentada ao Curso de Pós-Graduação em Engenharia Agrícola, Área de Concentração em Engenharia de Água e Solo da Universidade Federal de Santa Maria (UFSM, RS), como requisito parcial para obtenção do título de **Mestre em Engenharia Agrícola.**

Aprovada em 26/08/2021

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

Cesar Eugenio Quintero, Dr. (UNER) – (Videoconferência)

Giovana Ghisleni Ribas, Dr. (GDM Seeds) - (Videoconferência)

Santa Maria, RS
2021

AGRADECIMENTOS

Aos meus pais, Paulo e Edriane, por me proporcionarem a vida, ensinarem valores, proporcionarem experiências, e principalmente, pelo apoio e confiança incondicional, mesmo muitas vezes sem entender claramente os propósitos;

Aos meus avós, por me ensinarem o valor da família, trabalho duro, honestidade, resiliência e bondade;

Ao meu irmão Vinícius, pela compreensão e apoio em todos os momentos que foi necessário;

Aos meus orientadores, Nereu Augusto Streck e Alencar Junior Zanon, pelas oportunidades a mim dadas, persistência, exemplo, confiança e liberdade para com o meu trabalho.

Ao meu amigo e orientador, Cleber Maus Alberto, por me abrir as portas da ciência e filosofia desde 2014, agradeço pelo companheirismo, desafios impostos e oportunidades, que me propiciaram desenvolvimento acadêmico e pessoal, pela amizade que formamos nesse período, e pelo aceite em participar da banca deste trabalho.

Ao Cesar Quintero, por ser a principal pessoa para que esse trabalho fosse concretizado; que ensinou que sonhos e desejos podem ser concretizados com trabalho duro, muito obrigado pela parceria e ensinamentos durante a jornada, serei eternamente grato!

A todos os colegas da Equipe FieldCrops, principalmente os amigos da equipe arroz, Anderson, Ary, Ioran, Giovana, Pablo, Michel e Vladison, obrigado por todos momentos e experiencias compartilhadas!

E a todos amigos e familiares que não pude citar, mas foram essenciais na construção de minha trajetória academia e pessoal. E a todos que de uma forma ou outra foram conselheiros, amigos e apoiadores.

MUITO OBRIGADO!

EPÍGRAFE

“Knowing what you want in life is extremely important,
but knowing exactly what you don't want is liberating.”

RESUMO

POTENCIAL E LACUNA DE PRODUTIVIDADE EM ARROZ IRRIGADO NA ARGENTINA E FATORES DE MANEJO QUE AFETAM A PRODUTIVIDADE

AUTOR: Lorenzo Dalcin Meus
ORIENTADOR: Nereu Augusto Streck

Resumo: Devido à superconcentração da produção de arroz na Ásia, o estudo e compreensão das cadeias produtoras de arroz fora deste continente são fundamentais para garantir a segurança alimentar global. O objetivo deste trabalho foi quantificar o potencial de produtividade (Yp) e a lacuna de produtividade (Yg) de arroz irrigado na Argentina; identificar as principais práticas de manejo que explicam as lacunas; identificar se a atual estagnação nos ganhos de produtividade na Argentina está sendo causado pelo produtores atingirem o teto do Yp ou pode ser revertido com o aumento da produtividade por meio do ajuste em práticas de manejo; e validação dos modelos SimulArroz e ORYZA para a Argentina. O estudo foi feito através da análise de dados de campo de mais de 2.700 lavouras em 10 safras e por estimativas com o modelo de simulação de cultura ORYZA v3 e SimulArroz. O potencial de rendimento médio do arroz irrigado para a Argentina subtropical estimado pelo modelo SimulArroz variou de 3,8 a 15,6 Mg ha^{-1} e de 7,6 a 14,3 Mg ha^{-1} no ORYZA v3. O Yp foi maior no Sul (15,1 Mg ha $^{-1}$) e menor no Norte (13,4 Mg ha $^{-1}$), e os maiores valores de Yp foram encontrados nas datas de semeadura de setembro e outubro. O Yg na Argentina é 53% do Yp, variando de 47 a 56% entre as regiões. Os principais fatores de manejo que afetam a produtividade dos agricultores são a ausência de rotação de culturas, datas de semeadura e irrigação. O aumento da produção de arroz na Argentina se as lavouras atingissem a lacuna explorável seria de 916.091 toneladas de arroz anuais, ou um aumento de 42% na produção de arroz da Argentina sem aumentar a área semeada. A estagnação nos ganhos de produtividade de arroz na Argentina pode ser revertida com a adoção de práticas de manejo que aumentem a produtividade média de grãos. Há espaço para aumentar a produtividade média de arroz na Argentina, diminuindo a lacuna de produtividade.

Palavras-chave: Oryza sativa L.¸ potencial de produção, lacuna explorável, fatores de manejo.

YIELD POTENTIAL AND GAP IN FLOODED RICE IN ARGENTINA AND MANAGEMENT FACTOR AFFECTING GRAIN YIELD

AUTHOR: Lorenzo Dalcin Meus
ADVISOR: Nereu Augusto Streck

Abstract: Due to the over concentration of the rice production in Asia, the study and comprehension of rice producing chains outside this continent are key do guarantee the global food security. The objective of this work was quantify the Yield potential (Yp), and Yield gap (Yg) of irrigated rice in Argentina; identify the main management practices that explain the gaps; identify that current yield plateau in Argentina is being caused by the ceiling of the Yp or it can be reverted by increasing the yield trough adjusting management practices; and validating the SimulArroz and ORYZA models to Argentina. The study was done by analyzing field data from more than 2,700 field across 10 growing seasons, and by estimations with the crop simulation model SimulArroz and ORYZA v3. The average irrigated rice yield potential for subtropical Argentina estimated by the SimulArroz model ranged from 3.8 to 15.6 Mg ha^{-1}, and from 7.6 to 14.3 Mg ha^{-1} in the ORYZA v3. Yp was higher in Southern (15.1 Mg ha^{-1}) and lower in Northern (13.4 Mg ha^{-1}), and the highest values of Yp were found in the sowing dates of September and October. The Yg in Argentina is 53% of the Yp, ranging from 47 to 56% across regions. The main management factors affecting farmers yield is absence of crop rotation, sowing dates and irrigation. The increase in the rice production in Argentina if the fields close the exploitable gap would be 916,091 tons of rice annually, or an increase of 42% in the Argentina rice production without increase the sowed area. The yield plateau in rice production in Argentina can be changed by adopting management practices that increase the average grain yield. There is room to increase the average rice yield in Argentina by closing the yield gap.

Key words: *Oryza sativa L.*¸yield potential, exploitable gap, management factors.

CAPÍTULO 1 - LISTA DE FIGURAS

CAPÍTULO 1 - LISTA DE TABELAS

CAPÍTULO 2 - LISTA DE FIGURAS

CAPÍTULO 2 - LISTA DE TABELAS

SUMÁRIO

1 INTRODUÇÃO

No cenário atual, onde a população mundial deve aumentar em 2 bilhões nos próximos 30 anos, atingindo 9,7 bilhões de pessoas até o ano de 2050, crescem também os desafios socioeconômicos, entre eles, a necessidade de garantir a segurança alimentar (ONU, 2020). Com o elevado crescimento populacional e aumento na demanda por alimentos, a agricultura mundial tem dois principais objetivos no século XXI, aumentar a produção de grãos e a eficiência no uso de recursos, num cenário de diminuição das áreas agricultáveis e mudanças climáticas (Yuan et al., 2021; Cassman & Grassini, 2020; Gaffney et al., 2019). Nesse cenário, a pesquisa por manejos que visem aumentar a eficiência no uso de recursos na produção de arroz (*Oryza sativa* L.), tem papel fundamental na segurança alimentar.

A Argentina tem papel fundamental na produção agrícola mundial, sendo o quinto maior exportador de produtos agrícolas do mundo. A zona de produção de arroz na Argentina concentra-se no Nordeste do país, nas latitudes entre 27 e 34º S, o clima da região é subtropical úmido (Fernandes et al., 2017). Quanto a produção de arroz, a Argentina é a quinta maior produtora de arroz da América, produzindo 1,3 Mt de arroz em cerca de 200 mil hectares por ano (USDA, 2020). Apesar da área relativamente pequena de produção de arroz, a Argentina desempenha um papel importante no mercado de exportação de arroz, sendo o 13º no mundo e o sexto maior exportador fora da Ásia (FAOSTAT, 2021). Além disso, o cultivo de arroz na Argentina costuma ser em grande escala, mecanizado e com pouco subsídio governamental.

O arroz, é o segundo cereal mais produzido no mundo, fundamental para segurança alimentar do planeta, pois é base alimentar para mais de 50% da população mundial (Deng et al., 2019). Atualmente, a área cultivada com arroz no mundo é de 162 milhões de hectares, com uma produção de aproximadamente 755 milhões de toneladas (FAOSTAT, 2021). Essa produção dobrou nos últimos 40 anos, devido a avanços no melhoramento (genético) das plantas e manejo da cultura, mas também devido ao aumento da área plantada.

Apesar do aumento na produtividade média de arroz nos últimos anos, ainda há uma considerável diferença entre as produtividades atingidas em experimentos de estações de pesquisa de arroz (15 Mg ha^{-1}) (INTA, 2020) e produtividade média atual de arroz na Argentina (6,5 Mg ha^{-1}) (Ministerio de Agricultura, Ganaderia y Pesca, 2021). Essa diferença entre a produtividade atingível e a produtividade atual é chamada de lacuna de produtividade, e é um incentivo para continuar com esforços científicos visando minimizá-la.

Estudos sobre lacuna de produtividade vêm aumentando, motivados pela crescente demanda mundial de alimentos e energia para atender ao aumento populacional (Yuan et al., 2021; Cassman & Grassini, 2020). O estudo da lacuna de produtividade permite identificar os principais fatores que limitam o aumento da produtividade das culturas, direcionando linhas de pesquisa, além de aprimorar as atuais práticas de manejo (Xavier et al., 2021; Van Ittersum et al., 2013). Na América do Sul, estudos sobre lacunas de produtividade vem aumentando nos últimos anos, especialmente no Brasil (Junior et al., 2021; Ribas et al., 2021; Pilleco et al., 2020; Monteiro & Sentelhas, 2014) e Uruguai (Tseng et al., 2021; Deambrosi et al., 2015).

O potencial de produtividade, é a produtividade de uma cultivar sem limitações de nutrientes, estresses bióticos e água, ou seja, a taxa de crescimento da planta ou da cultura é determinada pela disponibilidade de radiação solar, temperatura do ar, CO2 atmosférico e genética (Van Ittersum & Rabbinge, 1997; Fischer, 2014). A partir da determinação do potencial de produtividade, a lacuna de produtividade pode ser estimada através da diferença entre a produtividade potencial e a produtividade média dos agricultores (Lobell et al., 2009).

A produtividade média é definida como a produtividade efetivamente alcançada numa determinada região, essa reflete o estado atual de solos e clima, utilização de tecnologia e habilidades médias dos produtores. Para a produtividade média ser representativa de determinado local, o número de anos utilizados para sua estimativa deve compreender variabilidade anuais de produtividade, sendo necessário cerca de 10 anos de dados para culturas irrigadas, como o arroz (Van Ittersum et al., 2013).

É necessário que pesquisadores, extensionistas, consultores e produtores atuem conjuntamente para identificar os fatores chave que conciliem a máxima produtividade com maior lucro e menor impacto ambiental (Cassman et al, 2003; Royal Society of London, 2009). Estudos afirmam que a produtividade que proporciona o maior retorno econômico é a que atinge cerca de 75 a 85% do potencial produtivo da cultura (Grassini, et al., 2015), o que constitui a motivação para este estudo. Além disso, a validação de modelos de crescimento e desenvolvimento de arroz para a Argentina pode direcionar esforços para pesquisa, ensino e extensão sobre o potencial de produtividade da cultura e os principais fatores limitantes da produtividade na Argentina.

Para seguirmos de maneira sustentável e sem causar impacto ambiental, precisamos conhecer o potencial de produtividade dos sistemas de produção, a lacuna e os fatores que estão causando as principais lacunas nas lavouras. Até o momento não existem trabalhos com essa abordagem para a Argentina. Por essa razão, é fundamental para a soberania alimentar global, bem como para a sobrevivência dos produtores de arroz locais, que sejam realizados esforços para aumentar a produção de arroz e reduzir a lacuna de produtividade existente.

O potencial e lacunas de produtividade é um dos temas agronômicos mais estudados atualmente no mundo. Todavia, em países em desenvolvimento, este tema ainda carece de resultados sólidos para muitas culturas, como por exemplo arroz irrigado na Argentina. 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). Assim, em nível internacional, a contribuição científica foi de determinar o potencial, 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 e a lacuna de produtividade de arroz irrigado na Argentina.

1.1.2 Objetivos específicos

1. Validar o modelo SimulArroz 1.1 e Oryza v3 para a simulação de crescimento e desenvolvimento de arroz irrigado na Argentina.
2. Identificar os fatores biofísicos e de manejo que potencialmente explicam a lacuna de produtividade nas lavouras de arroz irrigado na Argentina.
3. Determinar a perda de produtividade por atraso na época de semeadura de arroz irrigado na Argentina com base em dados de lavouras e simulações de modelos agrícolas.

2 REVISÃO BIBLIOGRÁFICA

2.1 A cultura do Arroz

O arroz (*Oryza sativa* L.) é uma monocotiledônea que pertence à família Poaceae e gênero Oryza, o qual possui cerca de 20 espécies conhecidas. A espécie *Oryza sativa* L. é a principal do gênero, a qual pertencem à maioria das cultivares de arroz utilizadas no mundo, sendo seu centro de origem o continente asiático (Oliveira, 2017). O *Oryza sativa* L. é uma planta megatérmica, com adaptação a ambientes alagados, de cultivo anual, porte ereto, com altura variando de 60 a 150 cm, pertencente a subfamília Oryzoideae (Boldrini et al., 2005). É uma cultura agrícola adaptada a latitudes que variam de 50ºN (Checoslováquia) a 35ºS (Uruguai), ao nível do mar, e em elevadas altitudes (2000 m de altitude no Nepal) (Castro et al., 1987).

A cultura desempenha uma importante função socioeconômica, visto que é um dos alimentos mais importantes para a nutrição humana, compondo a base alimentar de mais de 3 bilhões de pessoas no mundo. Atualmente é o segundo cereal mais cultivado no mundo, em uma área de 168 milhões de hectares (FAO, 2021).

2.1 Potencial e lacunas de produtividade do arroz

O potencial de produtividade (PP) é a produtividade máxima atingível pela cultura em condições ideais, sendo determinada pela radiação solar interceptada pelo dossel vegetal, temperatura do ar, CO2 atmosférico e características genéticas, sem a influência de limitações por nutrientes, água e outros estresses de ordem biótica e abiótica (Evans, 1993). A determinação do potencial de produtividade pode ocorrer através de métodos diretos, que envolvem a condução de experimentos de campo em condição potencial, ou por meio de métodos indiretos, que utilizam modelos de simulação de culturas agrícolas (Van Ittersum et al., 2013). Esses modelos de simulação devem funcionar no passo de tempo de um dia, levar em consideração os processos de crescimento e desenvolvimento fundamentais das culturas, forçados por variáveis meteorológicas diárias, condições de solo e atributos ecofisiológicos, terem flexibilidade para simular práticas de manejo e um número mínimo de coeficientes genéticos (Li et al., 2017; Ribas et al., 2019).

A produtividade média (PM) é a produtividade alcançada nas lavouras comerciais de uma determinada região, refletindo, assim, os solos, o clima, a utilização de tecnologia e a habilidades médias dos produtores. Para a produtividade média ser representativa de determinado local, o número de anos utilizados para sua estimativa deve compreender a variabilidade anual da produtividade (Fischer et al., 2014). Para estimar a PM, o ideal é que sejam coletados dados em lavouras, através da aplicação de questionários, com o objetivo de obter informações técnicas e de manejo utilizadas em cada lavoura, uma vez que, dados de órgãos governamentais muitas vezes não abrangem as particularidades das lavouras dos municípios (Grassini et al., 2014). A lacuna de produtividade (LP) é a diferença entre potencial de produtividade e a produtividade média obtida por produtores de uma região (LOBELL et al., 2009).

Estudos do potencial e das lacunas de produtividade auxiliam na identificação dos fatores biofísicos e de manejo capazes de reduzir as produtividades de lavouras. Depois de identificar esses fatores, é possível direcionar pesquisas a fim de melhorar as práticas de manejo e reduzir a lacuna de produtividade existente (Djik et al., 2017). Assim, conhecer o potencial e as lacunas de produtividade de uma região possibilita um planejamento eficiente do investimento de recursos em cada lavoura, maximizando a eficiência do uso de recursos, garantindo a lucratividade e a sustentabilidade da atividade agrícola (Gaffney et al., 2017).

2.2 Estimativa do potencial de produtividade a partir de modelos agrícolas

Estudos sobre lacuna de produtividade vêm aumentando nos últimos anos, motivados pela crescente demanda mundial por alimentos e energia (Cafaro et al., 2019). Essa pressão por aumento na produção de alimentos e de energia está levando a repensar a agricultura para um novo patamar, o da “intensificação sustentável” (Mueller et al., 2012).

Os estudos de lacunas de produtividade permitem identificar os principais fatores biofísicos e de manejo que limitam o aumento da produtividade dos agricultores e direcionar novas linhas de pesquisa, além de aprimorar as atuais práticas de manejo (Van Ittersum et al., 2013). Essa nova abordagem motivou a criação do projeto Global Yield Gap Atlas - GYGA (www.yieldgap.org), um esforço mundial para reduzir a lacuna de produtividade de várias culturas ao redor do planeta, uma das bases do projeto é o uso de modelos matemáticos como ferramentas para determinação do potencial de produtividade.

Modelos matemáticos estão sendo cada vez mais utilizados na agricultura, sendo integrados ao conceito de agricultura 4.0, onde softwares serão parte ativa e farão parte dessa “nova agricultura”, pois são ferramentas de baixo custo operacional, que auxiliam na tomada de decisão e manejo de agroecossistemas (Rosa et al., 2015).

Na modelagem agrícola, para ser representativo e confiável, cada modelo matemático precisa ser calibrado e validado em diferentes ambientes. Após a validação, os modelos agrícolas podem ser utilizados para simular o crescimento, desenvolvimento e produtividade da cultura em função das condições meteorológicas que ocorrem durante a estação de crescimento (Li et al., 2017; Shin et al., 2010).

Os modelos agrícolas podem ser divididos em dois grupos: modelos empíricos/estatísticos e modelos dinâmicos mecanísticos. Os modelos agrícolas empíricos/estatísticos geralmente são obtidos através de técnicas de regressão linear ou múltipla e estabelecem uma relação entre o rendimento da cultura e os fatores que o afetam (clima, pragas), incluindo análise de probabilidades (Silva, 2001).

Para a cultura do arroz existem modelos dinâmicos de simulação da produtividade de grãos mais complexos, como o CERES-rice (Singh et al., 1993) e o ORYZA (Kropff et al., 1994; Bouman et al., 2001; Li et al., 2017), e outros mais simplificados, como o InfoCrop (Aggarwal et al., 2006) e o SimulArroz (Rosa et al., 2015). Os modelos ORYZA e SimulArroz são modelos ecofisiológicos dinâmicos baseados em processos. Estes modelos utilizam a radiação solar como principal forçante ambiental para o cálculo diário do acúmulo de matéria seca, e a temperatura do ar mínima e máxima como base do cálculo da taxa de desenvolvimento da fenologia (Bouman et al., 2001; 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 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), e atualmente está sendo calibrado para utilização no Rio Grande do Sul.

O SimulArroz (www.ufsm.br/simularroz), foi desenvolvido pelo Grupo de Agrometeorologia 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). O SimulArroz é um modelo mais simples que o ORYZA, mas ajustado para o cultivo de arroz no RS e de fácil uso, podendo ser utilizado para projeções de produtividade, simulação de cenários de mudanças climáticas, bem como determinação do potencial produtivo (Ribas et al., 2017; Ribas et al., 2020). A atual versão do SimulArroz (versão 1.1) tem uma lista de onze cultivares de arroz que podem ser selecionadas pelo usuário. Em 2016 foi lançada uma nova versão do SimulArroz (versão 1.1) que contempla a opção de três cultivares híbridas de arroz irrigado.

3 RESULTADOS E DISCUSSÕES

3.1 CAPÍTULO 1 – Assessing factors related of yield plateau in flooded rice in Argentina

(Artigo será submetido para a revista Field Crops Research)

Assessing factors related of yield plateau in flooded rice in Argentina

Highlights

- Rice yield potential and gap in Argentina was assessed by process-based crop models and field analysis. The yield potential is 14.1 Mg ha^{-1} and the yield gap is 7.4 Mg ha^{-1} (53% of the yield potential).
- There is a loss of 100 kg ha^{-1} per day with the delay of the sowing date of irrigated rice after October 15^{th} in Argentina.
- There is room to increase the average rice yield in Argentina by closing the yield gap with better management practices, such as enhancing weed control and anticipating the sowing window.

Abstract: Rice grain yield per area in Argentina has not been growing for 15 years. The objective of this work was quantify the Yield potential (Yp), and Yield gap (Yg) of irrigated rice in Argentina; identify the main management practices that explain the gaps; and identify that current yield plateau in Argentina is being caused by the ceiling of the Yp or it can be reverted by increasing the yield trough adjusting management practices. The study was done by analyzing field data from more than 2,600 field across 10 growing seasons, and by estimations with the crop simulation model ORYZA v3. The estimated Yp for flooded rice in Argentina is 14.1 Mg ha-1, ranging from 13.4 to 15.1 Mg ha−1 according to buffer zones, year, and regions. Yp was higher in Southern (15.1 Mg ha^{-1}) and lower in Northern (13.4 Mg ha^{-1}). The Yg in Argentina is 53% of the Yp, ranging from 47 to 56% across regions. The main management factors affecting farmers yield is absence of crop rotation, sowing dates and irrigation. The yield plateau in rice production in Argentina can be changed by adopting management practices that increase the average grain yield. There is room to increase the average rice yield in Argentina by closing the yield gap.

Key words: *Oryza sativa L.*¸yield potential, exploitable gap, management factors.

Introduction

Yield plateaus has been reported for different crops worldwide (Brisson et al., 2010; Cassman & Grassini, 2020; Peng et al., 2020). This trend of yield plateaus are specially alarming in regions that have potential to become future world breadbaskets, like Argentina, due to the large amount of land and water to expand agriculture area and to the abundant solar radiation availability (Bourne, 2014; Cassman, 1999). The question behind this yield plateau is, whether farmers have reached 75 to 85% of the yield potential (Xavier et al., 2021) or whether there are lacks in the crop management practices that are preventing the productivity increase.

While the rice yield per area is stagnated in the last 15 years (Figure 1), in this same period the rice grain yield in South America increased 1.5 Mg ha^{-1} (FAOSTAT, 2021). Argentina is the fifth largest rice producer in America, producing 1.3 Mt of rice in around 200 thousand hectares per year (USDA, 2020). Despite the relatively small area of rice production, Argentina plays an important role in the rice export market, being the 13th on world and the sixth larger exporter outside Asia (FAOSTAT, 2021). In addition, rice cultivation in Argentina are often large scale, mechanized and with little governmental subsidy. The rice production zone in Argentina is concentrated in the Northeast, in latitudes between 27 and 34º S, the climate of the region is subtropical humid (Fernandes et al., 2017).

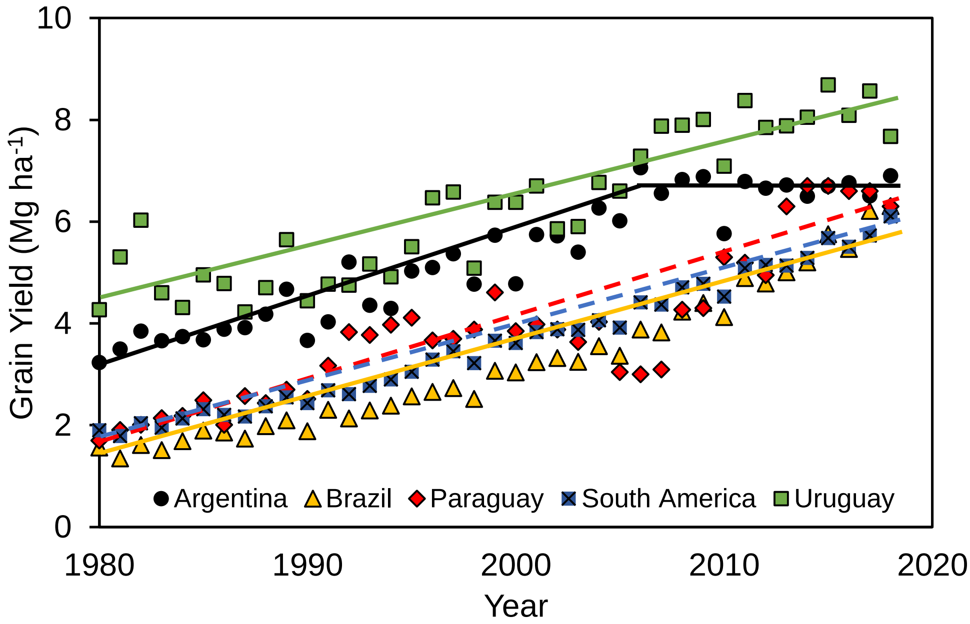

Figure 1 – Trends of subtropical rice grain yield among South America producer countries. Source: Faostat, 2021.

The yield gap (Yg) is the difference between Yp and yield actual or average farmers yield (Ya) (Lobell et al., 2009). Yield potential (Yp) is determined by solar radiation, temperature, water supply, cultivar traits influencing length of the crop cycle and capture and conversion of solar radiation into grain. In case of water-limited crops, the yield is also determined by precipitation and soil properties and landscape characteristics influencing the water balance, in this case the water limited yield potential (Yw) will be the maximum attainable yield (FAO & DWFI, 2015; Van Ittersum et al., 2013). In irrigated systems, like flooded rice in Argentina, yield potential is driven mainly by solar radiation and thermal time during crop growth. With the estimate of Yp and Yg it is possible to identify how much the productivity can be increased and, based on that, to estimate the capacity to increase production in the current agricultural area of a region, aiming to meet the future demand for food with minimum environment impact and maximum profit for farmers (Grassini et al., 2011a; Heilmayr et al., 2020).

Determining the magnitude of the Yg provides us an estimate of how much the production can increase in the current crop area, by improving management practices that can reduce the impact of yield limiting factors (Grassini et al., 2015). This is crucial information for countries such as Argentina, which are facing a yield plateau at about 6.5 Mg ha^{-1} since 2005 while neighboring countries had increased their productivity in recent years (Figure 1). Rice yield potential and gaps have been widely studied recently (Stuart et al., 2016; Espe et al., 2016; Tseng et al., 2021; Ribas et al., 2021). However, bottom-up approaches which integrates Yp estimated by crop model simulations with information collected in farmers' fields, across a large number of farms and years, integrating public research and extension and farmers are still rare (Yuan et al., 2021).

The hypothesis is that still are room to increase the rice grain yield in Argentina, and the stagnation in the actual yield achieved by farmers is caused by management practices that are limiting the yield. To test it, we use field data from farmers, covering more than 200,000 hectares during 10 growing seasons (2009 to 2019). We also tested and validate a rice simulation model with experiments conducted under potential conditions, to robustly quantify the rice

Yp Argentina. The objective was to (a) quantify the Yp, and Yg of irrigated rice in Argentina, (b) to identify the main management practices that explain the yield gaps, and (c) to identify that current yield plateau in Argentina is being caused by the ceiling of the Yp or it can be reverted by increasing the yield trough adjusting management practices.

Material and methods

Characterization of production systems based on homogeneous climatic zones

Northeastern Argentina, the main region producing rice in Argentina, was divided into homogeneous climatic zones (CZs) using the framework developed by the Global Yield Gap Atlas (http://www.yieldgap.org/) (Wart et al., 2013). According to this approach, it is possible to characterize the study region considering three biophysical attributes that drive crop productivity and its inter-annual variability: (i) degree-days of total annual growth (AGDD, base temperature 0 ° C), (ii) annual seasonality of temperature (standard deviation of monthly average temperatures) and (iii) aridity index (AI, values increase in more humid regions and decrease in more arid regions). Due to the fact that rice is irrigated in Argentina, the aridity index were excluded for this analysis.

Of the 23 original agro-climatic zones in the area, only three remained after excluding the aridity index, and of these three, only two climate zones were selected according to the biophysical criteria defined by the framework of the Global Yield Gap Atlas (GYGA, 2020; Van Wart et al., 2013) for having a rice harvest area greater than 5% of the country's total area (Figure 2A - ZCs 602 and 702) per MapSPAM raster layer (You et al., 2009).

For each climatic zone, reference weather stations (RWS) were selected in representative areas according to the harvest area map (Figure 2B). Details on the RWS are in the Supplementary Table S1. In total, seven stations were selected and around each one an area of 100 km was delimited, which was cut whenever there was overlap of other RWS or by the limits of the ZCs (Figure 2A). The climatology (mean) of minimum temperature (Tmin), maximum temperature (Tmax) and solar radiation (Rad) of CZs 602 and 702 are shown in Figure 3.

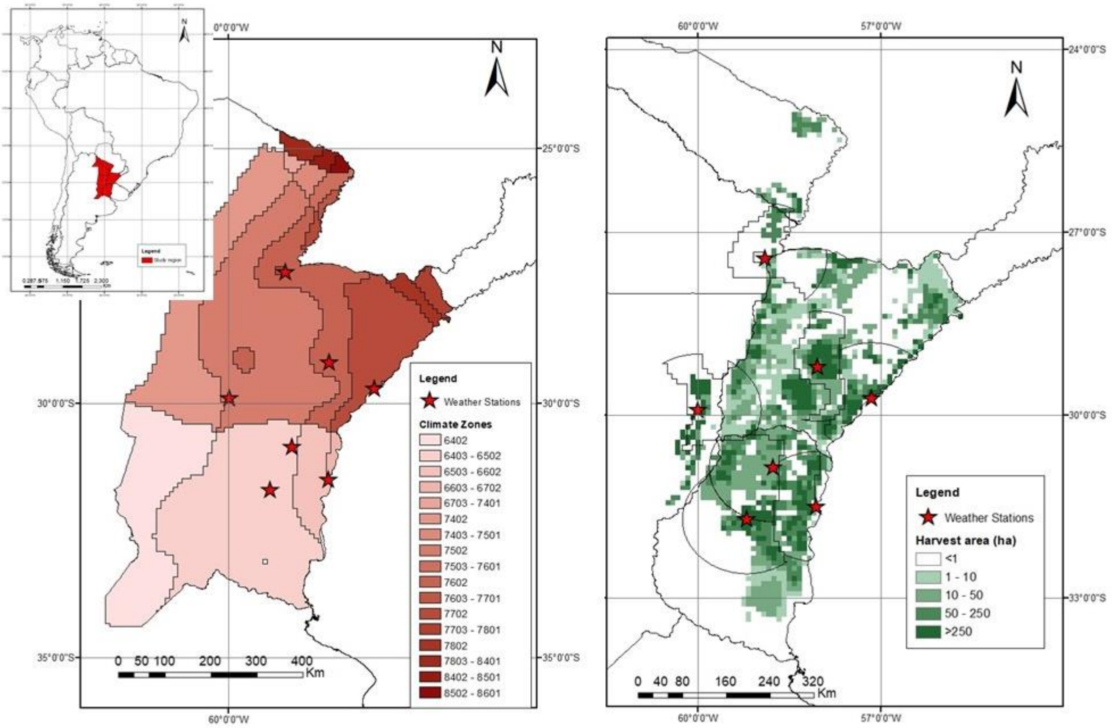

Figure 2 – Map of Argentina and the selected Climatic Zones (according to original GYGA coding (Van Wart et al. 2013b). Stars indicate the location of the reference weather station used to create a 100km radius buffer zone. Letters inside the blue circle represent the buffer zone identification. (B) Harvest area of irrigated rice in Argentina.

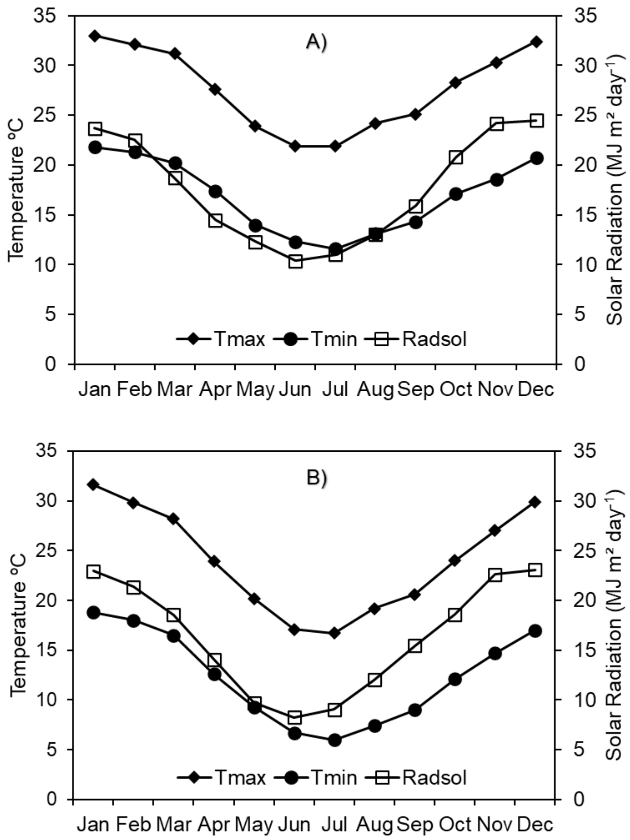

Figure 3 - Monthly average incident solar radiation (Radsol) and maximum (Tmax) and minimum temperature (Tmin) for two locations representative of the A) Climate Zone 6602 and B) Climate Zone 7602, of the flooded rice producing area in Argentina. Each datapoint represent means of meteorological variables calculated based on five years (Radsol) or 30 years (Tmax and Tmin) of measured weather data.

Estimating yield gap and yield potential for flooded rice

Firstly, the ORYZA v3 model was validated to assess its ability to reproduce the main interactions between cultivar, environment and management in rice fields in Argentina. The calibration of the ORYZA v3 model used was performed by Ribas, 2020, and the model validation was performed using independent data from Argentina field experiments and varieties trials (2011-2019) (Supplementary Material F1). The model was evaluated by comparing simulated data with data observed in well-managed field experiments with the most sowed cultivar in Argentina (IRGA 424 RI) in different locations and growing seasons. The root mean square error (RMSE) for grain yield validation was 0.52 Mg ha^{-1} and the normalize root mean square error (RMSEn) was 4% (Supplementary Material F1).

Yield Potential (Yp) was simulated with ORYZA model in order to portray the recommended management practices for high-yield fields. The sowing window ranged from late September to early November, the cultivar used was IRGA 424 RI (intermediate maturity group – 135 days) and the plant population density was 200 pls m^{-2} (Supplementary Table S1). Daily weather data, including solar radiation, minimum and maximum temperature to run ORYZA were retrieved from the RWS in buffer zone for a period of 10 years (Figure 1). 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 small variation in simulated yield (Yp) among years in a weather station (coefficient of variation = 9%). Yp was then used for calculating Yg for flooded rice. The Yg was calculated as the difference between Yp and Ya, and expressed as percentage of Yp. The Ya data source per province was provided by Argentina's Ministerium of Agriculture, Livestock and Fish – MAGYP (http://datosestimaciones.magyp.gob.ar/), in the period from 2010 to 2019.

Identification of causes for yield gaps

The farmers management data was collected during 10 growing seasons (2009-2018) totalizing around 2,700 fields evaluated. The survey included major management practices such as sowing date, plant density, fertilization, irrigation, pesticides application etc.

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 (Grassini et al., 2015b). 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. Association between field classes and management variables (e.g., fertilizer, seed density, fungicide application) was evaluated using the Chi-square ($\chi 2$) test at 0.05%, 0.01% and 0.1% probability using the software Sigmaplot 12.

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.

The data matrix was submitted to assumptions, where multicollinearity (Inflation of variances, number of conditions of the matrix and determinant of the matrix) was tested among the independent variables linked to the statistical model (“metan” packagen). Subsequently, machine learning supervised by the Random Forest algorithm was used to define which independent variables were informative (package “random Forest”). With the reconstruction of the informational data matrix, a regression tree model was applied, using grain yield as a dependent variable and the other variables as informational, the significance and probabilities were based on the non-parametric test x^2 concomitantly, crossvalidations were performed to define the degree of information of the regression tree (“rpart”, “party”, “rpart.plot” packages).

Results and Discussion

Flooded rice yield potential and yield gap in Argentina

The estimated Yp for flooded rice in Argentina is 14.1 Mg ha^{-1}, ranging from 13.4 to 15.1 Mg ha$^{−1}$ according to buffer zones, year, and regions. Yp was higher in Southern (15.1 Mg ha$^{−1}$) and lower in Northern (13.4 Mg ha$^{−1}$) (Figure 3). In Argentina, Yp is similar to the Yp reported in Uruguay (14 Mg ha^{-1}), lower than the reported in Brazil (14.8 Mg ha^{-1}) (Ribas et al., 2021), and greater than the reported in the United States (9,4 Mg ha^{-1}), China (12.4 Mg ha^{-1}), Africa (9 Mg ha^{-1}) and Indonesia (9.1 t ha$^{−1}$) (Espe et al., 2016; Van Ittersum et al.,2016; Deng et al., 2019; Agustiani et al., 2018). The Yp difference across Argentina can be explained by a greater availability of solar radiation and larger longer photoperiod during flowering and grain filling phases, provided by in the Argentinean subtropical and temperate climate conditions in comparison to the tropical climate of South and Southeast Asia. The area covered by the buffer zones corresponds to 58% of the national harvest area. According to van wart et al. (2013), a coverage of 50% of the production area is enough to obtain a robust estimate of the yield potential on a national scale.

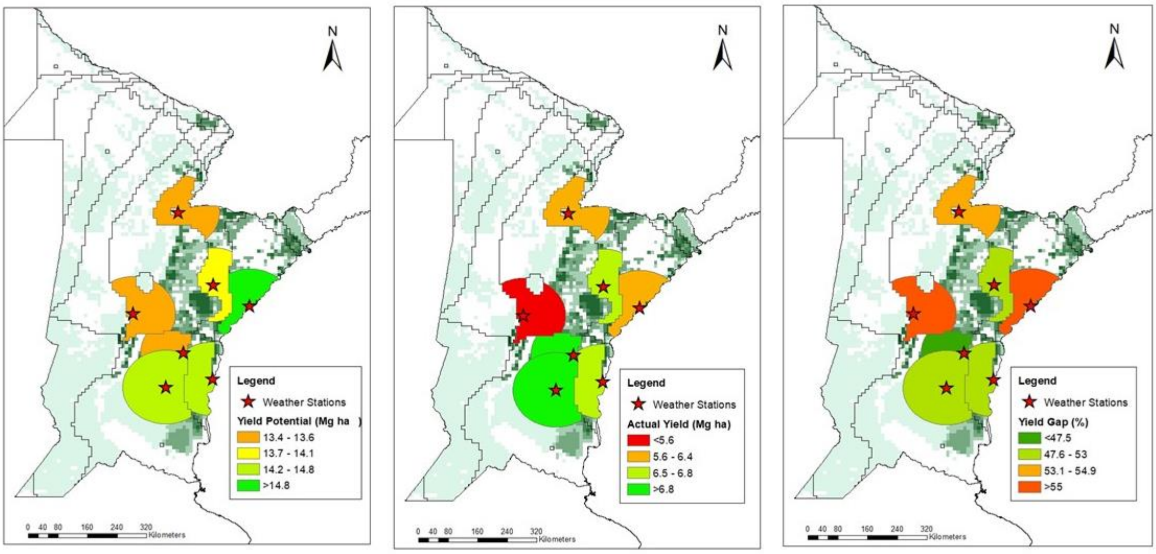

Figure 4. (A) Yield potential – Yp, (B) Actual yield (Ay) and (C) Yield Gap (Yg) of irrigated rice in Argentina estimated by the ORYZA v3 model during ten growing season (2009-2019).

The Yg in Argentina is 53% of the Yp, ranging from 47 to 56% across buffer zones. These Yg in Argentina are larger than in USA (27%Yp), China (33%Yp) and Uruguay (43%Yp), as reported by Espe et al. (2016), Van Ittersum et al. (2016), Carracelas et al. (2019), and lower than Africa (60%Yp) as reported by Deng et al. (2019). The Yg in Argentina tended to be larger in Western, and smaller in Center and Southern. The large Yg in Argentina suggests that the yield plateau observed since 2005 (Figure 1) is not linked to the ceiling of the yield gap. Instead, it indicates that Ar gentina still has a large potential to increase rice production in the existing cultivated area. Hence, management practices need to be improved aiming to close the Yg in Argentina.

Understanding the factors affecting the yield gap in Argentina.

Analysis of management practices from 2,784 fields surveyed during ten growing seasons allowed identification of candidate factors explaining Yg (Table 1). The average grain yield in the surveyed fields was 7,89 Mg ha^{-1} and showed the same yield plateau during the surveyed period (Supplementary Figure 1). Differences in sowing date, soil tillage system and crop development cycle duration between HY and LY fields were statistically significant ($p < 0.001$) and seem to be the major drivers to differentiate the HY and LY fields (Table 1; Figure 5), where LY are sowed five days earlier and have a crop development cycle 11 days larger. This difference may be caused by factors such as the use of longer-cycle cultivars that have more time to accumulate photoassimilates, or due to early sowing, where most of the development cycle occurs in mild temperatures, compared to fields sown at the end of the sowing window, enhancing the photothermal quotient (Jing et al., 2010). Studying rice in Brazil and Uruguay, Duarte Junior et al. (2021) and Roel et al. (2007) also found that sowing date and crop development cycle duration was one of most important management practices to achieve high yields in subtropical South America.

Fertilization is also a key factor between HY and LY. N indigenous in soil, Potassium (K), Phosphorus (P) and Sulfur (S) fertilization statistically differed between the most and less productive fields. However, increasing only Nitrogen fertilization does not increase grain yield in the analyzed data. These results suggest that should be occurring an over fertilization with Nitrogen in LY fields, reducing both grain yield and farmers profitability, and may be causing environmental damage. Regarding to phytosanitary management, the use of seed treatment with fungicides, insecticides and micronutrients are also higher in HY (Table 1).

Table 1 - Comparison of rice grain yield, management practices and applied inputs between the highest terciles of field yields (HY) and lowest terciles (LY) of irrigated rice fields in Argentina. Values indicate the mean differences (HY – LY) between the upper and lower yield terciles (p<0.01***, p<0.05**, p<0.1*). DAE – Days after crop emergence.

Variables	Units	**Low yield Fields (LY)**	**High yield Fields (HY)**	HY-LY	p Value
Grain yield	kg ha^{-1}	**6465**	**9712**	3247	<0.001
Crop development cycle	days	**132**	**143**	11	<0.001
Irrigation onset	DAE	**23**	**22**	-1	0.011
Days to complete the field inundation	days	**5**	**5**	0	Ns
Sowing date	DOY	**272**	**267**	-5	<0.001
Emergency date	DOY	**292**	**287**	-5	<0.001
Emerged plants	pl m^{-2}	**206.5**	**197.5**	-9	Ns
Sowing density	kg ha^{-1}	**100**	**94**	-6	<0.001
Continuous rice	%	**64.8**	**35.3**	29.5	<0.001
Fields with crop rotation	%	**41.6**	**58.4**	-16.8	<0.001
Conventional soil tillage	%	**20.7**	**79.3**	58.6	<0.001
Minimum soil tillage	%	**80.5**	**19.5**	-61	<0.002
Perform seed treatment	%	**40.1**	**59.9**	19.8	0.003
Seed treatment with safener	%	**13.8**	**86.2**	72.4	<0.001
Seed treatment with Micronutrient	%	**47.3**	**52.6**	5.3	<0.001
Herbicide spray pre sowing	%	**40.7**	**59.3**	18.6	<0.001
Herbicide spray at VE	%	**49.5**	**50.5**	1	Ns
Pre-emergent herbicide spray	%	**42.6**	**57.4**	14.8	0.014
Foliar fungicide	%	**17.8**	**82.2**	64.4	<0.001
Foliar insecticide	%	**15.4**	**84.6**	69.2	<0.001
N on soil analysis		**42.50**	**68.20**	25.7	<0.001
P on soil analysis		**5.50**	**5.20**	-0.3	Ns
K on soil analysis		**140.00**	**79.00**	-61	Ns
K_2O fertilizer amount	kg ha^{-1}	**69**	**108**	39	<0.001
P_2O_5 fertilizer amount	kg ha^{-1}	**42**	**55**	13	<0.001
S fertilizer amount	kg ha^{-1}	**4**	**21**	17	NS
N fertilizer amount Applied on sowing	kg ha^{-1}	**12.00**	**13.00**	1	NS
N fertilizer amount	kg ha^{-1}	**88**	**74**	-14	<0.001
N at Panicle Differentiation	**kg ha^{-1}**	**32**	**28**	**-4**	**<0.001**
N at pre irrigation	kg ha^{-1}	**46**	**46**	0	<0.001

K split fertilization	kg ha^{-1}	**60**	**66**	6	NS

Herbicide spraying before sowing and the use safeners in the seed treatment were 18,6% and 72,4% higher in HY fields. The use of herbicide safeners allows the farmers to increase the doses of pre-emergent herbicides, increasing the weed control during early development cycle until the irrigation onset and formation of the water table. In systems where rice is drill (direct) seeded, there is a concurrency between the emergence of rice and weed seedlings afforded by aerobic conditions due the absence of puddling and water table (Rao et al., 2007). In this case, effective weed control is crucial to minimize weed competition that can reduce the yield (Baghel et al., 2020).

The crop rotation is the major management practice affecting grain yield in the Argentinean fields, where, on average the cultivation of continuous rice can decreases the yield by 16,4% (Figure 5). The same tendency was observed in Brazil, where crop rotation with soybean enhanced the rice grain yield by 18% (Ribas et al., 2021). Soil fallow period during summer also was significant, increasing the yield as the fallow years increase. The role of fallow among production systems is still debated (Chen et al., 2018). But there are strong evidences that fallow enhance the crop yield providing support for crop production by suppressing weeds, regenerating soil fertility, controlling erosion, and sequestering carbon (Liu et al., 2016; Huang et al., 2013).

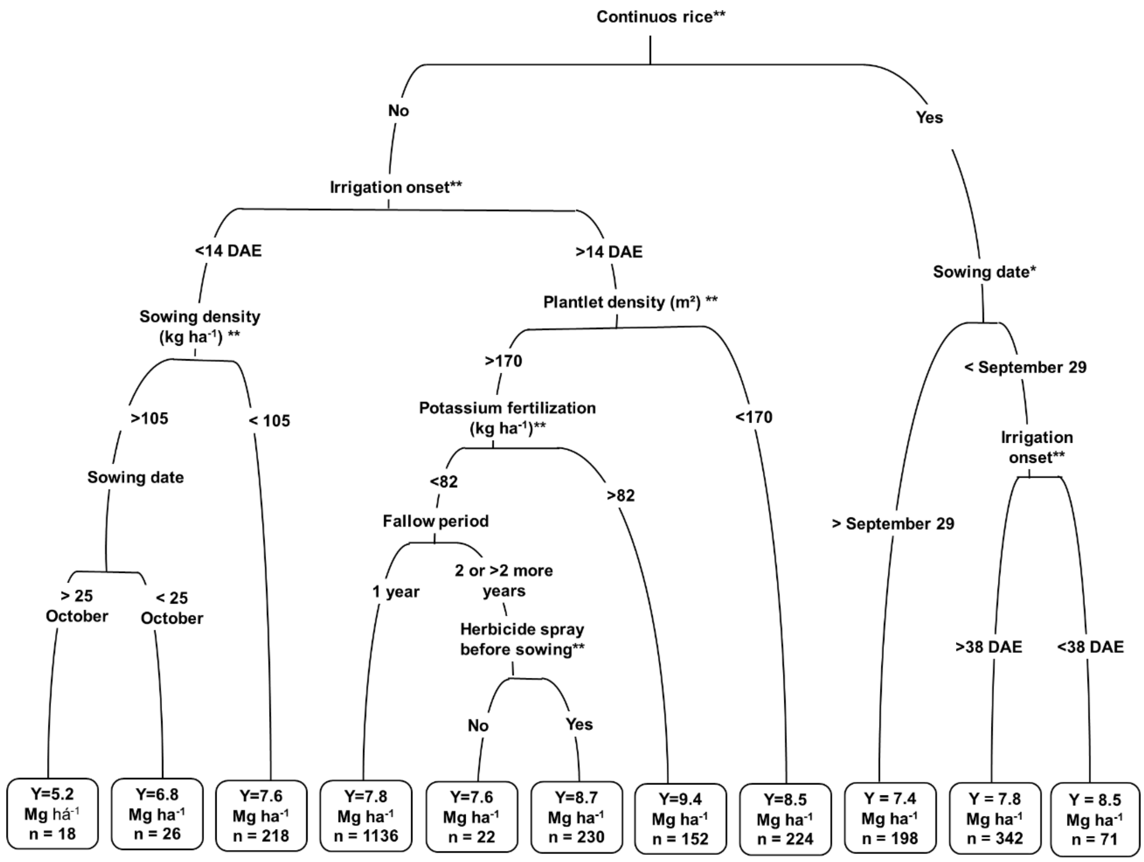

Figure 5. Regression tree model showing sources of variation in grain yield due to management practices. Boxes are splitting nodes, with bottom boxes representing terminal nodes. Values within each terminal node indicate average of grain yield (in Mg ha^{-1}) at a 13% moisture content basis and the percentage of observations in each terminal node. **p<0.001, *p<0.01.

Timing of sowing and crop emergency in HY fields were, on average, 5 days earlier than LY fields (Table 1). Besides the higher solar radiation, subtropical rice production regions present higher risk of crop damage due to low temperatures, narrowing the optimal sowing window when aiming high yields. The yield penalty over sowing dates earlier than 5th October was 50 kg ha^{-1} d^{-1} (Figure 6a), explained by lower soil temperatures (16-19 ^{o}C) that is typical in this time of year in southern subtropical climates, weed competition and flood problems affecting plant establishment. Furthermore, the yield potential in sowing dates near the boundaries of the sowing window (September and December) are lower in subtropical regions (Duarte Junior et al., 2021).

Crop development cycle longer than 142 days also penalizes the grain yield (Figure 6c). These results indicate strong interactions between genotype, environment and management among Argentinian rice farms. Besides longer development cycles present higher theoretical yield potential (Sheehy and Mitchell, 2015), the longer the plant stays in the field the more it will be exposed to pests, diseases and adverse conditions, so management becomes key between HY and LY, as shown in Table 1, where insecticide and fungicide application is 69.2% and 64.4% higher in HY fields than LY, respectively.

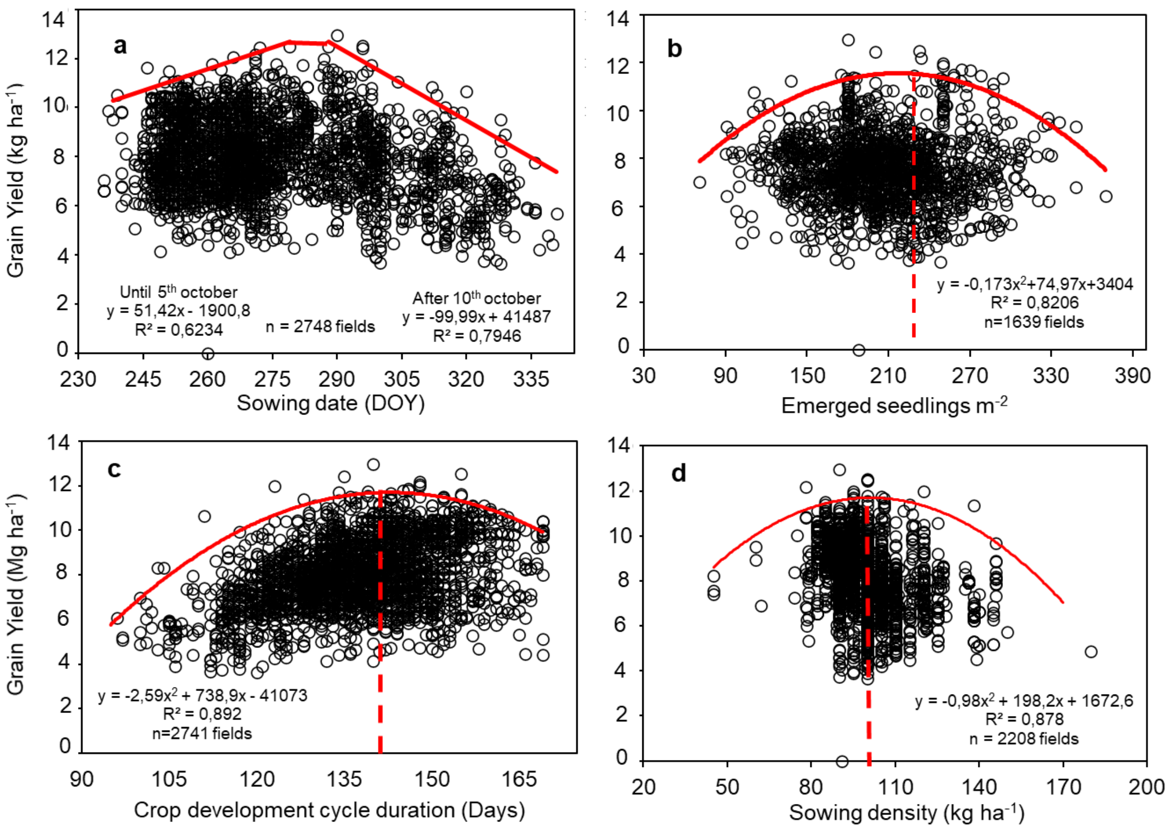

Figure 6 – Relation between grain yield and a) sowing date, b) emerged seedlings, c) crop development cycle duration and d) sowing density in irrigated rice in Argentina according to fields

surveyed during ten growing seasons (2009-2018). The red dashed line represents the maximum point, that is 218 emerged plantlets m^{-2} and 96 kg ha^{-1} in the Figure 6b and 6d, respectively.

Sowing density also differed statistically between HY and LY fields (Figure 5), where HY fields use -6 kg $seed^{-1}$ ha^{-1} than LY fields, which reflects in plant density (-90 seedlings m^{-2} than in LY fields) (Table 1). The relationship between grain yield and sowing and plant density is also related to the environment, and so on management. Sowing and seedling density that maximizes yield is 96 kg ha^{-1} and 218 emerged seedlings m^{-2}, respectively (Figure 6b and 6d). A consistent relation between sowing date and density was also showed in Figure 5, where lower sowing densities are more productive in late sowings and fields without fungicide application. Although not evaluated in this study, rice blast (*Magnaporthe oryzae*) is the major disease that affects rice in Argentina (Bastida et al., 2019) and around the world, affecting productivity and economics (Nalley et al., 2016), and its development is closely related to plant spacing, density and canopy density (Katsantonis et al., 2017), so that higher plant density can promote fungi infection, reducing grain yield. The incidence of blast increases in late sowings (Ogoshi et al., 2018), which reinforces the importance of the sowing dates to minimizes disease problems. Whereas less seed density shows an higher yield in HY fields, our beliefs is this management practice plays as fine-tuning, and should be carried carefully by the farmers, since the reduction of the sowing density, especially at the edges of the sowing window, can cause a reduction in the main yield component, which is the number of plants per area, which can compromise the yield.

The results obtained in this study represent the Yp that can currently be achieved for irrigated rice in different regions of Argentina, given today's technology and cultivars. These results indicate that, different from Asian countries, the rice yield plateau during the last 15 years in Argentina is being caused by lack of appropriate management practices. LY farms can increase yield by adopting management practices that are already being used in HY fields. Furthermore, studies quantifying potential gains in high-yielding vs. low-yielding systems could indicate investments, helping to point more cost-effective and environmentally safer managements aiming high-yielding systems (Tseng et al., 2020). Our results can also be used in future studies about economics and rice yield gaps in South America. With higher Yp than tropical environments and large room to increase irrigated area, Argentina can contribute to future rice demand and contribute to the world's food security.

This study also provided information that can be used by local farmers and consultants when planning management decisions based on the Yp. On a national and global scale, this study provided information for future food security studies, as it suggests that there is still room to increase rice production by closing the yield gap. More studies though should be performed to quantify how much is the yied gap caused by phytosanitary problems and refine the information about how the sowing date affects the yield gap in Argentina.

Conclusions

a) The Yp for flooded rice in Argentina ranged from 13.4 to 15.1 Mg ha^{-1} across fields and regions. The average Yp and Yg of irrigated rice in Argentina is 14.1 Mg ha^{-1} and 7.4 Mg ha^{-1}, respectively.

b) The management practices that are most affecting rice yield in Argentina are crop rotation, weed control, sowing date, and plant density.

c) The yield plateau in rice production in Argentina can be changed by adopting management practices that increase the average grain yield.

There is room to increase the average rice yield in Argentina by closing the yield gap.

References

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.

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.

S. Huang, X.H. Pan, Y.N. Sun, Y. Zhang, X.N. Hang, X.C. Yu, W.J. Zhang. Effects of long-term fertilization on the weed growth and community composition in a double-rice ecosystem during the fallow period **Weed Biol. Manag**., 13 (2013), pp. 10-18.

W. Liu, S. Hussain, L.S. Wu, Z.G. Qin, X.K. Li, J.W. Lu, F. Khan, W.D. Cao, M.J . Geng Greenhouse gas emissions, soil quality, and crop productivity from a mono-rice cultivation system as influenced by fallow season straw management. **Environ. Sci. Pollut.** R, 23 (2016), pp. 315-328.

Song Chen, Shaowen Liu, Xi Zheng, Min Yin, Guang Chu, Chunmei Xu, Jinxiang Yan, Liping Chen, Danying Wang, Xiufu Zhang, Effect of various crop rotations on rice yield and nitrogen use efficiency in paddy–upland systems in southeastern China, The Crop Journal, Volume 6, Issue 6, 2018, Pages 576-588, https://doi.org/10.1016/j.cj.2018.07.007.

Jing, Qi & Spiertz, Huub & Hengsdijk, H. & Keulen, & Cao, W & Dai, T. (2010). Adaptation and performance of rice genotypes in tropical and subtropical environments. NJAS Wageningen Journal of Life Sciences 57 (2010) 2. 57. 10.1016/j.njas.2010.04.002.

Fernandez, J.P.R., Franchito, S.H., Rao, V.B. and Llopart, M. (2017), Changes in Koppen–Trewartha climate classification over South America from RegCM4 projections. Atmos. Sci. Lett, 18: 427-434. https://doi.org/10.1002/asl.785

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.

KATSANTONIS, D., KADOGLIDOU, K., DRAMALIS, C., & PUIGDOLLERS, P. (2017). Rice blast forecasting models and their practical value: A review. *Phytopathologia Mediterranea, 56*(2), 187-216. Retrieved April 14, 2021, from http://www.jstor.org/stable/44809338

Krauss, M., Berner, A., Perrochet, F., Frei, R., Niggli, R., Mader, P. Enhanced soil quality with reduced tillage and solid manures in organic farming – a synthesis of 15 years. Scientific Reports, v.10, (2020). https://doi.org/10.1038/s41598-020-61320-8

Stein Emil VollsetEmily GorenChun-Wei YuanJackie CaoAmanda E SmithThomas HsiaoCatherine BisignanoGulrez S AzharEmma CastroJulian ChalekAndrew J DolgertTahvi FrankKai FukutakiSimon I HayRafael LozanoAli H MokdadVishnu NandakumarMaxwell PierceMartin PletcherToshana RobalikKrista M SteubenHan Yong WunrowBianca S ZlavogChristopher J L Murray. Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the Global Burden of Disease Study, **The Lancet**. vol. 396issue 10258(2020)pp: 1285-1306.

Fliessbach A., Oberholzer H.R., Gunst L., Mäder P. “Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming”. Agriculture, Ecosystems & Environment;118:273-84. 2007

Peng Z K, Wang L L, Xie J H, Li L L, Coulter J A, Zhang R Z, Luo Z Z, Cai L Q, Carberry P, Whitbread A. 2020. Conservation tillage increases yield and precipitation use efficiency of wheat on the semi-arid Loess Plateau of China. *Agricultural Water Management*, **231**, 106024.

S.M. Ogle, A. Swan, K. Paustian. **No-till management impacts on crop productivity, carbon input and soil carbon sequestration.** Agric. Ecosyst. Environ., 149 (2012), pp. 37-49

FAO, **Save and Grow: A Policymaker's Guide to the Sustainable Intensification of Smallholder Crop Production.** Food and Agriculture Organization of the United Nations (FAO), Rome (2011)

N. Verhulst, B. Govaerts, E. Verachtert, A. Castellanos-Navarrete, M. Mezzalama, P. Wall, J. Deckers, K.D. Sayre **Conservation agriculture, improving soil quality for sustainable production systems?**

M.K. Gathala, J.K. Ladha, V. Kumar, Y.S. Saharawat, V. Kumar, P.K. Sharma, S. Sharma, H. Pathak. **Tillage and crop establishment affects sustainability of South Asian rice–wheat system**
Agron. J., 103 (2011), pp. 961-971

Y. Singh, V.P. Singh, G. Singh, D.S. Yadav, R.K.P. Sinha, D.E. Johnson, A.M. Mortimer
The implications of land preparation, crop establishment method and weed management on rice yield variation in the rice–wheat system in the Indo-Gangetic plains
Field Crops Res., 121 (2011), pp. 64-74

R. Lal, B.A. Stewart (Eds.), Advances in Soil Science: Food Security and Soil Quality, CRC Press, Boca Raton, FL, USA (2010), pp. 137-208

OGOSHI, C. et al. Effectiveness of fungicides for rice blast control in lowland rice cropped in Brazil. **Tropical and Subtropical agroecosystems**, v. 21, p. 505-511, 2018.

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).

Sheehy, J. E., & Mitchell, P. I. (2015). Calculating maximum theoretical yield in rice. Field Crops Research, 182, 68–75. https://doi.org/10.1016/j.fcr.2015.05.013.

3.2 CAPÍTULO 2 – Evaluation and application of crop models to determine rice yield potential in Argentina

(Será submetido para a revista Rice Science, IF:3,333, CiteScore 6,2)

Evaluation and application of crop models to determine rice yield potential in Argentina

Abstract: Due to the over concentration of the rice production in Asia, the study and comprehension of rice producing chains outside this continent are key do guarantee the global food security. The objective of this study was validating the SimulArroz and ORYZA models to Argentina; estimate the Yp of rice for different sowing dates in Argentina and estimate how much Argentina can increase rice production in the current agricultural area. The adjustment between simulated and measured values was at least 0.74. RMSEn values for phenology ranged from 4.6% to 9.4%, both models simulated grain yield relatively accurately at a high yielding level. The average irrigated rice yield potential for subtropical Argentina estimated by the SimulArroz model ranged from 3.8 to 15.6 Mg ha^{-1}, and from 7.6 to 14.3 Mg ha^{-1} in the ORYZA v3. The highest values of Yp were found in the sowing dates of September and October, and the months in the boundary of the sowing window presented a higher standard deviation. The increase in the rice production in Argentina if the fields close the exploitable gap would be 916,091 tons of rice annually, or an increase of 42% in the Argentina rice production without increase the sowed area.

1 INTRODUCTION

Rice (*Oryza sativa* L.) is the main staple food for nearly half the world's population, accounting for 21% of global calorie intake and using only 11% of the cropland (Fan et al., 2016; FAOSTAT, 2021). Due to the over concentration of the production of this cereal in Asia (90% of global rice production), in a scenario where global rice consumption is projected to increase from 480 million tons (Mt) milled rice in 2014 to nearly 550 Mt by 2030 (IRRI, 2016), the study and comprehension of rice producing chains outside this continent, like Argentina, are extremely important aiming to ensure world food security. Characterized as the 4th South American largest producer, rice production in Argentina is highly mechanized, with individual farmers managing large paddies (100-250 ha). The annual rice production is approximately 1.3 Mt, over an area of 200 thousand hectares (MAGYP, 2021).

The agricultural production in Argentina experienced a large growth after the implementation of the green revolution, from 60's to 2000's (Pellegrini & Fernández, 2018). After this period, since the middle 2000's, started to become evident a "plateau" in the yield of the major crops, as example, irrigated rice, following the same trend of some crops in developed countries around the world, like rice in China, maize in U.S.A. and wheat in European Union (Cassman & Grassini, 2020; Peng et al., 2020; Rong et al., 2021). Although these plateau in developed countries is explained by the ceiling of the yield potential, (Deng et al., 2019), in Argentina the average farm yield is lower than the yield achieved in neighboring countries. In this way, studies that make it possible to understand Argentina's rice yield potential and variation will provide a basis for enhance crop management and raising the country's food production.

For agricultural crops, the yield potential (Yp) can be defined as the yield of a crop that grows in conditions without stress or limitation by water, nutrients, diseases, insects and weeds (Evans, 1993). Therefore, crop growth and yield are determined only by intercepted solar radiation, air temperature, carbon dioxide and genetic factors (Van Ittersum & Rabbinge, 1997). The field determination of Yp is difficult, as the growth, development and yield of irrigated rice crops can be affected by biotic and abiotic factors, which compromise the achievement of Yp (Fischer, 2014). Due to the issues of current food production, it is clear that agriculture has to produce more in the existing cropped area and do it with less environmental impact, that is, via sustainable intensification (Cassman & Grassini, 2020). Several studies affirm that the yield that maximizes sustainability and profit, also called as “exploitable yield” (Van Ittersum et al., 2013) is when the grain yield is about 70 and 85% of the yield potential (Xavier et al., 2021; Yuan et al., 2021; Lobell et al., 2009; Grassini et al., 2015). Hence, reliable estimation of YP is necessary to enhance crop management and public policies.

Process-based models, like SimulArroz (Rosa et al., 2015) and Oryza (Li et al., 2017) are being one of the main tools to estimate Yp across crops and countries, due to the reliability and relatively easy use and extrapolation of these software’s. The SimulArroz model is already in use by the Brazilian government for zoning rice in southern Brazil and that is demonstrated elsewhere (Junior et al., 2021, Ribas et al., 2021; Ribas et al., 2017; Rosa et al., 2015) that SimulArroz describes very well the complex on farm differences in rice production systems in Brazil However, the SimulArroz model was not compared outside Brazil to a widely used process-based model such as ORYZA, and the evaluation in new regions is important to evaluate the predictive capacity of crop models (Junior et al., 2021; Alberto et al., 2013). Until now, there had been no case-study on the application of ORYZA (v3) and SimulArroz models and comprehensive, multi-year studies on the variation in Yp as a function of sowing date in Argentina. In order to fulfill the lack of information and to quantify the variability of the rice yield potential in Argentina, the objective of this study was (a) validate the capacity of SimulArroz and ORYZA models to simulate the rice development and production in Argentina; (b) to estimate the Yp of rice for different sowing dates in Argentina and (c) estimate how much Argentina can increase rice production in the current agricultural area.

2 MATERIALS AND METHODS

2.1 Study region

This study was performed for the northeast region of Argentina (Figure 1) where the rice production in Argentina is located, in a region called "Mesopotamia Argentina", for practical application, these regions were used in this study. The average yield in the 2004–2019 period was 6.6 t ha^{-1} and farmers in the South regions reported higher yields compared with farmers from the northern regions (MAGYP, 2021). This difference can be explained by the climatic conditions, as temperature and solar radiation differ between the rice-growing regions (Figure 1A). The aridity index (Figure 1B) increases westward, whereas temperature seasonality is lower in north (Figure 1C).

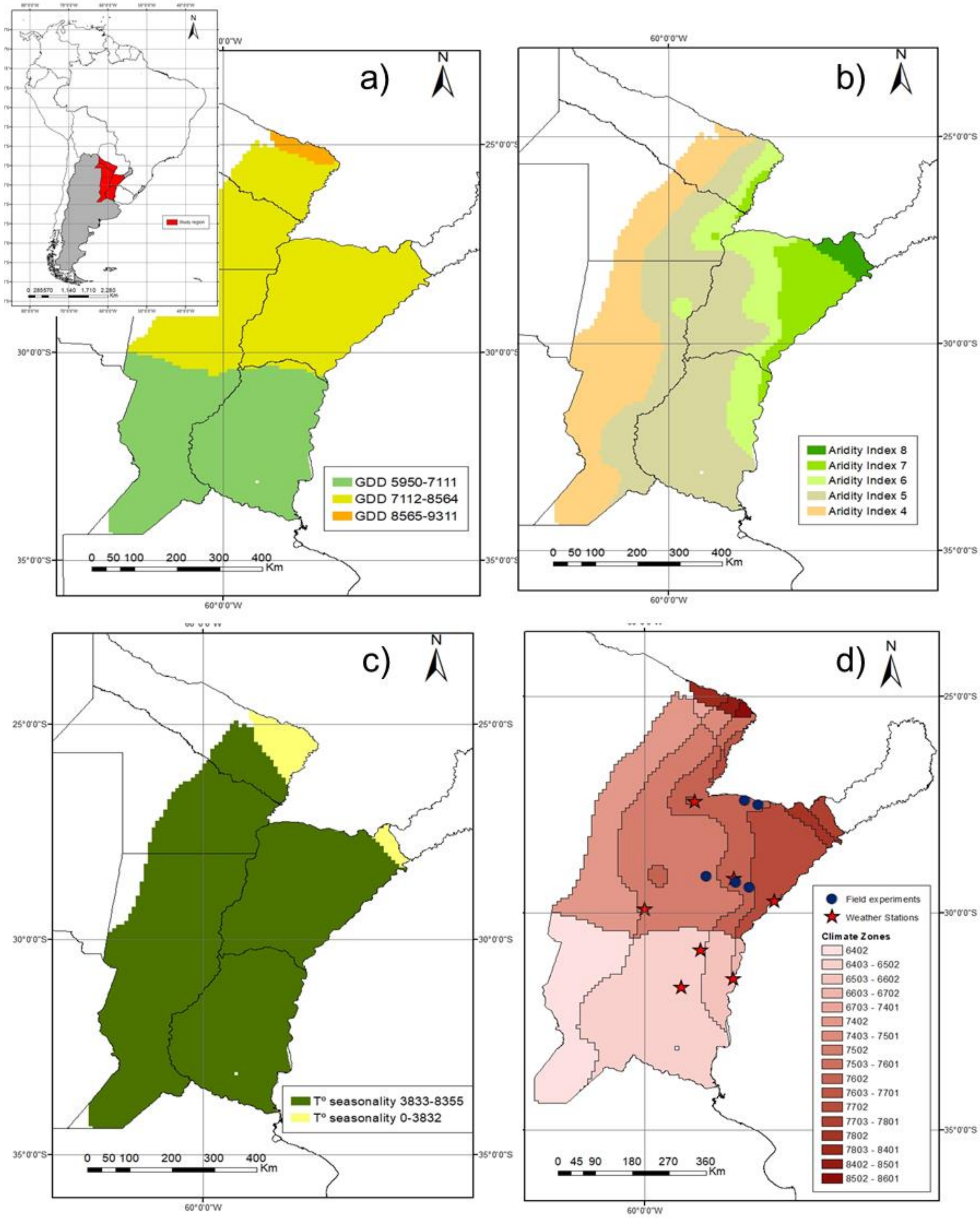

Figure 1- Division of Argentina rice growing region into climatic regions. (A) division in relation to the annual accumulation of growing degree days (GDD, ºC day^{-1} year^{-1}), (B) aridity index (rainfall/evapotranspiration), (C) temperature seasonality (ºC) and (D) representation of the 23 climatic regions present in the rice growing region in Argentina; the red stars represent the location of the reference weather stations (RWS) used to simulate the yield potential; the dark blue circles represent the location of the field experiments used to validate the

models. The small figure on the top is showing the map of South America, Argentina is highlighted in gray, and the study region in red.

2.2 The SimulArroz model

SimulArroz is a process-based model that calculates phenology, dry matter (DM) production and Yp for irrigated rice on a daily time step. Phenology is calculated with the thermal time approach (°C day^{-1}), using the lower and upper basal (temperatures below and above which plant growth is negligible, respectively) and optimum temperature (at which the development rate is maximum) (Streck et al., 2011). SimulArroz differs from other existing rice models in its capacity to calculate the number of leaves on the main stem (LN) and the final leaf number. The LN is based on Haun Stage (Haun, 1973) and is calculated using the Wang and Engel model modified for rice (Streck et al., 2008).

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

To run the SimulArroz model, users need to input daily weather data of maximum and minimum temperature (°C), solar radiation (MJ m^{-2} day^{-1}), and crop parameters, such as cultivar or maturity group, sowing or emergence date, plant density (plants m^{-2}), number of simulated years, technological level, and atmospheric CO2 concentration. Version 1.1 of the SimulArroz model, available for free download at www.ufsm.br/simularroz, was used in this study.

2.3 The ORYZA model

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

2.4 Models calibration and validation

In order to validate the SimulArroz and ORYZA models, field experiments were carried out in order to validate the models. Experiments were sown on five locals in Argentina (Figure 1d) during three growing seasons (2017/18, 2018/19 and 2019/20). The cultivar IRGA 424 RI was used in all experiments. All experiments were direct sown, flood irrigation started at V3. Weeds, insects, and diseases were prophylactically controlled. These experiments were used to validate both SimulArroz and ORYZA to Argentina. The calibration approach used in SimulArroz and ORYZA was the same used by Ribas et al., (2021) and Junior et al., (2021).

Because of the nature of each model, which have their own parameters, it is expected that different combination of data sets can be more efficient to validate different models. The SimulArroz model is already in use in Brazil, performing very well determining on farm differences, with much less parameters to be calibrated compared to ORYZA. However, a comparison of the two models in another countries and production regions is still needed in order to test if SimulArroz is suitable for estimating rice yield potential in other countries of South America, like Argentina.

2.5 Yield potential estimation

Estimating crop yield potential from crop models requires using a robust long-term weather database to represent the impacts of temperature and solar radiation variability among years (Grassini et al., 2015; van Ittersum et al., 2013). Unfortunately, the density of weather stations with reliable and long-term data is low in several parts of the world, including Argentina. To overcome this problem, one acceptable approach is the use of reference weather stations (RWS) and buffer zones, that allows the use of crop models to estimate the Yp. More information about the RWS can be found in Table 1.

Table 1 – Reference weather stations used as data source of long term (2008-2020) meteorological data to estimate the rice yield potential in Argentina.

Weather Station	Latitude	Longitude	Variables	Source
Uruguaiana	-29.712	-57.15	Maximum temperature Minimum temperature Solar radiation	INMET
Villaguay	-31.7	-59.2	Maximum temperature Minimum temperature Solar radiation	POWER NASA
Colonia Benites	-27.42	-58.9	Maximum temperature Minimum temperature Solar radiation*	INTA
Calchaqui	-29.9	-60	Maximum temperature Minimum temperature Solar radiation*	INTA
Mercedes	-29.19	-58.0443	Maximum temperature Minimum temperature Solar radiation*	INTA
Salto Grande	-31.5	-58.06	Maximum temperature Minimum temperature Solar radiation	INIA
Federal	-30.85	-58.77	Maximum temperature Minimum temperature Solar radiation*	INTA

* Lacks in the measured data were filled with data from Power-Nasa system (https://power.larc.nasa.gov/data-access-viewer/).

The cultivar IRGA 424 RI was used to simulate the Yp across the country, which is the highest yielding and most sown cultivar in Argentina. The sowing dates were set every five days, from August to February, aiming to capture the entire range of the sowing window. The runs were done from 2009/2010 to 2019/20 growing seasons, totalizing 10 growing seasons, time enough to achieve a robust Yp estimate in irrigated crops (Grassini et al., 2015). The plant density used for both models was set at 200 plants m^{-2} and the atmospheric CO2 concentration was 400ppm (Rosa et al., 2015). For the Simularroz model, the technological level was set to potential, meaning that simulated Yp was only a function of solar radiation and temperature (Lobell et al., 2009). Both models were run at 34 sowing dates, 10 years and 7 RWS, totaling 4,760 runs.

2.6 Increase in rice production with crops reaching 80% of potential yield

Once Yp is known, the yield gap (Yg) can be quantified. The difference between the exploitable yield and the Yg can be represented as the increase in the amount of rice that can be produced without increasing the environmental impact and the cultivated area, modified only with adjustments in crop management. In this study, the exploitable yield was settled as 80% of Yp, following the methodology proposed by Cassman et al. (2003) and Pilleco et al. (2020). Rice Yp was estimated at 14.1 Mg ha^{-1}, being the average Yp for the most used sowing dates in Argentina. Actual yield was obtained from the Ministerio de Agricultura, Ganaderia y Pesca (MAGYP) during the last five growing seasons

(2015 to 2020) and settled as the average of these values, since there is no trend in the yields.

Yield gap was determined by the difference between Yp and the average country yield, indicating how much yield is possible to increase in a field and/or country. The Yp and yield gap were estimated for direct sown flooded rice, since this is the dominant crop system. Harvested rice area in Argentina was set as the average harvest area of the last three available growing seasons (2018, 2019 and 2020). The increase in the rice production was determined by multiplying the yield per hectare achieved if the fields that had reached 80% of the yield potential by the number of cultivated hectares, and subtracting this value from the country's current production.

3 RESULTS AND DISCUSSION

3.1 Models calibration and evaluation

The first step in model evaluation tested the performance of SimulArroz and ORYZA models in simulating rice phenology and yield for the IRGA 424 RI cultivar under potential conditions. There was a satisfactory agreement between simulated and measured YP (Figure 2). The adjustment between simulated and measured crop variables are presented in Table 2 for the validation data set. The adjusted linear correlation coefficient (R2) between simulated and measured values was at least 0.74. RMSEn values for phenology ranged from 4.6% to 9.4% (Table 2). Measured grain yield ranged from 13 to 15.9 Mg ha^{-1}, and simulated values ranged from 12.3 to 14.7 Mg ha^{-1} (Table 2), both models simulated grain yield relatively accurately at a high yielding level. Evaluating the performance of ORYZA v3 in Thailand, Boling et al. (2011) reported a RMSE of 0.6 Mg ha^{-1} for rice grain yield. Also using the Oryza v3, Heinemann et al. (2019) reported an RMSE of 0.4 Mg ha^{-1} for rice yield in central Brazil.

Table 2 - Evaluation results for SimulArroz and ORYZA v3 simulations of crop growth and development variables over three growing seasons (2017/18, 2018/19 and 2019/20) and five locals for the cultivar IRGA 424 in the validation data set.

Model	Variable	N	Xmean	Xsim	R^2	RMSE	RMSE (%)	BIAS
SimulArroz	Grain Yield (Mg ha^{-1})	7	13.2	13.4	0.75	0.4	4.6	0.01
	R1 (days)	108	56.5	60.7	0.97	4.9	8.5	0.05
	R4 (days)	108	89	97.6	0.97	8.9	9.4	0.05
	R9 (days)	94	120.6	125.7	0.97	10.2	8	0.02
Oryza v3	Grain Yield (Mg ha^{-1})	7	13.2	13.6	0.74	0.5	5.1	0.03
	R1 days	108	56.5	56.1	0.98	3.3	5.8	0
	R4 days	108	89	89.2	0.98	5.1	5.7	-0.01
	R9 days	94	120.6	117	0.97	7.5	6.2	-0.03

N, number of data pairs; Xmean, mean of measured values; Xsim, mean of simulated values; R2, adjusted linear correlation coefficient between simulated and measured values; RMSE, absolute root mean square error; RMSEn, normalized root mean square error (%); BIAS, comparative BIAS index.

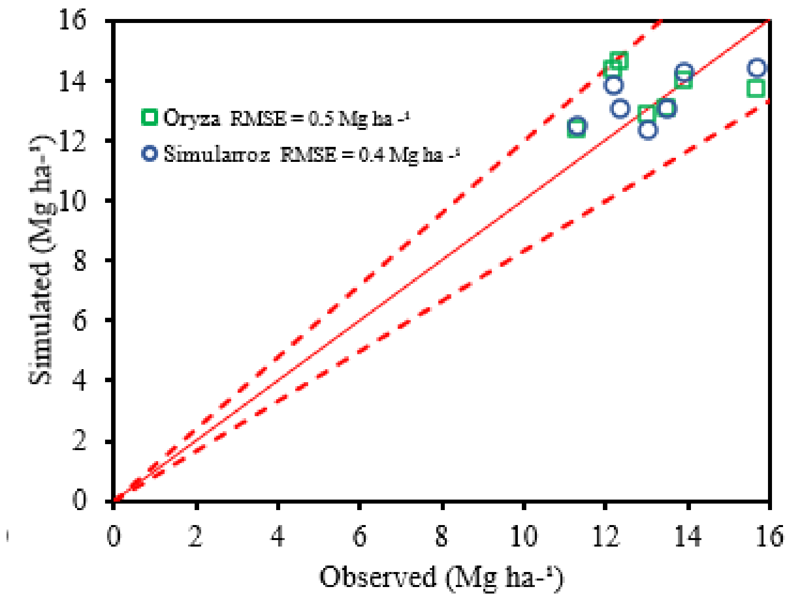

Figure 2 - Comparison between the yield potential observed in the experiments vs. the yield potential simulated by ORYZA and SimulArroz models. The solid diagonal is the 1:1 line. Dotted diagonal lines represent 20% of the range of yield variation, respectively. The root mean square errors (RMSE) are shown in the panel. The observed data were obtained from five sites in Argentina during three growing seasons (2016, 2017 and 2019).

Figure 3 shows a comparison between independent observed phenology against simulated values using ORYZA and SimulArroz models. Both models presented a reasonably good agreement between observed and simulated values, with most of the points within the +/– 10% variation envelope. The RMSE variated from 3.3 to 7.5 days in ORYZA and from 4.9 to 10.2 in the SimulArroz model. Ribas et al. (2020) when calibrating the SimulArroz for South Brazil found a RMSE of 8 days for R1, R4 and R9. Heinemann et al. (2019) when calibrating ORYZA v3 for central Brazil, found an RMSE of 2.86 d and 2.45 d for flowering and maturity, respectively. Small differences in simulating phenology between the models can be explained by different approaches of calculating thermal time in the models (Junior et al., 2021; Yuan et al., 2017).

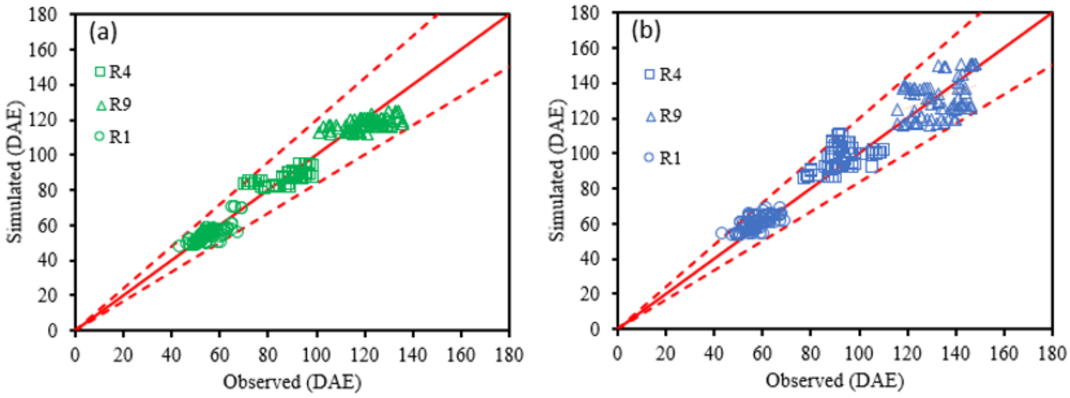

Figure 3 - Comparison between the phenology of rice observed (Counce et al., 2000 scale) in 11 experiments carried out during three growing seasons in Argentina (2017/18, 2018/19, 2019/20) compared to the phenology simulated by (a) ORYZA and (b) SimulArroz models. Circles represent the R1 stage (panicle differentiation), squares represent the R4 stage (flowering), and triangles represent the R9 stage (maturity). The solid red diagonal is the 1:1 line. Dotted diagonal lines represent the 20% (+/-) range of variation. RMSE - Root Mean Square Error.

3.2 Yield potential according to sowing date

The average irrigated rice Yp for subtropical Argentina estimated by the SimulArroz model ranged from 3.8 to 15.6 Mg ha^{-1}, and from 7.6 to 14.3 Mg ha^{-1} in the ORYZA v3 (Figure 4). With the exception of the sowing dates in December and January, the SimulArroz presented higher yield potential values than ORYZA v3. The Yp of rice found for Argentina in both model is superior to the Yp of Bangladesh (11.7 t ha^{-1}), Indonesia (9.1 t ha^{-1}), and Philippines (8.7 t ha^{-1}), as reported by Timsina et al. (2016), Agustiani et al. (2018), and Silva et al. (2016). It can be explained by the higher availability of solar radiation in subtropical rice production regions, near to the latitude of 30°, when compared to lower latitudes, where these studies were conducted.

The highest values of Yp were found in the sowing dates of September and October in both models, it occurred due to the higher availability of solar radiation and longer photoperiod during flowering and grain filling phases, provided by the subtropical climate (Ribas et al., 2021). Furthermore, near the boundaries of the sowing window (August and January), low temperatures can also reduce rice yield by increasing the spikelet sterility (Espe et al., 2016). These decrease in the Yp was clearly seem in the farmers reported yields (Figure 4), and understood and replied by the SimulArroz model. However, the Oryza v3 model was not able to capture these losses caused by cold temperatures. Previous work has shown that the ORYZA model does not simulate cold-induced sterility well and that structural changes to the model are required to correct this (Li et al., 2020; Espe et al., 2016).

The lower standard deviation was found in September, October and November sowing dates (Figure 4), what can indicate that this window is the best to avoid yield fluctuation across years. According to Junior et al. (2021) the best environmental conditions (i.e., solar radiation and temperature) for rice fields in the subtropics of the southern hemisphere subtropics occur during the summer season (December–January– February), the sowing dates before 14 November correspond to the critical stages of rice development (i.e., reproductive and grain-filling stages) with the period with greatest availability of solar radiation, which is directly linked to rice yield and prevents yield losses caused by extreme temperatures during flowering (Huang et al., 2016; Stansel, 1975; Wrege et al., 2012).

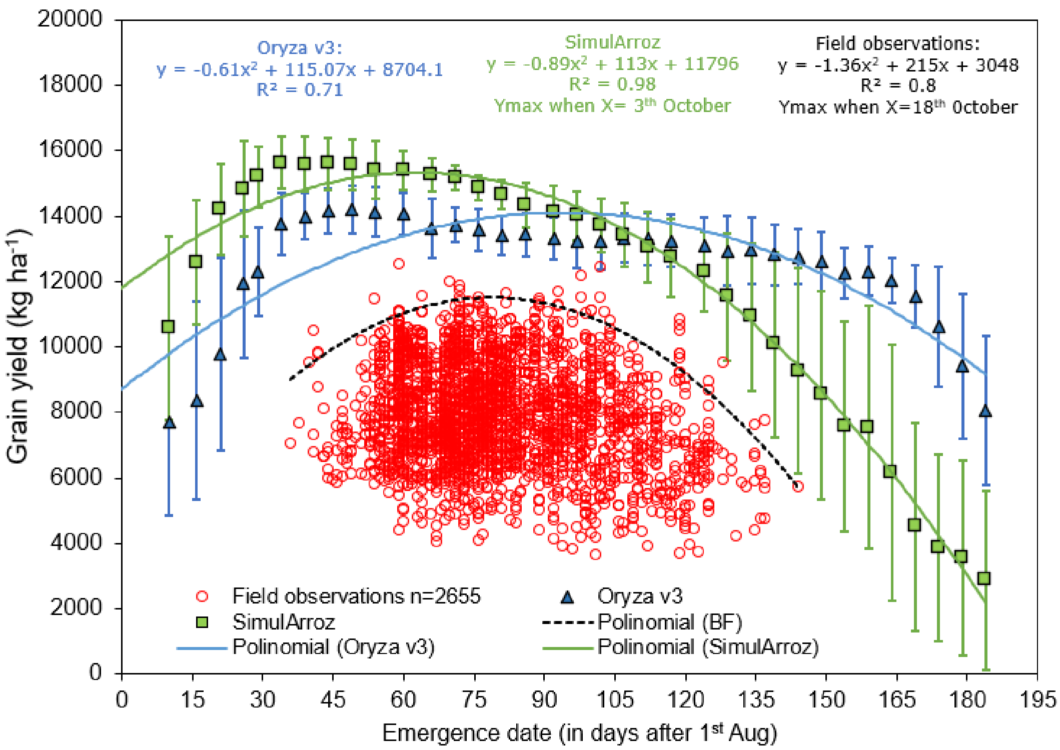

Figure 4 – Rice grain yield as a function of sowing date (expressed as days after 1st August) in subtropical Argentina. Green squares represent the average yield potential simulated with the SimulArroz and the blue triangles represent the yield potential simulated with the ORYZA v3 model, both were run for 10 growing seasons (2009-2019) and seven reference weather stations (RWS) representing the climate zones where rice is grown in Argentina (n = 4760). Red circles represent the observed yield of field experiments and farm fields (n = 2655) during 11 growing seasons (2009-2020). BF = Boundary Function of the of the top 5% percentile. Bars indicate the standard deviation for simulated yield potential.

According to the observed field data, the farmers emerging dates start from September 10, when the Yp is higher, and most of the farmers fields are sowed to emerge around October 15, not coincidentally, the window where the models found the smallest standard deviation between places and years. According to Fischer (2015), this is the result of farmers, even if empirically, balancing potential yields against exposure to risk. Hence, regarding the differences between observed yield and simulated Yp in early sowing dates, it can be explained by the fact that both SimulArroz and Oryza does not capture the soil temperature, or factors like excess of soil moisture during crop establishment (Bouman et al., 2001; Rosa et al., 2015).

3.3 Increase in irrigated rice production if the fields close the exploitable gap

The increase in the rice production in Argentina if the fields close the exploitable gap would be 916,091 tons of rice (Table 3) or an increase of 42% in the Argentina rice production without increase the sowed area, just adjusting management practices. This increase would be of fundamental importance to guarantee global food security, since the annual deficit of rice in the world around 2030 should be of 2 million tons (Deng et al., 2019). Hence, projections made by the Food and Agriculture Organization (FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 2014) point to an increase of the world's population of approximately 30% by 2050, and it is necessary to increase agricultural production by 60% to meet the demand for food. Thus, Argentina, which is already one of the major global food suppliers, will become even more prominent in the global food security in this scenario.

Table 3. Increase in irrigated rice production in Argentina if the farmers reach 80% of the yield potential.

Actual sowed area (Average 2018 to 2020)	Actual farmers yield (Average 2018 to 2020)	Paddy rice actual production (Average 2018 to 2020)	Yield Potential	Production per ha with 80% of the Yp	National production if the fields reach 80% of Yp	Possible increase (80%Yp - Actual)
188918 ha	6.6 Mg ha^{-1}	1,260,248 Mg	14.1 Mg ha^{-1}	11.52 Mg	2,176,339	916,091 Mg

4. CONCLUSIONS

The SimulArroz and ORYZA v3 models were able and reliable to simulate the rice development and yield potential in Argentina;

The average irrigated rice Yp for subtropical Argentina estimated by the SimulArroz model ranged from 3.8 to 15.6 Mg ha^{-1}, and from 7.6 to 14.3 Mg ha^{-1} in the ORYZA v3. The higher Yp were found in September and October emergence dates;

Argentina can increase, in the current agricultural area the rice production in 919,091 tons of paddy rice annually, just closing the exploitable gap.

5. REFERENCES

AGUSTIANI, N., DENG, N., RATTALLINO EDREIRA, J. I., GIRSANG, S. S., SYAFRUDDIN, S., SITARESMI, T., PASUQUIN J. M. C., AGUS F., & GRASSINI, P. (2018). Simulating rice and maize yield potential in the humid tropical environment of Indonesia. European Journal of Agronomy, 101,10–19. https://doi.org/10.1016/j.eja.2018.08.002

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.

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., & VAN LAAR, H. H. (2001). ORYZA 2000: Modeling lowland rice. Los Baños, Philippines: International Rice Research Institute, and Wageningen: Wageningen University and Research Centre.

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.

CASSMAN, Kenneth G.; GRASSINI, Patricio. A global perspective on sustainable intensification research. Nature Sustainability, v. 3, n. 4, p. 262-268, 2020.

CONNOR, D. J., LOOMIS, R. S., & CASSMAN, K. G. (2011). Crop ecology. Productivity and management in agricultural systems. Cambridge, UK: Cambridge University Press.

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.

EVANS, L. T. (1993). Crop evolution, adaptation and yield. Cambridge, UK: Cambridge University Press.

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.

FAN, X., TANG, Z., TAN, Y., ZHANG, Y., LUO, B., YANG, M., LIAN, X., SHENG, Q., MILLER, A., XU, G., 2016. Overexpression of a pH-sensitive nitrate transporter in rice increases crop yields. Proc. Natl. Acad. Sci. U. S. A. 113, 7118–7123.

FAOSTAT. Food and Agriculture Organization of the United Nations Statistics Division. Agricultural production [Database]. FAO, Rome, Italy. Available in: < http://faostat.fao.org/home/>. (accessed on Jul. 2021).

FERNANDEZ, J.P.R., FRANCHITO, S.H., RAO, V.B. AND LLOPART, M. (2017), Changes in Koppen–Trewartha climate classification over South America from RegCM4 projections. Atmos. Sci. Lett, 18: 427-434. https://doi.org/10.1002/asl.785

GRASSINI, P., VAN BUSSEL, L. G. J., VAN WART, J., WOLF, J., CLAESSENS, L., YANG, H., BOOGAARD, H., DE GROOT, H., VAN ITTERSUM, M. K., & CASSMAN, K. G. (2015). How good is good enough? Data requirements for reliable crop yield simulations and yield-gap analysis. Field Crops Research, 177, 49–63. https://doi.org/10.1016/j.fcr.2015.03.004

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.

HUANG, M., SHAN, S., CAO, F., & ZOU, Y. (2016). The solar radiationrelated determinants of rice yield variation across a wide range of regions. Wageningen Journal of Life Sciences, 78, 123–128. https://doi.org/10.1016/j.njas.2016.05.004

JUNIOR AJD, STRECK NA, ZANON AJ, et al. Rice yield potential as a function of sowing date in southern Brazil. Agronomy Journal. 2021;1-12. https://doi.org/10.1002/agj220610.20610

LI, T., ANGELES, O., MARCAIDA, M. III, MANALO, E., MANALILI, M. P., RADANIELSON, A., & MOHANTY, S. (2017). From ORYZA2000 to ORYZA (v3): An improved simulation model for rice in drought an nitrogen-deficient environments. Agricultural and Forest Meteorology, 237–238, 246–256. http://doi.org/10.1016/j.agrformet.2017.02.025

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

MINISTERIO DE AGRICULTURA, GANADERIA Y PESCA. Agricultura - Estimaciones agrícolas. 2021 (Acesso < https://datos.magyp.gob.ar/dataset/estimaciones-agricolas>.)

PELLEGRINI P, FERNÁNDEZ R J. 2018. Crop intensification, land use, and on-farm energy-use efficiency during the worldwide spread of the green revolution. Proceedings of the National Academy of Sciences the United States of America, 115, 2335–2340.

PENG Z K, WANG L L, XIE J H, LI L L, COULTER J A, ZHANG R Z, LUO Z Z, CAI L Q, CARBERRY P, WHITBREAD A. 2020. Conservation tillage increases yield and precipitation use efficiency of wheat on the semi-arid Loess Plateau of China. *Agricultural Water Management*, **231**, 106024.

PILECCO, I. B.; SILVA, M. R.; RIBAS, G. G.; DUARTE JUNIR; A. J.; STRECK, N. A.; ZANON, A. J. (2020). Can Brazil Produce Enough Rice To Meet Demand In 2028? Ciência e Natura, V42. DOI:10.5902/2179460X42318

RIBAS, G. G., STRECK, N. A., DUARTE JUNIOR, A. J., NASCIMENTO, M. F., ZANON, A. J., & SILVA, M. R. (2017). Number of leaves and phenology of rice hybrids simulated by the SimulArroz model. Revista Brasileira de Engenharia Agrícola e Ambiental, 21(4), 221–226. http://doi.org/10.1590/1807-1929/agriambi.v21n4p221-226

ROSA, H. T.,WALTER, L. C., STRECK, N. A., DE CARLI, C., RIBAS, G. G., & MARCHESAN, E. (2015). Simulation of rice growth and yield in Rio Grande do Sul with the SimulArroz. (In Portuguese, with English abstract.) Revista Brasileira de Engenharia Agrícola e Ambiental, 19(12), 1159–1165. https://doi.org/10.1590/1807-1929/agriambi. v19n12p1159-1165

RONG, LIANG-BING et al. Yield gap and resource utilization efficiency of three major food crops in the world–A review. **Journal of Integrative Agriculture**, v. 20, n. 2, p. 349-362, 2021.

SILVA, J. V., REIDSMA, P., LABORTE, A. G., & VAN ITTERSUM, M. K. (2016). Explaining rice yield gaps in central Luzon, Philippines: An application of stochastic frontier analysis and crop modelling. European Journal of Agronomy, 82, 223–241. https://doi.org/10.1016/j.eja.2016.06.017

SOLTANI, A., ZEINALI, E., GALESHI, S., & NIARI, N. (2001). Simulating G F D L predicted climate change impacts on rice cropping in Iran. Journal of Agricultural Science and Technology, 3(2), 81–90. https://jast.modares.ac.ir/article-23-3377-en.html

STRECK, N. A.; LAGO, I.; OLIVEIRA, F. B.; HELDWEIN, A. B.; AVILA, L. A. DE; BOSCO, L. C. Modeling the development of cultivated rice and weedy red rice. Transactions of the ASAE, v.54, p.371-384, 2011. https://doi.org/10.13031/2013.36234

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

STUART, A. M., PAME, A. R. P., SILVA, J. V., DIKITANAN, R. C., RUTSAERT, P., MALABAYABAS, A. J. B., LAMPAYAN, R. M., RADANIELSON, A. M., & SINGLETON, G. R. (2016). Yield gaps in rice-based farming systems: Insights from local studies and prospects for future analysis. Field Crops Research, 194, 43–56. https://doi.org/10.1016/j.fcr.2016.04.039

STANSEL, J. W. (1975). The rice plant – Its development and yield. In Miller, J. E.(Ed.) , Six decades of rice research in Texas (pp. 9–21). Beaumont, TX: Texas Agricultural Experiment Station.

TIMSINA, J.,WOLF, J., GUILPART, N., VAN BUSSEL, L., GRASSINI, P., VANWART, J., HOSSAIN A., RASHID H., ISLAM S., & VAN ITTERSUM, M. (2016). Can Bangladesh produce enough food to meet future demand? Agricultural Systems, 163, 36–44. https://doi.org/10.1016/j.agsy.2016.11.003

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).

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

VAN ITTERSUM, M. K. et al. Yield gap analysis with local to global relevance-A review. **Field Crops Research**, [s. l.], v. 143, p. 4–17, 2013. Disponível em: <http://dx.doi.org/10.1016/j.fcr.2012.09.009>.

WREGE, M. S., STEINMETZ, S., REISSER JÚNIOR, C., & ALMEIDA, I. R. (2012). Atlas climático da região Sul do Brasil: Estados do Paraná, Santa Catarina e Rio Grande do Sul. Brasília, DF: Embrapa.

XAVIER, A.I.S.; ARBAGE, A.P.; SILVA, M.R. DA; RIBAS, G.G.; MEUS, L.D.; SANTOS, G.A. DE A. DOS; STRECK, N.A.; ZANON, A.J. Economic and productive analysis of irrigated rice crops using a multicase study. Pesquisa Agropecuária Brasileira, v.56, e02037, 2021. DOI: https://doi.org/10.1590/S1678-3921. pab2021.v56.02037.

YUAN, S. ET AL., (2021). A roadmap towards sustainable intensication for a larger global rice bowl. *Nature*. https://doi.org/10.21203/rs.3.rs-401904/v1.

4 DISCUSSÃO

Neste estudo avaliamos os modelos agrícolas SimulArroz v1.1 e Oryza v3 para a determinação do crescimento, desenvolvimento e potencial produtivo de lavouras de arroz irrigado na Argentina. Os modelos mostraram bom desempenho, apresentando variação do NRMSE entre 4,6% a 9,4% (Tabela2 – Capítulo 2). Com este trabalho de tese foi possível identificar similaridade nos erros encontrados neste trabalho em relação à literatura, além de consonância entre os dados simulados pelos modelos e observados em lavouras comerciais, sendo possível afirmar que os dois modelos estão capturando a variação de ambiente.

O potencial reportado na Argentina com o modelo Oryza v3 (14,1 t ha^{-1}) foi similar ao reportado no Uruguai (14 t ha^{-1}), e maior que os reportados na China, (12.4 t ha^{-1}) e África (9 t ha^{-1}), porém inferior aos valores estimados para o Brasil (14.8 t $há^{-1)}$. Já quando analisamos a lacuna de produtividade no Argentina (7,4 t ha^{-1} ou 53%) observamos que foi maior em relação aos EUA (27%) e China (33%), Uruguai (43%), similar a do Brasil (51%) 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; RIBAS et al., 2021). O que mostra o potencial de aumento na produção de arroz na Argentina realizando apenas ajustes nos manejos das lavouras.

Sob ponto de vista das melhores lavouras de arroz da Argentina foi observado que estão produzindo ao redor de 9,7 t ha^{-1}, ou cerca de 69% do potencial, enquanto que as demais lavouras do país estão produzindo 53% do potencial. 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. Porém inferiores aos reportados na China por Dent et al. (2019).

Nesse sentido, este estudo mostrou que as produtividades médias das lavouras nas diferentes regiões orizícolas do estado do RS não alcançaram a chamada “produtividade atingível” (80% do Yp, VAN ISTTURSEM et al., 2013), indicando o quanto, ainda, é possível melhorar o manejo de arroz no RS (Tabela 3 – Capítulo 2). Além disso, trabalhos afirmar que a maior faixa de lucratividade das lavouras acontece quando elas estão próximas dos 80% do Yp (Fischer, 2015; Xavier et al., 2021). Portanto, esse resultado serve como estímulo para que agricultores, técnicos e instituições de pesquisa do país trabalhem em cima dos resultados gerados nesse trabalho visando diminuir as lacunas de produtividade e aumentar a lucratividade dos orizicultores da Argentina.

Foi provado por este trabalho que a estagnação nos ganhos de produtividade por área nas lavouras nos últimos anos está sendo provocada por falhas nos manejos das lavouras. Ainda há espaço para aumentar a produção por área de maneira sustentável, reduzindo o impacto ambiental e aumentando o lucro dos produtores. Caso todas as lavouras do país produzissem 80% do potencial, a produção anual de arroz na Argentina ultrapassaria 2 milhões de toneladas de arroz em casca.

Os principais fatores de manejo que estão diminuindo as produtividades das lavouras na Argentina foram identificados como 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 aos agricultores. As informações aqui relatadas podem ser usadas como ponto de partida e de subsídio para ajustar o manejo atual das lavouras de arroz irrigado visando aumentar as produtividades médias.

5 CONCLUSÃO

a) Os modelos de simulação de culturas SimulArroz e ORYZA v3 foram confiáveis e capazes de simular o desenvolvimento do arroz e potencial de produtividade na Argentina.

b) O potencial de produtividade médio de arroz irrigado para a Argentina subtropical, estimado pelo modelo SimulArroz variou de 3,8 a 15,6 Mg ha^{-1}, e de 7,6 a 14,3 Mg ha^{-1} no ORYZA v3 em função de épocas de semeadura e locais.

c) Os maiores potenciais de produtividade foram encontrados quando as datas de emergência das lavouras foram em setembro e outubro.

d) O potencial de produtividade para arroz irrigado na Argentina, segundo as metodologias da plataforma GYGA seguidas nesse trabalho, é de 14.1Mg ha^{-1}. A lacuna de produtividade no país é de 53% do potencial produtivo.

e) A Argentina pode aumentar, na atual área agrícola, a produção de arroz em 919.091 toneladas de arroz em casca anualmente, apenas fechando a lacuna explorável.

f) As práticas de manejo que mais estão afetando a produtividade de arroz irrigado na Argentina são rotação de culturas, controle de plantas daninhas, época de semeadura e densidade de plantas.

A estagnação nos ganhos de produtividade por área na Argentina nos últimos anos pode ser revertida com a adoção de práticas de manejo que aumentem o rendimento médio as lavouras. Há espaço para aumentar o rendimento médio, via diminuição da lacuna de produtividade.

6 REFERÊNCIAS

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.

ARAMBURU MERLOS, F. et al. Potential for crop production increase in Argentina through closure of existing yield gaps. **Field Crops Research**, [s. l.], v. 184, p. 145–154, 2015. Disponível em: <http://dx.doi.org/10.1016/j.fcr.2015.10.001>.

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

BOUMAN, B. A. M., KROPFF, M. J., TUONG, T. P., WOPEREIS, M. C. S., TEN BERGE, H. F. M., & VAN LAAR, H. H. (2001). ORYZA 2000: Modeling lowland rice. Los Baños, Philippines: International Rice Research Institute, and Wageningen: Wageningen University and Research Centre.

CASSMAN, Kenneth G.; GRASSINI, Patricio. A global perspective on sustainable intensification research. Nature Sustainability, v. 3, n. 4, p. 262-268, 2020.

CASSMAN, K. G. et al. M Eeting C Ereal D Emand W Hile P Rotecting N Atural R Esources and I Mproving E Nvironmental Q Uality. **Annual Review of Environment and Resources**, [s. l.], v. 28, n. 1, p. 315–358, 2003.

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.

CONAB. Companhia Nacional de Abastecimento. Portal de informações - Evolução Estimativas. Disponível em: <https://portaldeinformacoes.conab.gov.br/safra-evolucao-dashboard>. Acesso em: 17 janeiro 2021.

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.

EVANS, L.T. **Crop evolution, adaptation, and yield**. Cambridge University Press, Cambridge, UK, 1993..

FAOSTAT Database – **Produção Agrícola (FAO)**. Disponível em: <http://faostat.fao.org/>. Acesso em: 5 janeiro 2021.

FERNANDEZ, J.P.R., FRANCHITO, S.H., RAO, V.B. AND LLOPART, M. (2017), Changes in Koppen–Trewartha climate classification over South America from RegCM4 projections. Atmos. Sci. Lett, 18: 427-434. https://doi.org/10.1002/asl.785

GAFFNEY, Jim et al. Science-based intensive agriculture: Sustainability, food security, and the role of technology. Global Food Security, v. 23, p. 236, 2019.

GRASSINI, P. et al. Drivers of spatial and temporal variation in soybean yield and irrigation requirements in the western US Corn Belt. **Field Crops Research**, [s. l.], v. 163, p. 32–46, 2014. Disponível em: <http://dx.doi.org/10.1016/j.fcr.2014.04.005>.

GRASSINI, P., VAN BUSSEL, L. G. J., VAN WART, J., WOLF, J., CLAESSENS, L., YANG, H., BOOGAARD, H., DE GROOT, H., VAN ITTERSUM, M. K., & CASSMAN, K. G. (2015). How good is good enough? Data requirements for reliable crop yield simulations and yield-gap analysis. Field Crops Research, 177, 49–63. https://doi.org/10.1016/j.fcr.2015.03.004

GUILPART, N. et al. Rooting for food security in Sub-Saharan Africa. **Environmental Research Letters**, [s. l.], v. 12, n. 11, 2017.

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.

JUNIOR AJD, STRECK NA, ZANON AJ, et al. Rice yield potential as a function of sowing date in southern Brazil. Agronomy Journal. 2021;1-12. https://doi.org/10.1002/agj220610.20610

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.

LI, T., ANGELES, O., MARCAIDA, M. III, MANALO, E., MANALILI, M. P., RADANIELSON, A., & MOHANTY, S. (2017). From ORYZA2000 to ORYZA (v3): An improved simulation model for rice in drought an nitrogen-deficient environments. Agricultural and Forest Meteorology, 237–238, 246–256. http://doi.org/10.1016/j.agrformet.2017.02.025

LOBELL, D. B.; CASSMAN, K. G.; FIELD, C. B. Crop Yield Gaps: Their Importance, Magnitudes, and Causes. **Annual Review of Environment and Resources**, [s. l.], v. 34, n. 1, p. 179–204, 2009.

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

MINISTERIO DE AGRICULTURA, GANADERIA Y PESCA. Agricultura - Estimaciones agrícolas. 2021 (Acesso < https://datos.magyp.gob.ar/dataset/estimaciones-agricolas>.)

MUELLER, N. D. et al. Closing yield gaps through nutrient and water management. **Nature**, [s. l.], v. 490, n. 7419, p. 254–257, 2012. Disponível em: <http://dx.doi.org/10.1038/nature11420>.

MUKHERJEE, N. et al. Implication of Changing Consumption Pattern On Food. [s. l.], 2011.

PILECCO, I. B.; SILVA, M. R.; RIBAS, G. G.; DUARTE JUNIR; A. J.; STRECK, N. A.; ZANON, A. J. (2020). Can Brazil Produce Enough Rice To Meet Demand In 2028? Ciência e Natura, V42. DOI:10.5902/2179460X42318

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.

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

ROSA, H. T.,WALTER, L. C., STRECK, N. A., DE CARLI, C., RIBAS, G. G., & MARCHESAN, E. (2015). Simulation of rice growth and yield in Rio Grande do Sul with the SimulArroz. (In Portuguese, with English abstract.) Revista Brasileira de Engenharia Agrícola e Ambiental, 19(12), 1159–1165. 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

TSENG, MC.; ROEL, A.; MACEDO, I.; MARELLA, M.; TERRA, J.; ZORRILLA, G.; PITTELKOW, C. M. Field-level factors for closing yield gaps in high-yielding rice systems of Uruguay, Field Crops Research, Volume 264, 2021. https://doi.org/10.1016/j.fcr.2021.108097.

TIMSINA, J. et al. Can Bangladesh produce enough cereals to meet future demand? **Agricultural Systems**, [s. l.], v. 163, p. 36–44, 2018. Disponível em: <http://dx.doi.org/10.1016/j.agsy.2016.11.003>.

VAN DIJK, Michiel et al. Disentangling agronomic and economic yield gaps: An integrated framework and application. Agricultural Systems, v. 154, p. 90-99, 2017.

VAN ITTERSUM, M. K. et al. Yield gap analysis with local to global relevance-A review. **Field Crops Research**, [s. l.], v. 143, p. 4–17, 2013. Disponível em: <http://dx.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**, [s. l.], v. 52, n. 3, p. 197–208, 1997.

VAN LOON, M. P. et al. Impacts of intensifying or expanding cereal cropping in sub-Saharan Africa on greenhouse gas emissions and food security. **Global Change Biology**, [s. l.], v. 25, n. 11, p. 3720–3730, 2019.

XAVIER, A.I.S.; ARBAGE, A.P.; SILVA, M.R. DA; RIBAS, G.G.; MEUS, L.D.; SANTOS, G.A. DE A. DOS; STRECK, N.A.; ZANON, A.J. Economic and productive analysis of irrigated rice crops using a multicase study. Pesquisa Agropecuária Brasileira, v.56, e02037, 2021. DOI: https://doi.org/10.1590/S1678-3921. pab2021.v56.02037.

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

ZHENG, H. et al. Closing water productivity gaps to achieve food and water security for a global maize supply. **Scientific Reports**, [s. l.], v. 8, n. 1, p. 2–11, 2018. Disponível em: <http://dx.doi.org/10.1038/s41598-018-32964-4>.

YUAN, S. ET AL., (2021). A roadmap towards sustainable intensication for a larger global rice bowl. *Nature*. https://doi.org/10.21203/rs.3.rs-401904/v1.