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Optimizing rice management to reduce methane emissions and maintain yield with the CSM-CERES-rice model

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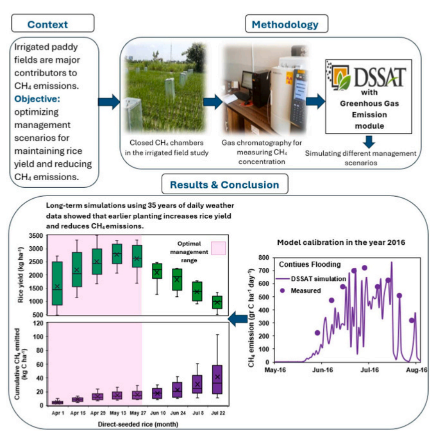
HIGHLIGHTS

- Optimal paddy field management was explored using the novel GHG emissions subroutine integrated into DSSAT v4.8.2.
- Based on simulation, no-tillage resulted in a 29 % reduction in CH_4 compared to intensive tillage.
- Our simulation finding on different sowing depths didn't notably affect CH_4 emissions or yield.
- Based on the simulation model, an optimal 10-transplant-per-ridge led to lower emissions than higher plant populations.
- Simulation identified the optimal strategy as early cultivation for direct-seeded rice with 250 kg ha^{-1} N fertilizer.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Irrigated paddy fields are major contributors to methane (CH_4) emissions, significantly impacting global warming. Flood irrigation, the traditional method for rice cultivation, significantly increases water consumption and CH_4 emissions.
OBJECTIVE: The primary objective of this study was to quantify the benefits of deficit irrigation in reducing CH_4 emissions and maintaining yield compared to traditional flood irrigation using a systems analysis approach.
METHODS: The field study was conducted from May to August in both 2015 and 2016 at the Rice Research Institute in Amol, northern Iran. The site has a warm temperate climate, with the soil characterized as silty clay loam. The data collected during these two years were used for the calibration and evaluation of the CSM-CERES-Rice model. Calibration was performed using the data collected in 2016 while the model's performance was evaluated using data collected in 2015. Following model calibration and evaluation, a seasonal analysis was employed to assess alternative management practices for single growing seasons. This analysis feature of DSSAT

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allowed us to evaluate alternate management scenarios with the model using 35 years of long-term historical daily weather data from 1984 to 2018 obtained from a local weather station.

RESULTS AND CONCLUSIONS: The simulation revealed that early rice planting, in April or May, yielded the highest production and the lowest CH_4 emissions, when using the direct seeding method. This strategy resulted in a 15 % increase in yield, 13 % better irrigation efficiency, and a 9 % reduction in CH_4 emissions compared to transplanting. Among tillage systems, no-tillage further reduced CH_4 emissions by 29 % without compromising yield or irrigation efficiency. Although sowing depth did not significantly affect CH_4 emissions or yield, an optimal depth of 10–15 cm was identified. Additionally, maintaining a plant population of 10 transplants per hill exhibited the lowest CH_4 emissions compared to higher plant populations. Higher nitrogen fertilization rates increased both yield and CH_4 emissions. In conclusion, the best approach among different strategies was early cultivation for direct-seeded rice coupled with a nitrogen fertilizer rate of 250 kg ha^{-1}, resulting in both the highest yield and the lowest emissions simultaneously.

SIGNIFICANCE: The findings from this study offer a comprehensive exploration, identifying specific agronomic practices that optimize rice cultivation by enhancing yield, conserving water, and significantly reducing CH_4 emissions, thereby providing actionable insights for policymakers and farmers in fostering sustainable agriculture.

1. Introduction

Irrigated paddy fields are a major source of CH_4 emissions due to anaerobic methanogenesis triggered by waterlogging (Ito et al., 2022). Paddy fields contribute around 20 % of atmospheric CH_4, impacting global warming (Li et al., 2021). Therefore, accurate quantification of CH_4 emissions from paddy fields is crucial for developing effective mitigation policies. CH_4 emissions from paddy fields result from the anaerobic breakdown of organic matter in the soil, influenced by factors such as irrigation and drainage (Zhang et al., 2011), fertilization (Ma et al., 2007), organic matter content (Wang et al., 2010), rice cultivar (Khosa et al., 2010), air temperature (Watanabe et al., 2005), and soil properties such as texture, pH, redox potential, and C/N ratio (Xu et al., 2003). CH_4 escapes via the rice plant's aerenchyma (90 %), ebullition (10 %), and diffusion (1 %) (Meena, 2021). Effectively managing rice cultivation emerges as one of the most promising strategies to mitigate CH_4 emission. Direct-seeded rice (DSR) is an effective method for mitigating CH_4 emissions as it uses less water during early growth than transplanted rice (TPR). Susilawati et al. (2019) reported that DSR reduced CH_4 emissions by 47 % compared to TPR, without significantly affecting grain yield. DSR also provides water conservation and cost savings (Kaur and Singh, 2017). A study by Rahman et al. (2012) found that dry direct seeding achieved higher yields compared to other cultivation methods in Bangladesh. Pathak et al. (2013) observed lower CH_4 emissions from dry-seeded fields (0.6 to 4.9 kg ha^{-1}) compared to puddled transplanted fields (42.4 to 57.8 kg ha^{-1}) in Punjab, India. Tillage systems also affect CH_4 emissions. No-tillage helps conserve soil water by increasing infiltration and reducing evaporation, while mitigating GHG emissions and improving nutrient cycling (Ogle et al., 2019). Wihardjaka et al. (2023) reported a 15.58 % reduction in CH_4 emissions with no-tillage compared to intensive tillage, though grain yield was 26 % lower.

Nitrogen (N) plays a key role in controlling emissions (Oertel et al., 2016), but fertilization can increase CH_4 emissions by inhibiting methanotrophic bacteria (Zhang et al., 2020). Linquist et al. (2012) found that low N rates (79 kg N ha^{-1}) increased CH_4 emissions by 18 %, while high rates (249 kg N ha^{-1}) decreased emissions by 15 %. Improved water management is also essential for reducing CH_4 emissions in paddy fields. Islam et al. (2022) found that water-saving techniques such as alternate wetting and drying (AWD) reduced CH_4 emissions by 28 % compared to continuous flooding (CF) without significant yield loss. Pathak and Wassmann (2007) showed that switching from CF to AWD could reduce global warming potential by 15 %. Innovations in rice cropping that enhance nitrogen use efficiency (NUE) and reduce GHG emissions are crucial for food security and climate adaptation. Zhu et al. (2015) found that increasing plant population and reducing basal nitrogen application improved NUE and decreased CH_4 emissions, while maintaining yield.

During the past two decades, several models have been developed to simulate GHG emissions, including the WHCNS Rice model (Liang et al., 2022), the DNDC model (Abdalla et al., 2020), the DAYCENT model (Begum et al., 2020), and the Methane Emissions from Rice Ecosystems (MERES) model (Matthews et al., 2000; Pathak et al., 2004, 2005; Farmer et al., 2023), though MERES is no longer available. Zhou et al. (2023) used CERES-Rice and CH_4 estimation equations to identify optimal sowing windows for direct-seeded rice, finding that delayed sowing significantly increased yield while reducing CH_4 emissions. Moradi-Majd et al. (2022) used the DAYCENT and DNDC models to study greenhouse gas emissions in Khuzestan, Iran. They found the highest methane emissions in rice fields and the lowest in sugarcane fields. Zhao et al. (2020) used the DNDC model to show that a 20 % reduction in fertilization with moistening irrigation reduced CH_4 emissions in paddy fields. Zhu et al. (2019) combined GIS and the DNDC model to recommend an optimal fertilization rate of 210 kg N ha^{-1} to balance rice production and GHG emissions. While the DNDC model is highly effective for simulating greenhouse gas emissions, it struggles with crop management and does not account well for differences in cultivars and hybrids.

The Cropping System Model (CSM) in DSSAT (Jones et al., 2003; Hoogenboom et al., 2019, 2023) is one of the most widely used crop modeling systems and includes models for over 40 crops, simulating the soil and plant water, nitrogen, phosphorus, and carbon balances. The CSM-CERES-Rice model has been widely used for different rice cropping systems (Jintrawet, 1995; Cheyglinted et al., 2001; St'astna et al., 2002; Kumar and Sharma, 2004; Sarkar and Kar, 2006; Devkota et al., 2015; Ahmad et al., 2019; Kaeomuangmoon et al., 2019; Jha et al., 2019). It has been tested in diverse agro-environments (Yao et al., 2005; Singh et al., 2007; Lamsal and Amgain, 2010; Vilayvong et al., 2012; Darikandeh et al., 2023a, 2023b) and has shown higher accuracy in simulating grain yield under various irrigation strategies compared to models such as AquaCrop and ORIZA2000 (Amiri et al., 2014; Akinbile et al., 2020). Recently the capabilities for the simulation of CH_4 emissions from flooded soils were incorporated in DSSAT v4.8.2 (Hoogenboom et al., 2023). The existing scientific literature on the use of the CSM-CERES-Rice model to analyze the impact of various management options on CH_4 emissions in rice cultivation is very limited. Our goal was, therefore, to first evaluate the performance of CSM-CERES-Rice for the simulation of CH_4 emissions and then apply the model to identify the most effective strategies for maintaining yield and mitigating methane emissions, considering local conditions in Iran. We hypothesized that implementing deficit irrigation could reduce CH_4 emissions compared to flood irrigation.

2. Material and methods

2.1. Experimental site description

A pilot study was conducted over a two-year period, from May to August in 2015 and 2016, at the experimental field of the Rice Research Institute in Amol, a city situated in northern Iran (36°28′N, 52°27′E; elevation: 29.8 m above sea level). The experimental design was a randomized complete block, where each block was subdivided into 7 irrigation plots (treatments) with 3 replications, totaling 21 plots (Yousefian et al., 2023; Yousefian et al., 2024). To reduce uncertainty in measurements, each plot was intentionally kept small, with an area of 3 m × 8 m, for greater control over variables such as soil type, weather, and management practices. Methane emissions were measured by installing separate chambers for each irrigation plot to assess methane production under different irrigation treatments (Yousefian et al., 2024). All experimental design and measurements were the same for both years. However, it should be noted that methane measurements were only conducted during the second year of the experiment conducted in 2016.

The site is categorized as a warm temperate climate with long term mean annual rainfall and temperature of 800 mm and 16 °C. During the rice cropping seasons from May to August for 2015 and 2016, the total daily rainfall was 106.6 mm and 69 mm, the average daily maximum temperature was 31.5 °C and 31.1 °C, the average daily minimum temperature was 22 °C and 21.7 °C, and the average daily solar radiation was 20.2 and 19.9 MJ m^{-2} day^{-1} (Yousefian et al., 2023). Detailed weather data for both years are presented in Fig. 1 are based on measurements from a weather station located near the Rice Research Institute.

2.2. Soil properties

Soil sampling was done to a depth of 30 cm, where the depth of rice roots is 20 to 25 cm from the soil surface. The dominant soil type in the experimental site is silty clay loam with Total Neutralizing Value (TNV) of 5 % and the electrical conductivity of the saturated paste extract (ECe) of 0.962 ds m^{-1}. Available Phosphorus and Potassium in this soil were 10 and 180 g soil kg^{-1}, respectively (Yousefian et al., 2023). Information on soil properties is presented in Table 1.

2.3. Crop management practices

The rice cultivar of this study was Hashemi, which is a prominent local cultivar and has consistently accounted for the largest cultivated area in the region in recent years. Prior to germination, damaged or empty seeds were separated from healthy ones using saltwater solution. The seeds were also disinfected to eliminate potential contaminants; healthy seeds were planted in the nursery. Crop establishment began once the rice seedlings developed four leaves, which occurred 25 days after planting in 2015 and 27 days in 2016. The rice plants were then transplanted into the main field (Table 2).

One month prior to transplanting, land preparation was initiated. To prepare the land, the surface soil was plowed to a depth of 20 cm, as the primary tillage method. Subsequently, each plot was irrigated with 1000 l of water to moisten the surface soil and promote weed seed germination. Weed control was done through the application of Treflan herbicide in the experimental field. Following this, the surface soil was softened, as the second tillage operation, and any residual effects of the herbicide were removed. Both tillage operations were carried out under dry conditions using a rotary tiller attached to a tractor.

The soil was subjected to a three-stage application of 150 kg of urea (CH_4N_2O) fertilizer and 100 kg of potassium sulfate (K_2SO_4). The

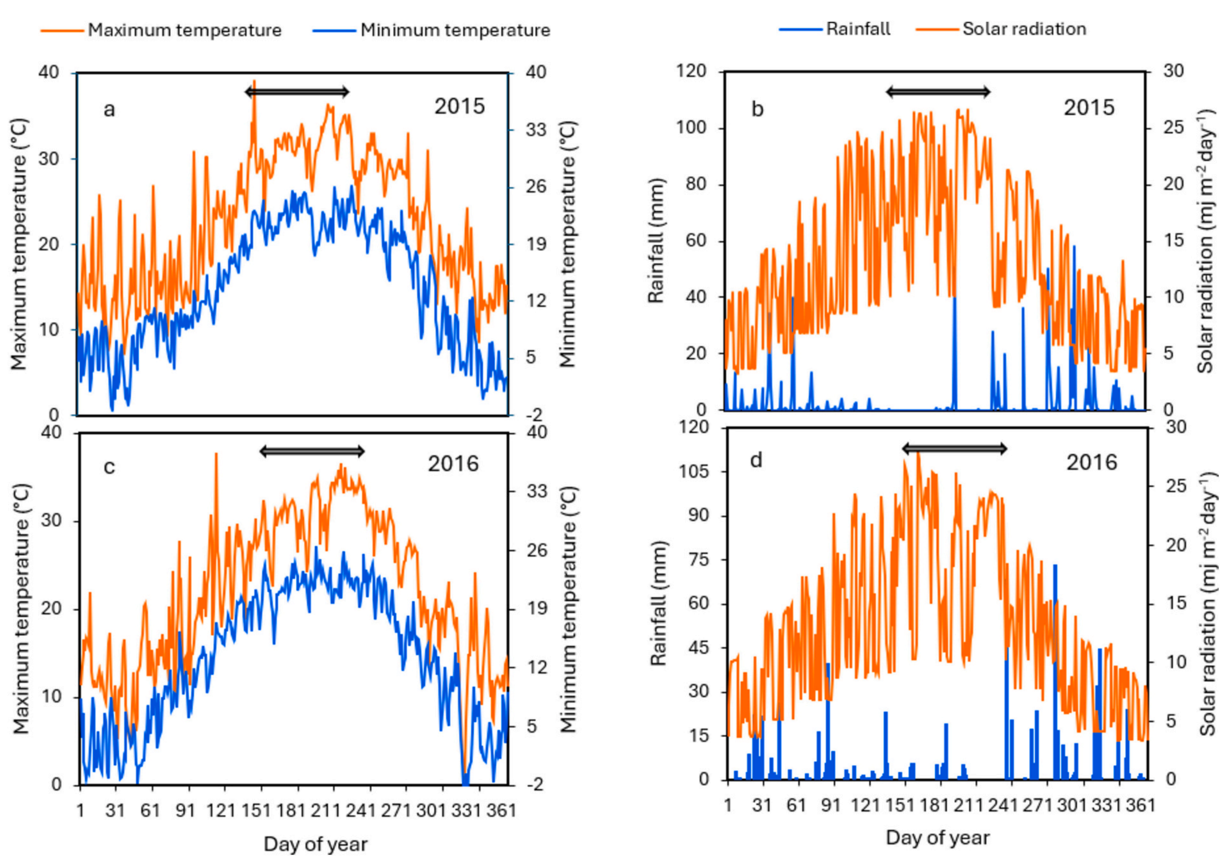

Fig. 1. Daily average maximum and minimum air temperature (a, c) and rainfall/solar radiation data (b, d) for 2015 and 2016 in Amol, Iran (Horizontal double-headed arrow represents the rice growing season).

Table 1
Soil properties at the experimental site.

Soil depth (cm)	Clay (%)	Silt (%)	Sand (%)	Organic carbon (%)	Total N (%)	EC (ds.m^{-1})	PH	Stable organic carbon (%)
0–15	33	47	20	2.12	0.21	0.78	7.8	1.27
15–30	31	49	20	1.47	0.14	0.65	7.8	1.21

Source: (Yousefian et al., 2023).
N: Nitrogen.
EC: Electrical Conductivity.
PH: Potential of Hydrogen.

Table 2
Agronomic practices at the experimental site for the early maturing Hashemi rice cultivar.

Year	Nursery establishment date	Transplanting date	Harvesting date	Tillage depth (cm)	Plant population (Plant m^{-1})	Transplanting depth (cm)	Crop row spacing (cm)
2015	10 th April	24 th May	27 th Augus	10	20	10	35
2016	12 th April	27 th May	28th August	10	20	10	35

Source: (Yousefian et al., 2023).

fertilizer distribution was as follows: 40 % was applied one week before transplanting, 30 % was applied during the middle of tillering, i.e., four weeks after transplanting, and the remaining 30 % was applied at the time of maximum tillering, i.e., six weeks after transplanting. Additionally, a single-stage application of 100 kg of triple superphosphate ($Ca(H_2PO_4)_2$. H_2O) was performed one week before transplanting (Yousefian et al., 2023).

2.3.1. Irrigation treatments

The water quality was appropriate for rice cultivation, with an average salinity of 0.85 ds m^{-1} and a pH ranging between 7.1 and 7.6. The water source for the experimental field was from a deep well located nearby (Yousefian et al., 2023). There were seven irrigation treatments, consisting of six deficit irrigation treatments and one continuous flooding treatment as the control (Table 3). The deficit irrigation treatments included regulated deficit irrigation and partial root zone drying, with transplanting on ridges and irrigation applied in the furrows.

The puddling was implemented only for the flooding treatment, and it was done one week prior to the start of flooding. Transplanting was manually performed for both flooding (full irrigation) and furrow (deficit irrigation) treatments. The bund height for both furrow and flooding irrigation was maintained at 15 cm in the field. For furrow (deficit irrigation) treatments, the width distance (the distance between each two rice plants from the furrow) was 35 cm, and the length distance (the distance between two rice plants on the ridge) was 15 cm. For flooding treatments, the distance between rice plants was the same, with a spacing of 23 cm by 23 cm.

In regulated deficit irrigation, all furrows were simultaneously irrigated, whereas in partial root zone drying, irrigation alternated between furrows. Irrigation was carried out using plastic hoses connected to the end of PVC pipes. The quantity of water utilized in the various treatments was measured using a volumetric water meter. To establish the irrigation schedule, soil moisture was assessed by employing a tensiometer installed within the ridges, reaching a depth of 10 cm. Once the moisture level reached the threshold, irrigation was conducted (Yousefian et al., 2023). Alizadeh (1999) and (Yousefian et al., 2023) stated that in the context of rice cultivation, the following values on the tensiometer were designated: 10, i.e., matric suction of −10 kPa, represented permanent saturation of the root zone, 30, i.e., matric suction of −30 kPa, indicated field capacity, and 60, i.e., matric suction of −60 kPa, represented severe water stress. Table 3 presents the specific details for each irrigation treatment.

Table 3
Irrigation scheduling for each treatment during the rice growing season.

Irrigation treatment	Treatment description	Irrigation events	Irrigation interval (day)	Total amount of irrigation (mm)
RDI10	Regulated Deficit Irrigation at a matric potential of −10 kPa	45	1	651
PRD10	Partial Root Zone Drying at a matric potential of −10 kPa	58	1	554
RDI30	Regulated Deficit Irrigation at a matric potential of −30 kPa	33	2	589
PRD30	Partial Root Zone Drying at a matric potential of −30 kPa	38	2	497
RDI60	Regulated Deficit Irrigation at a matric potential of −60 kPa	21	3	517
PRD60	Partial Root Zone Drying at a matric potential of −60 kPa	26	3	464
CF	Continuous Flooding (Control treatment)	7	7	816

Note: The starting date of the irrigation applications for all treatments is one day prior to transplanting.
Source: (Yousefian et al., 2023).

2.4. Measurement technique for methane (CH_4) emissions in the field experiment

Ten days after transplanting, 21 rectangular cube chambers with a metal frame of 100 × 100 × 40 cm^3 were installed in the paddy field for each plot to collect methane gas. The glass walls of the chambers were insulated with aquarium glue to prevent air leakage, and the metal bases were inserted into the soil up to ten cm to ensure no exchange between the inside and outside air. Every Sunday at 10:00 am, methane gas sampling from the chambers was conducted using a suction pump, and the samples were transferred to the laboratory using aluminum foil. The total amount of methane gas collected from the chambers during the week was measured using gas chromatography (Yousefian et al., 2024). Considering that the field area covered by the chamber was 0.16 m^2, the obtained values were added together at the end of the season to calculate the total amount of methane gas emitted from the field surface based on kg ha^{-1} (Yousefian et al., 2024).

2.5. CSM-CERES-Rice model

In this study, the CSM-CERES-Rice model of Decision Support System for Agrotechnology Transfer-DSSAT v4.8.2 (Hoogenboom et al., 2023) was employed. This version incorporates a novel subroutine for GHG emissions. The soil module consists of soil organic matter modules and GHG modules. Two modules for soil organic matter are available: 1) CERES (Godwin) and 2) CENTURY (Parton). In this study, the CENTURY module (Gijsman et al., 2002) was selected as it is more suitable for simulating low-input systems and conducting long-term sustainability analyses.

The CERES-Rice model (Singh et al., 1990; Buresh et al., 1991; Singh et al., 1993; Ritchie et al., 1987, 1998) is a management-oriented and physiologically-based model that incorporates principles of carbon, nitrogen, water, and energy balance. Its purpose is to simulate the growth and development of rice plants. The model operates on a daily time scale, calculating the growth and development of rice plants. The final crop yield is determined when the harvest maturity data is predicted. The model execution requires three categories of minimum data inputs. Firstly, site-specific weather information covering the entire growing season, preferably for the entire year. Secondly, soil surface characteristics and soil profile data. Thirdly, crop management from the experiment, along with observations such as yield, yield components, and key phenological dates such as the first flowering and maturity dates.

Minimum required weather data include the latitude and longitude of the weather station, daily total incoming solar radiation values (MJ m^{-2} day^{-1}), daily maximum and minimum air temperature (°C), and daily total rainfall (mm). Soil profile data includes upper and lower horizon depths (cm), percentages of sand, silt, and clay content, organic carbon content, pH in water, and root abundance information. Crop management data include critical details such as planting date, initial soil conditions at or before transplanting, planting density, row spacing and plant density, variety, transplant weight and age, dates and amounts of irrigation and fertilizer application. These inputs collectively enable the model to simulate growth and development of rice and predict final yield, as well as many other processes, such as GHG emissions.

2.5.1. Model calibration and evaluation

The CSM-CERES-Rice model was used in this study as it is far superior with respect to the simulation of rice growth, development, yield, especially in response to different crop management practices and genetics, compared to other crop models such as DNDC and DayCent. The model was calibrated using data from the control treatment of this experiment conducted in 2016, which consisted of continuous flood irrigation as a non-stressed treatment. The General Likelihood Uncertainty Estimation (GLUE) approach (Beven and Freer, 2001; Ferreira et al., 2024) was used to estimate the Genotype-Specific Parameters (GSPs) of the Hashemi rice cultivar. Although Gao et al. (2020) showed that the Markov Chain Monte Carlo method was more realistic for estimating cultivar coefficients for the flowering date, other studies, such as Buddhaboon et al. (2018), have demonstrated that GLUE can provide reasonable GSPs for all processes beyond flowering. Once the model input data were properly defined, the GSPs were estimated with GLUE, first for phenological parameters, and then for the yield and yield components parameters. The model's performance, including its response to irrigation, was evaluated using an independent data set obtained from the 2015 field experiment. During both the calibration and evaluation phase, the simulated panicle date, anthesis date, maturity date, biomass, and yield were compared with the measured values obtained from both experiments.

2.5.2. Evaluation statistics

The statistical indices that were used for model evaluation included the normalized root mean square error (NRMSE) (Wallach and Goffinet1987), absolute relative error (ARE) (Hazewinkel and Ed.), 2001), index of agreement (d-stat) (Willmott 1982; Willmott et al. 1985), and coefficient of determination (r^2) (Legates and McCabe, 1999).

The NRMSE, ARE, d-Stat, and r^2 were calculated as follows:

$$NRMSE = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - S_i)^2}}{\overline{M}} \quad (1)$$

$$ARE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{(M_i - S_i)}{M_i}\right| \times 100 \quad (2)$$

$$d - Stat = 1 - \left[\frac{\sum_{i=1}^{n}(M_i - S_i)^2}{\sum_{i=1}^{n}(|S_i - A| - |M_i - A|)^2}\right] \; 0 \le d \le 1 \quad (3)$$

$$r^2 = \frac{\sum_{i=1}^{n} S_i \times O_i - \sum_{i=1}^{n} S_i \times \sum_{i=1}^{n} O_i}{\sqrt{\sum_{i=1}^{n} S_i^2 - \left(\sum_{i=1}^{n} S_i\right)^2} \times \sqrt{\sum_{i=1}^{n} O_i^2 - \left(\sum_{i=1}^{n} O_i\right)^2}} \quad (4)$$

Where, n is the number of measurements.

M_i is the i^{th} measured value for the studied variables.

S_i is the i^{th} simulated value for the studied variables.

A is the mean of measured variables.

Low values for NRMSE and ARE, and a d-Stat and r^2 approaching 1, are desirable.

2.5.3. Scenario analysis

To compare various combinations of crop management practices, the seasonal analysis (Thornton et al., 1995) of DSSATv4.8.2 was utilized. The simulations were conducted using 35 years of daily weather data (1984–2018) from a weather station located near the Rice Research Institute. The analysis encompassed a diverse set of scenarios, including sowing dates that consisted of nine transplanting dates and nine dry direct seeding dates. Additionally, we examined the impact of three different sowing depths, eight plant populations, three tillage depths, and six N fertilizer application rates. By exploring these scenarios, the aim was to determine the most effective combination of these management practices for achieving desirable outcomes in rice production. A schematic diagram illustrating the model-based approach used in this study is presented in Fig. 2.

3. Results and discussion

3.1. Model calibration

The final values of the 11 genetic parameters of rice cultivar that determine vegetative and reproductive growth and development of the CSM-CERES-Rice model following calibration with GLUE are shown in Table 4.

3.2. Rice phenology and growth

As part of the calibration and evaluation process, the simulated data for panicle date, anthesis date, maturity date, biomass, and grain yield were compared with the observed values. Close agreement was observed between simulated and measured values for phenology. For calibration using the data from 2016, the average NRMSE across all irrigation treatments for panicle date, anthesis date, and maturity date was 0.11, 0.2, and 0.2, respectively, while the ARE was 1.58 %, 3.22 %, and 2.17 % (Table 5). In the growth phase, the average NRMSE across all irrigation treatments for biomass and yield was 0.09 and 0.13, respectively, with ARE values of 8.13 % and 13 % (Table 5).

The experimental data collected in 2015 were used for independent model evaluation. The model simulated the number of days from transplanting to maturity with no difference between simulated and measured dates, while the simulated panicle date and anthesis date were two days earlier compared to the observed values (Table 5). The NRMSE

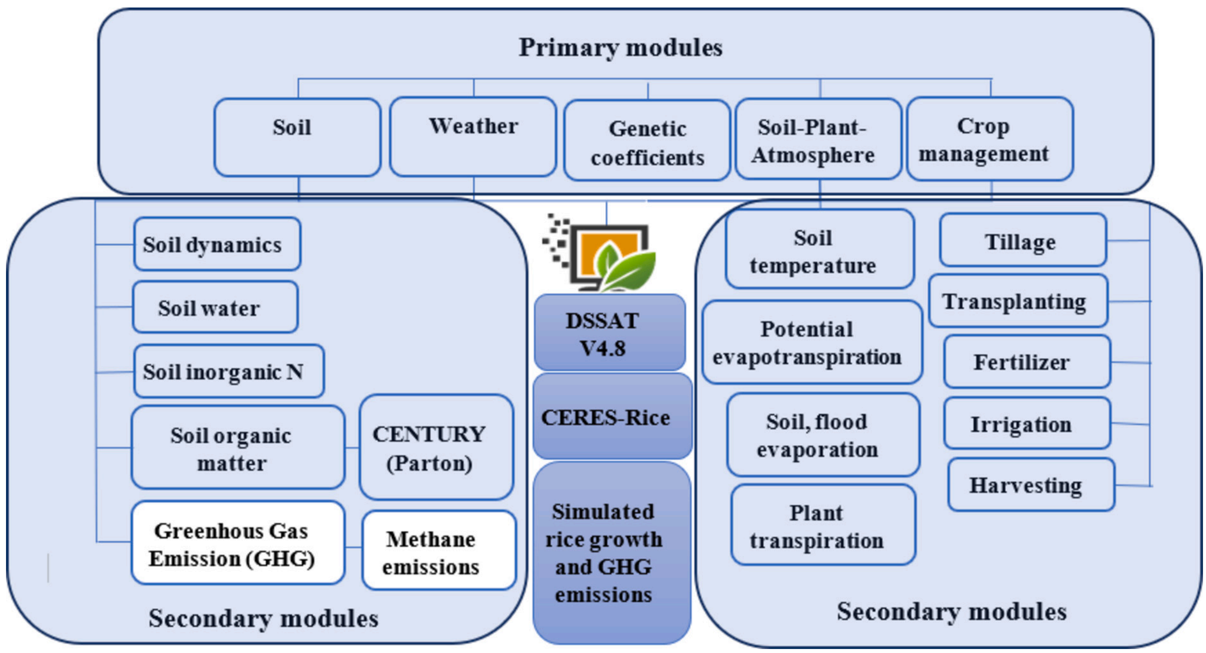

Fig. 2. Modules of the DSSAT Cropping System Model that were used in this study.

Table 4
Calibrated genetic parameters of rice cultivar *Hashemi* after 100,000 repetitions using GLUE.

Genetic coefficient	Description	Unit	Range of values	Calibrated values
P1	Basic vegetative phase of the plant	Photothermal day	150–800	168.3
P2R	Photoperiod sensitivity in panicle initiation	Photothermal day	5–300	84.28
P2O	Critical photoperiod of development occurring at a maximum rate	hour	11–13	12.90
P5	Grain filling duration	Photothermal day	150–850	399.90
G1	Potential spikelet number coefficient	–	50–70	50
G2	Single grain weight	g	0.01–0.03	0.024
G3	Tillering coefficient	–	0.7–1.30	1.16
PHINT	Phyllochron interval	Photothermal day	55–90	75
THOT	°C temperature above which spikelet sterility is affected.	°C	25–34	31.5
TCLDP	°C temperature bellow which panicle initiation is further delayed.	°C	12–18	15
TCLDF	°C temperature bellow which spikelet sterility is affected by low temperature.	°C	10–20	15

and ARE for biomass were 0.02 and 1.27 %, and for yield were 0.04 and 3.05 %, respectively, which were better than the statistics for the calibration.

The regression line between simulated and measured biomass and grain yield had values of 0.95 and 0.86 for r^2 for calibration (2016), and 0.98 and 0.84 for r^2 for model evaluation (2015) for the seven irrigation treatments (Fig. 3a, b), demonstrating the model's ability to simulate rice growth and development in response to different irrigation levels in the warm temperate environment. The slight disparities between the simulated and measured may have been due to factors other than those considered by the model, such as weeds, diseases, and pests (Ahmad et al., 2011). However, these differences were not significant, and the model successfully simulated biomass and grain yield during both growing seasons.

3.3. Daily CH_4 emissions

The Continuous Flooding (CF) treatment showed the highest agreement between simulated and recorded data points for the daily CH_4 emissions, with a d-Stat value of 0.59 (Fig. 4g). For the other irrigation treatments (Fig. 4a to 4f), the model exhibited less agreement with the recorded data, with d-Stat values ranging from 0.43 to 0.56. Differences between simulations and measurements were observed during the middle period of the growing season, where the simulated methane levels were higher compared to the measured methane levels (Fig. 4a – f).

3.4. Yield and CH_4 emissions

A comparison of mean yield and CH_4 emissions between simulated and measured values for each irrigation treatment throughout the rice growing season for 2016 is shown in Fig. 5a, b. Both the mean simulated and measured emissions were higher, between 350 and 550 g ha^{-1}, for the CF treatment compared to deficit irrigation treatment, which led to lower methane emissions, between 50 and 155 g ha^{-1}, compared to CF treatment. This implies that altering irrigation practices to deficit irrigation could help mitigate methane emissions. Altering the irrigation treatments did not significantly influence either simulated or measured yield. The maximum yield occurred under CF, ranging from 4030 to 3900 kg ha^{-1}, while the minimum yield occurred under PRD60 and RDI60, ranging from 3200 to 3500 kg ha^{-1}. For the other deficit irrigation treatments (RDI10, PRD10, RDI30, and PRD30), yields were very similar to those under CF, suggesting that these irrigation practices could be effective strategies for CH_4 mitigation without compromising yield.

Table 5
Comparison of Simulated and Measured Phenology and Growth Characteristics, and Error Metrics for CSM-CERES-Rice Model Calibration and Evaluation (2016 and 2015) with Seven Irrigation Treatments for Rice Cultivar Hashemi.

	Transplanting date	Crop characteristics	Simulated (DAT)	Measured (DAT)	NRMSE	ARE
		Phenology				
	27 th May, 2016	Panicle date	30	27	0.11	1.58
Calibration		Anthesis date	60	62	2	3.22
		Maturity date	90	92	2	2.17
		Growth				
	27 th May, 2016	Biomass (kg ha^{-1})	8006	8764.29	0.09	8.83
		Yield (kg ha^{-1})	3862.41	4431	0.13	13
		Phenology				
	24 th May, 2015	Panicle date	28	30	0.06	6.66
Evaluation		Anthesis date	63	65	2	3.07
		Maturity date	95	95	0	0
		Growth				
	24 th May, 2015	Biomass (kg ha^{-1})	8792.14	8894.86	0.02	1.27
		Yield (kg ha^{-1})	4359.14	4501.14	0.04	3.05

DAT: Days After Planting.
NRMSE: Normalized Root Mean Square Error.
ARE: Absolute Relative Error.

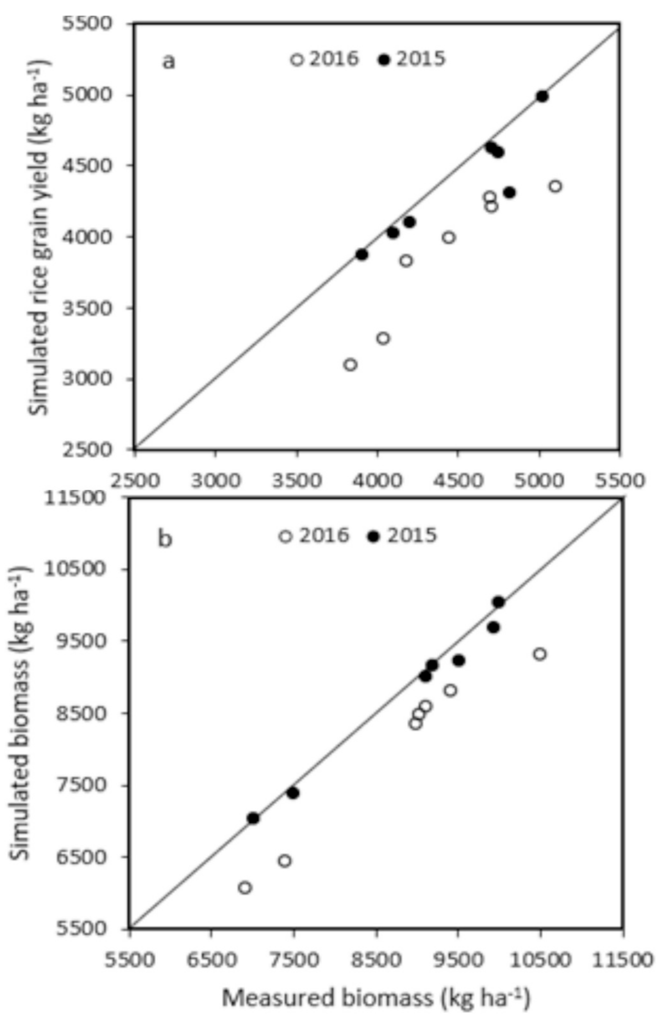

Fig. 3. Simulated and measured yield (a) and biomass (b) of rice cultivar Hashemi at Amol, Iran.
for the 2015 and 2016 growing seasons.

Overall, the results obtained from both the simulated and measured CH_4 emissions highlight the potential of implementing deficit irrigation to achieve a reduction of more than 50 % in methane emissions from paddy fields, while no significant differences in yield were observed between the CF treatment and the deficit irrigation treatments. The results from Chidthaisong et al. (2018) support our findings, showing that there was no significant difference in rice grain yield between Alternate Wetting and Drying (AWD) and CF treatments, but there was a notable disparity in methane emissions, with CF emitting 49 % more methane compared to AWD.

3.5. Scenario analysis

The seasonal analysis program of DSSAT was used to assess alternative management practices for a single rice growing season. We defined different management scenarios using long-term observed historical weather data from 1984 to 2018. The scenarios included nine transplanting dates, nine dry direct seeding dates, three tillage depths, three sowing depths, eight plant populations, and six nitrogen fertilizer rates. This approach generated simulated distributions for the desired traits, including yield, CH_4 emissions, and irrigation use efficiency.

3.5.1. Transplanting and dry direct seeding

The long-term simulation results showed that planting rice earlier in April and May, instead of June and July, resulted in a gradual increase in yield for both transplanting and dry direct seeding methods (Fig. 6a, e). During transplanting, the highest yield and irrigation use efficiency occurred between April 29 and May 27, ranging from 2100 to 2601 kg ha^{-1} and 3.4 to 3.9 kg ha^{-1} mm^{-1}, respectively (Fig. 6a, b). Methane emissions during this period were lower, between 15.8 and 17.7 kg C ha^{-1}, compared to higher emissions in June and July, which ranged from 18 to 36.5 kg C ha^{-1} (Fig. 6c). For dry direct seeding, the highest yield and irrigation use efficiency were also between April 15 and May 27, ranging from 2189.7 to 2616.4 kg ha^{-1} and 3.6 to 3.8 kg ha^{-1} mm^{-1}, respectively (Fig. 6e, f). Methane emissions during this period were also lower, between 8.6 and 16 kg C ha^{-1}, compared to the higher emissions in June and July, which ranged from 17.7 to 41.8 kg C ha^{-1} (Fig. 6g). This increase in yield in May and April was probably due to the favorable temperature for grain growth and development. Additionally, when rice was planted earlier, there was a decrease in methane gas emissions compared to later planting for both the transplanting and dry direct seeding methods (Fig. 6c, d). This decrease in emissions was likely because the cooler temperatures in April and May reduced the activity of bacteria that produce methane.

Based on these simulation results, the dry direct seeding method proved to be the most advantageous, with a 15 % increase in yield, a 13 % increase in irrigation use efficiency, and a 9 % reduction in methane emissions compared to the transplanting method. It is evident that the

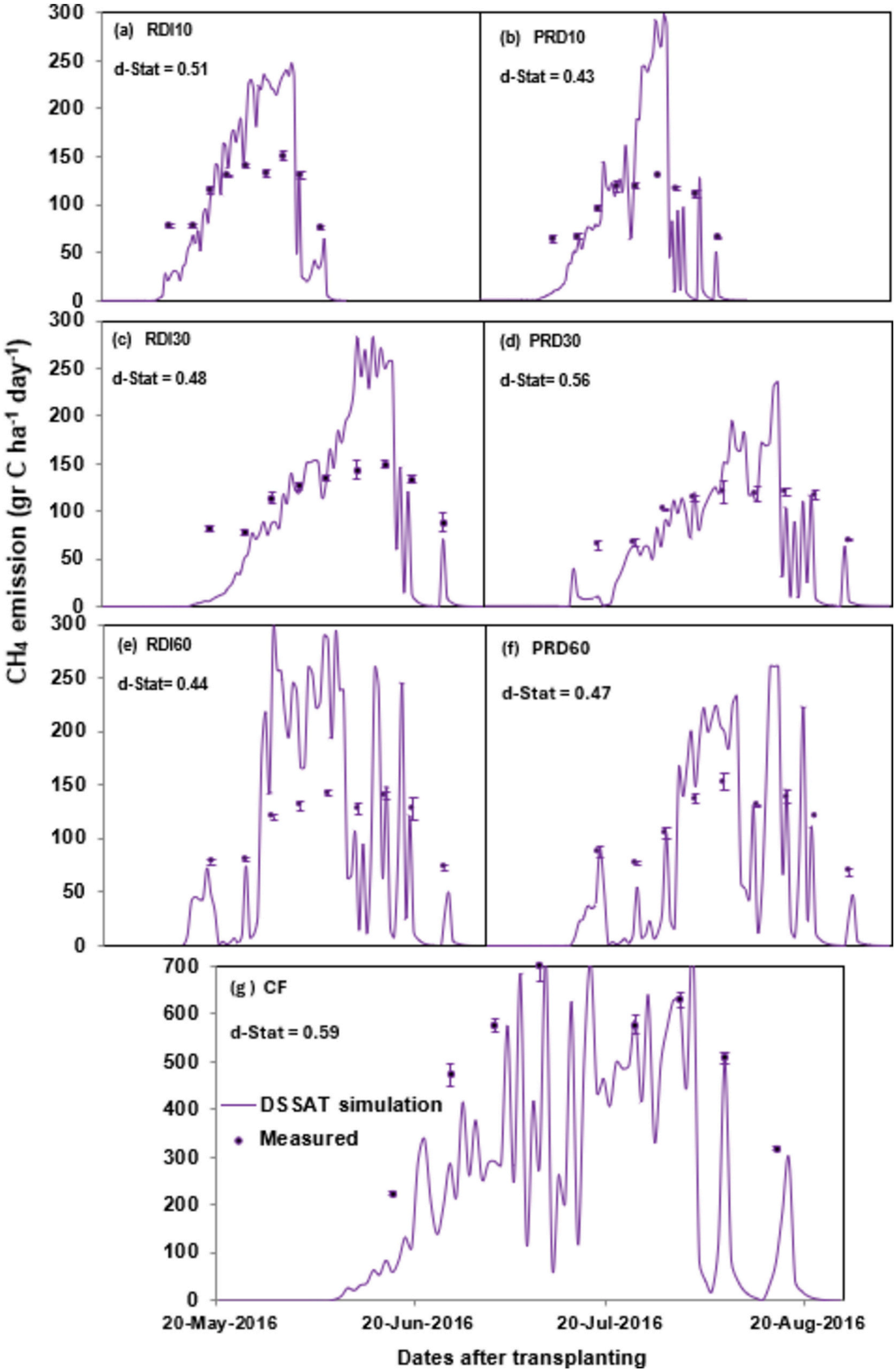

Fig. 4. Comparison between measured and simulated daily fluxes of CH_4 emissions from paddy field.
under various irrigation managements. Regulated Deficit Irrigation at −10 kPa (a); Partial Root zone Drying at −10 kPa (b); Regulated Deficit Irrigation at −30 kPa (c); Partial Root zone Drying at −30 kPa (d); Regulated Deficit Irrigation at −60 kPa (e); Partial Root zone Drying at −60 kPa (f); Continuous Flooding(g).
(The error bars show the standard deviation of methane measurements from three replications.)

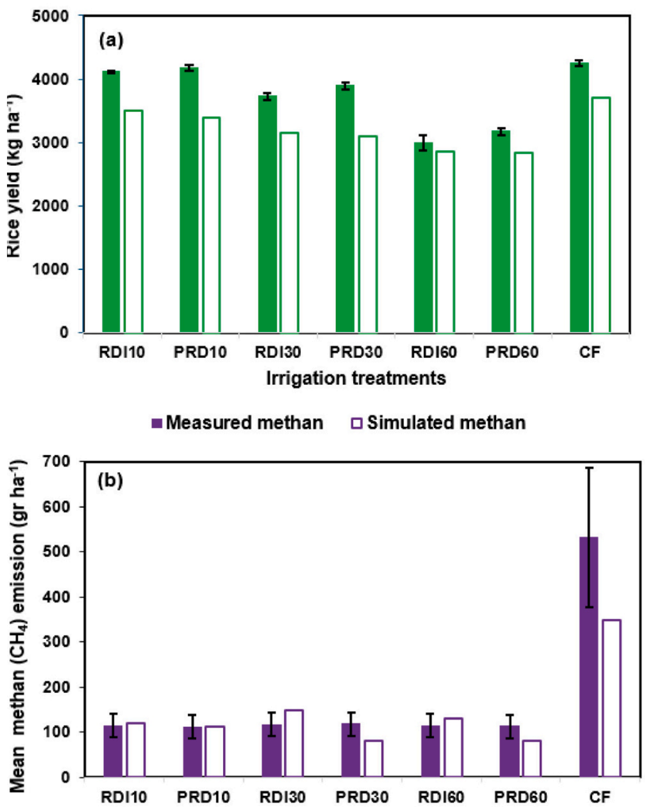

Fig. 5. Simulated and measured yield (a) and mean CH_4 emissions (b) for Regulated Deficit Irrigation at −10 kPa (RDI10); Partial Root zone Drying at −10 kPa (PRD10); Regulated Deficit Irrigation at −30 kPa (RDI30); Partial Root zone Drying at −30 kPa (PRD30); Regulated Deficit Irrigation at −60 kPa (RDI60); Partial Root zone Drying at −60 kPa (PRD60); Continuous Flooding (CF).
(The error bars show the standard deviation of yield and methane measurements from three replications for the measured data.)

most favorable scenario in the region involves early rice cultivation using the dry direct seeding method. This approach not only enhances yield and irrigation use efficiency but also mitigates cumulative CH_4 emissions. These results closely align with findings from Lun (2008), who reported that dry direct-seeded rice yielded 22 % higher compared to puddle-transplanted flooded rice. Liu et al. (2015) found that dry direct-seeded rice improved yields due to increased root growth in aerobic conditions. Rahman and Masood (2014) reported that dry direct-seeded rice used less water (432 mm) and yielded more than puddle transplanted rice (1210 mm) in Bangladesh, with higher panicle density. Kumar and Ladha (2011) showed a 24 % to 79 % reduction in CH_4 emissions with dry direct seeding compared to conventional flooded rice. Joshi et al. (2013) found higher methane emissions in continuously flooded rice fields.

In contrast to our study, Zhuo et al. (2023) revealed the opposite trend in a study conducted in China. They found that rice yield gradually increased but CH_4 emissions gradually decreased with a delayed sowing date. This discrepancy suggests that the relationship between sowing date, rice yield, and methane emissions may vary depending on factors such as geographic location, climate conditions, rice varieties, and specific management practices. It highlights the importance of considering regional variations and conducting localized studies to understand the specific dynamics and optimize crop management strategies accordingly.

3.5.2. Tillage depth

The lowest emissions occurred for the no-tillage scenario, with 13.5 kg C ha^{-1} (Fig. 7c) with no significant difference in yield between no-tillage, normal, and intensive tillage (Fig. 7.a). Tillage also did not affect irrigation use efficiency, with the same value of 3.9 kg ha^{-1} mm^{-1} across all scenarios (Fig. 7b). Optimal management for reducing CH_4 emissions while maintaining yield and irrigation use efficiency was observed in the no-tillage condition, which led to a significant reduction of 29 % of CH_4, compared to the intensive tillage in the paddy field. Our results suggest that keeping the soil undisturbed can create a more stable anaerobic environment, which can limit the growth and activity of methane-producing microorganisms. This finding highlights the potential of no-tillage as an effective strategy to mitigate CH_4 emissions without compromising yield and irrigation use efficiency.

These results align with findings from Guo et al. (2021), who reported that no-tillage reduced CH_4 emissions by 18.3 % for a 6-year field experiment in a rice-wheat system, with no significant effect on crop yield. Similarly, Wihardjaka et al. (2023) found a 15.6 % reduction in CH_4 emissions with no-tillage compared to intensive tillage. Zhang et al. (2016) observed an 8.5–14.7 % decrease in CH_4 emissions from paddy fields with no-tillage, while Kim et al. (2016) reported a 20–27 % reduction in mono-rice paddies. Ali et al. (2009) noted that no-tillage decreases soil temperature due to crop residue mulching, inhibiting methanogenic bacteria.

3.5.3. Sowing depth

Yield and irrigation use efficiency were very similar, ranging from 2593 to 2600 kg ha^{-1} and 3.9 to 4 kg ha^{-1} mm^{-1}, respectively, for the different sowing depths (Fig. 7e, f). Methane emissions at depths of 5–15 cm were also similar, ranging from 16.3 to 17.2 kg C ha^{-1} (Fig. 7g). These results indicate that sowing depth does not have a significant effect on CH_4 emissions, yield, or irrigation use efficiency. This may be due to simplifications in the CERES-Rice model's structure regarding the effects of sowing depth on emissions and yield.

3.5.4. Plant population

An increase in plant population, i.e., the number of transplants per ridge, initially resulted in a decrease in yield and then reached a stable level (Fig. 8a), while the pattern of CH_4 emissions exhibited the opposite trend. As the plant population increased, the amount of CH_4 emissions also increased gradually, eventually reaching a stable level (Fig. 8c).

The optimal strategy was identified at a plant population of 10 transplants per ridge, resulting in the highest yield of 2733 kg ha^{-1} and an irrigation use efficiency of 4.2 kg ha^{-1} mm^{-1} (Fig. 8a, b). This strategy resulted in the lowest emissions of 13.5 kg C ha^{-1}, indicating a significant reduction in emissions compared to other plant populations (Fig. 8c). Our findings indicate the importance of carefully considering plant population management to achieve optimal yield while mitigating CH_4 emissions. Aligned with our results, Zhu et al. (2015) demonstrated that a further increase in plant population, compared to a moderate increase, significantly decreased rice yield. This increased plant population resulted in a significant rise in CH_4 emissions. They reported that the primary cause of yield decline with higher planting density is a decrease in panicle number rather than grain number or weight. Additionally, excessive planting density can increase CH_4 emissions due to higher aboveground biomass, which contributes to greater organic matter decomposition and enhances CH_4 production and transport. Peng et al. (2002) and Li et al. (2014) found that planting density, when too sparse, may not result in high yields in major rice cropping areas, particularly in Asia. Thus, moderately dense planting is increasingly recommended to further increase rice yield (Ma et al., 2013; Chen et al., 2014; Wang et al., 2014; Zhu et al., 2015).

3.5.5. Nitrogen fertilizer

The simulation results demonstrated that increasing the nitrogen fertilizer rate led to a simultaneous increase in yield, irrigation use efficiency, and CH_4 emissions, with most substantial increases for a nitrogen fertilization rate of 250 kg ha^{-1}, resulting in a yield of 4002 kg

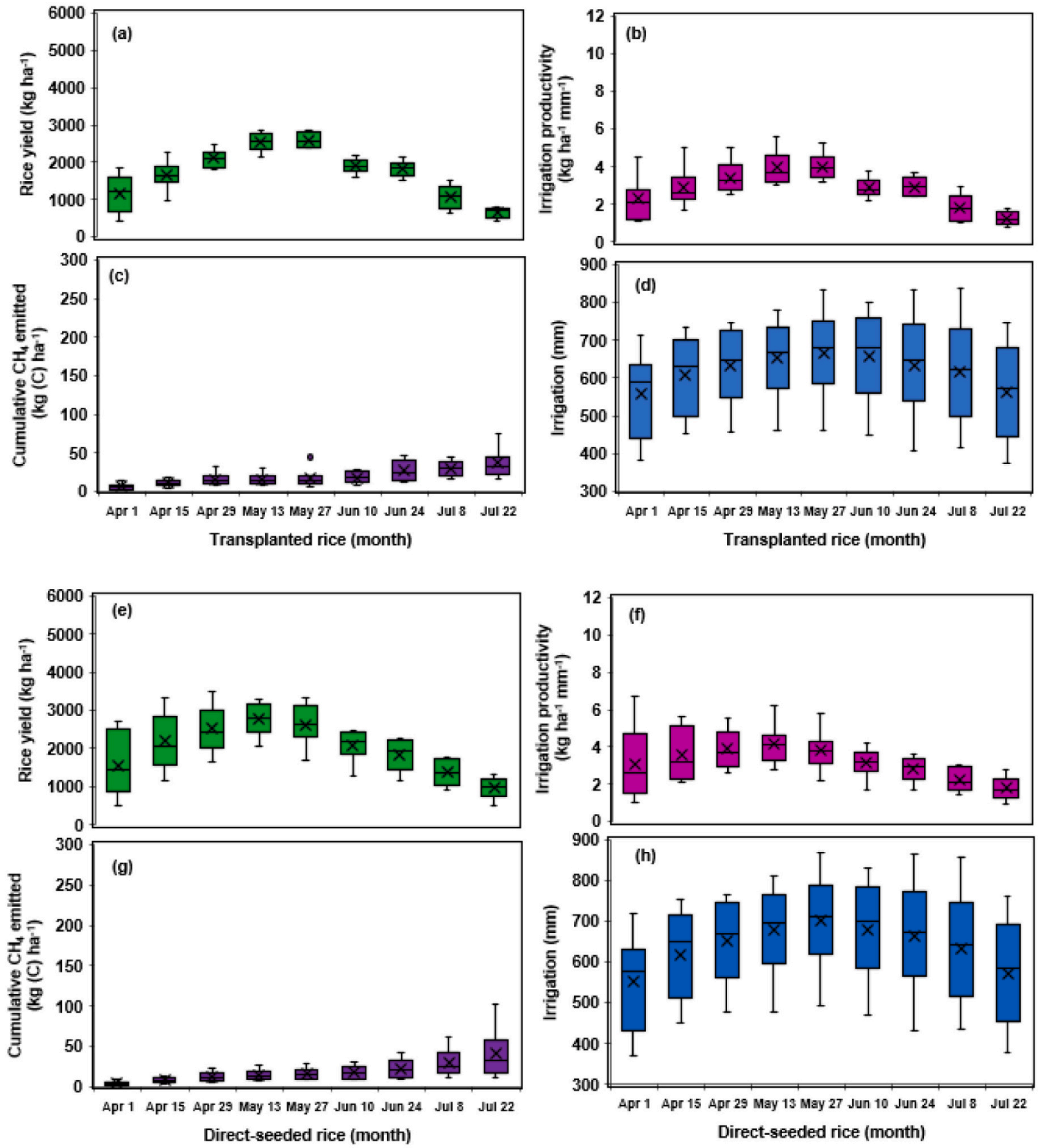

Fig. 6. Simulated rice yield (a), irrigation use efficiency (b), cumulative CH_4 emitted (c), and irrigation depth (d) as functions of transplanting date; and simulated rice yield (e), irrigation use efficiency (f), cumulative CH_4 emitted (g), and irrigation depth (h) as functions of dry direct seeding date. (The box and whisker plots represent the outcome distribution for 35 simulations for the years 1984–2018, with the median as the horizontal line and the mean as the cross. The box represents the interquartile range (IQR), and the whiskers indicate data spread. Individual points outside the whiskers are outliers, representing values outside the typical range.)

ha^{-1}, irrigation use efficiency of 6.2 kg ha^{-1} mm^{-1}, and CH_4 emissions 62.3 kg C ha^{-1} (Fig. 8e, f, g) Previous studies have shown contradictory results, suggesting that N fertilizer can either stimulate (Shang et al., 2011) or inhibit CH_4 emissions (Xie et al., 2010; Dong et al., 2011) for rice. Our findings align with Zhang et al. (2016), who found that CH_4 emissions and rice yield increased with higher N fertilizer rates. Zhang et al. (2019) also noted that N fertilization boosts crop residue input, stimulating methanogens and increasing CH_4 emissions. However, Hu et al. (2020) found that higher N fertilization reduced CH_4 emissions in a study in China. One likely reason for these differences may be variations in soil types, as soils with higher organic matter content or different redox potentials can influence methanogenic activity differently. Temperature and rainfall can also affect microbial activity and thus the overall CH_4 production or oxidation rates. Rice variety could also play a role, as some types develop root structures that increase oxygen in the soil, supporting CH_4-consuming bacteria. Meta-analyses suggest that higher N input decreases CH_4 emissions by limiting carbon substrates for methanogens (Banger et al., 2012), though N enrichment may still increase CH_4 emissions overall (Liu and Greaver, 2009; Banger et al., 2010; Tian et al., 2010; Lu et al., 2012).

3.6. *Insights from modeling to policy recommendations*

In this study, we identified the optimal combination of earlier

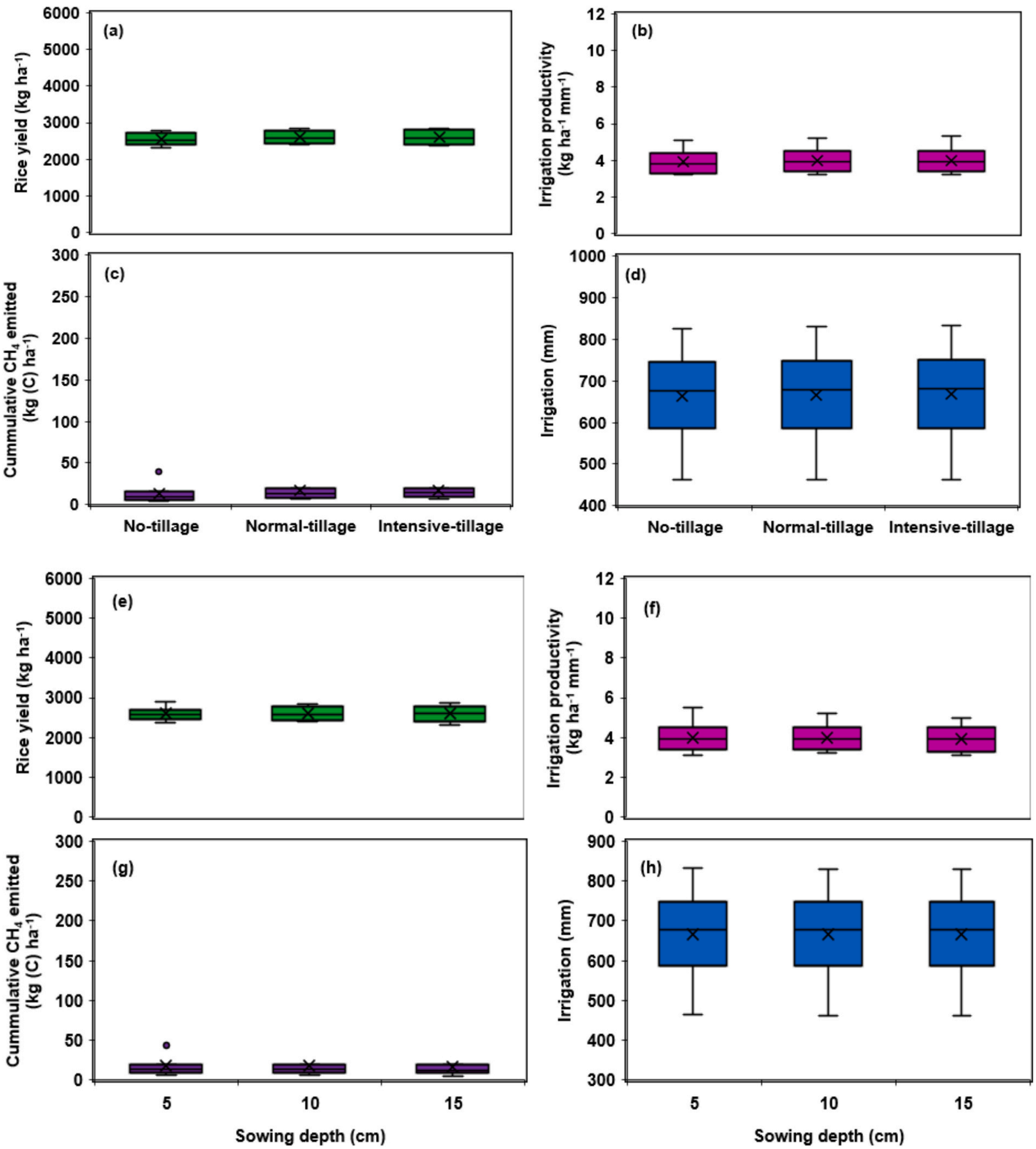

Fig. 7. Simulated rice yield (a), irrigation use efficiency (b), cumulative CH_4 emitted (c), and irrigation depth (d) as functions of tillage conditions; and simulated rice yield (e), irrigation use efficiency (f), cumulative CH_4 emitted (g), and irrigation depth (h) as functions of sowing depths. (The box and whisker plots represent the outcome distribution for 35 simulations for the years 1984–2018, with the median as the horizontal line and the mean as the cross. The box represents the interquartile range (IQR), and the whiskers indicate data spread. Individual points outside the whiskers are outliers, representing values outside the typical range.)

cultivation for dry direct-seeded rice with a nitrogen fertilizer application rate of 250 kg ha^{-1}, which resulted in the highest yield and lowest methane emissions. The findings demonstrate the potential of using the CSM-CERES-Rice to identify the best management practices for rice. To translate these results into real-world applications, policymakers could support sustainable practices, such as deficit irrigation, by providing grants or subsidies tailored to regional socio-economic needs, particularly in resource-limited areas where transition costs may be higher. Additionally, technical assistance, such as training programs and extension services, can be offered to guide farmers in regions with varying environmental conditions in effectively implementing and managing these sustainable practices. For example, in water-scarce regions, training on deficit irrigation could help farmers save water, while in resource-limited areas, subsidies could ease the cost of adopting new methods. (Smith et al., 2007; Piñeiro et al., 2020; Osuafor and Ude, 2021; Anugwa et al., 2022).

3.7. Limitations of the study

One of the limitations of this study is that the experiment was conducted in a small-scale paddy field in northern Iran for two years. Although the flexibility of the CSM-CERES-Rice model allowed us to simulate different management scenarios over the long-term using 35 years of daily weather data from the region, the findings are site-specific.

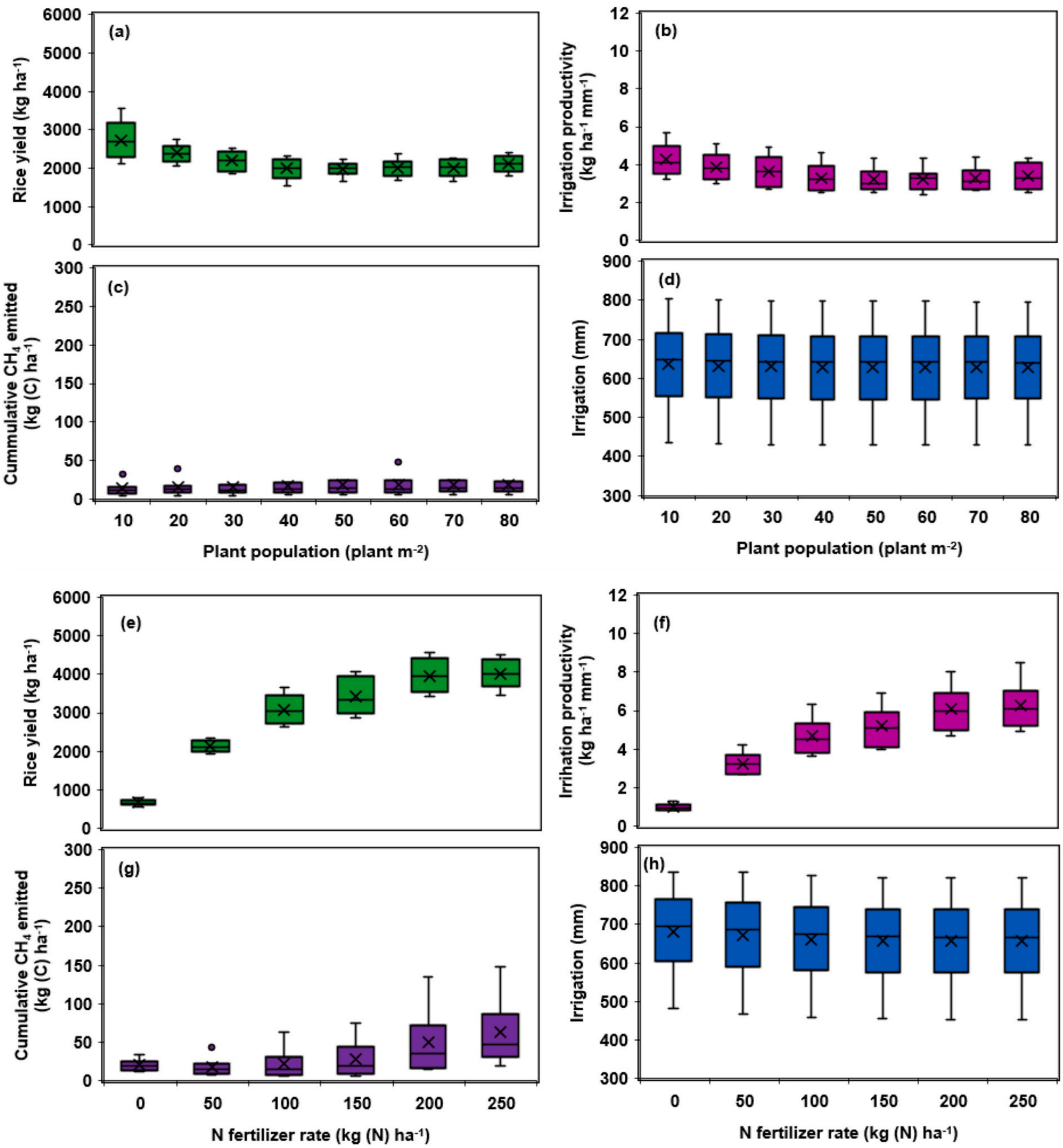

Fig. 8. Simulated rice yield (a), irrigation use efficiency (b), cumulative CH_4 emitted (c), and irrigation depth (d) as functions of plant populations; and simulated rice yield (e), irrigation use efficiency (f), cumulative CH_4 emitted (g), and irrigation depth (h) as functions of N fertilizer rates. (The box and whisker plots represent the outcome distribution for 35 simulations for the years 1984–2018, with the median as the horizontal line and the mean as the cross. The box represents the interquartile range (IQR), and the whiskers indicate data spread. Individual points outside the whiskers are outliers, representing values outside the typical range.)

These findings may not directly apply to regions with different environmental or socio-economic conditions, as factors such as climate, soil, and resource availability can greatly impact results. However, the CSM-CERES-Rice model is adaptable and can be calibrated with local data to offer region-specific insights. The optimized rice management practices were developed without considering economic evaluation that includes production costs and grain prices. For example, the long-term analysis on the effect of nitrogen fertilizer on yield showed that the maximum yield occurred at 250 kg Nha^{-1}. However, we did not conduct cost-benefit analyses in the model to determine if this is economically feasible. Although these limitations create challenges associated with adopting these practices in real-world contexts, at the same time it showed how systems analysis and modeling can be used for multi-objective optimization.

4. Conclusion

This study highlights the utility of a novel subroutine for GHG emissions in the CSM-CERES-Rice model for optimizing rice management strategies in northern Iran. The calibration results showed that using deficit irrigation can significantly reduce methane emissions by 50 % without significantly affecting yield compared to flood irrigation. Following model calibration, simulations of management scenarios indicated that among different scenarios, shifting to dry direct seeding one month earlier has more benefits, with a 15 % increase in yield, a 13 % increase in irrigation use efficiency, and a 9 % reduction in methane emissions compared to the transplanting method. Under no-tillage condition, there was a significant reduction of 29 % of CH_4 compared to the intensive tillage. The simulation results indicated that the different sowing depths did not have a significant effect on CH_4 emissions or yield. Plant population of 10 transplants per ridge, resulting in the highest yield and irrigation use efficiency of 2733 kg ha^{-1} and 4.2 kg ha^{-1} mm^{-1}. Simultaneously, this strategy resulted in the lowest emissions of 13.5 kg C ha^{-1}, indicating a significant reduction in emissions compared to other plant populations. The most substantial increments in yield, irrigation use efficiency, and CH_4 emissions were observed at a nitrogen fertilization rate of 250 kg ha^{-1}, resulting in 4002 kg ha^{-1}, 6.2 kg ha^{-1} mm^{-1}, and 62.3 kg C ha^{-1} respectively. Further studies should focus on the impact of N_2O emissions from paddy fields, particularly due to the deficit irrigation and nitrogen fertilizer use in this study, which could affect overall GHG emissions.

CRediT authorship contribution statement

Dorsa Darikandeh: Writing – original draft. **Ali Shahnazari:** Writing – review & editing, Supervision. **Mojtaba Khoshravesh:** Supervision. **Mostafa Yousefian:** Data curation. **Cheryl H. Porter:** Validation, Software. **Gerrit Hoogenboom:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

The corresponding author and co-authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data availability

Data will be made available on request.

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