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

Felipe Tonetto

IRRIGAÇÃO POR ASPERSÃO EM ARROZ: AVALIAÇÃO ECONÔMICA, USO DA ÁGUA E RENDIMENTO DE GRÃOS EM RESPOSTA À DISPONIBILIDADE HÍDRICA

Santa Maria, RS
2024

Felipe Tonetto

IRRIGAÇÃO POR ASPERSÃO EM ARROZ: AVALIAÇÃO ECONÔMICA, USO DA ÁGUA E RENDIMENTO DE GRÃOS EM RESPOSTA À DISPONIBILIDADE HÍDRICA

Tese apresentada ao Curso de Doutorado do Programa de Pós-Graduação em Engenharia Agrícola, Área de Concentração Engenharia de Água e Solo, da Universidade Federal de Santa Maria (UFSM, RS), Como requisito parcial para a obtenção do grau de **Doutor em Engenharia Agrícola.**

Orientadora: Prof.ª Dr.ª Mirta Teresinha Petry

Santa Maria
2024

Tonetto, Felipe
IRRIGAÇÃO POR ASPERSÃO EM ARROZ: AVALIAÇÃO ECONÔMICA,
USO DA ÁGUA E RENDIMENTO DE GRÃOS EM RESPOSTA À
DISPONIBILIDADE HÍDRICA / Felipe Tonetto.- 2024.
81 p.; 30 cm

Orientadora: Mirta Teresinha Petry
Coorientador: Juliano Dalcin Martins
Tese (doutorado) - Universidade Federal de Santa
Maria, Centro de Ciências Rurais, Programa de Pós
Graduação em Engenharia Agrícola, RS, 2024

1. Oryza sativa L. 2. manejo da água 3.
sustentabilidade 4. aspersão 5. Kc I. Petry, Mirta
Teresinha II. Dalcin Martins, Juliano 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.

Declaro, FELIPE TONETTO, para os devidos fins e sob as penas da lei, que a pesquisa constante neste trabalho de conclusão de curso (Tese) foi por mim elaborada e que as informações necessárias objeto de consulta em literatura e outras fontes estão devidamente referenciadas. Declaro, ainda, que este trabalho ou parte dele não foi apresentado anteriormente para obtenção de qualquer outro grau acadêmico, estando ciente de que a inveracidade da presente declaração poderá resultar na anulação da titulação pela Universidade, entre outras consequências legais.

Felipe Tonetto

IRRIGAÇÃO POR ASPERSÃO EM ARROZ: AVALIAÇÃO ECONÔMICA, USO DA ÁGUA E RENDIMENTO DE GRÃOS EM RESPOSTA À DISPONIBILIDADE HÍDRICA

Tese apresentada ao Curso de Doutorado do Programa de Pós- Graduação em Engenharia Agrícola, Área de Concentração Engenharia de Água e Solo, da Universidade Federal de Santa Maria (UFSM, RS), Como requisito parcial para a obtenção do grau de **Doutor em Engenharia Agrícola.**

Aprovado em 07 de junho de 2024:

Mirta Teresinha Petry, Dra. (UFSM)
(Presidente/Orientadora)

Juliano Dalcin Martins, Dr. (UFSM)

Eduardo Anibele Streck, Dr. (IFFAR - SVS)

Mara Grohs, Dra. (IRGA)

Robson Giacomeli, Dra. (UFSM)

Zanandra Boff de Oliveira, Dr. (UFSM)

Santa Maria, RS
2024

AGRADECIMENTOS

A Deus por ter me dado esta oportunidade, por ter me guiado e pela sua proteção. Agradeço a ele também todas as coisas que ocorrem em minha vida e por tudo o que possuo.

Aos meus pais, Helvio e Celia, pelos conselhos, sugestões, carinho e todo o apoio que me deram em minha vida.

Ao meu irmão, Gilnei, pelo seu apoio, amizade e companheirismo em minha jornada.

A professora e orientadora Drª Mirta Teresinha Petry, pela orientação, conselhos, compreensão e pelo exemplo de dedicação e responsabilidade com a pesquisa.

Ao PPGEA/UFSM pela oportunidade de realizar o curso de Doutorado, pelo conhecimento que me foi transmitido e por tudo que aprendi em cada momento do curso.

Aos demais professores do PPGEA, pelos ensinamentos, exemplos e auxílios durante as disciplinas e demais atividades no curso de Doutorado nesse período.

Aos colegas do Laboratório de Irrigação, pelo auxílio nas tarefas do laboratório, pelo aprendizado e pela amizade ao longo do curso. Um especial agradecimento aos colegas: Bruna de Villa, Murilo Brum de Moura, Jamilson Elia Slim, Alessandra Machado Ferreira, Andressa Fuzer Gonsalves e ao Cassio Miguel Ferrazza.

A secretária do departamento de engenharia agrícola pelo auxílio e orientações durante este período.

A todos que de uma forma ou de outra que colaboraram para a conclusão deste trabalho.

A todos, muito obrigado!

A maior recompensa para o trabalho do homem não
é o que ele ganha com isso, mas o que ele se torna
com isso.
(John Ruskin)

RESUMO

IRRIGAÇÃO POR ASPERSÃO EM ARROZ: AVALIAÇÃO ECONÔMICA, USO DA ÁGUA E RENDIMENTO DE GRÃOS EM RESPOSTA À DISPONIBILIDADE DE ÁGUA

AUTOR: Felipe Tonetto
ORIENTADORA: Mirta Teresinha Petry

O cultivo do arroz por aspersão é uma alternativa à inundação contínua (IC), pelo menor consumo de água e menor custo operacional, sobretudo nas operações de preparo do solo e mão de obra. Entretanto, a manutenção dos parâmetros de crescimento e rendimento em níveis próximos aos da IC é o principal fator a ser superado. Portanto, o momento de irrigara e a frequência de irrigação necessitam ser investigadas, de modo a auxiliar o produtor na tomada de decisão em trocar um sistema bem conhecido e altamente produtivo por um sistema ainda pouco usado no arroz. Dentre esses desafios estão os estudos para calibrar os coeficientes de cultivo e determinar o manejo de irrigação mais adequado para se atingir alta produtividade com baixo consumo de água. Assim, experimentos foram conduzidos durante as safras 2020/21, 2021/22 e 2022/23 em Argissolo Bruno-Acinzentado, visando determinar o requerimento hídrico e derivar os coeficientes de cultura do arroz aeróbico, avaliar os parâmetros de crescimento, a produtividade da água e da cultura e retorno do arroz cultivado sob aspersão. Duas cultivares de arroz de terras baixas (IRGA-424 RI e IRGA-431 CL) foram submetidas a três manejos de irrigação: (i) irrigações diárias; (ii) irrigações alternadas e; (iii) sequeiro. Medições da umidade do solo foram realizados durante todo o ciclo. Parâmetros de crescimento foram avaliados em alguns estádios do ciclo. O coeficiente de cultivo basal (K_{cb}) calibrado pelo modelo SIMDualK$_c$ foi de 0,15, 1,08 e 0,80, enquanto os coeficientes de cultura (K_c) foram 0,72, 1,13 e 0,95, para os estádios inicial, médio e final, respectivamente. Os valores de K_{cact} para o arroz irrigado por aspersão foram maiores do que para o arroz de sequeiro, principalmente na fase intermediária ($K_{c\ act\ mid}$ = 1,13 vs 0,82). A produtividade foi de 7.600 (±1.400) e 7.200 (± 1.800) kg ha^{-1}, com irrigação diária e alternada, respectivamente. A evapotranspiração da cultura foi de 694 (±20) e 450 mm para o irrigado e sequeiro, respectivamente. Os parâmetros de crescimento e rendimento foram afetados pelo déficit hídrico, mas não pelo manejo de irrigação. Os manejos ID e IA proporcionaram lucro operacional ao produtor.

Palavras chaves: *Oryza sativa* L., manejo da água, sustentabilidade, aspersão e Kc.

ABSTRACT

SPRINKLER IRRIGATION IN RICE: ECONOMIC EVALUATION, WATER USE AND GRAIN YIELD IN RESPONSE TO WATER AVAILABILITY

AUTHOR: Felipe Tonetto
ADVISOR: Mirta Teresinha Petry

Sprinkler rice cultivation is an alternative to continuous flooding (CF), due to its lower water consumption and lower operating costs, especially in terms of soil preparation and labor. However, maintaining growth and yield parameters at levels close to those of the CF is the main factor to be overcome. Therefore, the timing of irrigation and the frequency of irrigation need to be investigated to help growers make the decision to switch from a well-known and highly productive system to one that is still little used in rice. Therefore, the timing of irrigation and the frequency of irrigation need to be investigated to help growers make the decision to switch from a well-known and highly productive system to one that is still little used in rice. Among these challenges are studies to calibrate crop coefficients and determine the most appropriate irrigation management to achieve high yields with low water consumption. Furthermore, experiments were conducted during the 2020/21, 2021/22 and 2022/23 harvests to determine the water requirement and derive the crop coefficients of aerobic rice, evaluate the growth parameters, water and crop productivity, and return of rice grown under sprinklers. Two lowland rice cultivars (IRGA-424 RI and IRGA-431 CL) were subjected to three irrigation managements: (i) daily irrigations; (ii) alternating irrigations and (iii) rainfed. Soil moisture measurements were taken throughout the cycle. Growth parameters were assessed at certain stages of the cycle. The basal crop coefficient (K_{cb}) calibrated by the SIMDualK_c model was 0.15, 1.08 and 0.80, while the crop coefficients (K_c) were 0.72, 1.13 and 0.95 for the early, middle, and late stages, respectively. The K_{cact} values for sprinkler-irrigated rice were higher than for rainfed rice, especially in the middle phase ($K_{c\ act}$ mid = 1.13 vs 0.82). Rice yields were 7,600 (±1,400) and 7,200 (±1,800) kg ha^{-1}, with daily and alternate irrigation, respectively. Crop evapotranspiration was 694 (±20) and 450 mm for irrigated and rainfed crops, respectively. Growth and yield parameters were affected by water deficit, but not by irrigation management. ID and IA management provided the producer with an operating profit.

Key words: *Oryza sativa* L., Irrigation management, sustainability, sprinkler irrigation e Kc.

LISTA DE FIGURAS

CAPÍTULO I

LISTA DE TABELAS

CAPÍTULO I

CAPÍTULO II

LISTA DE ABREVEATURAS E SIGLAS

a_{DP} e b_{DP} -	Parâmetros para estimativa de percolação
AF-	Área Foliar
ANEEL-	Agência Nacional de Energia Elétrica
ASW-	Available Soil Water - Água disponível no solo (mm)
AWD-	Alternate Wetting and Dry- Alternado inundado e seco (mm)
B/G -	Blue/Green
BRS -	Brasil Sementes
Bt -	Horizonte B textural
b0-	Coeficiente de regressão
CAMNPAL -	Cooperativa Agrícola Mista Nova Palma
CGDD -	Cumulative growing degree-days- Graus-dia acumulado de crescimento
COFINS -	Contribuição para o Financiamento da Seguridade Social
CONAB -	Companhia Nacional de Abastecimento
CEPEA- ESALQ	Centro de Estudos Avançados em Economia Aplicada – Escola Superior de Agricultura Luiz de Queiroz
CPFL -	Companhia Paulista de Força e Luz
CN -	Curva Número da percolação profunda
CRi -	Ascensão capilar (mm)
CT -	Custo Total
CU -	Coeficiente de uniformidade
cv -	Unidade de medida de força cavalo-vapor
D -	Demanda energética do conjunto moto-bomba (kWatt)
DAE -	Dias Após e Emergência
DP -	Percolação profunda
Dri -	Esgotamento da água do solo na zona radicular no dia i
Dri-1 -	Esgotamento da água do solo na zona radicular no dia i-1
EF-	Curva Número
E_s-	Evaporação da água do solo (mm)
$E_s/ET_{c\ act}$ -	Relação de evaporação de água do solo com a evapotranspiração atual.
ET_c -	Evapotranspiração da cultura (mm)
$ET_{c\ act}$ -	Evapotranspiração da cultura ajustada (mm)

ET_o -	Evapotranspiração de referência (mm)
FC -	Floating Continous, inundação contínua
fc -	Fração de cobertura do solo pelo dossel vegetativo
FDR -	Frequency Domain Reflectometer - Reflectometria de domínio de frequência
FP -	Fora de Ponta
h -	Altura da planta (m)
ho -	Horas de operação
IA -	Irrigation alternate, irrigação alternada
IAC -	Instituto Agronômico de Campinas
IC -	Índice de carregamento
ICMS -	Imposto sobre circulação de mercadorias e serviços
Ii -	Lâmina de irrigação
ID -	Irrigation Daily, irrigação diária
IN -	Inundação contínua
INMET -	Instituto Nacional de Meteorologia
IRGA -	Instituto Rio Grandense do Arroz
JPEG -	Join Photographic Expert Grup
Kc -	Coeficiente de cultura
Kcb -	Coeficiente de cultura basal
Kc act -	Coeficiente de cultura real
Kcb end -	Kcb para o período final de desenvolvimento da cultura
Kcb ini -	Kcb para o período inicial de desenvolvimento da cultura
Kcb mid -	Kcb para o período intermediário de desenvolvimento da cultura
Ke -	Coeficiente de evaporação
Ks -	Coeficiente de estresse
Ky -	Fator de resposta ao rendimento
LO-	Lucro Operacional
MPa-	Mega Pascal
NBRWUR -	Razão de uso não benéfico da água
NRMSE-	Raiz quadrada do erro médio normalizada
NS -	Não Significativo
PASEP -	Programa de Formação do Patrimônio do Servidor Público

Pi - Precipitação
Pini - Esgotamento de água do solo na fase inicial
PIS - Programa de Integração Social
Pmed - Esgotamento de água do solo na fase média
Pfinal - Esgotamento de água do solo na fase final
p - Fração de depleção da água do solo para condição sem estresse
Pn - Potência nominal do motor em cv
FAO-PM ETo Equação de determinação da evapotranspiração de referência de Penman- Monteith proposta pela FAO
R^2- Coeficiente de determinação
RB - Receita Bruta
RAW- Água prontamente disponível do solo (mm)
REW- Água prontamente evaporável (mm)
RGE - Concessionária Rio Grande Energia
RGB - Red - Green - Blue
R/G - Red-Green
Rhmax - Umidade relativa máxima
Rhmin - Umidade relativa mínima
RMSE - Raiz quadrada do erro médio
ROi - Escoamento superficial
SWB - Balanço Hídrico do Solo
SWC - Soil water content - Conteúdo diário de água do solo
t - tempo
TaE - Trial and Error -Tentativa e Erro
TAW - Água total disponível no solo (mm)
TE - Tarifa de energia
TEW - Água total evaporável (mm)
Tc - Transpiração da cultura (mm)
Tc act - Transpiração atual da cultura (mm)
TUSD - Tarifa de Uso do Sistema de Distribuição
TWU - Total de água utilizado (m^3)
U2 - Velocidade do vento a 2 m de altura
VC - Valor de comercialização

WP -	Water Productivity - produtividade da água (kg m^{-3})
WP_{IRRI} -	Water Productivity irrigation -produtividade da água de irrigação(kg m^{-3})
WP_{T} -	Produtividade da água total utilizada (kg m^{-3})
Ya -	Rendimento real de colheita (Mg)
Ze -	Camada de solo evaporável (m)
Zr -	Comprimento radicular (m)
ΔASW -	Variação da água disponível do solo
θ_{CC} -	Conteúdo volumétrico de água no solo na capacidade de campo (cm^{3} cm^{-3})
θ_{PMP} -	Conteúdo volumétrico de água no solo no ponto de murcha permanente (cm^{3} cm^{-3})
θ_{sat} -	Conteúdo volumétrico de água no solo saturado (cm^{3} cm^{-3})
η -	Eficiência do motor (%)
2 G-R-B -	2 Green- Red -Blue

SUMÁRIO

1. INTRODUÇÃO GERAL

O arroz é um alimento básico de aproximadamente 4 bilhões de pessoas ao redor mundo (IRRI, 2019). Em 2022, a produção mundial superou 776 milhões de toneladas (FAO, 2022). O Brasil cultivou 1479,6 mil hectares de arroz na safra agrícola de 2022/23, sendo 303 mil hectares de sequeiro (CONAB, 2023). O método mais comum de irrigação para a produção mundial do arroz é a inundação. No Brasil, o arroz irrigado concentra 90% da produção e 77% da área, enquanto o arroz de sequeiro ocupa 23% da área (CONAB, 2024).

A crescente pressão de fatores socioeconômicos, somadas às alterações climáticas, têm impulsionando modificações nos sistemas tradicionais de arroz para sistemas que economizem água, sem penalizar o rendimento (CHLAPECKA et al., 2021; PETRY et al., 2024;). Dentro deste contexto, o arroz é cultivado sob sistemas de irrigação por aspersão, gotejamento ou superfície (sulcos ou faixas) (PEREORA et al., 2021), sendo caracterizado como arroz aeróbico. Esses sistemas alternativos à inundação contínua (IC) visam um menor consumo de água (BOUMAN et al., 2007), além de reduzir a emissão de gases de efeito estufa (LINQUIST et al., 2012) e acumulação de metais pesados no grão, como o mercúrio e arsênico (CARRACELAS et al., 2019b).

No Sul do Brasil, o cultivo do arroz em aspersão (pivô central) surge como alternativa à inundação, devido a sua praticidade e facilidade de operação (PINTO et al., 2018). Parfitt e Scivittaro (2017) observaram uma redução de 40% no uso da água na irrigação por aspersão em relação à inundação. De acordo com Santos et al. (2017) além dos custos de produção refletirem o processo decisório do produtor, a eficiência econômica e a gestão do empreendimento, também são indicadores relevantes do sucesso da atividade rural, pois quanto menor o custo de produção, maior será a rentabilidade do produtor. Este método de irrigação pode resultar em melhor retorno econômico e melhor sustentabilidade desse sistema de produção (PINTO et al., 2016).

Os pivôs centrais são de fácil operação, o que favorece a sua utilização (STEVENS et al., 2012), conforme referido anteriormente, mas o manejo da irrigação ainda requer atenção especial (VORIES et al., 2017; PINTO et al., 2020), principalmente a superação de incertezas referidas a: 1) ao momento e a quantidade de água para aplicar na irrigação, 2) ao limiar de umidade do solo a ser adotado para manter um crescimento e produtividade adequados para o arroz, e 3) informações confiáveis sobre a performance agronômica do arroz sob pivôs centrais em solos drenáveis, ou em solos com características físicas diferentes daquelas de terras baixas que são atualmente empregues em IC. Observações de campo combinadas com técnicas de modelagem podem fornecer informações confiáveis sobre estratégias de irrigação e sistemas de cultivos a serem adotados por produtores.

Para fins de manejo de irrigação e determinação do uso consuntivo de água ou evapotranspiração da cultura (ET_c) é extremamente importante. Usualmente, a ET_c de uma cultura é estimada pela multiplicação da evapotranspiração de referência (ET_o) por um coeficiente de cultivo (K_c), onde a ET_o é influenciada basicamente pelas condições meteorológicas, enquanto o K_c depende da planta, do estádio de desenvolvimento, área foliar e altura da planta (KOOL et al., 2014). No arroz irrigado por aspersão assim como nos demais cultivos, o K_c varia com a idade da planta, o estádio de desenvolvimento, além do local de cultivo e das condições meteorológicas. Valores de K_c podem ser facilmente encontrados na literatura (ALLEN et al., 1998), entretanto, esses se aplicam para cereais, onde o consumo de água é máximo e necessitam ser calibrados para as condições ambientais do local de plantio. Assim, estudos para estimativa do K_c para o arroz irrigado por aspersão são necessários na tentativa de melhorar o atendimento da demanda e da eficiência hídrica.

No arroz irrigado por aspersão assim como nos demais cultivos, o K_c varia com a idade da planta, o estádio de desenvolvimento, além do local de cultivo e das condições meteorológicas. Valores de K_c podem ser facilmente encontrados na literatura (ALLEN et al., 1998), entretanto, esses se aplicam para cereais, onde o consumo de água é máximo e necessitam ser calibrados para as condições ambientais do local de plantio. Assim, estudos para estimativa do K_c para o arroz irrigado por aspersão são necessários na tentativa de melhorar o atendimento da demanda e da eficiência hídrica da cultura. O K_c pode ser obtido pela combinação de robustas observações à campo com diferentes tratamentos de manejo da irrigação com modelos de balanço hídrico do solo robustos e confiáveis, a exemplo do SIMDualKc, usado por PAREDES et al. (2014, 2017a e 2017b), o qual foi utilizado para desenvolver estratégias adequadas de gestão da água na irrigação.

Considerando a possibilidade que a irrigação por aspersão possa otimizar os sistemas de cultivo de arroz, torna-se evidente a importância de determinar o coeficiente de cultura, a necessidade hídrica e obter de um manejo adequado de irrigação que auxilie o produtor irrigante na tomada de decisão e resulte em um melhor retorno econômico.

2. OBJETIVO GERAL

O objetivo deste estudo é estimar o requerimento hídrico (ET_c) do arroz, com ênfase à derivação dos coeficientes de cultivo (K_{cs}) para o arroz aeróbico, e avaliação do desempenho geral do crescimento de duas cultivares de arroz irrigado por aspersão (Capítulo I); avaliar o uso da água da água, rendimento e retorno econômico do arroz irrigado por aspersão sob diferentes estratégias de irrigação (Capítulo II).

3. CAPÍTULO I - EVAPOTRANSPIRATION AND CROP COEFFICIENTS OF SPRINKLER IRRIGATED AEROBIC RICE IN SOUTHERN BRAZIL USING THE SIMDUALKC WATER BALANCE MODEL

(Paper published on the Journal of Irrigation Science)

Abstract: Flooding rice (*Oryza sativa L.*) is commonly used in lowlands of Southern Brazil. The sustainability of this production system is threatened by an increase in the production costs, excessive water uses and an incipient plateau in yield due to biophysical limitations. Sprinkler irrigation is considered a feasible strategy to improve crop and water productivity but requires proper assessment since advances in irrigation scheduling and crop performance are not yet conclusive. A study was therefore developed to evaluate water use and overall growth performance of two sprinkler irrigated rice cultivars. Field experiments from 2020/21 to 2022/23 growing seasons, compared three treatments: (i) daily irrigation (DI), (ii) irrigation in alternate days (AI), and (iii) rainfed (RF). The season water applied for the DI treatments were 532 mm in 2020/21, 514 mm in 2021/22 and 614 mm in 2022/23, and for AI they were 490 mm, 474 mm and 621 mm for the same crop seasons. Soil water content was maintained close to field capacity in the irrigated plots. Soil moisture was daily measured using FDR sensors. Measurements of crop growth parameters were taken throughout the growing seasons. The SIMDualKc model was used to assess evapotranspiration and derive crop coefficients for each treatment. The model was calibrated with the 2020/21 DI treatment and validated with all other sets of the three growing seasons. The model accurately simulated the soil water dynamics in the root zone, with RMSE < 4.4 mm and normalized RMSE < 7%. The calibrated basal crop coefficients adjusted to climate were 0.15, 1.08(±0.01) and 0.80(±0.01), while the single crop coefficients (K_c) were 0.72(±0.04), 1.13(±0.01), and 0.95 (±0.01) for the initial, mid-season, and end-season stages, respectively. Grain yield was 7,600 (±1,400) and 7,200 (±1,800) kg ha^{-1}, with daily and alternate days irrigation, respectively, which are comparable with flooding irrigation. Results showed that sprinkler irrigation may be a proficient water-saving technology, without decreasing yields and contributing to improve the sustainability of rice systems in Southern Brazil.

Key-words: Rice cultivars performance, soil water balance, water saving irrigation, water use, yield assessment

1. Introduction

Rice is the main staple food crop in the world, the primary one for about half of the world's population, particularly in Asia. The most common irrigation method in rice production worldwide is flooding. However, aimed to decrease water use, flooding variants are applied such as dry seeding, anticipated cut-off, and intermittent water application. More recently, aerobic rice is often used with sprinkler or surface irrigation (Pereira et al. 2021). Rice is also a fundamental food in Brazil, where it is grown mainly in lowlands of Southern Brazil under continuous flooding irrigation (Sousa et al. 2021). There, the standard rice system consists of intense conventional tillage (plowing, harrowing, and leveling) in early Spring, followed by dry sowing. These fields are generally flooded by V3 to V5 stages (Counce et al. 2000), hence around 15-25 days after sowing (Sosbai 2018; Carracelas et al. 2019), and remaining with a 10 cm water layer over the ground until near harvest. However, most of these rice fields are not precise leveled, which leads to poor uniformity of water application and to larger water use.

Common continuous flooding (CF) systems require large amounts of irrigation water and much labor force, thus rising in labor and pumping costs (Ávila et al. 2015; Clegert et al. 2016). CF systems have various negative environmental impacts that are difficult to control, which lead to shift for more environmentally friendly systems that require less labor and allow better control of water and chemicals use. Alternatives to CF include: a) alternate wetting and drying (AWD), where alternate cycles of flooding and soil drying are used (Lindquist et al. 2015a; Carrijo et al. 2017, 2018; Carracelas et al. 2019; LaHue and Linquinst, 2021; Mote et al. 2021); b) intermittent irrigation, in which the soil surface is maintained saturated but without ponding (Bouman et al. 2007; Li et al. 2022), and where water is applied as a sheet on leveled strips (Carracelas et al. 2019; Aramburu et al. 2022); c) aerobic rice, which include surface irrigated (Alberto et al. 2011; Chowdury et al. 2013), sprinkler-irrigated (Spanu et al. 2010; Vories et al. 2013; Borja Reis et al. 2018; Pinto et al. 2020), or drip irrigated rice (Coltro et al. 2017; Parthasarathi et al. 2018). Common objectives of all these strategies consist of reducing water use without decreasing grain yield and, at same time, improving the sustainability of rice production.

In the Southern Brazil, sprinkler irrigation using center-pivot systems has increased in the last years (Parfitt et al. 2017; Pinto et al. 2020), also driven by the need to control weed species that are difficult to manage under flooding (Avila et al. 2021). Sprinkler-irrigation by center pivots is known after a few decades but with contradictory results (Muirhead et al. 1989). Recently, with new rice cultivars sprinkling shows advantages over hand-managed intermittent and AWD systems, mainly to maintain a shallow water sheet on the soil surface if soils are permeable or the paddies are not precision leveled, so resulting in non-uniform water infiltration into the fields (Vories et al. 2013). Non-uniformity also causes problems in weed control (Ávila et al. 2015) and nutrient availability, resulting in lower yields (Vories et al. 2017; Carrijo et al. 2017). Moreover, sprinkler irrigation allows farmers to include rice in crop rotations and eases other agronomics practices such as weeds control (Ulguim et al. 2021). This approach may result in improved economic returns and sustainability (Pinto et al. 2016).

The easy-to-use center pivots favors their use (Stevens et al. 2012) as referred before, but irrigation management still requires adequate attention (Vories et al. 2017; Pinto et al. 2020). Overcoming related uncertainty which mainly refers to: 1) the timing and amount of irrigation water to apply, 2) the soil moisture threshold to be adopted to maintain appropriate rice growth and productivity, and 3) reliable information about rice agronomic performance under center pivots in drainable soils, or in soils with physical characteristics different of those of lowlands currently used in CF. Field observations combined with modeling approaches may provide robust and reliable information about the irrigation strategies and cropping systems to be adopted by farmers. This is the case of using the soil water balance model SIMDualKc (Rosa et al. 2012), tested for center-pivot irrigated maize (Paredes et al. 2014), malt barley (Paredes et al. 2017a) and pea (Paredes et al. 2017b), and more recently for rice with drainage lysimeters measurements (Anupoju and Kambhammettu 2020). This model may perform as a decision support system relative to the timing and amount of water to apply. Alternative cropping and rotation systems may also be simulated with SIMDualKc, as tested by Miao et al. (2016). Irrigation schedules with SIMDualKc at the farm level should lead to suitable crop yields aligned with optimized water use when combining irrigation water with precipitation and available soil water (Pereira et al. 2020; Jovanovic et al. 2020) with consideration of economic returns (Paredes et al. 2017a).

The widely accepted method to estimate crop water demand, the crop evapotranspiration (ET_c), is the FAO K_c-ET_o approach (Allen et al. 1998), where ET_c is the product of the grass reference evapotranspiration (ET_o) by a crop coefficient (K_c). Although the K_c-ET_o approach has been widely used for rice, its application for sprinkler irrigation rice is yet limited (Spanu et al. 2009; Moratiel and Martinez-Cob 2013; Alberto et al. 2014). A first Brazilian study on rice sprinkling (Arf et al. 2003) did not search for K_c values but, more recently, Pereira et al. (2021) reported on standard K_c and K_{cb} values for aerobic rice. Therefore, it is opportune to search for K_c, water use and yields for rice under sprinkling.

When adopting the FAO K_c-ET_o approach, searching for K_c is important because, while ET_o is well standardized, it is required to obtain K_c/K_{cb} from performing the soil water balance

(SWB) simulation against observed water use and to relate the latter with yield. Focusing on the standard K_c allows its transfer to different locations and climates (Allen et al. 1998; Pereira et al. 2021) since the standard K_c refers to a crop grown under pristine conditions, free of pests and diseases, and without fertilizer restrictions or soil salinity problems (Pereira et al. 2015a; Pereira et al. 2021). Standard K_c refers to standard sub-humid climate conditions (minimum relative air humidity of 45% and wind speed at 2 m height of 2 m s^{-1}), thus when transferred must be adjusted to the local climate (Allen et al. 1998; Pereira et al. 2021). Thus, yet with few research information, it is required to find K_c and K_{cb} values for local conditions of sprinkler irrigated rice, however cropped under near pristine conditions. K_c may then be obtained by coupling robust and reliable field observations of different irrigation scheduling treatments with well proved soil water balance models, e.g., SIMDualKc used by Paredes et al. (2014, 2017a and 2017b) which were used to develop appropriate strategies for irrigation water management.

The existing SWB models are for lowland paddy fields adopting CF (Mao et al. 2004), AWD (Yu and Cui 2022) or rainfed (Inthavong et al. 2011). The use of SWB models for sprinkler rice is not yet reported in literature. Nevertheless, the model SIMDualKc (Rosa et al. 2012), many times used for aerobic crops as referred before, has also been used for anaerobic rice (Anupoju and Kambhammettu 2020), thus having a wider applicability. A SWB is supposed to account for the water inputs and outputs of the paddy field system, on the one hand rainfall, irrigation, upflow, soil water reserve and, on the other hand, soil evaporation, transpiration, deep percolation, and runoff (Fukai and Mitchell 2022). Using SIMDualKc has the advantage of well performing the partition of ET using the FAO dual K_c approach (Allen et al. 1998, 2005). This model is well known in Brazil, which is an advantage (e.g., Martins et al. 2013; González et al. 2015; Paredes et al 2018; Petry et al. 2023). Alternatively, crop models, e.g., DSSAT (Jeong et al. 2014) and AquaCrop (Xu et al. 2019), that may be used if able to simulate the overall rice system behavior and yields.

Hypothesizing that sprinkler irrigation can improve the rice cropping systems, the objectives of this study in the subtropical climate region of Southern Brazil are to: (i) calibrate and validate the SIMDualKc model and estimate the basal and single crop coefficients for aerobic rice; ii) investigate the daily and seasonal variation of the actual crop evapotranspiration of aerobic rice; (iii) assess the soil water balance of upland aerobic rice and compare water use with flooded rice paddies (iv) evaluate the impact of the different irrigations strategies on agronomic features, mainly yields. Innovation consists of modeling sprinkler irrigated aerobic rice and accurately performing the soil water balance.

2. Materials and Methods

2.1 Study site characteristics

The research was conducted in the cropping seasons of 2020/2021, 2021/2022, and 2022/2023 in an experimental area at the Federal University of Santa Maria (29°41'24" S, 53°48'42" W and 105 masl). The climate is characterized as humid subtropical "Cfa," according to the Köppen-Geiger classification (Kottek et al. 2006). In this type of climate, there is no well-defined dry season, but rather hot summers and temperate winters (Alvares et al. 2013). Precipitation is distributed evenly throughout the year, summing around 1700 mm.

During the three experimental seasons, meteorological data were obtained from an automatic weather station from the National Institute of Meteorology (INMET) located approximately 150 m from the experimental site. The collected daily weather data included maximum and minimum air temperature (T_{max} and T_{min}, ºC), global solar radiation (R_s, MJ m^{-2} day^{-1}), wind speed measured at 2 m height (U_2, m s^{-1}), maximum and minimum relative humidity (RH_{max} and RH_{min}, %) and rainfall (mm). The reference evapotranspiration was computed daily with the FAO-PM ET_o equation (Allen et al. 1998). Some of the weather conditions recorded during the experimental periods in all growing seasons are shown in Figure 1 and the average monthly climate data are presented in Table 1.

Table 1 shows that precipitation during the experimental growing seasons is much lower than in the long-term average data series; differently, ET_o values were quite similar.

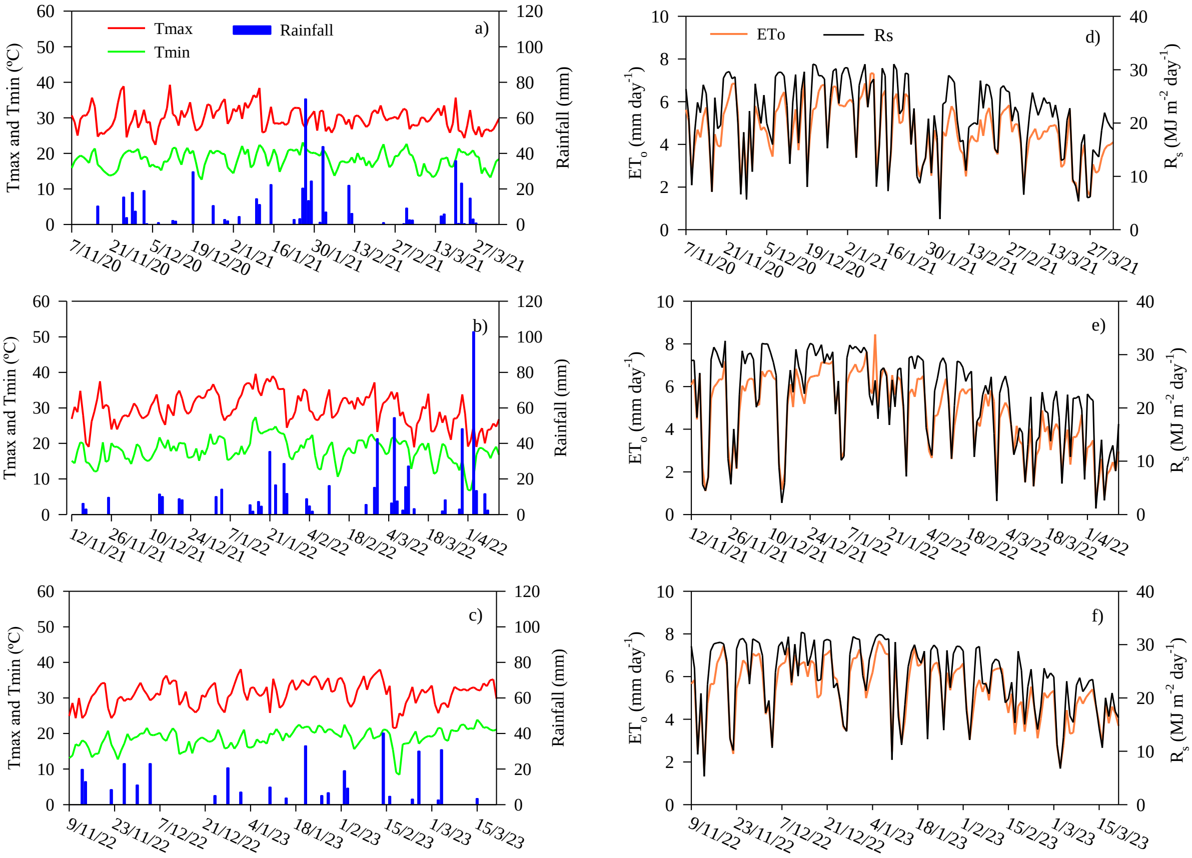


Fig. 1- Weather data relative to the three-years (2020/21, 2021/22 and 2022/23) of experimentation: (a; b and c) maximum and minimum temperature, and precipitation; (c; d and e) reference evapotranspiration and solar radiation.

Table 1 Average monthly climate data for the experimental growing seasons (2020-2023) and for the long time series 1990-2022, Santa Maria, Brazil.

(continua)

Season/month	T_{max} (ºC)	T_{min} (ºC)	RH_{min} (%)	U_2 (m s^{-1})	ET_o (mm day^{-1})	Rainfall (mm)
			2020/2021			
Nov	29.8	17.9	38.0	1.8	1.7	55
Dec	30.4	18.4	37.7	1.7	5.3	69
Jan	30.9	19.4	44.4	1.7	5.0	187
Feb	29.7	18.1	48.6	1.3	4.5	82
Mar	28.9	17.7	50.5	1.3	3.7	104
Apr	27.7	16.2	44.3	1.7	4.0	0
			2021/2022			
Nov	28.0	16.6	46.2	1.3	4.6	19
Dec	30.4	17.9	42.3	1.5	5.8	63
Jan	33.2	20.5	43.1	1.7	5.9	127
Feb	30.9	18.3	46.0	1.4	4.8	86
Mar	28.0	17.2	56.8	1.4	3.6	288
Apr	23.0	15.3	68.3	1.3	2.2	14

Table 1 Average monthly climate data for the experimental growing seasons (2020-2023) and for the long time series 1990-2022, Santa Maria, Brazil.

(conclusão)

Season/month	T_{max} (ºC)	T_{min} (ºC)	RH_{min} (%)	U_2 (m s^{-1})	ET_o (mm day^{-1})	Rainfall (mm)
			2022/2023			
Nov	29.0	16.5	42.0	1.8	5.5	75
Dec	31.1	18.2	38.7	1.8	5.9	49
Jan	32.7	19.8	39.7	1.6	5.9	65
Feb	31.3	18.2	42.4	1.3	5.0	106
Mar	31.5	21.1	55.0	1.3	4.1	37
			Long time average (1990-2022)			
Nov	27.3	17.7	51.5	1.8	4.7	157
Dec	29.6	19.9	51.0	1.8	5.3	166
Jan	30.1	20.9	54.3	1.6	5.1	171
Feb	29.4	20.3	58.2	1.5	4.4	132
Mar	28.1	18.8	58.6	1.4	3.7	137
Apr	25.2	15.8	60.4	1.4	2.6	152

The soil is a well-drained Ultisol (Soil Survey Staff 2022), with a loam texture to a depth of 0.70-0.80 m, followed by a Bt clayey horizon. To determine the soil hydraulic properties three undisturbed soil samples of 71 cm^3 were taken at every 0.10 m soil layer and at each site before the experimental implementation (Table 2). The soil water retention at –10 kPa, used as estimator of the water content at field capacity (θ_{FC}), was determined with the pressure plate apparatus (Soil Moisture Equipment Corp., S. Barbara, CA, USA). The water retention at the wilting point (θ_{WP}) was set using the pedotransfer functions (PTF) developed by Michelon et al. (2010). The particle size distribution was determined using the Pipette Method (Day 1965). The mean and standard deviation results of the three fields used in this study are summarized in Table 2.

Table 2 Mean and standard deviation of soil textural and hydraulic characteristics of the soils of the experimental sites.

Soil depth (m)	Texture (%)			θ (cm^3cm^{-3})		
	Sand	Silt	Clay	θ_{sat}	θ_{FC}	θ_{PWP}
0.0-0.10	41±1.8	39±2.2	21±2.1	0.50±0.03	0.37±0.01	0.16±0.01
0.1-0.2	42±0.8	36±1.4	23±1.6	0.47±0.03	0.35±0.02	0.16±0.02
0.2-0.3	39±0.9	37±4.3	24±4.0	0.46±0.02	0.33±0.02	0.15±0.01
0.3-0.4	42±1.2	30±5.9	28±1.2	0.48±0.01	0.33±0.03	0.15±0.00
0.4-0.5	41±1.1	23±1.7	37±5.2	0.52±0.05	0.37±0.03	0.18±0.00

θ_{sat} - volumetric soil water content at saturation; θ_{FC} - volumetric soil water content at field capacity; θ_{PMP} volumetric soil water content at the permanent wilting point.

2.2 EXPERIMENTAL DESIGN AND TREATMENTS

During the 2020/21 and 2021/22 growing seasons, the experiments were designed in a randomized 3x2 bifactorial scheme in stripes with 12 x 4.10 m and four replicates. Factor A comprised the irrigation strategies, while factor B comprised two rice cultivars. The irrigation strategies were: a) DI, using daily irrigation depths of 8 mm, aiming at no stress; b) AI, alternate irrigation, applied every other day with depths of 16 mm; and c) RF, rainfed. Two of the most planted rice cultivars in paddy fields of Rio Grande do Sul were used: IRGA 424 RI and IRGA 431 CL, respectively of intermediate and precocious cycle duration and herbicide-resistant to the chemical group of the imidazolinones (Clearfield®). In the 2022/23 growing season, the cultivar IRGA 431 RI was cropped in a completely randomized design with the two referred sprinkler irrigation strategies in six replications.

Experiments were sown by November 7, 2020, November 12, 2021, and November 9, 2022 with a seedling rate of ~112 kg ha^{-1}, and a row-spacing of 0.17 m using a direct-tillage drill (12-rows continuous flux, model Ceres 1870 (Stara Corp, Não-Me-Toque, RS, Brazil). Sowing was performed on black oat crop residues. Seeds were treated with 25 g L^{-1} Pyraclostrobin + 225 g L^{-1} Methyl Thiophanate + 250 g L^{-1} Fipronil using a spray volume of 1000 ml for each 100 kg of seeds. At sowing, 15 kg ha^{-1} of N, 60 kg ha^{-1} of P, and 60 kg ha^{-1} of K were applied. For all growing seasons, the N at topdressing was split into three applications: 90 kg ha^{-1} at the beginning of tillering (V3 to V4), 40 kg ha^{-1} in the V6 stage (panicle initiation), and 30 kg ha^{-1} in the form of urea in the R1 stage, i.e., the panicle differentiation, when the newly formed panicle becomes visible (Counce et al. 2000). Weed control and other agronomics practices throughout the crop seasons followed technical recommendations for rice in Southern Brazil (Sosbai, 2018).

2.3 SOIL MOISTURE MEASUREMENTS AND IRRIGATION MANAGEMENT

Soil water content was measured using FDR sensors (Frequency Domain Reflectometer), model CS616, connected to an analogic multiplexer (AM16/32) and a CR1000 datalogger (Campbell Scientific, Logan, UT, USA). In the crop seasons of 2020/21 and 2021/22, measurements were taken to a soil depth of 0.4 m, while in 2022/23 the soil water content was measured to a depth of 0.5 m. All sensors were installed few days after sowing. The sensors have been carefully inserted with the aim of disturbing the soil as little as possible. First, the sensors were carefully buried in the ground to ensure complete contact between the probes and the soil surrounding them. The datalogger was set to store data every 15 minutes. All measurements were verified using the oven-dry soil water content (θ) at the same soil depth.

The datalogger was then set to store hourly measurements. The sensors were re-inserted or eventually replaced if the measurements deviated more than 0.1% from the oven dry value. In the 2020/21 and 2021/22 seasons two sensors per plot and two plots per cultivar and irrigation treatment were used, while in the 2022/23 crop season three sensors were used in four plots per treatment.

In the 2020/21 and 2021/22 seasons, irrigation was carried out using a semi-portable sprinkler system, with half-circle sprinklers type Pingo® (Tigre Ltda, Joinville, SC, Brazil), spaced 12 x 12 m, operating at a pressure of 350 kPa and a rate of 9.8 mm h^{-1}. During the 2022/23 crop season, the sprinklers used were half-circle, type MIDI (Tigre Ltda, Joinville, SC, Brazil), with a rate of 17.7 mm h^{-1}, operating at 420 kPa. Sprinklers were raised at 1.80 m above the soil surface. The distribution uniformity of the systems was assessed in all growing seasons, between the sowing date and crop emergency, using the Christiansen method (1942). The average uniformity coefficient (CU) was 80 and 74% for the 2020-2022 crop seasons and 2022/23, respectively. Catch cans were randomly placed in some irrigated plots throughout all crop seasons to ensure the intended water depth was adequately applied in each treatment. Irrigations were homogeneously applied in all irrigated treatments during the crop germination and initial development. Irrigations were applied either after sunset or at dawn to minimize the wind effects on the water distribution pattern.

Irrigations were scheduled to maintain the soil water content equal to or above field capacity. The mean value of θ_{FC} was 0.34 $cm^3\ cm^{-3}$. The irrigations were set to daily apply gross irrigation depths of ≈8 mm (as commonly used by farmers when rice is cropped under center pivot in Southern Brazil), or a depth of ≈16 mm under the alternate irrigation treatment (AI). The soil water data were downloaded and analyzed twice a week. A higher water depth was applied on the next irrigation whenever the soil water content dropped below the established threshold (θ_{FC}).

2.4 CROP OBSERVATIONS

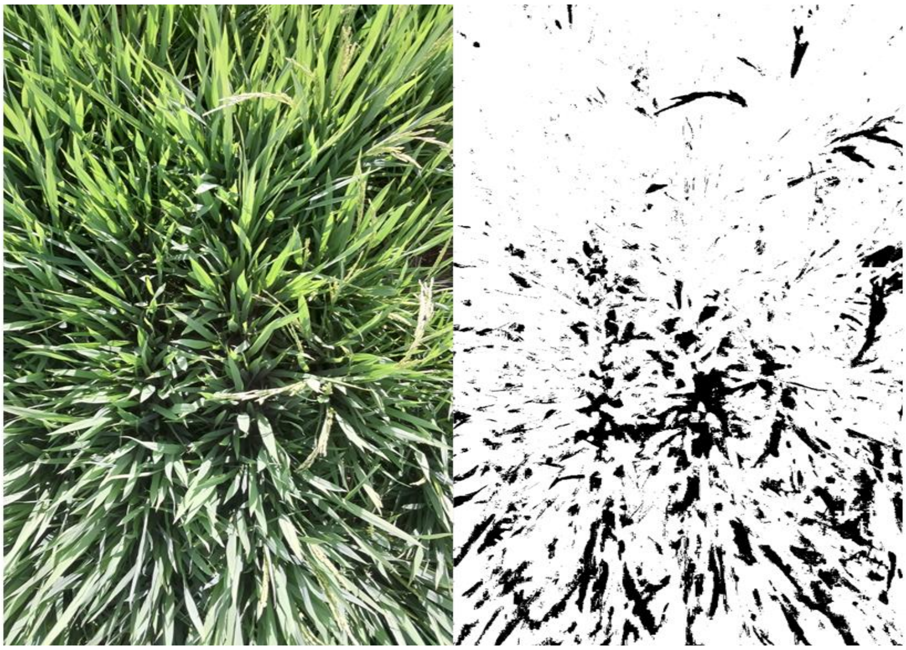
Plant emergency was counted when 50% of the prophyll from the coleoptile had emerged, at stage S3, according to the Counce et al. (2000) scale. Plant height was measured with a millimeter ruler from the soil surface to the last collared leaf on the main stem. Three plants per plot were selected and targeted at the V2 stage (collar formed on the 2nd leaf on the main stem), and measurements were performed from V2 to maturity (R9). Measurements were taken every week from plant emergency to panicle exertion, the R3 stage (Counce et al. 2000), and in two weeks intervals thereafter.

The fraction of ground covered by green crop vegetation was determined from photos taken in the center of each plot. The camera was installed upon a tripod, 1.50 m above the canopy, tilted at 90° from the horizontal, to achieve the maximum possible visualization within the plot and minimize external effects on the plotting area. The field of view was 1.00 m wide and 1.00 m long, covering five seeding rows. The image size was 2290 x 4080 pixels, in JPEG file format (Joint Photographic Experts Group), with an 8 MB size for each image. The images were taken between 2:00 p.m. and 4:00 p.m. to avoid the influence of the shadow of the canopy on days with clear sky. The images were imported into the Android Version of the Canopeo Matlab app described by Patrignani and Ochsner (2015). The Canopeo uses the RGB (red-green-blue) image system for analyzing and classifying all pixels in the image. The analyses of the pixels follow the ratios of R/G and B/G (Liang et al. 2012) as well as the excess green index (Chen et al. 2010). The result is a binary image where white pixels correspond to a green canopy, according to the selection criteria, while black pixels correspond to a non-green area (Figure 2). Thus, the fraction of green-covered space (f_c) ranges from 0 (no green canopy) to 1 (100% of green cover), according to:

$$R/G < P_1 \text{ and } B/G < P_2 \text{ and } 2G\text{-}R\text{-}B > P_3 \qquad (1)$$

where P_1 and P_2 are parameters that typically have values close to 1 with pixels that are predominantly in the green bands (~500-570 nm), while P_3 is the parameter that sets the minimum excess of green vegetation. The default parameters of P_1 and P_2 were set at 0.95, while the P_3 was set of 0.20.

A) f_c= 0.35



B) f_c = 0.85

Fig. 2 Examples of fraction of ground cover (fc), with measurements performed at (a) 09/12/2022 and (b) 04/02/2023.

The growing period of aerobic rice was estimated using the cumulative growing degree days method (CGDD), as proposed by McMaster and Wilhelm (1997), using a base threshold temperature of 12ºC (Sánchez et al. 2014; SOSBAI 2018), and the upper temperature threshold of 36 ºC (Gao et al. 1992).

Root development and distribution were analyzed at the R9 stage using the soil profile method (Böhm 1979). Trenches were open vertically across three plant rows (0.50 x 0.50 m); spatulas were used to expose the root system carefully. A frame of 0.50 x 0.50 m with a grid of 0.05 x 0.05 m mesh in nylon threads were fixed at the lateral of the trench. Photographs were then taken to analyze the root distribution on the soil profile. Only a few roots were found deeper than 0.35 m in the irrigated and rainfed treatments in the 2020/21 and 2021/22 growing seasons. Root distribution was not evaluated during the 2022/23 crop season.

2.5 CROP HARVEST AND GRAIN YIELD

After reaching the R9 stage (Counce et al. 2000), the crop was manually harvested with a sickle. In the first two cropping seasons, an area of 2.55 m^2 (5 rows x 3 meters) was harvested in the center of each plot. In the 2022/23 growing season, an area of 4.012 m^2 (8 rows x 2.95 m) was harvested and mechanically threshed. In the 2020/21 and 2021/22 crop seasons, the crop was harvested when seed moisture was 15-16%. In the 2022/23 growing season, the grain moisture content at harvest ranged from 14 to 20%. Canopy green percentage at harvest was approximately 60% on the DI plots and less than 40% on the RF and the AI irrigated plots. The grain moisture for each plot was further converted to 14% using an automatic semi-portable DICKEY-john GAC500 XT® device (Dickey-john Corp., Auburn, IL, USA) representing the actual crop yield (Y_a).

Aiming at comparing the irrigation scheduling strategies two water productivity indicators were computed: the irrigation water productivity (ratio between Y_a and the total irrigation) and the water use productivity (ratio between Y_a and the corresponding water use) as defined by Pereira et al. (2012).

2.6 Modelling the soil water balance with the SIMDualKc model

Real-time irrigation management requires that the soil water balance (SWB) is computed daily for the plant root system depth to detect soil water depletion in this layer. The SWB equation used in the SIMDualKc model (Rosa et al. 2012) is:

$$D_{r,i} = D_{r,i-1} - \left(P_i - RO_i\right) - I_i - CR_i + ET_{c\,act,i} + DP_i \qquad (2)$$

where $D_{r,i}$ and $D_{r,i-1}$ are, respectively, the soil water depletion in the root zone at the day i and at the end of the previous day i-1 (mm), P_i is the precipitation (mm), RO_i is the runoff (mm), I_i is the net irrigation depth that infiltrated in the soil (mm), CR_i is the capillary rise (mm) when there is a water table close to the surface, which did not occur in this application; DP_i is the water percolation through the root zone bottom (mm). The $ET_{c\ act,\ i}$ is the actual crop evapotranspiration (mm); from irrigation to rainfed, in different cropping conditions.

The simulation of the SWB requires a set of inputs:

(i) daily meteorological data to compute ET_o, (mm dia^{-1}), precipitation (mm), minimum relative humidity (RH_{min}, %) and wind speed observed at 2 m height (U_2, m s^{-1}).

(ii) physical and water holding characteristics for each soil layer (Table 2), initial values for the thickness of the soil evaporation layer (Z_e, m) and the readily and total evaporable water (REW and TEW, mm); and the soil moisture at sowing (expressed as % of TAW).

(iii) Initial values for the parameters of algorithms used to estimate runoff, with CN from Allen et al. (2007), and deep percolation a_{DP} and b_{DP} following Liu et al. (2006).

2.7 STATISTICAL INDICATORS, PARAMETRIZATION, AND CALIBRATION PROCEDURES

The calibration and validation of SIMDualKc model for the SWB simulation of the sprinkler irrigated aerobic rice were performed using independent data sets. The calibration used the daily irrigated treatment of the 2020/21 while the other data sets were used for validation procedure. The calibration consisted of searching the parameters that minimized the errors of the simulation, i.e., the deviation between model simulated daily soil water content (SWC) and the field observed SWC. The optimized/calibrated parameters included the basal crop coefficients for the initial, mid-season and end-season stages ($K_{cb\ ini}$, $K_{cb\ mid}$ and $K_{cb\ end}$), as well as the soil water depletion fraction for no stress (p) at the same stages (p_{ini}, p_{mid}, p_{end}). The initial K_{cb} and p values used were those suggested values by Pereira et al. (2020b). The initial values for CN and the DP parameters were those obtained by Petry et al. (2023) in a study conducted at the same site.

A trial-and-error (TaE) procedure was used, firstly focusing the K_{cb} and p values aiming to minimize the differences between the available soil water observed and simulated by the model, as proposed by Pereira et al. (2015). Simultaneously, graphs were plotted to support performing a qualitative analysis observing whether there were trends or biases of over or under-estimation by the model and when they occurred. The goodness-of-fit indicators referred below were computed for each step computation and used to assess the optimization procedure. After the errors in estimation got quite smaller, the TaE procedure was applied to adjust the soil evaporation, deep percolation, and the curve number parameters. Then, after the related minimization, the TaE was applied to all parameters until errors decreasing were much smaller, likely non-noticeable.

The goodness-of-fit indicators used were computed from the pair of observed and predicted values, respectively O_i and P_i, (where i=1, 2, …, n), and whose means are $\bar{O}$ and $\bar{P}$. The indicators used to assess the model accuracy were those described by Moriasi et al. (2007) and Pereira et al. (2015, 2020b):

(i) The regression coefficient (b_0) of a linear regression through the origin between observed and predicted values. A b_0 close to 1.0 indicates that the model is able to reproduce the observed data.

(ii) The coefficient of determination (R^2) of the ordinary least squares regression between O_i and P_i, with R^2 describing the proportion of the variance in measured data that are explained by the model;

(iii) The root mean square error (RMSE), with values ranging between 0.0 and a positive value expressed in the same units of the analyzed variable, which should be as small as possible;

(iv) The normalized RMSE (NRMSE, %), which is the ratio of the RMSE to the mean of the observed data, and which target value should preferably be smaller than 10%;

(v) The modeling efficiency (EF, dimensionless), proposed by Nash and Sutcliffe (1970), that indicates the relative magnitude of the residual variance compared to the variance of the measured data.

Obtaining positive EF values close to 1.0 should be the target; zero or negative values mean that the variance of estimated residuals is similar to the variance of the measured data, so implying that there is no gain and it is likely better to use the average of the observed values instead of those obtained in the simulation.

In addition, the results were submitted to a mathematical assumptions test model. Analysis of variance (ANOVA) of the grain yield data was performed using the F test. If significant, the factors mean were subjected to a Tukey’s test with a 5% probability of error using the statistical package SISVAR (Ferreira 2011).

3. Results and Discussion

3.1 Crop growth stages and cumulative growing degree days

Temperature is one of the most relevant factors determining rice shoots and root growth. Therefore, growth and development of rice are strongly related with growing degree days (GDD). The length of the growth stages was determined throughout all growing seasons from sowing to harvest (Table 3) as a function of cumulative GDD (CGDD). Rice is sensitive to low temperatures during the cycle, particularly during the initial stage and anthesis. Therefore, the sowing date must be planned to avoid the occurrence of low temperatures during germination, since the minimum critical temperature for *Oryza sativa* is 11.3 ºC. (±1.1 ºC) (Sanchez et al 2014); differently, for the sub-specie *indica*, the mostly used in Brazil, the minimum temperature for that stage is 10 ºC (Yoshida 1981; Sanchez et al. 2014). In the current study, a base temperature of 12°C was used as this is the critical sub-temperature for most stages, particularly for leaf and panicle initiation and during flowering. The observed CGDD for germination ranged from 70 to 72 ºC over the three growth seasons. The minimum temperature during the seedling stage was 13.3ºC in the 2021/22 growing season, 15.9ºC in 2020/21 and 13.1ºC for 2022/23. As reported by Krishnan et al. (2013) low temperatures and their fluctuations within the day affect the germination percentage in aerobic rice, slowing its process when the temperature drops below the range of 7-11ºC. Contrarily, germination can be faster with temperatures above 20ºC. Rapid germination is essential for crop establishment, but it is not significant for the final stand. As observed in the field, the germination/emergence stage spanned for almost thirty days, which is on the range of those reported by Sosbai (2018) for rice sown through November in southern Brazil.

The duration of the different stages was quite similar for the DI and AI treatments (Table 3). Differently, the beginning of the crop growth stage was delayed in 58 ºC of CGDD (5 days) in the 2020/21 crop season for the RF treatment, mainly due to the unfavorable soil moisture during the seedling and crop establishment periods. Due to water stress during the 2020/21 and 2021/22 growing seasons, the start of the mid-season was delayed for RF. Senescence started early in the RF plots (Table 3) due to soil water stress.

All treatments were harvested on the same date for logistic purposes because plots were manually threshed. Rice seed moisture content should be ranging 15 to 22% for hand threshing to prevent rice yield reduction (Nalley et al. 2016). The R9 stage (physiologic maturity), when the entire panicle became brown, was observed when CGDD was 1604 ºC (135 days) and 1584 ºC (133 days) in the 2021/21 and 2021/22 growing seasons for the IRGA 424 RI, a medium cycle cultivar, while the early maturity cultivar IRGA 431 CL reached physiologic maturity with 1490 ºC, 1539 ºC, and 1572 ºC (125, 128, and 125 days) during the 2020/21, 2021/22, and 2022/23 growing seasons.

Table 3 The beginning of the aerobic rice growth stages for each crop season, and cumulated growing degree days (CGDD, oC) from sowing to harvest, for all experiments.

Crop Season	Treatment	FAO crop stages (phenology stage*)				
		Sowing date	Start Crop Development (at V3/V4)	Start Mid-season (at VF/R0)	Start Late season (at R8)	Harvest (after R9)
2020/21	Irrigated	07/11/2020	253	733	1411	1730
	Rainfed		311	779	1386	1730
2021/22	Irrigated	12/11/2021	216	727	1527	1713
	Rainfed		216	834	1534	1713
2022/23	Irrigated	09/11/2022	235	671	1339	1675

* according to the Counce et al. (2000) scale; CGDD values were estimated using 12 °C as base temperature and 36 °C as cut-off temperature.

3.2. Crop characteristics

Crops characteristics, such as crop height (h) and the fraction of ground cover (f_c), are presented as means of both cultivars (IRGA 424 RI and IRGA 431 CL) for 2020/21 and 2021/22 in Table 4 and Figure 3. Those means are used because differences between cultivars did not exceed 3%. Both plant height and f_c varied little between the DI and AI treatments over the three years and both were higher than those of the RF treatment (Table 4) since it was often water stressed. Maximum plant height was observed at the R7 stage for the irrigated treatments (±1400 CGDD; ±120 DAS). Similar findings wones were reported by Reavis et al. (2021). Plants were slightly higher during the 2020/21 and 2021/22 growing seasons than in 2022/23. This is likely related to the cultivar since early cultivars are often smaller than those of medium cycle (Sosbai 2018) as observed for the cultivar IRGA 431 CL in 2022/23. Consequently, f_c was also slightly smaller during the latter growing season compared to the previous ones. The h results align with those obtained by Spanu et al. (2009) with aerobic rice in Italy, which attained a maximum plant height of 0.83 m in treatments where the soil moisture was maintained above field capacity. In Southern Brazil, Avila et al. (2015) reported mean final plant heights of 0.77 m and 0.78 m for the AWD and CF irrigation, respectively. Moratiel and Martínez-Cob (2013) reported a crop height ranging between 0.6-0.7 m in a semi-arid climate in Spain for a three years experiment. Under a lateral-move sprinkler system, Pinto et al. (2020) reported a decrease in plant height when soil water tension increased from 10 to 40 kPa. Thus, while literature values for f_c were not available, those for h indicate that high values are attained when there is no water stress.

Table 4 Plant height (h) and fraction of soil covered (fc) of aerobic rice for the three treatments and a three-year experiment.

Treatments	Observations		Crop stages		
			Crop Development	Mid-season	Late season
2020/21					
DI	72	h (m)	0.11 (0.07) – 0.28 (0.06)	0.38 (0.05) – 0.81 (0.05)	0.83 (0.03) – 0.74 (0.04)
		f_c	0.10 (0.01) – 0.74 (0.01)	0.84 (0.09) – 0.93 (0.00)	0.86 (0.00) – 0.70(0.00)
AI	72	h (m)	0.11 (0.02) – 0.23 (0.02)	0.32 (0.03) – 0.74 (0.00)	0.81 (0.03) – 0.77 (0.04)
		f_c	0.12 (0.01) – 0.72 (0.00)	0.83 (0.00) – 0.93 (0.00)	0.88 (0.00) – 0.74 (0.00)
RF	72	h (m)	0.10 (0.01) – 0.19 (0.04)	0.22 (0.02) – 0.47 (0.02)	0.49 (0.03) – 0.43 (0.02)
		f_c	0.10 (0.01) – 0.38 (0.09)	0.48 (0.01) – 0.79 (0.01)	0.76 (0.01) – 0.45 (0.05)
2021/22					
DI	72	h (m)	0.08 (0.02) -0.41 (0.05)	0.48 (0.05) – 0.80 (0.05)	0.78 (0.04) - 0.68 (0.05)
		f_c	0.12 (0.02) – 0.77 (0.04)	0.84 (0.03) – 0.95 (0.02)	0.82 (0.01) – 0.69 (0.03)
AI	72	h (m)	0.08 (0.01) – 0.41 (0.05)	0.48 (0.02) – 0.81 (0.05)	0.78 (0.04) – 0.68 (0.05)
		f_c	0.12 (0.02) – 0.77 (0.03)	0.79 (0.04) – 0.92 (0.02)	0.79 (0.01) – 0.68 (0.01)
RF	72	h (m)	0.10 (0.02) – 0.29 (0.02)	0.33 (0.02) – 0.49 (0.02)	0.47 (0.03) – 0.41 (0.03)
		f_c	0.10 (0.03) – 0.52 (0.04)	0.54 (0.01) – 0.70 (0.07)	0.65 (0.05) – 0.35 (0.05)
2022/23					
DI	54	h (m)	0.16 (0.02) – 0.38 (0.03)	0.39 (0.03) – 0.72 (0.03)	0.75 (0.03) – 0.72 (0.02)
		f_c	0.12 (0.04) – 0.61 (0.09)	0.64 (0.03) – 0.92 (0.06)	0.88 (0.04) – 0.64(0.04)
AI	54	h (m)	0.18 (0.02) – 0.37 (0.03)	0.38 (0.03) – 0.75 (0.04)	0.75 (0.03) – 0.71 (0.03)
		f_c	0.11 (0.04) – 0.56 (0.10)	0.61 (0.04) – 0.92 (0.06)	0.88 (0.06) – 0.64(0.02)

NOTE: The values of plant height and the fraction of soil cover are means of both cultivars for each treatment within each crop stage. Standard deviations are in brackets

Plant height peaks occur between the R6 and R7 stages when the panicle starts to gain weight, while f_c peaks are attained at flowering/pollination and decrease slightly thereafter (Figure 3). From an $f_c = 0.10$ to $f_c = 0.70$ by the beginning of the mid-season, h and f_c increased linearly immediately after the 1st and 2nd nitrogen top-dressing in the plant tillering stage. Warmer days ($T_{max} > 35$ºC and $T_{min} > 13$ºC), combined with a high availability of solar radiation (Rs > 23 MJ m^2 day^{-1}) favored the overall shoot growth and the increase in h and f_c. The f_c showed a good correlation with plant height.

During the three-year field observations, the canopy did not fully shade the ground. In the 2021/22 growing season, a maximum f_c of 0.95 was observed around flowering/pollination (R3/R4) (Table 4). The top leaves of the rice are erect, narrow, and arranged in a shape that is constantly overlapping, favoring light penetration to the deeper canopy layers. However, as reported by Li et al. (2021), while this leaf arrangement increases light absorption, and favors photosynthesis and transpiration processes, it also may favor soil evaporation and soil surface temperature.

Shorter plants in aerobic rice are often associated with variations in soil temperature throughout the day (Liu et al. 2018). In paddy rice, the layer of water on the soil surface provides a heat buffer, improving nutrient use efficiency, plant growth, and biomass accumulation. A less variable soil temperature such as that produced by flooding irrigation, is more important during microsporogenesis, and is primarily protective against lower temperatures. Clerget at al. (2014, 2016) reported that under aerobic conditions less developed plants were observed due to reduced leaf growth and reduced length compared with plants under flooding irrigation.

The observed f_c values are in good agreement with f_c values up to 0.90 reported by Moratiel and Martínez-Cob (2013) in a study on sprinkled irrigated rice. The results are also in agreement with values reported by Pereira et al. (2021) regarding update parameters for aerobic rice, namely maximum values of h and f_c.

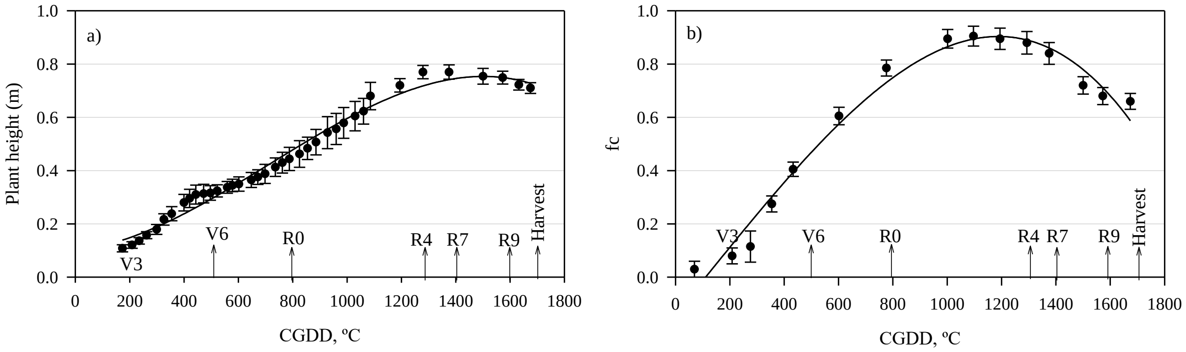


Fig. 3 Dynamics of the crop height (a) and the fraction of ground covered by the green canopy (b) of aerobic rice (cultivar IRGA 431CL) during the 2022/23 growing season in southern Brazil.

3.3 – Calibration and validation of SIMDualKc and determination of the basal crop coefficients

The calibration process, described in section 2.6, followed the process reported by Pereira et al. (2015). The initial and calibrated values relative to the crop, soil evaporation, runoff, and deep percolation are presented in Table 5. The K_{cb} curve obtained by simulating the SWC was adjusted to the climate. The daily irrigated treatment from the 2020/21 growing season was used to calibrate the model while all other data sets, relative to irrigated and rainfed treatments in the three growing seasons, were used in the validation process. The standard calibrated $K_{cb\ ini}$, $K_{cb\ mid}$ and $K_{cb\ end}$ values are those presented in Table 5. The K_{cb} values adjusted to the climate for both DI and AI were 0.15, 1.08 (±0.01) and 0.80 (±0.01), respectively, and are similar to the standard ones reported by Pereira et al. (2021).

Table 5 Initial and calibrated values of the parameters of the SIMDualKc model.

Parameters	Initial, default	Calibrated values	Source of parameters initial values
Crop parameters			
$K_{cb\ ini}$	0.15	0.15	Pereira et al. (2021)
$K_{cb\ mid}$	1.10*	1.10	Pereira et al. (2021)
$K_{cb\ end}$	0.7	0.85	Pereira et al. (2021)
Depletion factor (p)	0.35ASW	0.40TAW	Pereira et al. (2021)
Soil evaporation			
TEW (mm)	49	30	
REW (mm)	12	10	Soil characteristics
Z_e (m)	0.15	0.10	
Deep percolation			
a_{DP}	353**	345	Petry et al. (2023)
b_{DP}	-0.022**	-0.022	Liu et al. (2006)
Runoff (CN)	75	75	Allen et al. (2007)

K_{cb} = basal crop coefficients for initial ($K_{cb\ ini}$), mid-season ($K_{cb\ mid}$) and end season ($K_{cb\ end}$); Z_e = depth of the soil evaporable layer; TEW = total evaporable water; REW = readily available water; CN = curve number; a_{DP} and b_{DP} are the parameters of the percolation equation.

The daily dynamics of the available soil water (ASW) observed and simulated are presented in Figure 4 for: (a) the calibration with DI treatment in 2021/22, (b) the DI in 2022/23, validation, and (c and d) for AI respectively in 2020/21 and 2022/23. All cases evidence an excellent fitting.

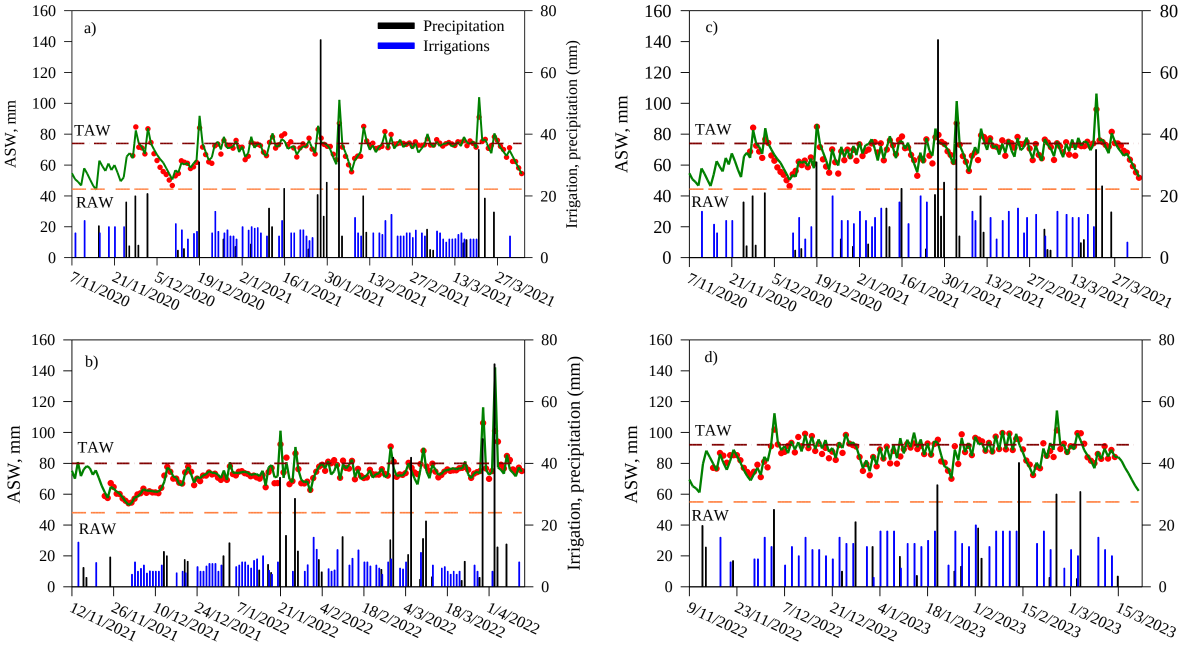


Fig. 4 Observed (●) and simulated (─) available soil water (ASW, mm) relative to the treatments :(a) DI, calibration, in 2020/21, (b) DI, validation, in 2021/22, (c) AI, validation, in 2020/21, and (d) AI, validation, in 2022/23. Irrigation (|) and precipitation.

Due to an adequate irrigation scheduling, the observed ASW remained close to θ_{FC} for all cases, with ASW deviating from TAW in some periods due to higher climatic demand relative to the irrigation water input. This was the case of the DI strategy in 2021/22 (Fig. 4b). Among all growing seasons, the soil water content fluctuated only from 0.31 cm^3 cm^{-3} to 0.35 cm^3 cm^{-3} for the irrigated treatments. The more significant oscillation in soil moisture observed in that growing season for DI, which may have been partly due to the delayed start of irrigation. Moreover, no water stress was observed in the irrigated treatments as the ASW was kept near TAW. Nevertheless, it could be better for all treatments to start irrigation earlier and to use more 1 mm d^{-1} as application depth.

Figure 5 shows the observed and simulated values of ASW for the RF treatment in the 2020/21 and 2021/22 growing seasons (the RF treatment was not applied in 2022/23). The ASW dynamics during the season evidence that precipitation has been much insufficient for satisfying the crop water requirements. The lack of rainfall made ASW to drop below RAW, reaching very low values during the crop development and the beginning of the mid-season during the 2020/21 season, and most of the time in the 2021/22 crop season. Nevertheless, model simulations performed very well. Sporadic peaks of the soil water were observed following precipitation, but ASW rarely rose above TAW. Most of the time, ASW remained below the RAW threshold in both growing seasons. This evidenced the inadequacy of rainfed rice in southern Brazil despite the high total precipitation.

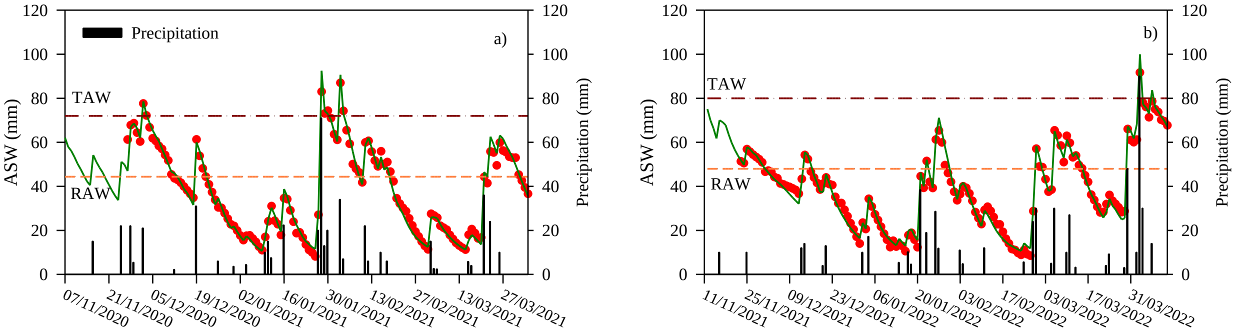


Fig. 5 Observed and simulated available soil water (ASW, mm) relative to the rainfed treatments during the growing seasons of 2020/21 (a) and 2021/22 (b).

The SIMDualKc model adequately reproduced the observed ASW throughout all growing seasons (Fig. 4 and 5). The goodness-of-fit indicators (Section 2.7) for all ASW simulations are presented in Table 5. They confirm excellent agreement between observed and simulated ASW values, with regression coefficient values (b_0) close to 1.0, which indicates high similarity between predicted and observed data. The high values of the determination coefficient (R^2), ranging from 0.80 to 0.98, suggest that the model could explain most of the variance in the observations. Likewise, the modeling efficiency was high, with EF values > 0.69, indicating that the variance of the residuals was elsewhere,much smaller than the variance of the observed ASW data. Consequently, the estimation errors were small, with an RMSE ranging from 2.4 to 4.40 mm, and representing less than 7% of the average observed ASW (i.e. NRMSE $\leq$ 7%). The results of the present study are comparable with those obtained with the SIMDualKc model in Brazil, e.g., Martins et al. (2013) for maize, Paredes et al. (2018) for bermudagrass, and by Petry et al. (2023) for soybean. Excellent results were also obtained elsewhere, for example by Paredes et al. (2017) for pea, Liu et al. (2022) for maize, Cancela et al. (2015) for vineyards, and by Ramos et al. (2023) for several tree orchards.

Table 6 Goodness-of-fit indicators relative to the simulation of the available soil water for all cases.

Treatments	b_0	R^2	RMSE (mm)	NRMSE (%)	EF
		2020/21 crop season			
Daily	1.01	0.88	2.8	4.0	0.86
Alternate	1.01	0.86	3.2	4.7	0.83
Rainfed	1.01	0.98	2.7	7.0	0.98
		2021/22 crop season			
Daily	1.00	0.80	4.4	6.1	0.69
Alternate	1.01	0.87	3.9	5.6	0.84
Rainfed	1.01	0.98	2.5	6.4	0.98
		2022/23 crop season			
Daily	1.00	0.89	2.4	2.8	0.87
Alternate	1.01	0.84	2.9	3.3	0.80
All cases	1.01	0.89	3.1	5.0	0.86

Notes: b_0 and R^2 are the coefficients of regression and determination, respectively; RMSE is the root mean square error; NRMSE it the normalized RMSE; and EF is the modelling efficiency.

3.4 - ET partitioning: the basal crop coefficient and the evaporation coefficient for aerobic rice

The standard and actual basal crop coefficient curves and the soil evaporation coefficient estimated by the SIMDualKc model are presented in Figure 6. It can be seen that the $K_{cb\ act}$ was equal to the standard K_{cb} during all growing seasons for DI and AI, because no water stress occurred. The calibrated standard basal crop coefficients for initial, mid, and end seasons ($K_{cb\ ini}$, $K_{cb\ mid}$, and $K_{cb\ end}$) were 0.15, 1.10, and 0.85, respectively. The calibrated $K_{cb\ mid}$ is only slightly higher than the one recommended by Pereira et al. (2021). The SIMDualKc model adjusted both the $K_{cb\ mid}$ and $K_{cb\ end}$ to climate as recommended by Allen et al. (1998). The actual $K_{cb\ mid}$ adjusted to local climate conditions was 1.08 (±0.01), which is lower than the one derived from field observations under center pivot by Vorries et al. (2013) reporting a $K_{cb\ mid}$ = 1.21. The actual $K_{cb\ mid}$ values obtained in the current study after climatic adjustment have shown very small variations among the three seasons of field observations, with $K_{cb\ mid}$ of 1.07, 1.08 and 1.10 for respectively 2020/21, 2021/22 and 2022/23 season and both irrigation treatments.

The calibrated $K_{cb\ end}$ = 0.85 is aligned with the values updated by Pereira et al. (2021). $K_{cb\ end}$ depends on the f_c by the harvesting time. While in CF and other alternative anaerobic rice, irrigation ends by the R7 stage, with sprinkling irrigation rarely stops before the R9 stage, resulting in higher $K_{cb\ end}$ values. The $K_{cb\ end}$ adjusted for the local climate was 0.8 (±0.01), likely reflecting slightly more humid and/or less windy conditions than under the standard climate conditions.

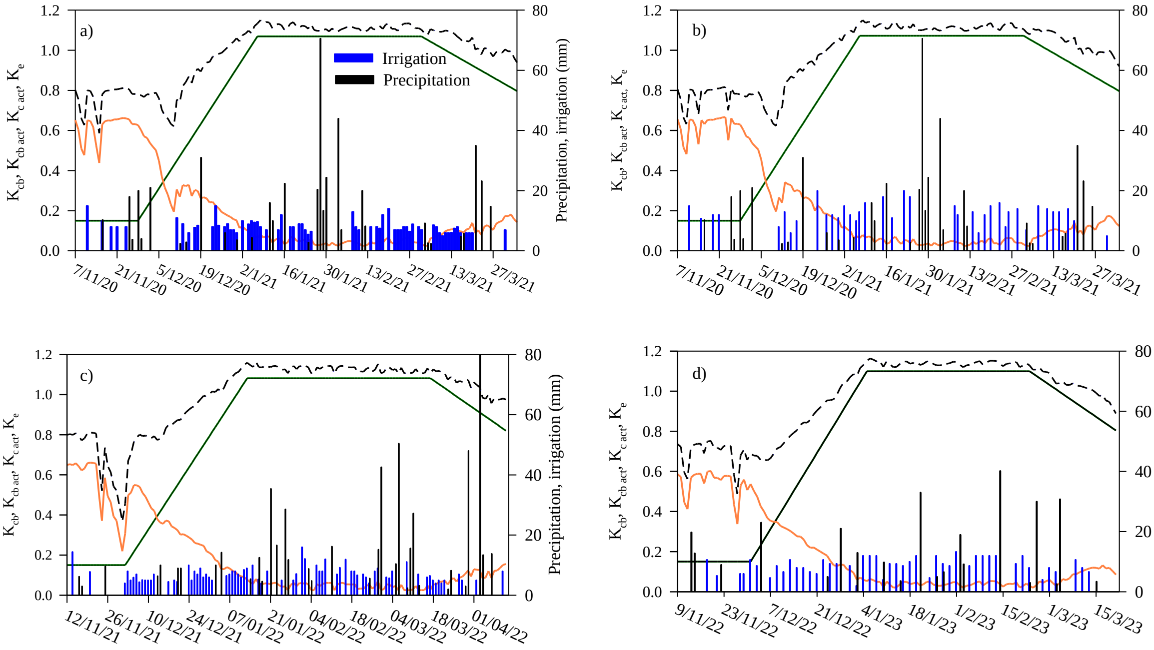


Fig. 6 Daily variation of the basal crop coefficient (Kcb, —), actual basal crop coeficiente ($K_{cb\ act}$ = K_{cb}, —), actual crop coefficient ($K_{c\ act}$, ---) and evaporation coefficient (K_e, —), for the daily irrigated treatment (a) in 2020/21 (calibration), (c) daily irrigated 2021/22 season, (b) alternate irrigated in 2020/21, and (d) alternate irrigated in 2022/23 season. Also depicted the applied irrigations (|, mm) and precipitation (|, mm).

The calibrated $K_{cb\ ini}$ (0.15) was smaller than the value modeled by Vories et al. (2013) under the center pivot in Missouri, USA ($K_{cb\ ini}$ = 0.20) but higher than the one reported by Alberto et al. (2014) in dry-seeding rice ($K_{cb\ ini}$ of 0.05 and 0.08). The green vegetation is sparse during the emergency and seedling stages (Fig. 2), resulting in low crop transpiration and small $K_{cb\ ini}$. As expected, K_e was higher through all crop growth stages for both irrigated treatments (Fig. 6).

The rainfed rice showed very different dynamics of the crop coefficients curve along the growing season for 2020/21 and 2021/22 (Figure 7). The actual K_{cb} values varied greatly during all crop growth stages, except the initial because it nearly coincides with the $K_{cb\ ini}$, which is 0.15. $K_{cb\ act}$ variation indicates that SWC was insufficient to maintain the crop transpiration rate at its potential. During the 2021/22 growing season, the soil water stress delayed the mid-season by 107ºC of CGDD (7 days) compared to the irrigated treatments, which was attributed to water stress during the previous stages. The actual $K_{cb\ end}$ for rainfed rice were 0.64 and 0.8, respectively for 2020/21 and 2021/22, due to rainfall occurring previously to the end-season. Results demonstrate that, despite average precipitation in southern Brazil is high its variability leads to large periods of water stress (Fig. 7).

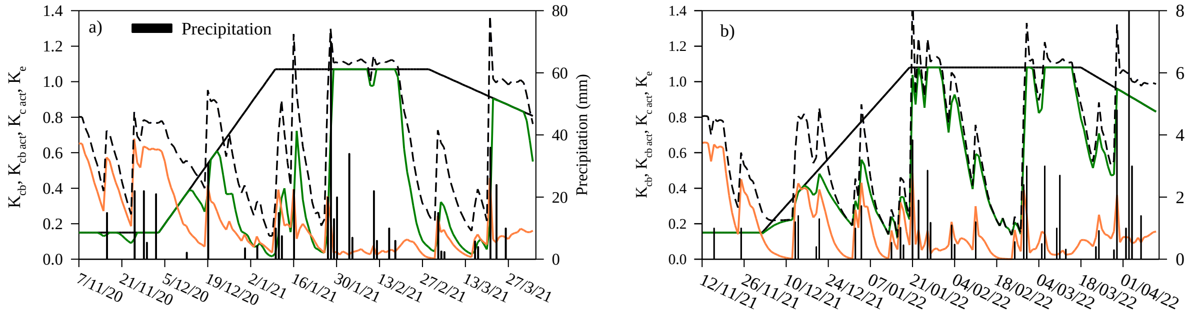


Fig. 7 Daily variation of the basal crop coefficient (Kcb, ▬), actual basal crop coefficient (Kcb act, - -), actual crop coefficient (Kc act, ▬) and evaporation coefficient (Ke, ▬), for the rainfed rice (a) in 2020/21 season and (b) in 2021/22 season. Also depicted the precipitation (|, mm).

3.5 – The effect of mulch on the soil evaporation and its coefficient (K_e)

Aerobic rice, dry seeding, and intermittent irrigation can save up to 30% of water relative to continuous flooding (Jabran et al. 2014). Soil management practices are commonly used in irrigation in southern Brazil aimed at improving water use and soil physical properties (Souza et al. 2016; Moraes et al. 2016). Mulch likely is the best approach to reduce soil evaporation and decreasing K_e. In the current study, rice was sown on a thick layer of black oat mulch (> 3.0 Mg ha^{-1}). Following the study by Martins et al. (2013), the model was parameterized to simulate the impacts of the organic mulch on E_s. Mulch density and fraction of soil surface covered with the mulch were inputted to SIMDualKc and it was assumed that for each 10% of soil surface covered with the organic mulch corresponds to a 5% reduction in the soil water evaporation (Allen et al. 1998; Rosa et al. 2012; Odhiambo and Irmak 2012). This estimation leads to decrease K_c and K_e but not K_{cb}. The model therefore computed a 50% reduction of soil evaporation for all growing seasons, which reduction was updated in the model throughout the crop seasons taking into consideration the degradation of the organic mulch. This allowed improving the K_c partition. For the 2020-21 season, it result K_e = 0.57 (±0.04) for DI and AI initial stage, dropping to K_e = 0.05 in the mid-season, as shown in Fig. 2 and represented in Figs 6 and 7. A slight increase during the late season was observed (Fig. 6 and 7) due to crop senescence. However, the average K_e at the initial stage was smaller, 0.49 in 2020/21 and 0.29 in 2021/22, reflecting the interannual differences in rainfall and irrigation (Fig. 6 and 7).

3.6 – The single crop coefficient for aerobic rice

Previous studies with rice under sprinkler irrigation (Borja Reis et al. 2018; Pinto et al. 2020) focused on the relationship between water use and grain yield but did not derive crop coefficients. Since $K_{c\ ini}$ depends on factors such as rainfall and irrigation during the initial period, soil management, mulch, soil moisture, and a combination of meteorological conditions that influence evaporation (Allen et al. 1998), $K_{c\ ini}$ were distinct by about 10% over the three years of experiments for the irrigated treatments (Table 7) due to differences in rainfall and irrigation. These $K_{c\ ini}$ are slightly lower than those reported for sprinkler irrigated rice by Alberto et al. (2011, 2014) in Philippines ($K_{c\ ini}$ ranging from 0.81 to 0.95), and by Moratiel and Martinez-Cob (2013) in Spain ($K_{c\ ini}$=0.92). Spanu et al. (2009), in a study in Sardinia, Italy, reported a K_c of 0.90 for the period from emergency to end of tillering. The smaller $K_{c\ ini}$ values in the current study are likely due to the effects of mulch which reduced K_e and, therefore, K_c. In contrast, Choudhury et al. (2013) reported $K_{c\ ini}$ = 0.62 for furrow irrigated rice in India, which smaller values may be due to differences in irrigation. The values in the current study are in the range of the $K_{c\ ini}$ values 0.67 to 1.14 reported for dry-seeding rice by Diaz et al. (2019), for a site at 100 km from ours, where the higher $K_{c\ ini}$ correspond to the wetter years.

The actual $K_{c\ mid}$ in the current study ranged between 1.12 and 1.14 (Table 7). These values are comparable to the standard $K_{c\ mid}$ reported for sprinkler irrigation by Pereira et al. (2021), and in the range of values (1.04-1.15) reported by Alberto et al. (2014). It is also close to $K_{c\ mid}$ = 1.06 reported by Moratiel and Martínez-Cob (2013) for sprinkler aerobic rice, and to $K_{c\ mid}$ of 1.16 reported by Choudhury et al. (2013) for aerobic rice with furrow irrigation. The $K_{c\ mid\ act}$ for rainfed rice was much lower (0.82) likely because the crop was highly affected by water stress namely in the mid-season (Figure 5 and 7), that leaded to smaller h and lower f_c (Table 3).

The $K_{c\ end}$ values for sprinkler-irrigated rice in the current study ranged from 0.92 to 1.02, which values varied as with the SWC at end-season. Values are close to the standard value $K_{c\ end}$ = 0.95 reported by Pereira et al. (2021). The observed higher values, result from irrigation until rice maturity (R9) and precipitation events just before harvest (Figure 6). The $K_{c\ end\ act}$ values for rainfed rice (0.76) were much lower than those of the irrigated treatments during the late season of 2020/21 but larger in 2021/22 ($K_{c\ end\ act}$ = 0.98) due to differences in SWC at that time.

Table 7 Single average crop coefficients relative to all irrigation treatments of aerobic rice during the three growing seasons.

Seasons	Treatments	Crop growth stages				
		Initial	Crop development	Mid-season	Late season	End-season
2020/21						
	Daily	0.72	0.72 – 1.12	1.12	1.12 – 0.94	0.94
	Alternate	0.77	0.77 – 1.12	1.12	1.12 – 0.92	0.92
	Rainfed	0.63	0.63 – 0.82	0.82	0.82 – 0.87	0.76
2021/22						
	Daily	0.68	0.68 – 1.13	1.13	1.13 – 0.97	0.97
	Alternate	0.67	0.67 – 1.13	1.13	1.13 – 0.96	0.96
	Rainfed	0.46	0.46 – 0.82	0.82	0.82 – 0.98	0.98
2022/23						
	Daily	0.71	0.71 – 1.14	1.14	1.14 – 1.02	1.02
	Alternate	0.70	0.70 – 1.14	1.14	1.14 – 1.02	0.89*
	All irrigated	0.71	0.71 – 1.13	1.13	1.13 – 0.97	0.97
	All rainfed	0.54	0.54 – 0.82	0.82	0.82 – 0.87	0.87

* lower value because the last irrigation was not performed

3.7 – ET partitioning and soil water balance components

The components of the soil water balance are presented in Table 8. The potential crop evapotranspiration (ET_c) estimated by the SIMDualKc model was similar for the experiments under sprinkler irrigation over the three years. The seasonal ET_c averaged 697±16 mm, while the $ET_{c\ act}$ for rainfed conditions averaged 453±3 mm. Mean daily ET_c values were 4.5, 4.7, and 5.2 mm dia^{-1}, respectively for the 2020/21, 2021/22, and 2022/23 growing seasons. The ET_c mainly depended on ET_o, since meteorological conditions determine the climatic demand of the atmosphere and K_c values were similar since no water stress occurred. In contrast, $ET_{c\ act}/ET_c$ for the rainfed treatments were 0.69 and 0.67 respectively for 2020/21 and 2021/22 due to water stress (Fig. 5).

Despite the numerous wetting events, from both precipitation and irrigation, E_s of irrigated treatments accounted for only about 20% of the ET_c (Table 8), likely due to the mulch control of soil water evaporation. The $E_s/ET_{c\ act}$ in the rainfed treatments were higher, 30% and 24% in 2020/21 and 2021/22 seasons, respectively, likely because mulch effects were smaller due to a lower canopy coverage. A much higher E_s/ET_c of about 50% was reported by Alberto et al. (2014) for aerobic irrigated rice without mulch. Mean E_s/ET_c = 33% was reported by Diaz et al. (2019) for a six-year CF rice.

The non-beneficial water use ratio (NBWUR) relating DP+RO to the sum of precipitation and irrigation remained lower than 35% for all cases over the three years of the study. Seasonal runoff accounted for 7-11% of precipitation on the irrigated treatments while it represented 3-10% in the rainfed treatment; the lower RO values in the rainfed rice were due to lower available water, thus less REW. The occurrence of RO is due to poor construction of bunds and non-laser controlled levelling that led to a slope of 2% as well as to adopting surface drainage for controlling wetland vegetation. For the southern Brazil, Ávila et al. (2015) reported much higher RO values, representing 40% and 28%, respectively for CF and AWD cropping systems due to lack of precise levelling.

Most of the NBWUR was due to DP, which accounted for 6-18% of seasonal irrigation, with the lower values observed in the 2021/22 season in the AI treatment. DP in rainfed rice accounted for 9-26% of seasonal precipitation. The DP values of the current study are much lower than those in the for the flooding method, e.g., Bouman et al. (2007) reported that DP was 45% of the total water input (precipitation and irrigation) for an area with shallow water table depth (WTD), while DP was 70% when the WTD was lower to 2.0 m. Ávila et al. (2015) reported field-measured losses by DP in the lowlands of Southern Brazil accounting for 14% and 17% for CF and AWD, respectively. These low values refer to a soil with very low permeability while soil in the current study had a median to low permeability.

Table 8 Field water balance components in sprinkler irrigated and rainfed rice computed with the SIMDualKc model for the 2020/21, 2021/22 and 2022/23 growing seasons.

Treatments	P	I	DP	RO	NBWUR	ΔASW	$ET_{c\ act}$	$T_{c\ act}$	E_s	$E_s/ET_{c\ act}$
	(mm)				(%)	(mm)	(mm)			(%)
2020/21 growing season										
Daily irrigated	484	523	310	33	33	-1	671	527	143	19
Alternate	484	482	265	36	30	-1	672	529	143	19
Rainfed	484	0	62	13	17	42	451	316	135	30
2021/22 growing season										
Daily irrigated	585	514	332	51	35	12	728	580	148	20
Alternate	585	474	270	64	33	14	727	580	147	20
Rainfed	585	0	53	58	27	-39	452	343	109	24
2022/23 growing season										
Daily irrigated	300	614	227	0	25	7	694	552	141	20
Alternate	300	621	241	0	30	10	690	552	138	20

Notes: P = precipitation, I = irrigation, DP = deep percolation, RO = runoff; NBWUR = non-beneficial water ratio; ΔASW = variation in available soil water; $ET_{c\ act}$ = actual crop evapotranspiration, $T_{c\ act}$ = actual crop transpiration; E_s= soil water evaporation; $E_s/ET_{c\ act}$ = soil water evaporation ratio.

3.8 – Assessing water use and grain yield for sprinkler and rainfed rice

The total yield of harvested grain obtained with the different irrigation strategies and both rice cultivars is shown in Table 9. The results show that the highest grain yield was obtained during the 2022/23 season (close to 10,000 kg ha^{-1} for the cultivar IRGA 431 CL with irrigation every other day), the driest year over the three-years of field experiments (Table 9), which is likely associated with better environmental conditions, namely solar radiation and air temperature along the season (Figure 1).

Table 9 Grain yield of aerobic rice under different water managements.

Irrigations strategies	2020/2021		2021/2022		2022/2023
	Grain Yield (kg ha^{-1})				
	IRGA 424 RI	IRGA 431 CL	IRGA 424 RI	IRGA 431 CL	IRGA 431 CL
Daily	7616 (±604) aA	8025 (±285) aA	6041 (±740) aA	6452 (±784) aA	9918 (1932) A
Alternate	6502 (±531) bB	7407 (±152) aA	5060 (±544) aA	6758 (±928) aA	10404 (951) A
Rainfed	518 (±102) cC	744 (±168) cB	0	0	-

Means followed by the same capital letters in the columns are not significantly different ($P<0.05$) and the same lowercase letters in the row for each season are not different by Tukey's test ($P<0.05$).

Duarte Jr. et al. (2021) argues that the potential rice yield under continuous flooding could reach nearly 14,000 kg ha^{-1}; however, due to weed control and climatic conditions, these levels are very difficult to achieve in commercial field conditions. The yield achieved in the current study was constrained by the use of rice cultivars are well adapted to flood irrigation but not proved to aerobic conditions. The climatic conditions could also have contributed to not reaching the potential rice yield. For example, the extreme temperatures during anthesis, where T_{max} reached 39.3ºC, may have resulted in a lower yield during the 2021/2022 growing season (yield below 6,500 kg ha^{-1}). The contrasting high and low temperatures at panicle initiation (R0 stage), may also have contributed to lower yield. Furthermore, from late February to early March 2022 (R2 stage), soil moisture settled below θ_{FC} (Fig. 5), which may have also contributed to the increase in spikelet sterility as earlier referred by Kato and Hatsura (2014).

The results in Table 9 show different productivity between the cultivars, with IRGA 431 CL (7161±701 kg ha^{-1}) generally performing better than IRGA 424 RI (6305±1061 kg ha^{-1}); nevertheless, these differences were not significant ($p<0.05$). However, there is evidence that IRGA 431 CL adapts better to aerobic conditions as the shoot and root growth pattern could be maintained similar to conditions when flooded irrigation was applied (results not shown). Furthermore, due to the high water and heat stress observed during the mid-season, the RF treatment did not produce any yield in 2021/22 (Fig 6), likely because the panicle formation was heavily affected (R0 stage) and grain yield too.

No statistical differences were observed between the irrigation strategies (DI and AI) because both strategies were very similar in terms of daily average irrigation and soil water content (SWC) threshold. Similar findings were reported by Kadiyala et al. (2012). Yield in 2021/22 may also have been affected by the lack of rainfall at the R0 stage and consequent decrease in nitrate uptake from the third topdressing N fertilization performed at this stage. These results contrast with those reported by Aramburu et al. (2022) for the same cultivars under solid set sprinkler irrigation but keeping soil water content between saturation and field capacity, thus adopting a threshold higher than that of the current study.

On the one hand, the productivity obtained in our experiments compares well with the productivity reported under sprinkler irrigation in southern Brazil (Table 10), especially considering the 2022/23 growing season (Table 9). The better yield performance in the studies by Pinto et al. (2020) and Aramburu et al. (2022) can be related to soil and moisture conditions, as these studies were conducted on Typic Albaqualf soils (Soil Survey Staff 2022), and soil moisture was maintained near saturation. The results are also in the range of those reported by Clerget et al. (2014) under monsoon climate conditions, but significantly higher than yields reported by Alberto et al. (2014), also in a monsoon climate zone. Likely, considering results in literature, the adopted SWC threshold in the current study was low. As shown in Table 10, AWD irrigation performed better than sprinkler irrigation on the hydromorphic soils in southern Brazil. Nevertheless, Carracelas et al. (2019) reported a productivity similar to ours when adopting the AWD method in hydromorphic soils. These conflicting results could be related to factors such as weed and disease control and nutrient availability under aerobic rice. These differences may be related to the use of rice cultivars that are not well adapted to aerobic conditions (Farooq et al. 2023). According to Kato et al. (2006), the use of rice cultivars adapted to flood irrigation under aerobic conditions in tropical/subtropical climate zones leads to lower yields than in temperate climate zones.

The results show that the rice grain yield was in the range of the one farmer's traditional flooding systems in Brazil and Uruguay obtain, i.e., around 8,000 kg ha^{-1} (CONAB, 2023). Even in non-tropical environments, the yield differences from aerobic rice to AWD and CF systems reported in the literature are relatively small compared to the results obtained in the current study.

Disagreements can be observed when comparing the irrigation water productivity (WP_{Irri}) with water use productivity (WP_{WU}) obtained in our study with the results in the literature for rice under sprinkler irrigation. The lower WP_{Irri} in our research, compared to those reported by Pinto et al. (2020) and by Aramburu et al. (2022), may be related to soil hydraulic characteristics and less to irrigation management. Standing water was not observed in our study due to the median texture of the topsoil. This is in contrast to the studies in which soil moisture was kept near saturation and the soil is typically hydromorphic, as in the studies cited above.

Compared to the AWD, the WP_{Irri} for sprinkler irrigation in our study was similar to that reported by Carracelas et al. (2019) in Uruguay (Table 10) but slightly higher than the values reported by Borja Reis et al. (2018) for the Brazilian lowland savannah. Among CF cases, Avila et al. (2015) found similar WP_{Irri} in the same environment as ours but on a hydromorphic soil. Because irrigation depth varied minimally with sprinkler and AWD (Table 10), better WP_{Irri} values are attributed to higher grain yield rather than to water, suggesting that other agronomic practices besides mulched soil, also need to be employed to keep well-drained upland. Some factors to improve farmer's crop yield through sprinkler irrigation are cultivars, that should be adapted to aerobic conditions, early sowing (i.e., from mid-October in southern Brazil), better planting density (Carracelas et al. 2023) and a higher irrigation threshold. Other examples for CF presented in Table 10 show lower WP_{Irri}, mainly because very large water depths were used.

A comparison of the results of the WP_{WU} with some studies in the literature shows that the values are close by, with the exception of the high WP_{WU} reported by Pinto et al. (2020) and Aramburu et al. (2022), which rank among the 10% highest yields for lowland areas in Rio Grande do Sul state. A lower WP_{WU} is reported for CF, indicating that high water use is traditional in flooded rice cropping systems. The total water input in our research (irrigation + precipitation) was approximately 10,000 m^3, while in the comparative studies with CF (Table 10), the total water use averaged 17,000 m^3. The total water input under CF varied between 11,700 and 14,300 m^3 in southern Brazil (Avila et al. 2915) and between 13,000 and 21,000 m^3 in Uruguay (Carracelas et al. 2019), all much above the one in the current study.

Table 10 Literature reported studies developed for rice under different irrigation methods with corresponding reported on grain yield, seasonal irrigation water input and irrigation water productivity (WP_{IRRI}).

(continua)

Local	Irrigation System	Grain Yield (kg ha^{-1})	Irr (mm)	P_n (mm)	WP_{IRRI} (kg m^{-3})	WP_{WU} (kg m^{-3})	Authors
Santa Maria, **RS**, Brazil	Sprinkler	7610 (DI)	523	535	1.46	0.72	Current study
		7226 (AI)	482	535	1.50	0.71	
Capão do Leão, **RS**, Brazil	Sprinkler	8811	300	385	2.94	1.30	Pinto et al. (2020)
Santa Maria, **RS**, Brazil	Sprinkler	9821	413	572	2.38	1.00	Aramburu et al. (2022)

Table 10 Literature reported studies developed for rice under different irrigation methods with corresponding reported on grain yield, seasonal irrigation water input and irrigation water productivity (WPIRRI).

(conclusão)

Santa Maria, **RS**, Brazil	Flooded	8657	616	710	1.41	0.65	Ávila et al. (2015)
Santa Maria, RS, Brazil	Flooded	12188	787	572	1.55	0.90	Aramburu et al. (2022)
Santa Maria, RS, Brazil	AWD	8584	385	710	2.23	0.78	Ávila et al. (2015)
Santa Maria, RS, Brazil	AWD	12142	570	572	2.13	1.06	Aramburu et al. (2022)
Lagoa da Confusão, TO, Brazil	Flooded	8667	1267	1070	0.68	0.37	Borja Reis et al. (2018)
	AWD	8500	825	1070	1.03	0.45	
Los Baños, Phillipines	Sprinkler	5300	600	601	0.88	0.44	Alberto et al. 2014
Los Baños, Phillipines	Sprinkler	7570	855	370	0.89	0.62	Clerget et al. (2014)
Uruguay	Flooded	9191	1133	565	0.81	0.54	Carracelas et al. (2019)
	AWD	7855	683	565	1.15	0.63	

Notes: Irri = irrigation depth; P_n = effective precipitation; WP_{IRRI} = irrigation water productivity; WP_{WU} = water use productivity.

Other alternatives, such as AWD, may bring better results. However, this technique requires farmers to have good knowledge about how to operate this system and a lot more manpower, which availability is decreasing in rural areas. AWD and CF are critical in soil preparation prior to planting and may cause severe damage to soil physical and hydraulic properties, as reported by Parfitt et al. (2017) and Goulart et al. (2020). Additionally, more energy and mechanization are required for lowland areas used for rice, which are not naturally flat but require laser levelling. Alternatively, sprinkler irrigation can increase crop yield using cultivars better adapted to aerobic conditions, adjusting plant density, sowing dates and adopting an improved irrigation threshold.

5. Conclusions

The results of this first application of the FAO dual crop coefficient approach to aerobic rice to assess crop evapotranspiration and water use revealed appropriate. The sprinkler irrigation treatments were established aiming to maintain soil moisture close or above to field capacity but the experiment failed in this theme. A rainfed treatment was also implemented. Independent soil moisture data sets were used to calibrate and validate the soil water balance SIMDualKc model and to derive both the actual dual and single crop coefficients ($K_{cb\ act}$ and $K_{c\ act}$). The model, after proper calibration, showed high accuracy in simulating ASW for all treatments in the three experimental seasons, and can further be used to support decision-making in irrigation scheduling.

The standard K_{cb} values were 0.15, 1.10 and 0.85, for the initial, mid and end-season, respectively. The K_{cb} values were derived from the calibration of the SWB model SIMDualKc against field measured SWC. The $K_{c\ act}$ values for sprinkler irrigated rice were higher than for the rainfed rice with large differences observed in the mid-season stage ($K_{c\ act\ mid}$ = 1.13 vs 0.82). The use of mulch from crop residues was able to control soil evaporation with E_s accounting for approximately 20% of the ET in the irrigated treatments. Differently, in the rainfed treatment, E_s increased to 24-30% of $ET_{c\ act}$, which was due to lower crop development, thus to a much lower fraction of ground cover and plant height. The rainfed rice yielded very poorly, thus allowing to conclude that this strategy should not be adopted by farmers.

Grain yield decreased by 23% compared to the average rice crop yield under flooding in southern Brazil, possibly due to not adopting aerobic cultivars, lower temperatures during microsporogenesis and changes caused by aerobic conditions, particularly in N uptake. Further research should investigate N management under sprinkler irrigation.

Water saving of up to 40% maybe achieved when using sprinkler irrigation. Water lost by RO was low and may be reduced with care in bunds construction and maintenance and precise land levelling. Deep percolation was also well controlled because irrigation rates were small. The mulch positively impacted water-saving, as soil evaporation was low throughout the growing season. The WP_{Irri}, ranging 1.07 kg m^3 to 1.68 kg m^3, was slightly higher than the ranges reported in the literature, apart from the high-yielding rice systems in laser-leveled hydromorphic lowland areas in southern Brazil. However, when considering the total water use by precipitation and irrigation, WP_{WU} was within the range of results reported for sprinkler and AWD but higher than for rice cultivated under CF.

Despite the high-water savings achieved in our study, future research should address crop and soil management practices to improve aerobic rice yield, namely the use of cultivars adapted to aerobic conditions, improving fertility management, and liming. In addition, studies should focus on the effectiveness of the aerobic rice production system in reducing greenhouse gas emissions, which could lead to mitigate impacts of climate change, as well as other agronomic practices that could improve the sustainability of this new rice agroecosystem. A main issue is to carefully assess the best soil moisture threshold and irrigation depths. Moreover, it is also required to assess the strategies using the economic water productivity ratio as indicator, thus considering the full costs of production and the full value of yields, i.e., allowing to perceive the economic viability of each strategy.

Author Contributions: MTP and JDM: conceptualization and methodology; FT, JES, RW and AFG: field work, data collection and data analysis; MTP data analysis, modeling, calibration and validation, MTP, PP, and LSP: formal analysis, writing, review and editing, project administration and funding acquisition. All authors have read and agreed to the published version of the manuscript.

6. REFERENCES

Alberto MCR, Quilty JR, Buresh RJ, Wasmann R, Haidar S, Correa Jr TQ, Sandro JM (2014) Actual evapotranspiration and dual crop coefficients for dry-seeded rice and hybrid maize grown with overhead sprinkler irrigation. Agric Water Manag 136:1‑12. http://dx.doi.org/10.1016/j.agwat.2014.01.005

Alberto MCR, Wassmann R, Hirano T, Miyata A, Hatano R, Kumar A, Padre A, Amante M (2011) Comparisons of energy balance and evapotranspiration between flooded and aerobic rice fields in the Philippines. Agric Water Manag 98:1417–1430. https://doi.org/10.1016/j.agwat.2011.04.011

Allen RG, Pereira LS, Raes D Smith M (1998) Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56. FAO, Rome. https://www.fao.org/3/x0490e/x0490e00.htm

Allen RG, Pereira LS, Smith M, Raes D, Wright JL (2005) FAO-56 Dual crop coefficient method for estimating evaporation from soil and application extensions. J. Irrig. Drain. Eng. 131:2–13. https://doi.org/10.1061/(ASCE)0733-9437(2005)131:1(2)

Allen RG, Wright JL, Pruitt WO, Pereira LS, Jensen ME (2007). Water requirements. In: Hoffman, GJ, Evans RG, Jensen ME, Martin DL, Elliot RL (Eds.) Design and Operation of Farm Irrigation Systems. 2nd Edition). ASABE, St Joseph, MI, pp. 208–288.

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLDM, Sparovek G (2013) Köppen’s climate classification map for Brazil. Meteorol Z 22:711–728. https://doi.org/10.1127/0941-2948/2013/0507.

Anupoju V, Kambhammettu BVNP (2020) Role of deficit irrigation strategies on ET partition and crop water productivity of rice in semi-arid tropics of south India. Irrig Sci 38:415–430. https://doi.org/10.1007/s00271-020-00684-1

Aramburu BB, Marchesan E, Giacomeli R Fleck AG, Prochnow MH, Pfeifer JG (2022) Morphophysiological and productive aspects of sprinkler and surface irrigated rice cultivars. Rev Bras Cien Agrar 17(3):1205. 2022. https://doi.org/10.5039/agraria.v17i3a1205

Arf O, Rodrigues RAF, Crusciol CAC, Sá ME, Buzetti S (2003) Soil management and nitrogen fertilization for sprinkler-irrigated upland rice cultivars. Sci Agric 60:345-352. https://doi.org/10.1590/S0103-90162003000200020

Avila LA, Marchesan E, Camargo, ER Merotto Jr A, Ulguim AR, Noldin JA, Andres A, Mariot CHP, Agostinetto D, Dornelles SHB, Markus C (2021) Eighteen years of Clearfield™ rice in Brazil: what have we learned? Weed Sci 69: 585–597. https://doi.org/10.1017/wsc.2021.49

Avila LA, Martini LFD, Mezzomo RF, Refatti JP, Campos R, Cezimbra DM, Machado SLO, Massey JH, Carlesso R, Marchesan E (2015) Rice water use efficiency and yield under continuous and intermittent irrigation. Agron J 107:442-448. https://doi.org/10.2134/agronj14.0080

Böhm W (1979) Methods of Studying Root Systems. Berlin: Springer-Verlag, 188p.

Borja Reis AF, Almeida REM, Lago BC, Trivelin PC, Linquist B, Favarin JL (2018) Aerobic rice system improves water productivity, nitrogen recovery and crop performance in Brazilian weathered lowland soil. Field Crop Res 218:59-68. https://doi.org/10.1016/j.fcr.2018.01.002

Bouman BAM, Feng L, Tuong TP, Lu G, Wang H, Feng Y (2007) Exploring options to grow rice using less water in northern China using a modeling approach. II. Quantifying yield, water balance components, and water productivity. Agric Water Manag 88:23–33. https://doi.org/10.1016/j.agwat.2006.10.005

Cancela JJ, Fandiño M, Rey BJ, Martínez EM (2015) Automatic irrigation system based on dual crop coefficient, soil and plant water status for Vitis vinifera (cv Godello and cv Mencía). Agric Water Manag 151:52-63.

Carracelas G, Hornbuckleb J, Rosasa J, Roel A (2019) Irrigation management strategies to increase water productivity in *Oryza sativa* (rice) in Uruguay. Agric Water Manag 222:161-172. https://doi.org/10.1016/j.agwat.2019.05.049

Carracelas G, Guilpart N, Cassman KG, Grassini P (2023) Distinguishing between yield plateaus and yield ceilings: A case study of rice in Uruguay. Agric Water Manag 292:108808. https://doi.org/10.1016/j.fcr.2023.108808

Carrijo DR, Akbar N, Borja Reis, AF, Li C, Gaudin ACM, Parikh SJ, Green PG, Linquist BA (2018) Impacts of variable soil drying in alternate wetting and drying rice systems on yields, grain arsenic concentration and soil moisture dynamics. Field Crop Res 222:101-110. https://doi.org/10.1016/j.fcr.2018.02.026

Carrijo DR, Lundy ME, Linquist BA (2017). Rice yields and water use under alternate wetting and drying irrigation: a meta-analysis. Field Crop Res 203:173‑180. http://dx.doi.org/10.1016/j.fcr.2016.12.002

Chen L, Zhang J, Su H, Guo W Guo (2010). Weed identification method based on probabilistic neural network in the corn seedling field. Proc Ninth Int Conf Machine Learning and Cybernetics, Qingdao, China. IEEE, New York. https://doi.org/10.1109/ICMLC.2010.5580822

Choudhury BU, Singh AK, Pradhan, S (2013). Estimation of crop coefficients of dry seeded irrigated rice–wheat rotation on raised beds by field water balance method in the Indo-Gangetic plains, India. Agric Water Manag 123:20–31. https://doi.org/10.1016/j.agwat.2013.03.006

Clerget B, Bueno C, Quilty JR, Correa Jr TQ, Sandro J (2014) Modifications in development and growth of a dual-adapted tropical rice variety grown as either a flooded or an aerobic crop. Field Crop Res 155:134–143. http://dx.doi.org/10.1016/j.fcr.2016.09.018

Clerget, B, Bueno C, Domingo AJ, Layaoen HL, Vial L (2016) Leaf emergence, tillering, plant growth, and yield in response to plant density in a high-yielding aerobic rice crop. Field Crop Res 199:52-64. http://dx.doi.org/10.1016/j.fcr.2016.09.018

Coltro L, Marton LFM, Pileco FP Pilecco AC, Mattei LF (2017) Environmental profile of rice production in Southern Brazil: A comparison between irrigated and subsurface drip irrigated cropping systems. J Clean Prod 153:491-505. https://doi.org/10.1016/j.jclepro.2016.09.207

Counce PA, Keisling, TC, Mitchell, AJ (2000) A uniform, objective, and adaptative system for expressing rice development. Crop Sci. 40:436–443. https://doi.org/10.2135/cropsci2000.402436x

Christiansen J (1042) Irrigation by Sprinkling. Forgotten Books: London, UK, p:124.

Day PR (1965) Particle fractionation and particle-size analysis. In: Black C A et al (ed) Methods of Soil Analysis Part I. Agronomy Monograph, Am Soc Agron, Madison, Wis 9:545–567. https://doi.org/10.2134/agronmonogr9.1.c43

Diaz MB, Roberti DR, Carneiro JV Souza VA, Moraes OLL (2019) Dynamics of the superficial fluxes over a flooded rice paddy in southern Brazil. Agric Forest Meteorol 276–277:107650. https://doi.org/10.1016/j.agrformet.2019.107650

Farooq MS, Fatima H, Rehman OU, Yousuf M, Kalsoom R, Fiaz S, Khan MR, Uzair M, Huo S (2023). Major challenges in widespread adaptation of aerobic rice system and potential opportunities for future sustainability. S Afric J Botany 159, 231-251. https://doi.org/10.1016/j.sajb.2023.06.017

Ferreira DF (2011) Sisvar: a computer statistical analysis system. Cienc agrotec 35:1039-1042. https://doi.org/10.1590/S1413-70542011000600001

Fukai S, Mitchell J (2022) Factors determining water use efficiency in aerobic rice. Crop Environ 1:24-40. https://doi.org/10.1016/j.crope.2022.03.008

Gao L, Jin Z, Huang Y, Zhang L (1992) Rice clock model: computer model to simulate rice development. Agric Forest Meteorol 60:1–16**.** https://doi.org/10.1016/0168-1923(92)90071-B

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

Inthavong T, Tsubo M, Fukai S (2011) A water balance model for characterization of length of growing period and water stress development for rainfed lowland rice. Field Crops Res. 121:291-301. https://doi.org/10.1016/j.fcr.2010.12.019

Jeong H, Jang T, Seong C, Park S (2014) Assessing nitrogen fertilizer rates and split applications using the DSSAT model for rice irrigated with urban wastewater. Agric Water Manag. 141:1-9. https://doi.org/10.1016/j.agwat.2014.04.009

Jovanovic N, Pereira LS, Paredes P, Pôças I, Cantore V, Todorovic M (2020) A review of strategies, methods and technologies to reduce non-beneficial consumptive water use on farms considering the FAO56 methods. Agric Water Manag 239:106267. http://dx.doi.org/10.1016/j.agwat.2020.106267

Kadiyala MDM, Mylavarapu RS, Li YC Reddy GB, Reddy MD (2012) Impact of aerobic rice cultivation on growth, yield, and water productivity of rice–maize rotation in semiarid tropics. Agron J. 104:1757–1765. https://doi.org/10.2134/agronj2012.0148

Kadiyala MDM, Mylavarapu RS, Li YC Reddy GB, Reddy KR, Reddy MD (2015) Uptake efficiency of 15N-urea in flooded and aerobic rice fields under semi-arid conditions. Paddy Water Environ 13:545–556. https://doi.org/10.1007/s10333-014-0473-8

Kato Y, Kamoshita A, Yamagishi J (2006) Growth of three rice (*Oryza sativa* L.) cultivars under upland conditions with different levels of water supply. 2. Grain yield. Plant Prod Sci 9, 435–445. https://doi.org/10.1626/pps.9.435

Kato Y, Katsura K (2014) Rice adaptation to aerobic soils: physiological considerations and implications for agronomy. Plant Prod Sci 17:1–12. http://dx.doi.org/10.1626/pps.17.1

Krishnan P, Ramakrishnan B, Raja Reddy K, Reddy VR (2011) High-Temperature Effects on Rice Growth, Yield, and Grain Quality. In: Donald L. Sparks (ed) Advances in Agronomy, v.111, Burlington: Academic Press, pp.87-206

Kottek M, Grieser J, Beck C et al (2006) World Map of the Koppen-Geiger climate classification updated. Meteorol Z 15:259–263. https://doi.org/10.1127/0941-2948/2006/0130

LaHue GT, Linquist B (2021) The contribution of percolation to water balances in water-seeded rice systems. Agric Water Manag 243:106445. https://doi.org/10.1016/j.agwat.2020.106445

Liang L, Schwartz MD, Fei S (2012) Photographic assessment of temperate forest understory phenology in relation to springtime meteorological drivers. Int J Biometeorol 56:343–355. https://doi.org/10.1007/ s00484-011-0438-1

Li S, Chen Y, Li T, Yu F, Zhang Y, Liu K, Zhang H, Gu J, Yang J, Liu L (2022) Alternate wetting and moderate soil drying irrigation counteracts the negative effects of lower nitrogen levels on rice yield. Plant Soil 481:367–384. https://doi.org/10.1007/s11104-022-05644-6

Li W, Fang H, Wei SM, Baret F (2021) Critical analysis of methods to estimate the fraction of absorbed or intercepted photosynthetically active radiation from ground measurements: Application to rice crops. Agric Forest Meteorol 297:108273. https://doi.org/10.1016/j.agrformet.2020.108273.

Liu Y, Pereira LS, Fernando RM (2006) Fluxes through the bottom boundary of the root zone in silty soils: parametric approaches to estimate groundwater contribution and percolation. Agric Water Manage 84:27–40. https://doi.org/10.1016/j.agwat.2006.01.018.

Liu Y, Yang S, Lu H, Wang Y (2018) Effects of biochar on spatial and temporal changes in soil temperature in cold waterlogged rice paddies. Soil Till Res 181:102-109. https://doi.org/10.1016/j.still.2018.04.008

Liu M, Paredes P, Shi H, Ramos TB, Dou X, Dai L, Pereira LS (2022). Impacts of a shallow saline water table on maize evapotranspiration and groundwater contribution using static water table lysimeters and the dual Kc water balance model SIMDualKc. Agric. Water Manage., 273, p.107887. https://doi.org/10.1016/j.agwat.2022.107887

Linquist B, Snyder R, Anderson F, Espino L, Inglese G, Marras S, Moratiel R, Mutters R, Nicolosi P, Rejmanek H, Russo A, Shapland T, Zong Z, Swelam A, Tindula G, Hill J (2015). Water balances and evapotranspiration in water and dry seeded rice systems. Irrig Sci 33, 375–385. https://doi.org/ 10.1007/s00271-015-0474-4

Mao Z, Dong B, Pereira LS (2004) Assessment and water saving issues for Ningxia paddies, upper Yellow River Basin. Paddy Water Environ 2(2):99-110. https://doi.org/10.1007/s10333-004-0048-1

Martins JD, Rodrigues GC, Paredes P, Carlesso R, Oliveira ZB, Knies AE, Petry MT, Pereira LS (2013). Dual crop coefficients for maize in southern Brazil: model testing for sprinkler and drip irrigation and mulched soil. Biosyst Eng 115:291–310. https://doi.org/10.1016/j.biosystemseng.2013.03.016

Matsui T, Kobayasi K, Yoshimoto M, Hasegawa T (2007) Stability of rice pollination in the field under hot and dry conditions in the river in a region of New South Wales, Australia. Plant Prod Sci 10:57–63. https://doi.org/10.1626/pps.10.57

McMaster GS, Wilhelm WW (1997) Growing degree-days: one equation, two interpretations. Agr Forest Meteorol 87::291-300. https://doi.org/10.1016/S0168-1923(97)00027-0

Miao Q, Rosa RD, Shi H, Paredes P, Zhu L, Dai J, Gonçalves JM, Pereira LS (2016) Modeling water use, transpiration and soil evaporation of spring wheat-maize and spring wheat-sunflower relay intercropping using the dual crop coefficient approach. Agric Water Manag 165, 211–229, https://doi:org/10.1016/j.agwat.2015.10.024

Michelon CJ, Carlesso R, Oliveira ZB, Knies AE, Petry MT, Martins JD (2010) Pedotransfer functions to estimate the water retention in some soils of Rio Grande do Sul state, Brazil. Ciencia Rural 40:848-853. (In Portuguese, with abstract in English). https://doi.org/10.1590/S0103-84782010005000055

Moraes M, Debiasi H, Carlesso R, Franchini JC, Rodrigues da Silva V, Bonini da Luz F (2016) Soil physical quality on tillage and cropping systems after two decades in the subtropical region of Brazil. Soil Till Res 155, 351-362. https://doi.org/10.1016/j.still.2015.07.015

Moratiel R, Martínez-Cob A (2013). Evapotranspiration and crop coefficients of rice (*Oryza sativa* L.) under sprinkler irrigation in a semiarid climate determined by the surface renewal method. Irrig Sci 31, 411–422. https://doi.org/10.1007/s00271-011-0319-8

Moriasi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel RD, Veith TL (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans ASABE 50:885–900. https://doi.org/10.13031/2013.23153)@2007

Mortazar A, Rejmanek H, Tindula G, Little C, Shapland T, Anderson F, Inglese G, Mutters R, Linquist B, Greer CA, Hill J, Snyder R (2017) Crop coefficient curve for paddy rice from residual energy balance calculations. J Irrig Drain Eng 143(2),04016076 https://doi.org/10.1061/(ASCE)IR.1943-4774.0001117

Mote K, Rao VP, Ramulu V, Kumar KA, Devl MU (2022) Performance of rice (*Oryza sativa* (L.)) under AWD irrigation practice — A brief review. Paddy Water Environ 20:1-21. https://doi.org/10.1007/s10333-021-00873-4

Muirhead WA, Blackwell J, Humphreys E, White RJG (1989) The growth and nitrogen economy of rice under sprinkler and flood irrigation in South East Australia: I. Crop response and N uptake. Irrig Sci 10(3):183-199. https://doi.org/10.1007/BF00257952

Nalley L, Dixon B, Tack J, Barkley A, Jagadish K (2016) Optimal harvest moisture content for maximizing mid-south rice milling yields and returns. Agron J 108:701–712. https://doi.org/10.2134/agronj2015.0408

Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models. 1. A discussion of principles. J Hydrol 10:282-290. https://doi.org/10.1016/0022-1694(70)90255-6

Odhiambo LO, Irmak S (2012) Evaluation of the impact of surface residue cover on single and dual crop coefficient for estimating soybean actual evapotranspiration. AgricAgr Water Manag 104:221-234. https://doi.org/10.1016/j.agwat.2011.12.021

Paredes P, Pereira LS, Rodrigues GC, Botelho N, Torres MO (2017a). Using the FAO dual crop coefficient approach to model water use and productivity of processing pea (*Pisum sativum* L.) as influenced by irrigation strategies. Agric Water Manag 189:5–18. https://doi.org:10.1016/j.agwat.2017.04.010

Paredes P, Rodrigues GC, Alves I, Pereira LS (2014) Partitioning evapotranspiration, yield prediction and economic returns of maize under various irrigation management strategies. Agric Water Manag 135, 27–39. http://doi.org/10.1016/j.agwat.2013.12.010. Corrigendum in Agric Water Manag 141:84. http://doi.org/10.1016/j.agwat.2014.04.001

Paredes P, Rodrigues GC, Cameira MR, Torres MO, Pereira LS (2017b) Assessing yield, water productivity and farm economic returns of malt barley as influenced by the sowing dates and supplemental irrigation. Agric Water Manag 179:132–143. https://doi.org/10.1016/j.agwat.2016.05.033

Parfitt JMB, Concenço G, Scivittaro WB, Andres A, Silva JT, Pinto MAB (2017) Soil and water management for sprinkler irrigated rice in Southern Brazil. In: Adv Int Rice Product 1-16. https://dx.doi.org/10.5772/66024

Parthasarathi T, Vanitha K, Mohandass S, Vered E (2018) Evaluation of drip irrigation system for water productivity and yield of rice. Agron. J. 110:2378‑2389. https://doi.org/10.2134/agronj2018.01.0002.

Patrignani A, Ochsner TE (2015) Canopeo: A powerful new tool for measuring fractional green canopy cover. Agron J 107:2312–2320. https://doi.org/10.2134/agronj15.0150

Pereira LS, Allen RG, Smith M, Raes D (2015a) Crop evapotranspiration estimation with FAO56: past and future. Agric Water Manag 147:4–20. https://doi.org/10.1016/j.agwat.2014.07.031.

Pereira LS, Cordery I, Iacovides I (2012) Improved indicators of water use performance and productivity for sustainable water conservation and saving. Agric Water Manag 108:39-51. https://doi.org/10.1016/j.agwat.2011.08.022

Pereira LS, Paredes P, Hunsaker DJ, López-Urrea R, Shad, ZM (2021) Standard single and basal crop coefficients for field crops. Updates and advances to the FAO56 crop water requirements method. Agric Water Manag 243:106466. https://doi.org/10.1016/j.agwat.2020.106466

Pereira LS, Paredes P, Jovanovic N (2020b) Soil water balance models for determining crop water and irrigation requirements and irrigation scheduling focusing on the FAO56 method and the dual Kc approach. Agric Water Manag 241:106357. http://dx.doi.org/10.1016/j.agwat.2020.106357

Pereira LS, Paredes P, Melton F, Johnson L, Wang T, López-Urrea R, Cancela JJ, Allen RG (2020a) Prediction of crop coefficients from fraction of ground cover and height. Background and validation using ground and remote sensing data. Agric Water Manag 241:106197. https://doi.org/10.1016/j.agwat.2020.106197.

Pereira LS, Paredes P, Rodrigues GC, Neves M (2015b) Modeling barley water use and evapotranspiration partitioning in two contrasting rainfall years. Assessing SIMDualKc and AquaCrop models. Agric Water Manag 159:239–254. https://doi.org/10.1016/j.agwat.2015.06.006

Petry MT, Magalhães TF, Paredes P, Martins JD, Ferrazza CM, Hünemeier GA, Pereira LS (2023) Water use and crop coefficients of soybean cultivars of diverse maturity groups and assessment of related water management strategies. Irrig Sci, https://doi.org/10.1007/s00271-023-00871-w

Pinto MAB, Parfitt JMB, Tim LC, Faria LC, Concenço G, Stumpf L, Nöreberg BG (2020) Sprinkler irrigation in lowland rice: Crop yield and its components as a function of water availability in different phenological phases. Field Crop Res 248:107714. https://doi.org/10.1016/j.fcr.2020.107714

Pinto MAB, Parfitt JMB, Timm LC, Faria LC, Scivittaro WB (2016) Sprinkler-irrigated rice yield in lowlands as a function of water availability and soil attributes**.** Pesqui Agropecu Bras 9:584‑1593 (In Portuguese, with abstract in English). https://doi.org/10.1590/S0100-204X2016000900058.

Ramos TB, Darouich H, Oliveira AR, Farzamian M, Monteiro T, Castanheira N, Paz A, Gonçalves MC, Pereira LS (2023) Water use and soil water balance of Mediterranean tree crops assessed with the SIMDualKc model in orchards of southern Portugal. Agric Water Manag 279, 108209. https://doi.org/10.1016/j.agwat.2023.108209

Reavis W, Suvočarev K, Reba ML, Runkle BRK (2021) Impacts of alternate wetting and drying and delayed flood rice irrigation on growing season evapotranspiration. J Hydrol 596:126080. https://doi.org/10.1016/j.jhydrol.2021.126080.

Rosa RD, Paredes P, Rodrigues GC, Alves I, Fernando RM, Pereira LS, Allen RG (2012) Implementing the dual crop coefficient approach in interactive software. 1. Background and computational strategy. Agric Water Manag 103:8–24. https://doi.org/10.1016/j.agwat.2011.10.013

Sánchez B, Rasmussen A, Porter JR (2014) Temperatures and the growth and development of maize and rice: a review. Glob Change Biol 20:408–417. https://doi.org/10.1111/gcb.12389

Soil Survey Staff (2022) Keys to Soil Taxonomy. 13th ed. Washington, DC: United States Department of Agriculture, Natural Resources Conservation Service.

Sosbai (2018) Rice Technical Recommendation from Research in Southern Brazil. Embrapa Clima Temperado. Pelotas, Brazil: EMBRAPA. 205 p. Original in Portuguese.

Sousa RO, Carlos FS, Silva LS, Scivittaro WB, Ribeiro PB, Lima CLR (2021) No-tillage for flooded rice in Brazilian subtropical paddy fields: history, challenges, advances and perspectives. Rev Bras Cienc Solo. 45:e0210102. https://doi.org/10.36783/18069657rbcs20210102

Souza JVRS, Saad JCC, Sánchez-Román RM, Rodríguez-Sinobas L (2016) No-till and direct seeding agriculture in irrigated bean: Effect of incorporating crop residues on soil water availability and retention, and yield. Agric Water Manage 170, 158-166. https://doi.org/10.1016/j.agwat.2016.01.002

Spanu A, Murtas A, Ballone F (2009). Water use and crop coefficients in sprinkler irrigated rice. Ital. J. Agron. 2:47–58. https://doi.org/10.4081/ija.2009.2.47

Stevens G, Vories E, Heiser J, Rhine M (2012) Experimentation on cultivation of rice irrigated with a center pivot system. In: TS Lee (ed) Irrigation Systems and Practices in Challenging Environments. InTech, 233-254.

Ulguim DR, Fruet BL, Merotto Junior A, Silva AL (2021) Status of weed control in imidazolinone-herbicide resistant rice in Rio Grande do Sul. Adv Weed Sci 29:e237355. https://doi.org/10.51694/AdvWeedSci/2021;39:00007

Vories E, Stevens W, Rhine M, Straatmann, Z (2017) Investigating irrigation scheduling for rice using variable rate irrigation. Agric Water Manag 179:314-323. https://doi.org/10.1016/j.agwat.2016.05.032

Vories ED, Stevens WE, Tacker PL, Griffin TW, Counce PA (2013) Rice production with center pivot irrigation. Appl Eng Agric 1:51–60, 2013. https://doi.org/10.13031/2013.42532

Xu J, Bai W, Li Y, Wang H, Yang S, Wei Z (2019) Modeling rice development and field water balance using AquaCrop model under drying-wetting cycle condition in eastern China. Agric Water Manag 213:289-297, https://doi.org/10.1016/j.agwat.2018.10.028

Yoshida S (1981) Fundamentals of Rice Crop Science. Laguna International Rice Research Institute, 269, Los Banos, Philippines.

Yu Q, Cui Y (2022) Improvement and testing of ORYZA model water balance modules for alternate wetting and drying irrigation. Agric Water Manag 271:107802. https://doi.org/10.1016/j.agwat.2022.107802

4. CAPÍTULO II - PARÂMETROS DE CRESCIMENTO, PRODUTIVIDADE E ANÁLISE ECONÔMICA DO ARROZ IRRIGADO POR ASPERSÃO

GROWTH PARAMETERS, PRODUCTIVITY AND ECONOMIC ANALYSIS OF SPRINKLER IRRIGATED RICE

(Paper submitted to Revista Ciência Agronômica)

RESUMO - A avaliação da viabilidade econômica do arroz irrigado por aspersão é importante para a tomada de decisão mais assertiva, de forma a obter o maior custo-benefício desse sistema, o que inclui a avaliação da adaptabilidade, rendimento de grãos e de engenho do arroz. O objetivo desse estudo foi o de avaliar os parâmetros de crescimento, da viabilidade econômica, da produtividade da água e da qualidade de grãos do arroz irrigado por aspersão. O experimento foi conduzido à campo na Universidade Federal de Santa Maria (UFSM), em Santa Maria/RS. O delineamento experimental utilizado foi de blocos ao acaso, bifatorial em faixas, com 4 repetições. O fator A representou três manejos de irrigação (irrigação diária, alternada e sem irrigação) e o fator B foi constituído de duas cultivares de arroz (IRGA 424 RI e IRGA 431 CL). Parâmetros morfológicos da cultura foram avaliados ao longo do ciclo da cultura. O custo operacional foi calculado de acordo com a média da região, enquanto o custo da irrigação incluiu o custo da aplicação da lâmina e a manutenção do sistema. A irrigação por aspersão aumenta a eficiência do uso da água, contudo reduz o acúmulo de matéria seca. A cultivar IRGA 431 CL destaca-se por reduzir o uso de água e melhorar a produtividade da água de irrigação sem afetar a produtividade de grãos, enquanto a IRGA 424 RI mostra maior produtividade e lucro com irrigação diária.

Palavras-chave: Terras altas. Sustentabilidade. Uso da água. Qualidade de grãos. Balanço agrícola.

ABSTRACT - Evaluating the economic viability of sprinkler-irrigated rice is important for more assertive decision-making in order to obtain the greatest cost-benefit from this system, which includes evaluating the adaptability, grain yield and yield of the rice. The aim of this study was to evaluate the growth parameters, economic viability, water productivity and grain quality of sprinkler-irrigated rice. The experiment was conducted in the field at Universidade Federal de Santa Maria (UFSM) in Santa Maria/RS. The experimental design used was a randomized block design, with four replications. Factor A represented three irrigation managements (daily irrigation, alternating irrigation and no irrigation) and factor B consisted of two rice cultivars (IRGA 424 RI and IRGA 431 CL). Morphological parameters of the crop were assessed throughout the crop cycle. The operating cost was calculated according to the average for the region, while the cost of irrigation included the cost of applying the blade and maintaining the system. Sprinkler irrigation increases water use efficiency, but reduces dry matter accumulation. The IRGA 431 CL cultivar stands out for reducing water use and improving irrigation water productivity without affecting grain yield, while IRGA 424 RI shows greater productivity and profit with daily irrigation.

Key words: Highlands. Sustainability. Water use. Grain quality. Agricultural balance.

1 INTRODUÇÃO

O Brasil cultivou 1479,6 mil hectares de arroz na safra de 2022/23, sendo 303 mil hectares de sequeiro (CONAB, 2023). Este tipo de cultivo apresenta baixa produtividade em comparação ao arroz irrigado por inundação, pois geralmente é cultivado em áreas recém abertas, sobretudo no Cerrado (LACERDA e NASCENTE, 2021) e o atendimento de sua demanda hídrica é dependente das precipitações que ocorrem ao longo do ciclo de cultivo (FUKAI, MIRTCHELL, 2022). Na Fronteira Oeste no estado do Rio Grande do Sul muitos produtores estão adotando o método de irrigação por aspersão no cultivo de arroz, sendo denominado também de arroz aeróbico. A prática de aspersão no cultivo de arroz necessita ser avaliada do ponto de vista do crescimento da planta, da produtividade e do retorno econômico.

Aumentar a produção de grãos e manter a sua qualidade, reduzindo ao mesmo tempo a quantidade de água utilizada, são grandes desafios para o setor orizícola em todo o mundo. Assim, produtores estão sendo desafiados a adotarem práticas de irrigação que reduzam o consumo da água, como o cultivo do arroz aeróbico, e manter a rentabilidade por volume de água utilizado (CHAMPNESS et al., 2023). A aspersão se torna um método interessante em áreas não sistematizadas e/ou com declividade superior a 2% (PARFITT et al., 2017). Segundo PINTO et al., 2016 o método de irrigação por aspersão busca atender à necessidade hídrica da cultura do arroz e diminuir as perdas que ocorrem no método por inundação. Em estudos conduzidos com aspersão, Pinto et al. (2018) observaram redução no uso de água entre 18 e 35% e também, que a umidade deve ser mantida próxima a capacidade de campo. Em pesquisas conduzidas em arroz sob aspersão, Scivittaro e Parfitt (2017) indicam uma redução de 40% no uso da água em relação à inundação. Assim, a irrigação por aspersão economiza água e pode ser um método capaz de ser adotado pelos produtores.

Uma das formas de validar a adoção da irrigação por aspersão é estimar a produtividade da água, avaliação econômica e da renda de engenho. Várias pesquisas têm avaliado a produtividade da água para diferentes manejos de irrigação utilizados na cultura do arroz, entre eles o de irrigação contínua, irrigação intermitente e irrigação por molhamento e secamento alternado (ALBERTO et al., 2020).

A utilização da aspersão é destacada por Stevans et al. (2012), que ressaltam a introdução desse sistema em áreas não tão apropriadas para o uso da inundação, ou que exijam elevado uso de máquina e trabalho para a construção de curvas de nível e manejo da água nessas condições. Com relação ao rendimento de grãos, o arroz pode ser produzido também em áreas de terras altas, sem inundação, com rendimentos condizentes com aqueles de terras baixas

(VORIES et al., 2013). No entanto, faz-se necessário realizar estudos abordando a viabilidade econômica da irrigação por aspersão em ambiente de terras altas.

A contabilidade de custos é uma técnica para identificar, aferir os custos dos produtos e/ou serviços de forma precisa para que se possa tomar uma decisão. Além dos custos de produção refletirem o processo decisório do produtor, a eficiência econômica e a gestão do empreendimento, também são indicadores relevantes do sucesso da atividade rural, pois quanto menor o custo de produção, maior será a rentabilidade do produtor (SANTOS, 2017).

Os custos da irrigação por aspersão são relacionados aos custos de bombeamento, somado ao custo da água e manutenção dos equipamentos, para sistemas de irrigação já instalados (TURCO et al., 2009). No Brasil, não há tarifação da água para irrigação, resumindo o custo para irrigar em gasto realizado para a aplicação da lâmina e manutenção dos equipamentos utilizados no sistema. De acordo com Almeida (2019), a energia elétrica consumida em sistemas de irrigação por pivô central está atrelada ao bombeamento e ao acionamento dos motores elétricos das torres. Este custo é variável conforme a demanda contratada, as taxas referentes ao uso do sistema, a bandeira tarifária e os impostos Estaduais e Federais. Além disso, no custo de produção incidem os custos com fertilizantes, máquinas agrícolas, benfeitorias, operações agrícolas, consumo de combustível, impostos, licenças e agroquímicos.

Portanto, o estudo dos fatores econômicos do sistema de produção é importante para demonstrar a viabilidade econômica de uma prática adotada em uma propriedade. Assim, o presente estudo teve como objetivo avaliar os parâmetros de crescimento, produtividade de grãos e da água e a viabilidade econômica do cultivo de arroz irrigado por aspersão.

2 MATERIAL E MÉTODOS

O experimento foi conduzido à campo nos anos agrícolas de 2020/2021 e 2021/2022, em área experimental do Sistema Irriga na Universidade Federal de Santa Maria, Santa Maria - RS, situada em Latitude de 29°41’24” S e Longitude de 53°48’42” W com altitude de 105 m. O clima da região é do tipo “Cfa” subtropical úmido, sem estação seca definida e com verões secos, segundo classificação de Köeppen-Geiger (KOTTEK et al., 2006). O solo é classificado como Argissolo Vermelho Distrófico arênico (EMBRAPA, 2006).

2.1 DELINEAMENTO EXPERIMENTAL

O delineamento experimental utilizado foi um esquema bifatorial 3x2, em faixas, com quatro repetições, em parcelas com dimensão de 4,10 m x 12 m. Foram testados três tratamentos de irrigação: (i) irrigações brutas diárias de ~ 8 mm; (ii) irrigações brutas alternadas de ~16 mm, visando manter conteúdo de água no solo próximo da capacidade de campo e; (iii) sem irrigação. As irrigações eram realizadas quando ocorriam precipitações. As cultivares de arroz utilizadas foram a IRGA-431 CL e IRGA-424 RI.

A semeadura ocorreu aos sete e doze dias do mês de novembro de 2020 e de 2021, respectivamente, na densidade 112 kg ha^{-1} de sementes, para ambas as cultivares, em espaçamento de 0,17 m entre linhas. A adubação de base foi conforme indicação da análise de solo e a de cobertura foi de um total de 160 kg ha^{-1} de nitrogênio, sendo dividida em 90 kg de N ha^{-1} aplicados no início do perfilhamento (estádio V3), 40 kg de N ha^{-1} no estádio V6 e 30 kg de N ha^{-1} na diferenciação da panícula (estádio R1). Foram aplicados 300 kg da fórmula 5-20-20 por hectare. Os demais tratos culturais foram realizados conforme as recomendações técnicas da pesquisa (SOSBAI, 2018). As irrigações foram realizadas por um sistema de aspersão convencional. As lâminas de irrigação aplicadas no experimento foram utilizadas para estimar o custo de irrigação com a utilização do equipamento pivô central.

2.2 PARÂMETROS DE DESENVOLVIMENTO DA CULTURA

A altura de plantas foi determinada com uma régua graduada em cm, em forma de T medindo-se a partir do solo até o ápice do limbo foliar da folha bandeira no estádio R9. A área foliar foi determinada de forma destrutiva, a partir da coleta de cinco plantas por unidade experimental, medindo-se o comprimento e largura de cada folha da planta mãe nos estádios V6, V8 e R4, conforme os estádios descritos por Counce et al. (2000). O produto das medidas de seu comprimento e largura, multiplicadas pelo coeficiente de 0,75 (CARLESSO et al., 1998). O índice de área foliar (IAF) foi calculado pela razão entre a AF de cada planta pela superfície ocupada pela mesma planta.

As plantas coletadas para o IAF foram utilizadas para a determinação da massa seca de raízes e da massa seca de parte aérea. Estas plantas foram pesadas e acondicionas em sacos de papel, posteriormente levadas para estufa de circulação forçada de ar, a uma temperatura de 65°C por um período de 72 horas.

2.3 PRODUTIVIDADE E QUALIDADE DE GRÃOS

A colheita foi realizada de forma manual em ambas as safras, 7 de abril de 2021 (ano I) e 14 de abril de 2022 (ano II), onde colheu-se 2,55 m² de cada parcela experimental e com isto a produtividade de grãos foi determinada a partir do peso resultante desta dentro de cada parcela experimental.

O rendimento de engenho de grãos do arroz foi determinado através do beneficiamento de quatro amostras com 100 g de grãos de arroz em casca retirados de cada tratamento, as quais foram processadas em testadora de grãos de arroz da marca Zaccaria, modelo PAZ^{-1}. Os grãos brunidos (polidos) foram pesados e o valor encontrado é considerado como rendimento de benefício, sendo estes resultados expressos em porcentagem. Os grãos brunidos foram colocados no *Trieur* e a separação dos grãos é processada por 30 segundos. Assim, os grãos que permaneceram no *Trieur* foram separados, no que resulta no rendimento de grãos inteiros, sendo os demais considerados como grãos quebrados e ambos expressos em porcentagem.

As frações de engenho avaliadas foram: grão inteiro, que é o grão descascado e polido que apresenta comprimento igual ou superior a três quartos do comprimento mínimo da classe que predomina; grão quebrado, que é o pedaço do grão de arroz descascado e polido que apresentar comprimento inferior a três quartos do comprimento mínimo da classe que predomina; renda do benefício: percentual de arroz beneficiado e polido, resultante do beneficiamento do arroz em casca.

2.4 ANÁLISE ECONÔMICA

A produtividade da água, também conhecido como eficiência de uso da água (WP, kg m^{-3}) é definido como a razão entre o rendimento real ou atual (Ya) e a água utilizada em m^{3} correspondente a essa produção. Ela pode ser analisada por três pontos de vista: produtividade total da água (WP_T), produtividade da água de irrigação (WP_{irrig}). Cada uma das frações da produtividade da água foi determinada pelas Equações a seguir:

$$WP_T = \frac{Ya}{TWU} \tag{1}$$

$$WP_{Irrig} = \frac{Ya}{IWU} \tag{2}$$

WP_T= Produtividade da água total (Kg m^{-3}), WPirrig= Produtividade da água de irrigação (Kg m^{-3}), Ya= produtividade de grãos (Kg ha^{-1}), TWU= total de água utilizada (m^{3}), IWU= água de irrigação usada (m^{3}). Os dados da lâmina total irrigada e precipitação durante o ciclo da cultura, nos dois anos de cultivo foram baixados da estação climatológica do INMET localizada na Universidade Federal de Santa Maria (UFSM).

Análise econômica foi estimada através da determinação da receita bruta e o lucro operacional da propriedade agrícola. Para isso foram levantadas os gastos e equipamentos envolvidos no cultivo em R$/hectare de arroz sob plantio direto, de acordo com o manejo realizado no experimento. O custo operacional da lavoura levou em consideração os gastos com combustível, corretivos, fertilizantes, agroquímicos, enquanto o custo da irrigação englobou a energia elétrica, e a quantidade de água aplicada.

A determinação do valor do litro do combustível foi realizada com base no levantamento da Agência Nacional de Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, a partir dos dados de 2022 chegando-se ao valor de R$5,52 reais. A cotação do arroz foi determinada através dos dados obtidos da base de dados do site do CEPEA- ESALQ no período de 01/01/2021 à 31/12/2022, a cotação determinada para o ano de 2021 foi de R$80,25 reais e para 2022 foi de R$78,78 reais.

Para a realização do estudo da viabilidade econômica da propriedade foram considerados as seguintes operações agrícolas (Tabela 1): depreciação de infraestrutura e maquinário, distribuição de calcário, passagem de rolo faca para manejo das plantas de cobertura, três aplicações de herbicida (uma antes do plantio, outra no ponto de agulha e em V3/V4), duas aplicações de fungicida e inseticida e a colheita. Os gastos de combustível em cada operação foram feitos com base em artigos científicos.

Tabela 1 Custos com combustíveis, lubrificantes e peças para realização das operações agrícolas.

Operação	Combustível (litros)	R$/ha
Rolo Faca	5,0	27,6
Pulverização	8,0	44,16
Plantio	12,8	70,66
Adubação de cobertura	8,07	44,54
Colheita	22,75	125,58
Lubrificantes e peças	45,02	45,02
	Total	357,56

Os custos com fertilizantes, sementes e agroquímicos foram baseados no manejo adotado na realização dos experimentos, estão descritos nas Tabelas 2 e 3 a seguir.

Tabela 2 Custos com corretivos, fertilizantes e sementes.

Produto	R$/unidade	R$/ha
Calcário	110,00	550,00
Adubo (5-20-20)	81,50	489,00
Sementes IRGA 424 RI	125,00	312,20
Sementes IRGA 431 CL	138,00	386,40
Ureia comum	139,00	973,00
TOTAL		R$2710,60

Tabela 3 Custos com defensivos agrícolas.

(continua)

Produto	Custo unitário (R$)	Total por hectare (R$/ha)
Óleo Mineral	18,00/litro	18,00
Glifosato	30,89/litro	185,34

Tabela 4 Custos com defensivos agrícolas

(conclui)

Basagran 600	98,00/litro	117,60
Clincher	172,50/litro	258,75
Mancozebe	19,71/quilo	98,54
Engeo Pleno S	9,65/litro	5,8
	Total	R$684,03

2.5 CÁLCULO DO CUSTO DA ENERGIA ELÉTRICA

Foram considerados custos variáveis os gastos com energia elétrica para o bombeamento, a demanda energética do sistema de irrigação e o custo da lâmina irrigada. Os cálculos dos custos com energia elétrica foram realizados a partir da escolha de um pivô central, que possui uma área de 46,34 hectares, motor de 100 cvs e eficiência do motor 90%.

A demanda energética foi estimada através da Equação 3 (BISPO, 2009):

$$D(kWh) = \frac{(Pn * 0.736 * h * IC)}{\eta} \tag{3}$$

Onde D é demanda em kWh, Pn é potencial nominal em cv, h é horas de operação, IC é o índice de carregamento e η é a eficiência do motor (90%). Para motores elétricos em operações agrícolas se utiliza um IC de 75%.

Após a realização do cálculo, Equação 5, chegou-se à demanda de 61,33 kWh. Utilizou-se como referência o valor de demanda contratada descrito na Tabela 4 adaptada de Reis et al. (2021). Com estas informações chegou-se o valor para demanda contratada para uso do pivô central de R$ 1343,13 para uso do pivô.

Tabela 5 Valor de demanda contratada referente a empresa CPFL no ano 2021.

Período de consumo	Mês					
	Nov/20	Dez/20	Jan/21	Fev/21	Mar/21	Abr/21
	Demanda (kW)					
Fora de ponta	21,6	21,6	21,6	21,6	21,6	21,6
Ponta	71,4	90,3	95,9	121,5	115,5	122,5

A unidade consumidora foi classificada como sendo pertencente ao grupo A e ao subgrupo A4. Para a realização do custo tarifário adotou-se a bandeira tarifária verde e o posto tarifário Fora de Ponta.

Depois de calcular a demanda contratada foi determinado o consumo energético, para motores maiores que 25 cvs, do motor do pivô através da equação proposta por Carvalho (2000):

$$Consumo\ (kWh) = 2.64 + 0.8 * potência(cv) \tag{4}$$

Substituindo-se o valor da potência do motor na Equação 4 obteve-se o consumo de 82,64 kWh, este valor foi usado para o cálculo do gasto com energia elétrica para o funcionamento do pivô.

A seguir foi realizado o levantamento do custo energético com base em dados obtidos da ANEEL 2023 e em tarifa praticada pela concessionária RGE (CPFL) praticada no ano de 2023, apresentado na Tabela 5.

Tabela 6 Tarifas incidentes na unidade consumidora para o Grupo A, subgrupo A4, para bandeira verde fora de ponta de acordo com a ANEEL e com a concessionária RGE do grupo CPFL em R$/kWh.

Grupo	Subgrupo	Bandeira	Tributo	Valor
A	A4	Verde (FP)	TUSD	94,21
			TE	276,25
			ICMS	17%
			PIS/PASEP	1,12%
			COFINS	5,22%

Onde TSUD é a é a tarifa de uso do sistema de distribuição; TE é a taxa de energia; ICMS é o imposto sobre circulação de mercadorias e prestação de serviços; PIS é o imposto para o programa de integração social e COFINS é a contribuição para a seguridade social.

O custo com energia elétrica foi calculado com base nas Equações 5 e 6 (BARREDA, 2023):

$$\mathrm{TUSD} = \left(\frac{\mathrm{R\$}}{\mathrm{kWh}}\right) = \left[\frac{\dfrac{\text{Tarifa sem imposto}}{1-(\mathrm{PIS}+\mathrm{COFINS})}}{1000}\right] \tag{5}$$

$$\mathrm{TE} = \left(\frac{\mathrm{R\$}}{\mathrm{kWh}}\right) = \left[\frac{\dfrac{\text{Tarifa sem imposto}}{1-(\mathrm{PIS}+\mathrm{COFINS})\,\mathrm{x}\,(1-\mathrm{ICMS})}}{1000}\right] \tag{6}$$

O valor de demanda contratada foi de R$21,90 por kWh (Tabela 5). Com a soma dos resultados das Equações 5 e 6 chegou-se à tarifa de R$ 0,46 por kWh. A determinação do gasto em kWh feito através da Equação:

$$Custo\ energia = t * \ consumo * Taxa \tag{7}$$

Onde: Custo com energia é o valor gasto pelo motor do conjunto moto-bomba para aplicar a lâmina bruta de irrigação; t = tempo gasto para aplicar a lâmina de irrigação; Consumo é o quanto o motor gasta em kWh para funcionar; Taxa é a taxa cobrada pela concessionária por kWh.

Após determinar o custo do consumo de conjunto moto-bomba somou-se ao custo da demanda contratada determinando-se o custo com energia mensal. Este valor foi dividido pela lâmina aplicada e determinou-se o valor gasto por mm irrigado. Também foi determinado o valor da demanda contratada dividido pelo número de irrigações resultando no valor da demanda por irrigação.

A receita bruta (RB) foi determinada pela multiplicação da produtividade em sacas por hectare e o valor de comercialização (VC) da saca (Equação 8). O Lucro operacional foi feito para um agricultor que utiliza apenas recursos próprios (sem financiamento), Equação 9, sendo calculado pela diferença entre o total de entradas e o Custo Total (CT). A cotação do arroz foi determinada através dos dados obtidos da base de dados do site do CEPEA- ESALQ no período de 01/01/2021 à 31/12/2022, a cotação determinada para o ano de 2021 foi de R$ 80,25 reais e para 2022 foi de R$ 78,78 reais.

$$RB = produtividade\ (scs\ ha^{-1}) * VC \tag{8}$$

$$LO\ =\ RB\ -\ CT \tag{9}$$

Onde RB é a receita bruta; VC é o valor comercial; LO é o lucro operacional; Custo total (CT) é o gasto total necessário para a realização de todas as atividades.

2.6 ANÁLISE ESTATÍSTICA

Os resultados obtidos para as diferentes variáveis repostas foram submetidos a análise da variância (teste F) e havendo significância será aplicado o teste Tukey, para a comparação de médias, ambos com 5% de probabilidade de erro, utilizando o software Sisvar.

3 RESULTADOS E DISCUSSÃO

3.1 INDICE DE ÁREA FOLIAR

Os valores de índice de área foliar pouco diferiram entre os manejos de irrigação para os dois anos de cultivo. Na Tabela 6 são apresentados os valores do índice de área foliar (IAF) nos estádios V6, V8 e R4.

Tabela 7 Valores índice de área foliar (IAF) (m2 m-2) referentes as cultivares IRGA 424 RI e IRGA 431 CL, durante os anos agrícolas de 2020/21 e 2021/22 em diferentes estratégias de manejo de irrigação (MI).

Safras	Manejo de irrigação	IAF (m^{2} m^{-2})					
		IRGA 424 RI			IRGA 431 CL		
		V6	V8	R4	V6	V8	R4
2020/21	Diário	1.0^{ns}NS	3.5^{ns}A	8.8^{ns}A	1.1A	3.0A	8.6A
	Alternado	1.0^{ns}	2.9^{ns}A	8.2^{ns}B	1.2A	3.2A	9.7A
	Sequeiro	1.1^{ns}	1.6^{ns}B	5.8bC	0.9B	2.0B	7.4aB
	CV (%)	12.5	23.9	7.7	12.2	23.9	7.7
2021/22	Diário	0,96^{ns}NS	3,32^{ns}NS	8.57^{ns}NS	1,1NS	2,97NS	8.77NS
	Alternado	0,94^{ns}	3,36^{ns}	8.12b	1,12	3,11	9.23a
	Sequeiro	-	-	-	-	-	-
	CV (%)	14,67	23.99	5,92	14,09	23.99	5,92

*Médias seguidas de mesma letra não diferem entre si pelo teste de Tukey em nível de significância 5% de probabilidade de erro. NS e ns: Não significativo pelo teste de Tukey ($p < 0,05$). Médias seguidas de mesma letra maiúscula para as estratégias de irrigação e minúsculas entre as cultivares (horizontal) não diferem entre si pelo teste Tukey em nível de 5% de probabilidade de erro.

Não se observou diferenças estatísticas nos manejos de irrigação para o IAF entre as cultivares nos estádios V6, V8 e R4, já no manejo de irrigação em sequeiro no estádio R4 a cultivar IRGA 431 CL apresentou maior IAF. Alvarez et al. (2012) encontraram IAF máximo de 5,8 m² m^{-2} aos 83 DAE para as cultivares adaptadas ao sequeiro (Caiapó e BRS Primavera). Menezes et al. 2021, encontraram um IAF máximo de 9,4 m² m^{-2} para a cultivar IRGA 424 RI sob inundação contínua (IC). No estádio R4, em 2021/22, observou-se um IAF 11,9% maior para a IRGA 431 CL na irrigação alternada (IA), 9,32 m² m^{-2}, em relação a IRGA 424 RI, 8,21 m² m^{-2}, indicando uma maior plasticidade dessa cultivar, tanto para o manejo alternado de irrigação, como para o estresse hídrico severo. O menor índice de área foliar do tratamento sequeiro no estádio R4 se deve ao menor crescimento das plantas, isto ocorreu devido a ausência ou baixos volumes pluviais até a metade do ciclo. Isto foi observado por Nguyen et al. (2009), indicando que o arroz é extremamente sensível à pequenas reduções na umidade do solo.

3.3 MASSA SECA DA PARTE AÉREA

Na tabela 7 são apresentadas a massa seca da parte aérea de plantas para as duas cultivares avaliadas, nos estádios V6, V8 e R4 para os diferentes manejos de irrigação, nos dois anos de cultivo.

Tabela 8 Massa seca da parte aérea (g planta-1) nos estádios V6, V8, R4 das cultivares IRGA 424 RI e IRGA 431 CL nas safras 2020/21 e 2021/22.

Safras	Manejo de irrigação	Massa Seca da parte aérea (g planta^{-1})					
		IRGA 424 RI			IRGA 431 CL		
		V6	V8	R4	V6	V8	R4
2020/21	Diário	0.69^{ns}NS	1.2^{ns}	3.4aA	0.72NS	1.63A	2.7bA
	Alternado	0.71^{ns}	1.3^{ns}	3.5aA	0.68	1.5AB	2.5bA
	Sequeiro	0.67^{ns}	0.9^{ns}	1.1^{ns}B	0.70	1.0B	1.2B
	CV (%)	2.6	24.8	10.8	2.6	24.8	10.8
2021/22	Diário	0.84^{ns}NS	1.86^{ns}A	$4,00^{ns}$NS	0.86NS	1.78A	3.83NS
	Alternado	0.85^{ns}	1.94^{ns}A	3.68^{ns}	0.84	1.77A	3.60
	Sequeiro	$0,83^{ns}$	$1,04^{ns}$B	-	0,81	0,94B	-
	CV (%)	2.71	18,44	7,74	2,71	18,44	7,74

*Médias seguidas de mesma letra não diferem entre si pelo teste de Tukey em nível de significância 5% de probabilidade de erro. NS e ns: Não significativo pelo teste de Tukey ($p< 0,05$). Médias seguidas de mesma letra maiúscula para as estratégias de irrigação e minúsculas entre as cultivares (horizontal) não diferem entre si pelo teste Tukey em nível de 5% de probabilidade de erro.

A massa seca da parte aérea (MS) não diferiu entre os tratamentos irrigados e cultivares, no ano de 2020/21. No ano agrícola 2021/22, a cultivar IRGA 424 RI teve maior massa seca (MS) da parte aérea em R4, em relação a cultivar IRGA 431 CL, o que está relacionado ao maior IAF e altura de plantas. A MS da parte aérea em R4 para o tratamento de sequeiro foi menos de 30% da MS da parte aérea de plantas irrigadas. Crusciol et al. (2012) obteve uma produção média de 2,34 g planta^{-1} de massa seca da parte aérea em cultivo de plantas de arroz em vaso, muito próximo ao observado na Tabela 7 no estádio R4. Oh-e et al. (2007) observaram um valor médio de 2,43 e 1,7 g planta^{-1} no florescimento, em dois anos consecutivos de observações, valores que se aproximam dos aqui verificados, sobretudo no ano 2020/21. Aramburu et al. (2022) observaram para o cultivo de arroz sob aspersão em várzea no estádio R4 valores em torno de 2,96 g planta^{-1} próximos aos da Tabela 7, em arroz sob aspersão em terras baixas, mantendo a umidade do solo próximo a saturação. As plantas de arroz cultivadas sob aspersão apresentaram crescimento semelhante ao observado em outros trabalhos.

3.4 MASSA SECA DE RAÍZES

A massa seca de raízes nos estádios iniciais V6 e V8 não diferiram entre os manejos de irrigação e cultivares e estão apresentadas na Tabela 8.

Tabela 9 Massa seca de raízes (g. planta-1) das cultivares de arroz irrigado IRGA 424 RI e IRGA 431 CL nos anos agrícolas 2020/21 e 2021/22.

			2020/21			
	IRGA 424 RI			IRGA 431 CL		
	V6	V8	R4	V6	V8	R4
			g planta^{-1}			
Sequeiro	0,58^{ns}	0,76^{ns}	0,74^{ns}B	0,58^{ns}	1,10	0,90B
Alternado	0,57^{ns}	0,82^{ns}	1,28bA	0,60	1,03	1,67aA
Diário	0,65^{ns}	0,76^{ns}	1,49nsA	0,60	1,06	1,39A
CV%	9,49	26,04	14,11	9,49	26,04	14,11
			2021/22			
	IRGA 424 RI			IRGA 431 CL		
			g planta^{-1}			
	V6	V8	R4	V6	V8	R4
Sequeiro	0,64^{ns}	1,08^{ns}	0,72^{ns}B	0,69^{ns}	1,02^{ns}	0,87B
Alternado	0,61^{ns}	1,17^{ns}	1,24bA	0,64	1,09	1,66aA
Diário	0,61^{ns}	1,09^{ns}	1,45^{ns}A	0,61	1,20	1,40A
CV%	9,44	21,39	14,11	2,47	19,05	9,27

*Médias seguidas de mesma letra não diferem entre si pelo teste de Tukey em nível de 5% de probabilidade de erro. NS e ns: Não significativo pelo teste de Tukey ($p< 0,05$). Médias seguidas de mesma letra maiúscula na coluna e minúscula na linha (cultivares) não diferem entre si pelo teste Tukey em nível de 5% de probabilidade de erro.

A massa seca de raízes nos estádios iniciais V6 e V8 não diferiram entre os manejos de irrigação e cultivares (Tabela 8). Essa não diferenciação ocorreu porque os dois manejos de irrigação proporcionaram um fornecimento adequado de água, corroborando com os resultados de Jiang et al. (2022), que não verificaram diferenças entre o número de raízes aos 45 dias após a semeadura entre o arroz inundado e o arroz de sequeiro. No estádio R4, houve diferença entre os tratamentos irrigados (ID e IA) e o tratamento sequeiro. Nesta fase a planta está mais dependente das condições hídricas e da ausência de precipitação pluviométrica, correspondente a fase de maior consumo de água. Estas condições resultam em menor crescimento da parte aérea e do sistema radicular no tratamento sequeiro. Aramburu et al. (2022) observaram 1,49 g. planta^{-1} de massa seca de raízes em R4 em irrigação por aspersão no ambiente de várzea, valores esses muito próximos aos observados neste estudo. Holzschuh et al. (2009) obtiverem massa seca de raízes de 0,69 g planta^{-1} aos 38 DAE (equivalente ao estádio V6) para a cultivar IRGA 417 o que corrobora com os observados neste experimento e para o mesmo estádio na safra 2021/2022.

3.5 PRODUTIVIDADE DE GRÃOS, PRODUTIVIDADE DA ÁGUA E PRODUTIVIDADE DA ÁGUA IRRIGADA

A produtividade de grãos, produtividade da água e produtividade da água irrigada, para as duas cultivares e dois anos agrícolas são apresentados na Tabela 9.

Tabela 10 Rendimento de grãos (Kg ha^{-1}), lâmina bruta irrigada (mm), precipitação, produtividade da água (WP) e da água irrigada (WP$_{IRRI}$), para duas cultivares de arroz em dois anos agrícolas.

Estratégias de irrigação	Rendimento de grãos (Kg ha^{-1})		Irrigação (mm)	Precipitação (mm)	WP Kg m^{-3}		WP$_{IRRI}$ Kg m^{-3}	
Cultivar	IRGA 424 RI	IRGA 431 CL			IRGA 424 RI	IRGA 431 CL	IRGA 424 RI	IRGA 431 CL
2020/21								
Diário	7616aA	8025aA	532	484	0.79	0.75	1.51	1.43
Alternado	6502bB	7407aA	490	484	0.67	0.76	1.33	1.47
Sequeiro	518cC	744cB	0	484	0.10	0.15	0	0
2021/22								
Diário	6041aA	6452aA	514	585	0.38	0.54	0.83	1.15
Alternado	5060aA	6758aA	474	585	0.56	0.58	1.25	1.30
Sequeiro	0	0	484	585	0	0	0	0

*Médias seguidas de mesma letra não diferem entre si pelo teste de Tukey em nível de 5% de probabilidade de erro. NS e ns: Não significativo pelo teste de Tukey ($p< 0,05$). Médias seguidas de mesma letra maiúscula na coluna e minúscula na linha (cultivares) não diferem entre si pelo teste Tukey em nível de 5% de probabilidade de erro.

Os resultados mostram que o maior rendimento de grãos foi obtido durante a safra 2020/21 em torno de 8.000 kg ha^{-1} para a cultivar IRGA 431 CL com a irrigação diária, no ano mais seco durante os dois anos de experimento a campo (Tabela 9), o que está provavelmente associado a melhores condições ambientais.

O rendimento no sequeiro foi afetado pelo déficit hídrico, uma vez que, o total de precipitações foi insuficiente para atender o requerimento hídrico durante o ciclo (>1016 mm). As condições climáticas também podem ter contribuído para não se atingir o rendimento potencial do arroz. Segundo o CONGRESSO BRASILEIRO de ARROZ IRRIGADO, 2005 o arroz irrigado demanda hídrica varia de 1037 a 1728 mm. O rendimento de grãos foi menor no ano de 2021/22; embora o total de precipitações foi maior nessa safra, a má distribuição impactou o rendimento, principalmente do arroz de sequeiro. A lâmina de água aplicada, tanto no manejo ID como no IA, juntamente com a menor ocorrência e distribuição irregular das precipitações (< 60 mm até o início da fase intermediária). A ocorrência de temperaturas elevadas no estádio da antese durante esse ano agrícola também pode ter afetado o rendimento. A produção de grãos apresentada na tabela 10 foi semelhante aos 5900 kg ha^{-1} reportados por Clerget el al. (2016). Entretanto, sob aspersão (convencional) Aramburu et al. (2022) observaram 9000 kg ha^{-1} rendimentos superiores, o que pode estar relacionado às características do terreno e um limiar de umidade no solo superior ao utilizado no atual estudo.

Tanto a WP e WP_{IRRI} foram maiores no ano de 2020/21. Menores valores de WP e WP_{IRRI} em 2021/22 estão relacionados ao menor rendimento obtido nesse ano. A menor WP obtida no sequeiro deve-se ao rendimento, muito inferior aos tratamentos irrigados. A WP_{IRRI} foi superior a WP, em ambos os anos agrícolas, indicando um incremento de 50% no rendimento por m^3 de água aplicada via irrigação. Os resultados evidenciam que, em anos de baixa precipitação, tanto a WP como a WP_{IRRI} podem ser potencializadas, desde que a demanda hídrica da cultura seja atendida, sobretudo nos estádios mais críticos ao déficit. Resultados semelhantes foram encontrados por Carrelhas et al. (2019), que obtiveram WP com irrigação intermitente (aeróbico) entre 0,71 kg/m^3 0,62 kg/m^3 usando o sistema de molhamento e secagem alternada, observaram 33% de economia de água em relação a IC, entretanto, a redução no rendimento foi da ordem de 15%. No mesmo estudo, os autores encontraram aumento na WP_{IRRI} variando entre 23 e 68%, quando menores alturas de lâmina foram aplicadas em diferentes fases do ciclo.

3.5 RENDA DE ENGENHO

O rendimento de engenho para as diferentes estratégias de irrigação, em dois anos agrícolas, é apresentado na Tabela 10.

Tabela 11 Tabela da percentagem de renda de benefício, percentual de grãos inteiros e percentual de grãos quebrados nos anos agrícolas 2020/21 e 2021/22.

Manejo Irrigação	IRGA 424 RI			IRGA 431 CL		
	Benefício (%)	Inteiros (%)	Quebrados (%)	Benefício (%)	Inteiros (%)	Quebrados (%)
			2020/2021			
Diário	71,0 NS ns	64,9 NS ns	6,1 NS ns	70,8 NS	65,2 NS	5,6 NS
Alternado	70,0 ns	64,0 ns	6,0 ns	69,8	63,9	5,95
CV (%)	2,75	3,42	11,37	2,75	3,42	11,37
			2021/2022			
Diário	68,35 B b	62,48 NS b	5,5 NS ns	70,47 NS a	64,22 NS a	6,25 NS
Alternado	69,3 A ns	63,0 ns	6,25 ns	69,85	63,62	6,22
CV (%)	2,64	1,31	11,91	2,64	1,31	11,91

*Médias seguidas de mesma letra não diferem entre si pelo teste de Tukey em nível de 5% de probabilidade de erro. NS e ns: Não significativo pelo teste de Tukey (p< 0,05). Médias seguidas de mesma letra maiúscula na coluna e minúsculas na linha não diferem entre si pelo teste Tukey em nível de 5% de probabilidade de erro.

Não se observou diferença para as duas estratégias de irrigação e cultivares entre a renda de benefício (grãos inteiros e grãos quebrados), no ano agrícola 2020/21. Em 2021/22, entretanto, a renda de benefício foi afetada pelos manejos de irrigação para a cultivar IRGA 424 RI. A cultivar IRGA 431 CL se mostrou superior em comparação a cultivar IRGA 424 RI, estes resultados corroboram com Müller et al. (2021) que verificaram um maior percentual de grãos inteiros e de renda na cultivar IRGA 431 CL em comparação a cultivar IRGA 424 RI. De acordo NASCIMENTO et al., 2022 a produção de arroz sob irrigação por pivô central em seu estudo apresentou rendimento de 67% de grãos inteiros no ano 2012/13 e 74% de grãos inteiros no ano 2013/14, resultados esses que corroboram os do atual estudo, para os manejos diário e alternado.

3.6 CUSTO OPERACIONAL

O custo operacional e os custos com a aplicação da lâmina são apresentados nas Tabelas 11 e 12, para os anos agrícolas 2020/21 e 2021/22, respectivamente, nos tratamentos de irrigação diária, alternada e sequeiro.

Tabela 12 Lâmina Bruta de irrigação (mm), custo total de lâmina de irrigação em R$ mm^{-1} ha^{-1} e custo total com irrigação (R$ ha^{-1}) nos anos agrícolas 2020/21 e 2021/22.

Safras	Manejos de irrigação	Lâmina Bruta (mm)	Custo total lâmina de irrigação (R$ mm^{-1} ha^{-1})	Custo total com irrigação (R$ ha^{-1})
2020/2021	Diário	665	1,46	970,9
	Alternado	612	2,00	1225
2021/2022	Diário	642	1,50	963,75
	Alternado	592	2,06	1220,55

Tabela 13 Custo de operacional, custo de irrigação e custo total em reais por hectare (R$ ha^{-1}) nos anos agrícolas 2020/21 e 2021/22.

(continua)

Safras	Manejo de irrigação	Cultivares					
		424RI			431CL		
		CO (R$ ha^{-1})	Custo Lâmina (R$ ha^{-1})	CT (R$ ha^{-1})	CO (R$ ha^{-1})	Custo Lâmina (R$ ha^{-1})	CT (R$ ha^{-1})
2020/2021	Diário	4746,85	970,9	5717,75	4915,05	970,9	5878,8
	Alternado		1225	5971,85		1225	6135,6
	Sequeiro		-	4746,85		-	-

Tabela 14 Custo de operacional, custo de irrigação e custo total em reais por hectare (R$ ha^{-1}) nos anos agrícolas 2020/21 e 2021/22.

(conclui)

2021/2022	Diário	4821,05	963,75	5791,95	4989,25	963,75	5953
	Alternado		1220,55	6046,05		1220,55	6209,8
	Sequeiro		-	4821,05		-	-

O custo operacional é afetado pelo custo dos insumos e mão-de-obra. Para Sorriso/MT, a CONAB divulgou um custo de R$ 5363,02 para a safra 2021/22. Para a safra 2022/23, o custo de produção para Balsas (Maranhão) foi de R$ 6151,10, sendo semelhantes aos valores dos gastos médios apontados neste estudo. Na safra 2022/23, o custo de produção levantado pela CONAB para Cachoeira do Sul foi de R$ 14429,98, enquanto o Instituto Rio-Grandense do Arroz (IRGA) estimou um custo de produção para o arroz irrigado no sistema cultivo mínimo de R$ 15496,86, na safra 2021/22, que significa um gasto 37% maior que a média dos valores do manejo de irrigação diário. A redução dos custos em lavoura de arroz aeróbico para o arroz por inundação está relacionada a diminuição das operações de preparo do solo, construção de taipas e mão de obra.

Os custos da irrigação (custo da energia para a aplicação da lâmina + manutenção do equipamento) encontram-se na Tabela 11. O custo da lâmina irrigada foi aproximadamente 27% menor para o manejo com irrigação diária, em relação ao alternado. Embora a lâmina bruta acumulada tenha sido semelhante, o maior tempo de irrigação para aplicar a lâmina no manejo alternado elevou o custo do mm irrigado. O custo da energia elétrica foi de R$ 0.46 kWh$^{-1,}$ no Rio Grande do Sul, o custo médio do mm irrigado com energia elétrica é de R$ 0.50 kWh^{-1}, indicando que os valores obtidos nesse trabalho se enquadram naqueles praticados pela maioria das operadoras de energia elétrica no RS. Ramos et al. (2012) considerou um custo de água de US$ 1,25 mm ha^{-1}, que convertendo em reais, por uma cotação de R$4,99 em 2024, corresponde a R$6,24 reais, muito maiores que os encontrados para esse trabalho.

3.6 LUCRO OPERACIONAL

O lucro operacional do cultivo do arroz sob aspersão é apresentado na Tabela 13. A redução no lucro operacional no ano de 2021/22 está relacionada mais ao rendimento e preço do produto, que ao aumento do custo operacional, indicando a relação direta entre preço e rendimento.

Tabela 15 Lucro operacional da propriedade em R$ nas safras 2020/21 e 2021/22 por hectare.

Safras	Manejo de irrigação	Cultivares	
		424RI	431CL
2020/2021	Diário	R$ 6133,76Ans	R$ 5403,20A
	Alternado	R$ 3486,83Bb	R$ 4864,23Aa
	Sequeiro	R$ -5137,37Cns	R$-5063,77B
		CV% 36,28	
2021/2022	Diário	R$ 3226,94Ab	R$ 2325,55NSa
	Alternado	R$ 111,09Bb	R$ 2139,81a
	Sequeiro	-	-
		CV(%) = 18,94	

*Médias seguidas de mesma letra não diferem entre si pelo teste de Tukey em nível de 5% de probabilidade de erro. NS e ns: Não significativo pelo teste de Tukey (p< 0,05). Médias seguidas de mesma letra maiúscula na coluna e minúscula na linha (cultivares) não diferem entre si pelo teste Tukey em nível de 5% de probabilidade de erro.

Martins (2018) obteve lucro operacional de R$ 2038,33/ha com o arroz de sequeiro em Selvíria (MS). Este valor é semelhante ao observado para a cultivar IRGA 431 CL no ano 2021/2022. Na safra 2020/2021 o tratamento em sequeiro obteve lucro operacional negativo, tal resultado está de acordo com o observado por Pascoaloto (2021), pois obteve um lucro operacional negativo no primeiro ano de cultivo do arroz de sequeiro devido à baixa precipitação (324 mm) ao longo do ciclo.

Para as condições do RS, Fagundes et al. (2021) obtiveram, em Pelotas – RS, LO negativo em 2019/20 (R$-168,76) e positivo em 2020/21 (R$1433,60), para o arroz irrigado por aspersão, valores esses que são 58% inferiores ao encontrados no atual trabalho.

4 CONCLUSÃO

A irrigação por aspersão aumenta a eficiência do uso da água, porém, reduz o acúmulo de matéria seca na parte aérea e nas raízes.

A cultivar IRGA 431 CL proporciona uma redução no uso de água e maior produtividade da água de irrigação, sem prejudicar a produtividade de grãos da cultura, em comparação a cultivar IRGA 424 RI.

As plantas do tratamento sequeiro apresentaram um crescimento inferior ao das observadas nos tratamentos ID e IA.

O lucro operacional do arroz de sequeiro foi negativo e não apresentou produtividade no ano agrícola de 2021/22, evidenciando que o produtor deve adotar um o método de irrigação em anos secos.

A cultivar de arroz IRGA 424 RI apresentou maior produtividade de grãos e lucro operacional no manejo de irrigação diário em ambas as safras.

A cultivar de arroz IRGA 431 CL não apresentou diferença significativa entre o manejo diário e alternado de irrigação quanto ao lucro operacional.

5 REFERÊNCIAS BIBLIOGRÁFICAS

AGÊNCIA NACIONAL DO PETRÓLEO, GÁS NATURAL E BIOCOMBUSTÍVEIS – ANP; Sistema de levantamento de preços; Relatório de defesa da concorrência; Período: janeiro de 2019 a dezembro de 2021; Municípios. https://www.gov.br/anp/pt-br/assuntos/precos-e-defesa-da-concorrencia/precos/precos-revenda-e-de-distribuicao-combustiveis/serie-historica-do-levantamento-de-precos. Visitado 27 de junho de 2024.

ALBERTO, C.M. PORTA, F.S.D.; GARRIDO, G.C.; ZANON, A.J.; POERSH, A.H.; DUARTE JUNIOR, A.J.; RIBEIRO, B.S.M.R.; RIBAS, G.G.; ROSSATO, I.G.; PILECCO, I.B.; MEUS, L.D.; SILVA, M.R. DA; NASCIMENTO, M. DE F. DO; SOUZA, P.M. DE; PEREIRA, V.F.; STRECK, N.A. (2020). USO DA ÁGUA EM ARROZ IRRIGADO. IN: MEUS, L.D.; SILVA, M.R. DA; RIBAS, G.G.; ZANON, A.J.; ROSSATO, I.G.; PEREIRA, V.F.; PILECCO, I.B.; RIBEIRO, B.S.M.R.; SOUZA, P.M. DE; NASCIMENTO, M. DE F. DO; POERSH, A.H.; DUARTE JUNIOR, A.J.; QUINTERO, C.E.; GARRIDO, G.C.; CARMONA, L. DE C.; STRECK, N.A (eds.) **Ecofisiologia do arroz visando altas produtividades**. Santa Maria: [s.n.], p. 145-164. 2020.

ALMEIDA, I. A.; Dimensionamento econômico para sistemas de irrigação pivô central telescópio: estudos de cenário para diferentes regiões do Brasil. Dissertação apresentada para obtenção do título de Mestra em Ciências, Área de concentração: Engenharia de Sistemas Agrícolas. Piracicaba. 2019.

ALVAREZ, R. de C. F.; CRUSCIOL, C. A. C.; NASCENTE, A. S.; Análise de crescimento e produtividade de cultivares de arroz de terras altas dos tipos tradicional, intermediário e moderno. Pesq. Agropec. Trop., Goiânia, v. 42, n. 4, p. 397-406. Out./Dez. 2012. https://revistas.ufg.br/pat/article/view/18228. Acesso em: Out. 20, 2023.

ANEEL, Agência Nacional de Energia Elétrica. Resolução Homologatória nº 3206. 13 de junho de 2013. Disponível em: https://www2.aneel.gov.br/cedoc/reh20233206ti.pdf. Acesso em: Set. 18, 2022.

ARAMBURU, B. B., MARCHESAN, E., GIACOMELI, R.; FLECK, A. G.; PROCHNOW, M.H.; PFEIFER, J.G.; Morphophysiological and productive aspects of sprinkler and surface irrigated rice cultivars. Rev Bras Cien Agrar 17(3):1205. 2022. https://doi.org/10.5039/agraria.v17i3a1205. Acesso em: Out. 18, 2023

BARREDA, A. R.; Estudo de Viabilidade econômica para a abertura do mercado livre de Energia para consumidores do grupo A. Trabalho de conclusão de curso apresentado ao curso de Engenharia de Energia da Universidade Federal do Pampa. p. 36. 2023.

BISPO, D.; SILVA, V. DE P. E; BELINOVSKI, K. D.; SILVA, S. F. DE P.; Análise na especificação do motor indução trifásico em função do seu carregamento. Conference: 24º Congresso Brasileiro de Manutenção At: Recife – PE. Setembro. 2009. DOI:10.13140/2.1.4595.2327. Acesso em: Jul. 10, 2023.

CARLESSO, R.; HERNANDEZ, M. G. R.; RIGHES, A. A.; JADOSKI, S. O.; Índice de área foliar e altura de plantas de arroz submetidas a diferentes práticas de manejo; Revista Brasileira de Engenharia Agrícola e Ambiental, v.2, n.3, p.268-272. 1998. Campina Grande, PB, DEAg/UFPB.

CARRACELAS, G.; HORNBUCKLEB, J.; ROSASA, J.; ROEL, A.; Irrigation management strategies to increase water productivity in *Oryza sativa* (rice) in Uruguay. Agric Water Manag 222:161-172. https://doi.org/10.1016/j.agwat.2019.05.049. 2019.

CARVALHO, J. A.; BRAGA JÚNIOR, R. A.; REIS, J. B. R. S.; Análise de custos na escolha do tipo de motor para acionamento de bombas em áreas irrigadas. Ciências agrotecnologia, v.24, n.2, p.434-440, abr./jun. 2000. https://docplayer.com.br/18388705-Analises-de-custos-na-escolha-do-tipo-de-motor-para-acionamento-de-bombas-em-areas-irrigadas.html. Acesso em: Jun. 06, 2023.

CEPEA- ESALQ - Centro de Estudos Avançados em Economia Aplicada – Escola Superior de Agricultura Luiz de Queiroz. Séries de Dados. Consulta ao Banco de dados do site. https://www.cepea.esalq.usp.br/br/consultas-ao-banco-de-dados-do-site.aspx; visitado em 28/06/2024.

CHAMPNESS, M.; BALLESTER, C.; HORNBUCKLE, J.; Decision support tool to predict panicle initiation in aerobic rice. Agronomy 2023, 13, 789. https://doi.org/10.3390/agronomy13030789. 2023.

CLERGET, B.; BUENO, C.; DOMINGO, A.J.; LAYAOEN, H.L.; VIAL, L.; Leaf emergence, tillering, plant growth, and yield in response to plant density in a high-yielding aerobic rice crop. Field Crop Res 199:52-64. 2016. http://dx.doi.org/10.1016/j.fcr.2016.09.018

CONGRESSO BRASILEIRO DE ARROZ IRRIGADO, 4.; REUNIÃO DA CULTURA DO ARROZ IRRIGADO, 26., 2005, Santa Maria, RS. Arroz irrigado: recomendações técnicas da pesquisa para o Sul do Brasil. Santa Maria, RS: SOSBAI, p. 159. 2005.

CONAB a, Companhia Nacional de Abastecimento; Boletim de safra de Grãos. Série Histórica - CUSTOS – Arroz Sequeiro – 2001 a 2023. https://www.conab.gov.br/info-agro/custos-de-producao/planilhas-de-custo-de-producao/itemlist/category/791-arroz. Acesso em: Out. 09, 2023.

CONAB b, Companhia Nacional de Abastecimento; Boletim de safra de Grãos. Série Histórica – CUSTOS- Arroz irrigado – 2001 a 2023. https://www.conab.gov.br/info-agro/custos-de-producao/planilhas-de-custo-de-producao/itemlist/category/791-arroz. Acesso em: Out. 24, 2023.

COUNCE, P. A.; KEISLING, T. C.; MITCHELL, A. J.; A uniform, objective, and adaptative system for expressing rice development. Crop Sci. 40:436–443. 2000. https://doi.org/10.2135/cropsci2000.402436x.

CRUSCIOL, C. A. C.; MANCUSO, M. A. C.; GARCIA, R. A.; CASTRO, G. S. A.; Crescimento radicular e aéreo de cultivares de arroz de terras altas em função da calagem. Bragantia, Campinas, v. 71, n. 2, p.256-263. 2012. https://doi.org/10.1590/S0006-87052012005000018. Acesso em: Set. 27, 2023.

EMBRAPA, Empresa Brasileira de Pesquisa Agropecuária. Sistema Brasileiro de Classificação de Solos. 2ª ed. Rio de Janeiro: EMBRAPA, 2006.

FAGUNDES, T.; SIQUEIRA, T. R. de; GREGORI, R. de; Análise de retorno financeiro de lavouras de arroz nos anos de 2019 e 2020 em três municípios do RS. XXVIII Congresso Brasileiro de Custos –Associação Brasileira de Custos. 17 a 19 de novembro de 2021. 2021. https://anaiscbc.emnuvens.com.br/anais/article/view/4873. Acesso em: Jul. 30, 2023.

FUKAI, S.; MITCHELL, J.; Factors determining water use efficiency in aerobic rice; Crop and Environment. Volume 1, Issue 1, pages 24-40. Mar. 2022.

HOLZSCHUH, M. J.; BOHNEN, H.; ANGHINONI, IBANOR; MEURER, E. J.; CARMONA, F. de C.; Costa, S. E. V. G. de A.; Resposta do arroz irrigado ao suprimento de amônio e nitrato. R. Bras. Ci. Solo. v. 33. p. 1323-1331. 2009. https://doi.org/10.1590/S0100-06832009000500025. Acesso em: Jul. 02, 2023.

IRGA, Instituto Rio Grandence do Arroz. Custo de Produção. Custo de produção do arroz irrigado sistema de cultivo mínimo custo de produção do arroz irrigado médio ponderado no rio grande do sul sistema de cultivo mínimo (semi-direto) SAFRA 2021/22. https://irga.rs.gov.br/custos-de-producao. 2022. Acesso em: Set. 10, 2023.

JIANG H, SONG Z, SU Q-W, WEI Z-H, LI W-C, JIANG Z-X, TIAN P, WANG Z-H, YANG X, YANG M-Y, WEI X-S and WU Z-H; Transcriptomic and metabolomic reveals silicon enhances adaptation of rice under dry cultivation by improving flavonoid biosynthesis, osmoregulation, and photosynthesis. Front. Plant Sci. 13:967537. 2022. doi: 10.3389/fpls.2022.967537

KOTTEK, M.; GRIESER, J.; BECK, C.; RUDOLF, B.; RUBEL, F.; World Map of the Köppen-Geiger climate classification updated. Meteorol. Z. 15(3), 259-263. 2006.

LACERDA, M. L.; NASCENTE, A. S.; Técnologias para o cultivo do arroz de terras altas em sistema plantio direto na região do Cerrado. EMBRAPA, Circular Técnica 94. Santo Antônio de Goiás, GO. Junho de 2021. p. 1-33. 2021.

MARTINS, J. T.; Doses e épocas de aplicação de etil-trinexapac em arroz de terras altas irrigado por aspersão. Dissertação apresentada à Faculdade de Engenharia de Ilha Solteira – UNESP como parte dos requisitos para obtenção do título de Mestre em Agronomia. Especialidade: Sistemas de Produção. p. 50. 2018.

MENEZES, C. T.; Avaliação de estações climáticas virtuais e do modelo oryzav3 para a região de arroz tropical irrigado. Dissertação apresentada ao Programa de Pós-Graduação em Agronomia, da Universidade Federal de Goiás, como requisito parcial à obtenção do título de Mestre em Agronomia. GOIÁS, 2021.

Mc CAULEY, G. N.; Sprinkler vs. flooded irrigation in traditional rice production regions of Southeast Texas. Agron. J. 82, 677–683. 1990.

MÜLLER, A.; Influência do manejo de produção e do beneficiamento na qualidade do arroz polido e integral. Dissertação apresentada ao Programa de Pós-Graduação em Engenharia

Agrícola, da Universidade Federal de Santa Maria, como requisito parcial para obtenção ao grau de Mestra em Engenharia Agrícola. Santa Maria- RS. 2021.

NGUYEN, H.T.; FISCHER, K.S.; and FUKAI, S.; Physiological responses to various water saving systems in rice. Field Crops Res. 112, 189–198. 2009.

Oh-e, I.; SAITOH, K.; and KURODA, T.; Effects of High Temperature on Growth, Yield and Dry-Matter Production of Rice Grown in the Paddy Field. Plant Prod. Sci. 10(4): 412 — 422. 2007.

PASCOALOTO, I.M.; CRUSCIOL, C.A.C.; NASCIMENTO, C.A.C. do; FERREIRA, C.M.; SILVA, M.A.S. da; SOUZA, L.G.M. de; ESPERANCINI, M.S.T. Timing of nitrogen application and cover crops on upland rice economic viability. Pesquisa Agropecuária Brasileira, v.56, e01924. 2021. https://doi.org/10.1590/S1678-3921.pab2021.v56.01924. Acesso em: Nov., 23, 2023.

PARFITT, J. M. B.; SCIVITTARO, W. B.; CONCENÇO, G. Importância Econômica da Cultura. IN: SCIVITTARO W. B.; PARFITT, J. M. B. Arroz Irrigado por Aspersão no Rio Grande do Sul. Sistemas de Produção, 24. Embrapa Clima Temperado Pelotas, RS. p.140. 2017.

PINTO, M. A. B.; PARFITT, J. M. B.; TIMM, L. C.; FARIA, L. C.; SCIVITTARO, W. B.; Produtividade de arroz irrigado por aspersão em terras baixas em função da disponibilidade de água e de atributos do solo. Pesq. agropec. bras., Brasília, v.51, n.9, p.1584-1593. 2016. DOI: 10.1590/S0100-204X2016000900058.

PINTO, J. M.; YURY. J.E.; COSTA, N.D.; CORREIA, R.C.; CALGARO, M. Impacto no desenvolvimento rural: o caso do melão no projeto lago de Sobradinho, III Congresso Internacional das Ciências Agrárias Cointer-PDVAGRO. 2018. Disponivel em: DOI: 7701>.IIICOINTERPDVAGRO.2018.00520

RAMOS, H.M.M.; BASTOS, E. A.; JÚNIOR, A. S. de A.; MAROUELLI, W. A.; Estratégias ótimas de irrigação do feijão-caupi para produção de grãos verdes. Pesq. Agropec. Bras., Brasília, v.47, n.4, p.576-583, abr. 2012.

REIS, L.; Estudo de redução de custos com energia em empresa metalúrgica. Trabalho de Conclusão de Curso apresentado à Área de Ciências Exatas e Engenharias da Universidade de

Caxias do Sul como requisito parcial para a obtenção do título de bacharel em Engenharia Elétrica. Caxias do Sul. p. 58. 2021.

SANTOS, M. P.; ZANON, A. J.; CUADRA, S. V.; STEINMETZ, S.; CASTRO, J. R.; HEINEMANN, A. B.; Yield and morphophysiological indices of irrigated rice genotypes in contrasting ecosystems. Pesquisa Agropecuária Tropical, v.47, n.3, p.253-264, 2017. http://dx.doi.org/10.1590/1983-40632016v4745955. Acesso em: Nov., 05, 2023.

SCHAFER, L. D. Custos da cultura do trigo em uma propriedade rural no norte de Rio Grande do Sul. Trabalho de Conclusão de Curso apresentado ao curso de Ciências Contábeis da Universidade de Passo Fundo, campus Passo Fundo, como parte dos requisitos para a obtenção do título de Bacharel em Ciência Contábeis. Passo Fundo. 2021.

SOSBAI. Rice Technical Recommendation from Research in Southern Brazil. Embrapa Clima Temperado. Pelotas, Brazil: EMBRAPA. 205 p. Original in Portuguese. 2018.

STEVENS, G.; VORIES, E.; HEISER, J.; RHINE, M.; Experimentation on cultivation of rice irrigated with a center pivot system. In: TS Lee (ed) Irrigation Systems and Practices in Challenging Environments. InTech, 233-254. 2012.

TURCO, J. E. P.; PIZZATTI, G. S.; PAVANI, L. C. Custo de energia elétrica em cultura do feijoeiro irrigado por pivô central, afetado pelo manejo da irrigação e sistemas de cultivo. Engenharia Agrícola, Jaboticabal, v. 29, n. 2, p. 311-320, 2009.

VORIES, E.D.; STEVENS, W. E.; TACKER, P. L.; GRIFFIN, T. W.; COUNCE, P.A.; Rice production with center pivot irrigation. Appl Eng Agric 1:51–60. 2013. https://doi.org/10.13031/2013.42532.