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Simulating the impact of water saving irrigation and conservation agriculture practices for rice–wheat systems in the irrigated semi-arid drylands of Central Asia

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ABSTRACT

Resource scarcity (labor, water, and energy) and high production costs are challenging the sustainability of conventional methods for rice and wheat establishment in Central Asia. Water saving irrigation and conservation agriculture (CA) practices (e.g., dry seeded rice, zero tillage wheat, residue retention) are potential alternative, resource-saving establishment methods. The Decision Support System for Agrotechnology Transfer (DSSAT) Cropping System Model (CSM) can both be a valuable ex-ante and ex-post tool to evaluate the effects of water saving irrigation and resource saving CA-practices. The CSM-CERES-Rice and CSM-CERES-Wheat models of DSSAT were evaluated using experimental data from the 2008 to 2010 rice and wheat seasons as monitored in Urgench, the Khorezm region of Uzbekistan for growth, development of these crops, as well as soil mineral nitrogen (N) and volumetric soil moisture content in these cropping systems. Thereafter, the models were used to explore the long-term impact of water saving irrigation and CA-practices on grain yield, soil organic carbon (SOC) dynamics, N dynamics, and water balance in a rice–wheat rotation for 39 years starting from 1971. The simulation results showed that the simulated yield of water-seeded rice without residue retention and flood irrigation (WSRF-R0-FI) is likely to remain the highest and constant over 39 years. The simulated yield of dry seeded rice (DSR) with alternate wet and dry (AWD) irrigation and varying levels of residue retention was penalized for the initial years. However, the simulated rice yield increased after 13 years of CA-practices and continued to increase for the remaining years. Wheat did not experience a yield penalty for any of the treatments and simulated yield increased over time across all CA-practices based treatments. In the long-term, the effect of tillage methods and different residue levels for both rice and wheat were apparent in terms of grain yield and SOC build up. The results of the sensitivity analysis showed that WSR using AWD irrigation with puddling (WSRF-R0-AWD-Puddled) could give equivalent yield with that of WSRF-R0-FI and that irrigation water for rice could be reduced from 5435 mm to 2161 mm (or by 60%). Deep placement of urea in DSR (CT-DSR-AWD-DPUS) has the potential to increase yields of DSR by about 0.5 $t\,ha^{-1}$. Despite the huge water saving potential through the adoption of water saving AWD irrigation in DSR, a major challenge will be to prevent N losses. Substantial amounts of N losses through leaching, immobilization by residue mulch, combined with gaseous losses through volatilization and denitrification are the major causes for the lower simulated yield of rice for the AWD treatments. During the rice season, the implementation of water saving irrigation can improve water use efficiency by reducing percolation and seepage losses, which is an option in particular for WSRF-R0-FI. For both crops, the water use efficiency can be improved by lowering evaporation losses e.g. through residue retention on the soil surface. The creation of a sub-surface hard pan (puddling) and deep placement of urea super granules/pellet (DPUS) fertilizer could be the key for water saving and better yields of rice. Because CA-practices require almost

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three times less irrigation water than conventional method, and provide a long-term positive impact on grain yields of both crops, the CA-practices should be considered for double, no-till, rice–wheat cropping systems in the irrigated semi-arid drylands of Central Asia.

1. Introduction

Wheat and rice are the major food crops in Central Asia and are produced on 15.2 and 0.23 Mha area, respectively (FAOSTAT, 2014). More than 70% of the rice is produced in rice–wheat systems in the irrigated lowlands of the Amu Darya and Syr Darya river basins (Aral Sea Basin). In Central Asia, rice is a highly remunerative crop, with a price several times higher than that of wheat, and even 2–3 times higher than the rice world market price (Djanibekov, 2008). However, due to a growing water scarcity, national policies aim at reducing the area of rice crops since extensive irrigation water is required with water-seeded rice (WSR) which is cultivated with a permanent 5–20 cm standing water depth (Devkota et al., 2013c). Similarly, the production of winter wheat, which is the main staple food in all five Central Asian countries, is threatened by a reduced availability of irrigation water, high production and energy costs, labor shortage, intensive soil tillage, declining soil fertility due to residue removal and burning, and excessive and inefficient water management practices (Devkota et al., 2015; Gupta et al., 2009; Hobbs et al., 2008).

In water saving alternate wet and dry (AWD) irrigation, rice field is irrigated when the soil metric potential at a 15 cm soil depth reaches 10 kPa, which can save a significant amount of irrigation water while maintaining yield equivalent to those using conventional methods (Belder et al., 2005; Humphreys et al., 2010; Sudhir-Yadav et al., 2011). Also, as AWD does not demand puddling, such practice may also contribute to overcome the disadvantages of conventional methods which lead to soil degradation and water logging (Timsina and Connor, 2001).

Conservation agriculture (CA) practices that involve minimum soil tillage, optimum amount of residue retention, and proper crop rotation (Hobbs et al., 2008) is practiced by farmers on more than 100 Mha worldwide (as of 2008) especially for the cultivation of upland crops (Derpsch, 2011). Minimum/zero soil tillage practices avoid the deleterious effects of puddling on the soil structure and fertility (Timsina and Connor, 2001), increase the overall water balance due to residue retention and bed planting (Kukal et al., 2010; Rejesus et al., 2011), improve soil quality and water- and nutrient-use efficiency (Humphreys et al., 2010; Singh et al., 2008b; Timsina and Connor, 2001), increase water storage and improve crop yield and water productivity (Wang et al., 2012), and increase soil organic matter content (Rasmussen, 1999). Thus, minimum soil tillage is increasingly practiced among rice farmers in the southern USA (Griggs et al., 2007), among dryland cereal farmers in southwestern Australia (D'Emden et al., 2008) and in parts of the Indo-Gangetic Plains (Humphreys et al., 2010). Among the CA-practices in rice–wheat systems, dry seeded rice (DSR) and zero tillage wheat on raised beds and flat is becoming increasingly popular also in South Asia (Jat et al., 2013). The long-term impact of continuous double zero-tillage practices with residue retention on sustaining crop yield, water and nutrient dynamics in rainfed and aerobic cropping systems is well known (Govaerts et al., 2007) but the long-term impact and fate of double zero tillage and residue retention with water saving irrigation in the irrigated rice–wheat systems has received much less attention.

Compared to conventional methods of crop establishment, the soil–crop–atmosphere interactions, soil hydrological, nitrogen (N), and soil organic carbon (SOC) dynamics differ under water saving irrigation and alternative resource conservation establishment methods (Devkota et al., 2013b, 2013c, 2013d). It has often been suggested that various CA-practices are potential suitable innovations to cope with the numerous unsustainable irrigation practices in the irrigated areas of Central Asia (Devkota et al., 2013c, 2013d, 2015). However, practical evidence within the different agro-ecological zones of Central Asia is still sporadic because long-term experimental results are lacking (Kienzler et al., 2012). The combination of crop simulation models and field experiments is a recognized ex-ante tool to increase the understanding of the long-term impacts of CA-practices combined with water saving irrigation also in the absence of long-term experimental results (Jones et al., 2003).

There are several crop and soil simulation models such as the Agricultural Production Systems Simulator (APSIM) (Keating et al., 2003), Cropping Systems Simulator (CropSyst) (Stöckle et al., 2003), and the Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003), that have rice and wheat models. The CERES-Rice and CERES-Wheat models of DSSAT Cropping Systems Model (CSM) simulate rice and wheat photosynthesis, growth, biomass partitioning, crop development, yield, N dynamics, and water balances as a function of input information including daily weather conditions, crop management practices, cultivar characteristics, soil properties, and soil water, carbon and nitrogen content, and can be used to simulate rice–wheat crop rotations (Jones et al., 2003; Timsina and Humphreys, 2006). In this study, we applied the CSM-CERES-Rice and CSM-CERES-Wheat models of DSSAT to simulate the impact of water saving irrigation and CA-practices (zero tillage, residue retention) in irrigated drylands of Central Asia. These models have also been used to simulate the impact of CA-practices in rainfed maize in Malawi (Ngwira et al., 2014), to simulate the effect of long-term no tillage in rainfed cereal systems in Mediterranean area (De Sanctis et al., 2012), irrigated rice–wheat systems in South Asia (Jeong et al., 2014; Timsina et al., 2008), and alternative crops for low input systems in semi-arid region of Burkina Faso (Soler et al., 2011). The tillage feature has only recently been added to the CSM of DSSAT (Porter et al., 2010) based on research findings by Andales et al. (2000). So far it has been tested for a limited set of environments, but the CSM model has shown already capable of simulating realistically long-term SOC and other soil processes (Li et al., 2015; Liu et al., 2013; Soler et al., 2011). The DSSAT models are capable to accurately predict yield variability caused by different management practices (Boote et al., 2010; Hoogenboom et al., 2012b; Jones et al., 2003). They also have been evaluated extensively with field data for a wide range of environmental conditions and crop management practices. Thus, the present study was designed with the objectives to evaluate the CERES-Rice and CERES-Wheat models, and to explore the long-term impact of water saving irrigation and CA-practices on rice–wheat rotation with a focus on grain yield, SOC and N dynamics, and the soil water balance.

2. Materials and methods

2.1. Study region

During 2008–2010, an experimental study was conducted in the Urgench, Khorezm region of Uzbekistan located in northwest Uzbekistan at 60.05–61.39°N latitude and 41.13–42.02°E longitude and with an elevation ranging from 90 to 138 m above sea level.

The climate is representative of the rice–wheat growing regions of Central Asia, is typically continental and arid, with long, hot and dry summers and short, very cold dry winters (Conrad et al., 2012). Potential evapotranspiration (ca. 1200 mm y^{-1}) greatly exceeds precipitation of about 100 mm in the Khorezm region whilst more than 70% of the precipitation generally occurs during the winter season. This small amount of rainfall plays a minor role in the soil–water balance. The rotation of winter wheat (October–July) and rice (July–October) is possible only with assured irrigation whilst the window for rice cultivation is limited (Devkota et al., 2013a).

2.2. Experimental design and treatments

Development rates, partitioning factors, yield and yield attributes are influenced by genotype, environment, and management practices. In order for the models to work properly for local conditions, the appropriate input parameters need to be obtained and the cultivar coefficients need to be calibrated (Hoogenboom et al., 2012a; Jones et al., 2003). In this study, these parameters were derived from experiments conducted in rice–wheat systems in 2008 and 2009 set-up in a randomized complete block design with four replications. For rice, seven treatments were implemented in 2008 but eight in 2009 combining two irrigation methods, i.e., alternate wet and dry (AWD) and continuous flood irrigation (FI). Furthermore, three establishment methods were included: i.e., (i) zero tillage dry seeded rice in raised bed (DSRB), (ii) zero tillage dry seeded rice in flat (DSRF), and (iii) conventional tillage flood irrigated water-seeded rice in flat (WSRF). These were combined with three levels of residue retention, i.e., the farmers' method of leaving standing stubbles (3–5 cm; R0), leaving 15–20 cm standing straw (R50) and leaving 35–40 cm standing straw (R100). During the rice seasons, all AWD treatments were irrigated at 1–5 days interval to maintain a 20 kPa soil water tension at 20 cm soil depth (alternate wet and dry; AWD irrigation). The WSRF-R0-FI treatment was irrigated twice a day to maintain a 5–15 cm standing water (equal to farmer's method of paddy rice cultivation) until one week before crop harvest. For wheat, the tested flat and bed establishment methods were combined with three residue levels (as in rice). Further details of the experimental design and treatments were described previously by Devkota et al. (2013b, 2013c). The details of treatments used for experimentation and simulations are explained in Table 1.

2.3. Crop management

The rice was dry seeded (DSR) with a tractor-drawn Indian Planter in zero tillage on flat and zero tillage on beds. These establishment options were compared with conventional methods, where rice was water-seeded (WSR) (24-h water-soaked, pre-germinated rice seed was seeded into the standing water in a field that had been ploughed and leveled 2–3 times) and AWD and FI irrigated. A short duration local rice variety (Nukus-2) was drill seeded on 18–21 June in 2008 and 2009 using the recommended seed rate of 140 kg ha^{-1} and fertilizer with 250:120:80 kg N:P_2O_5:K_2O ha^{-1} (Devkota et al., 2015). The wheat variety Krasnadar-99 was surface-broadcasted into the standing rice in all treatments, 17 days prior to the rice harvest in 2008 and 22 days prior to the harvest of rice in 2009. Wheat was seeded at a rate of 200 kg ha^{-1} and fertilized with 124:100:70 kg N:P_2O_5:K_2O ha^{-1} in 2008 and 233:140:70 kg N:P_2O_5:K_2O ha^{-1} in 2009.

2.4. Measurements

Crop phenology, growth and yield and yield attributing parameters for both rice and wheat were measured using standard methods (Devkota et al., 2013c). Soils for mineral (NH_4 and NO_3) N were sampled before the start of the experiment and prior to fertilizer application at the three main growth stages, and at each crop harvest and were analyzed using standard examination procedure (Devkota et al., 2013b). In addition, the soil moisture dynamics in the rice–wheat system were monitored through measurements taken on AWD treatments during rice cultivation and on all treatments during wheat cultivation in both years. Volumetric soil moisture was assessed in soil samples taken from predetermined points with 5 to 12 replications for each treatment. The soil samples were collected at 19 dates for rice in 2008, 15 dates for wheat in 2009, and 26 dates for rice in 2009. In bed plots, soils were sampled from both the top of the bed and the center of the furrow to obtain the average moisture content on the bed. The soils were sampled at 0–10, 10–20, 20–30, 30–50, and 50–80 cm depths before irrigation by using a tube auger. Samples were oven-dried for 48 h until constant weight and corrected for bulk density (Table 2). Hereafter, the moisture up to 30 cm soil depth of one treatment DSRF-R0-AWD is presented. The irrigation water inputs for all treatments during all three growing seasons was measured by three separate Standard Trapezoidal Cipolletti weirs (0.5 m crest

Table 1
Treatment details of the rice–wheat experiment in the Khorezm region of Uzbekistan 2008–2010.

Treatment no.	Short description	Detail description
1	WSRF-R0-FI	Water-seeded rice grown on flat, no residue retention, conventional tillage (CT), flood irrigation (FI) in rice followed by zero tillage wheat (ZTW) with no residue retention
2	DSRB-R0-AWD	Dry seeded rice grown on bed, no residue retention, alternate wet and dry (AWD) irrigation in rice followed by zero tillage wheat with no residue retention
3	DSRB-R50-AWD	Dry seeded rice grown on bed, 50% residue retention, AWD irrigation in rice followed by zero tillage wheat with 50% residue retention
4	DSRB-R100-AWD	Dry seeded rice grown on bed, 100% residue retention, AWD irrigation in rice, followed by zero tillage wheat with 100% residue retention
5	DSRF-R0-AWD	Dry seeded rice grown on flat, no residue retention, AWD irrigation in rice followed by zero tillage wheat with no residue retention
6	DSRF-R50-AWD	Dry seeded rice grown on flat, 50% residue retention, AWD irrigation in rice, followed by zero tillage wheat with 50% residue retention
7	DSRF-R100-AWD	Dry seeded rice grown on flat, 100% residue retention, AWD irrigation in rice followed by zero tillage wheat with 100% residue retention
8	WSRF-R0-AWD	Water-seeded rice grown on flat, no residue retention, CT, non-puddled, AWD irrigation in rice, followed by zero tillage wheat with no residue retention, new treatment in 2nd year
Simulations used for sensitivity analysis only		
9	WSRF-R0-AWD-Puddled	Same as treatment No. 8 but the field was puddled
10	CT-DSR-AWD	Not puddled, CT dry tillage and dry seeded rice (CT-DSR), planting in line as in treatment 5, no residue retention and AWD irrigation as in treatment 8 in rice followed by ZT wheat with no residue retention
11	CT-DSR-AWD-DPUS	Same as No. 10 but deeply placed urea super granules (DPUS)/pellets, 100% in soil

Table 2
Physical and chemical soil properties prior to the experimental onset in 2008 in the Khorezm region, Uzbekistan.

Depth (cm)	Texture (%)			Bulk density ($g\,cm^{-3}$)	LLL ($cm3\,cm^{-3}$ soil)	DUL ($cm3\,cm^{-3}$ soil)	SAT ($m3\,m^{-3}$ soil)	RGF	Soil organic carbon (%)	NH_4–N ($mg\,kg^{-1}$)	NO_3–N ($mg\,kg^{-1}$)	Initial total N (%)	Available phosphorus ($mg\,kg^{-1}$)	Exchangeable potassium ($mg\,kg^{-1}$)
	Sand	Silt	Clay											
0–10	23	58	19	1.35	0.12	0.25	0.43	1	0.36	5.4	5.3	0.05	27.9	98.5
10–20	33	49	18	1.41	0.12	0.23	0.42	0.5	0.30	6.5	4.4	0.05	25.9	95.0
20–30	26	62	12	1.42	0.10	0.23	0.40	0.23	0.26	6.3	5.2	0.04	21.9	89.3
30–60	29	63	8	1.52	0.09	0.22	0.38	0.10	0.23	6.3	4.0	0.03	19.2	81.4
60–90	49	43	8	1.57	0.09	0.18	0.36	0.01	0.19	5.2	3.9	0.03	17.6	76.8

LLL = lower limit, DUL = drained upper limit, SAT = saturated soil water content, RGF = root growth factor.

width) with automated data loggers (Divers) for level measurement (DL/N-70) (Devkota et al., 2013c).

2.5. Model inputs

2.5.1. Crop management data

Initial conditions like soil surface and subsurface conditions, initial soil water, nitrate and ammonium content for each soil layer (Table 2) and the amount of above and below ground residues from previous crop, the cultivar-specific parameters and genotypes, planting date, emergence date, planting method, density, distribution, planting depths and row spacing, fertilizer application types and rates, irrigation, organic amendments (amount of rice and wheat residues retention), tillage method, depth and date, harvesting dates parameters that were used for the CERES-Rice (Singh et al., 1993) and CERES-Wheat models (Jones et al., 2003) were obtained from Devkota et al. (2013b, 2015).

2.5.2. Soil profile data

The soil at the experimental site is a calcaric gleysoil, i.e., meadow soils in the irrigated areas. The soil suffers from shallow groundwater table (0.5–2 m) often with elevated groundwater salinity (2–16 $dS\,m^{-1}$ ECe 1:1 in 0–15 cm soil depth) and secondary salinization in the upper soil. The top 30 cm soil is typified by low soil organic matter (SOM) (0.4–0.5%), low organic N content (0.012–0.073%), relatively high P (0.10–0.21%) and K (1.0–2.2%) (Table 2). The soil-pH ranges from 5.56 to 5.78 depending on soil depth as does soil ECe (1.8–3.0 $dS\,m^{-1}$), available phosphorus from 17.6 to 27.9 $mg\,P\,kg^{-1}$ and exchangeable potassium from 76.8 to 98.5 $mg\,K\,kg^{-1}$. Five soil layers were sampled, including 0–10, 10–20, 20–30, 30–50 and 50–80 cm soil depth to provide required inputs such as volumetric water content at lower limit, drained upper limit, field capacity, soil texture, SOC, rooting depth, and soil pH (Table 2).

2.5.3. Daily weather data

The required daily weather data for DSSAT, e.g., rainfall, minimum and maximum air temperature, solar radiation, relative humidity, and wind speed were continuously measured from 1971 to 2010 (Devkota et al., 2013b).

2.6. Model parameterization and evaluation

The data sets for model parameterization and evaluation were taken from Devkota et al. (2013b, 2013c). Information on crop management, rice and wheat phenological development, total aboveground biomass accumulation, and yield and yield attributes from all 7 treatments in 2008 were used for the parameterization of the CERES-Rice and CERES-Wheat models. Similarly, all crop growth, phenology, yield and yield attribute datasets from the rice and wheat season 2009 plus the soil mineral N content and volumetric soil moisture content up to top 30 cm soil depths data were used for the evaluation of rice and wheat models independently and in crop rotation. The cultivar coefficients (Table 3) were derived for the rice variety Nukus-2 and the wheat variety Krasnadar-99 from the 2008 experimental data using repeated iterations until a close match was obtained between simulated and measured phenology and yield. The models were evaluated with the experimental data collected in 2009.

Table 3
Cultivar coefficients developed for the rice variety Nukus-2 and wheat variety Krasnador-99.

Genetic parameters	Description	Coefficients
Rice (Nukus-2)		
P1	Juvenile phase coefficient (GDD)	270
P2R	Photoperiodism coefficient (GDD h^{-1})	65
P5	Grain filling coefficient (GDD)	300
P20	Critical photoperiod (h)	12
G1	Spikelet number coefficient	52
G2	Single grain weight (g)	0.0250
G3	Tilllering coefficient	0.75
G4	Temperature tolerance coefficient	0.75
Wheat (Krasnador-99)		
P1V	Vernalization coefficient	5
P1D	Photoperiodism coefficient (GDD h^{-1})	66
P5	Grain filling duration coefficient (GDD)	600
G1	Kernel number coefficient	20.5
G2	Kernel weight coefficient	40
G3	Spike number coefficient	1.2
PHINT	Phyllochron interval	100

2.7. Model performance statistics

The model findings were assessed based on the mean, ratio between simulated and measured, standard deviation, R^2, root mean square value (RMSE) and *d*-stat (*d*) for phenology, periodic biomass partitioning, yield and yield attributes. It was assumed that the model reproduced experimental data best when the ratio between simulated and measured is close to 1, and R^2 and *d*-stat also close to 1 (Timsina and Humphreys, 2006; Yang et al., 2014).

$$\mathrm{RMSE} = \left(\frac{1}{n}\sum (Y_i - X_i)^2\right) 0.5$$

$$d = 1 - \frac{\sum_{i=1}^{n}(Y_i - X_i)^2}{\sum_{i=1}^{n}\left(|Y_i'| - |X_i'|\right)^2}$$

where Y_i and X_i are simulated and measured values, respectively, X_i is the mean of all measured values, and *n* is the number of measurements.

2.8. Crop rotation/sequence simulation

To explore the impact of water saving irrigation and CA-practices in a rice–wheat rotation on grain yield, nitrogen and SOC dynamics and the soil water balance, the model was run for a 39-year rice–wheat rotation from 1971 till 2010. The current recommended fertilizer doses, i.e., 250:120:80 kg N:P_2O_5:K_2O ha^{-1} for rice and 233:140:70 kg N:P_2O_5:K_2O ha^{-1} for wheat were used. For the dynamic simulation of SOC and N the CENTURY (Parton) option of CSM was selected for all treatments and for both crops and irrigation methods (Gijsman et al., 2002). The CENTURY model was initialized by providing estimates of the stable SOC (C; (SOM3 fraction) pool (g[C]/100 g[soil]) based on the historical field data using the methodology defined by Porter et al. (2010) as:

$$\text{Stable}\quad C = 0.015 \times (\text{Clay} + \text{Silt}) + 0.069$$

where stable C is the stable organic C (SOM3), clay is the soil clay content, and silt is the soil silt content. Once the stable C (SOM3) was estimated, the fraction of SOM1 and SOM2 were assumed to be 5% and 95% of the remaining non-SOM3 amount, respectively.

Given that the current version of DSSAT Version 4.6 does not simulate relay cropping (17 days overlapping with rice harvesting, where wheat was seeded 17 days prior to rice harvest), during long-term scenario analysis, it was assumed that the wheat was seeded the day following the rice harvest. Also, as the model automatically drill the seed 2 cm below soil surface; in the simulation of both crops this default was taken even though the Indian Zero Tillage planter does seed below 2 cm. Thus, the simulation result here is for the double zero tillage for both rice and wheat in treatments of DSR-AWD (Treatment No. 2 to 7; Table 1) and conventional tillage rice-zero tillage wheat for the treatments of WSRF-R0-FI and WSRF-R0-AWD. In the bed treatments, with 67 cm width beds (37 cm wide at the top, 30 cm wide furrows and 15 cm height), 2 rows of both crops were drill-seeded and furrow-irrigated. In all flat treatments, both crops were seeded at a row distance of 20 cm. The three residue levels in both crops were obtained by (i) a 95% harvest of the by-products (R0), (ii) 50% harvest of the total by-products (R50), and (iii) 20% harvest of the total by-products (R100). Because wheat total aboveground biomass accumulation did not differ significantly among treatments, the measured and simulated result of only three treatments, viz., WSRF-R0-FI, DSR-R50-AWD and DSR-R100-AWD are presented hereafter. Three more simulations resulting from the combination of different establishment and N application methods were used for sensitivity analyses (Treatment No. 9, 10 and 11; Table 1). The results of these scenarios were compared for grain yield, amount of irrigation water applied, drainage and runoff, N uptake, N leached, N mineralized, N immobilized, and SOC.

3. Results

3.1. Weather conditions

The mean annual temperature for the two study years was 13.4 °C with a minimum in January/February (−7 °C) and a maximum in June/July (40 °C). The average yearly frost-free period was 205 days (Fig. 1).

3.2. Model parameterization

3.2.1. Growth, development and yield

3.2.1.1. Rice. Similar to the measured values, the simulated results showed that at all growth stages, water-seeded flood irrigated rice (WSRF-R0-FI) had consistently the highest biomass accumulation followed by the R0-AWD treatments of DSR (Fig. 2). The simulated results showed furthermore a higher biomass accumulation under R0 compared to R100. The lowest biomass accumulation occurred with the retention of the highest amount of residue retention (R100). No significant difference in biomass accumulation was found between the DSRF and DSRB crop establishment methods. The leaf area index followed a similar trend as the total

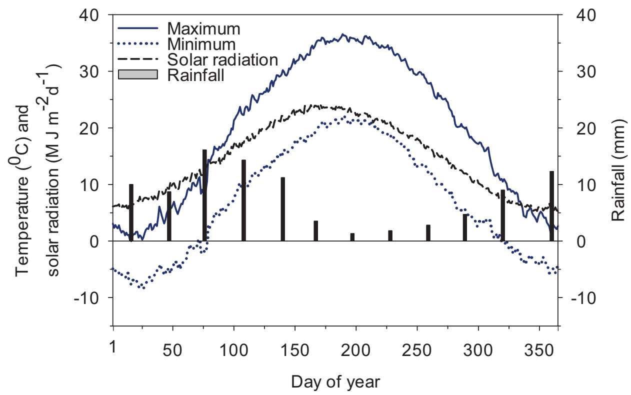

Fig. 1. Daily average maximum and minimum temperature (°C), monthly total rainfall (mm) and solar radiation (MJ m^{-2} d^{-1}) from 1971 to 2010.

aboveground biomass accumulation. When compared with the observed data, the model satisfactorily simulated LAI, which was lower under AWD irrigation than under flood irrigation as well as lower under higher levels of residue retention at all growth stages (Fig. 2).

3.2.1.2. Wheat. Measured and simulated values were similar among all seven treatments. There were no significant differences ($p > 0.05$) among establishment methods and residue retention levels (Fig. 2). Similar results were obtained for LAI. The goodness-of-fit of the parameterization results for rice and wheat (Table 4) showed that the simulated outcome were close to the measured data. This illustrates that the CERES-Rice and CERES-Wheat models of DSSAT are capable to simulate rice and wheat phenology, yield and yield attributes of both crops under water saving irrigation combined with CA-practices. The simulated results for both crops showed a difference of less than 3 days for anthesis and physiological maturity, a difference of less than 1.5 t ha^{-1} for total aboveground biomass accumulation and less than 0.2 t ha^{-1} for grain yield (Table 4).

3.3. Model evaluation

3.3.1. Rice

At all growth states, WSR-R0-FI had highest ($p < 0.01$) measured and simulated biomass accumulation followed by the R0-AWD treatments of DSR (Fig. 3). Measured and simulated results showed that R0 followed by R50 of DSR had the highest biomass accumulation in contrast to the R100 treatments, which had the lowest biomass production.

3.3.2. Wheat

The measured and simulated results of the grain yield of wheat among all treatments were not different ($p > 0.05$) among establishment methods and residue retention levels (Fig. 4). Similar to the findings with the parameterization data sets, the goodness-of-fit of the evaluation results for rice and wheat (Table 5) indicated that the measured and simulated parameters matched well and hence the CERES-Rice and CERES-Wheat model of DSSAT can accurately predict rice and wheat phenology, yield and yield attributes of the irrigated drylands of Central Asia. For rice, the simulated results show a difference of 2 days for anthesis and 4 days for physiological maturity, whilst total aboveground biomass accumulation differed between 10.7 and 12.2, i.e., by 1.5 t ha^{-1}, and grain yield by 0.6 t ha^{-1}. Similarly, for wheat, compared to the measured results, the simulated results showed the days to anthesis differed by 5 days, there was no difference in days to physiological maturity,

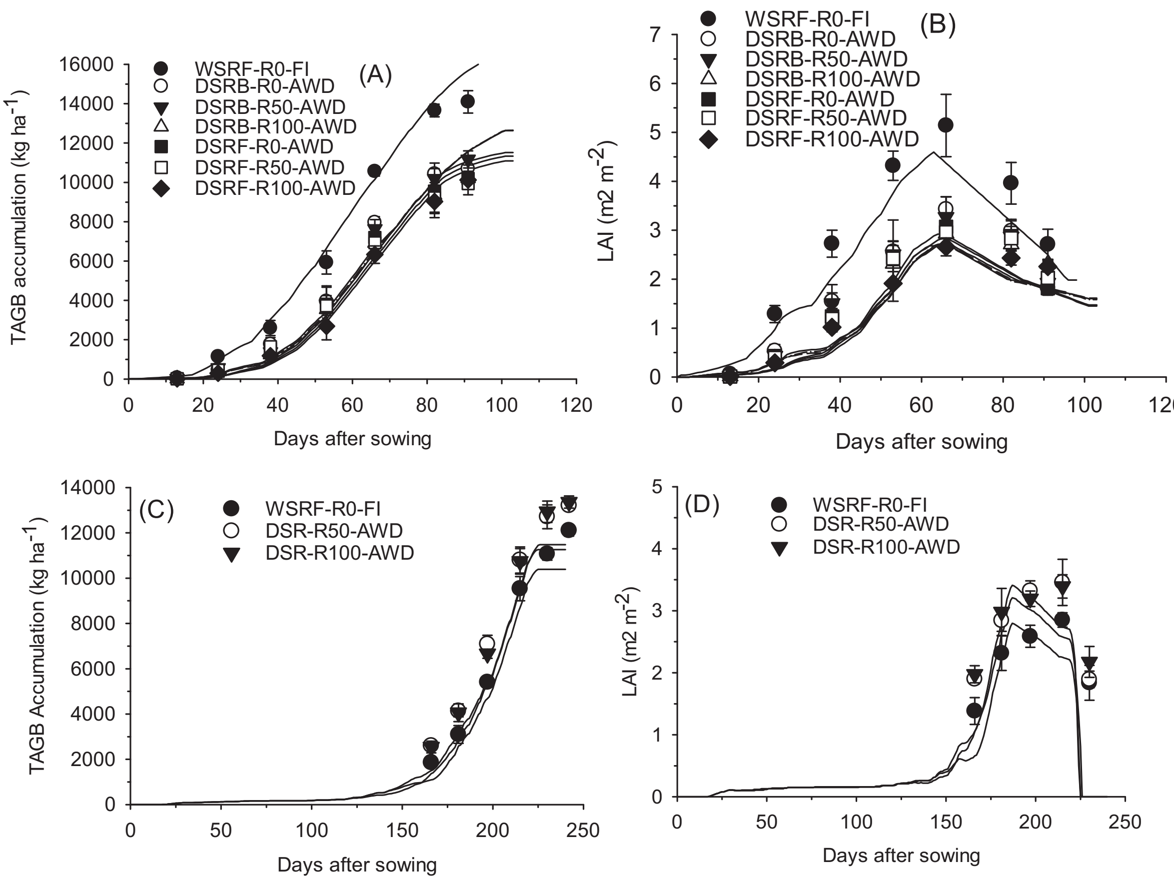

Fig. 2. Measured and simulated (A) total aboveground biomass (TAGB; kg ha^{-1})) accumulation of rice; (B) leaf area index of rice; (C) total aboveground biomass accumulation of wheat, and (D) leaf area index of wheat grown under different water saving irrigation combined with conservation agriculture practices at the experimental site in Urgench, Uzbekistan, 2008. WSRF-R0-FI: water seeded rice on flat, no residue retention, conventional tillage with continuous flood irrigation, DSRB-R0-AWD: dry seeded rice on bed, no residue retention, alternate wet and dry irrigation, DSRB-R50-AWD: dry seeded rice on bed, 50% residue retention, alternate wet and dry irrigation, DSRB-R100-AWD: dry seeded rice on bed, 100% residue retention, alternate wet and dry irrigation, DSRF-R0-AWD: dry seeded rice on flat, no residue retention, alternate wet and dry irrigation, DSRF-R50-AWD: dry seeded rice on flat, 50% residue retention, alternate wet and dry irrigation, DSRF-R100-AWD: dry seeded rice on flat, 100% residue retention, alternate wet and dry irrigation of rice, DSR-R50-AWD: dry seeded rice, 50% residue retention, alternate wet and dry irrigation, DSR-R100-AWD: dry seeded rice, 100% residue retention, alternate wet and dry irrigation. Lines are simulated, dots are measured values.

Table 4
Comparison of CERES-Rice and CERES-Wheat simulation findings for growth, phenology and yield with the observations for the 2008 growing season.

Parameters	Mean		Ratio	Standard deviation		R^2	RMSE	*d*-Stat	Observations
	Measured	Simulated		Measured	Simulated				
I. Rice									
Development and final harvest parameters									
Anthesis (days)	68	67	0.98	3	1	0.77	3	0.70	7
Maturity (days)	103	102	0.99	3	2	0.92	2	0.88	7
TAGB accumulation (kg ha^{-1})	10,919	12,580	1.15	1354	1599	0.66	1907	0.73	7
Grain yield (kg ha^{-1})	4916	5186	1.06	747	729	0.95	320	0.95	7
Growth parameters									
Leaf weight (kg ha^{-1})	1236	1247	1.92	811	739	0.97	220	0.98	48
Stem weight (kg ha^{-1})	3014	2485	0.84	2121	1707	0.93	873	0.94	48
Grain weight (kg ha^{-1})	3199	4192	1.62	1558	1063	0.95	1146	0.82	20
TAGB accumulation (kg ha^{-1})	5560	6004	1.25	4342	4745	0.99	908	0.99	48
Leaf area index	1.42	1.81	1.12	0.45	0.39	0.86	0.42	0.90	41
Leaf *N* (%)	2.64	2.05	0.82	1.10	0.94	0.49	1.02	0.78	34
Tiller number (No. m^{-2})	373	369	1.02	97	70	0.28	182	0.51	48
II. Wheat									
Development and final harvest parameters									
Anthesis day	200	197	0.98	1.3	0.9	0.76	4	0.34	7
Maturity day	230	229	1.00	0.70	0.80	0.90	1.46	0.37	7
TAGB accumulation (kg ha^{-1})	11,048	10,233	0.93	687	727	0.87	1119	0.59	7
Grain yield (kg ha^{-1})	5366	5329	1.00	386	262	0.89	399	0.60	7
Growth parameters									
Leaf weight (kg ha^{-1})	1173	1140	0.98	345	531	0.59	459	0.73	28
Stem weight (kg ha^{-1})	3174	2632	0.74	1847	1823	0.98	641	0.97	28
TAGB weight (kg ha^{-1})	4562	5054	1.04	2813	3468	0.97	1180	0.96	28
Leaf area index	2.54	2.37	0.89	0.67	1.11	0.86	0.65	0.86	28

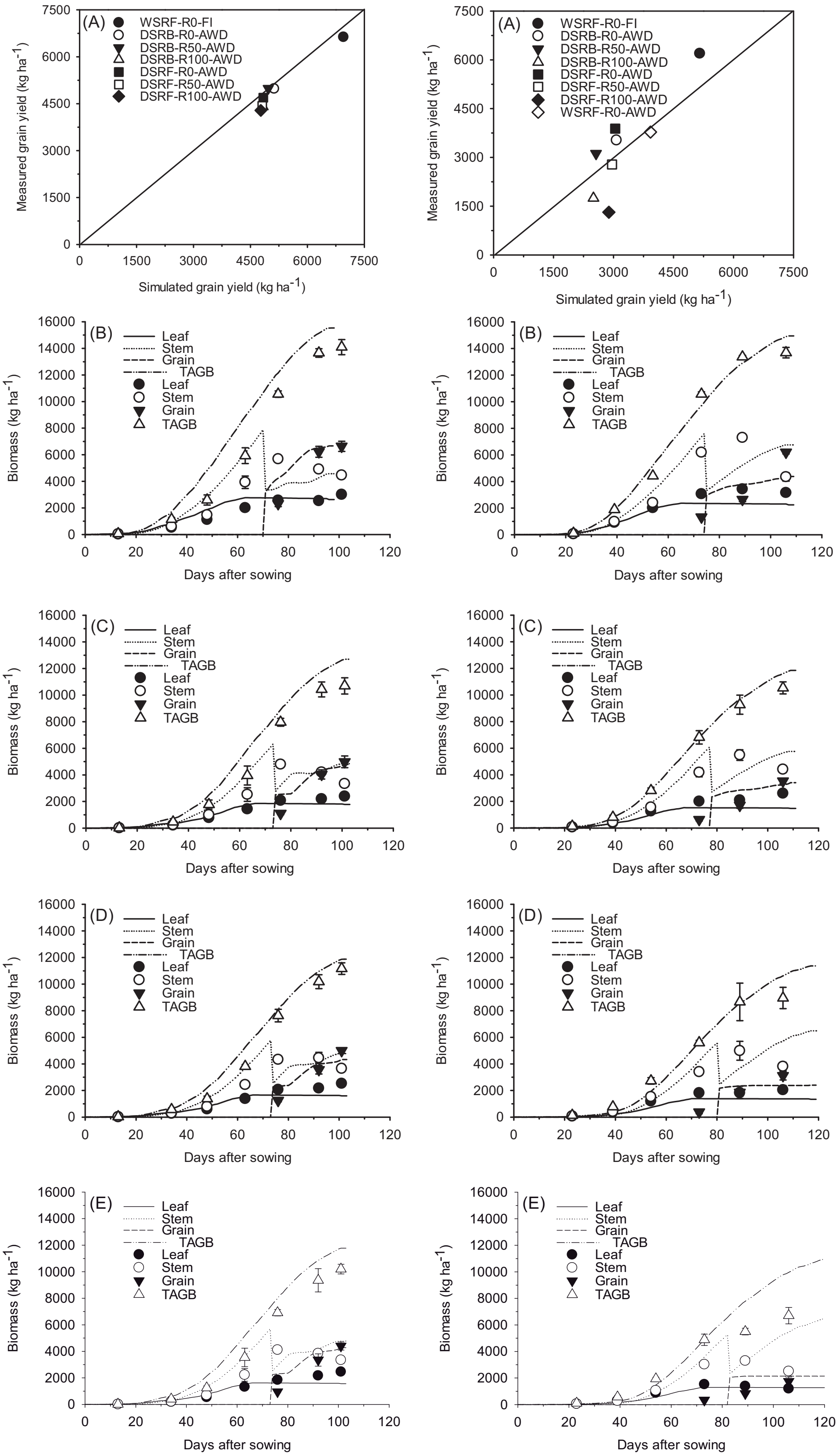

Fig. 3. (left hand side figures A through E) Simulated and measured grain yield of rice and biomass dynamics (kg ha^{-1}) based on the parameterization data of 2008 and (right hand side figures A through E) findings of these based on the evaluation datasets from 2009 from Urgench, Uzbekistan. (A) Grain yield of rice at harvest; (B) biomass dynamics in water seeded rice on flat, no residue retention, conventional tillage with continuous flood irrigation (WSRF-R0-FI); (C) biomass dynamics in dry seeded rice on bed, no residue retention, alternate wet and dry irrigation (DSRB-R0-AWD); (D) biomass dynamics in dry seeded rice on bed, 50% residue retention, alternate wet and dry irrigation (DSRB-R50-AWD); (E) biomass dynamics in dry seeded rice on bed, 100% residue retention, alternate wet and dry irrigation (DSRB-R100-AWD). Details on the legend see Table 1.

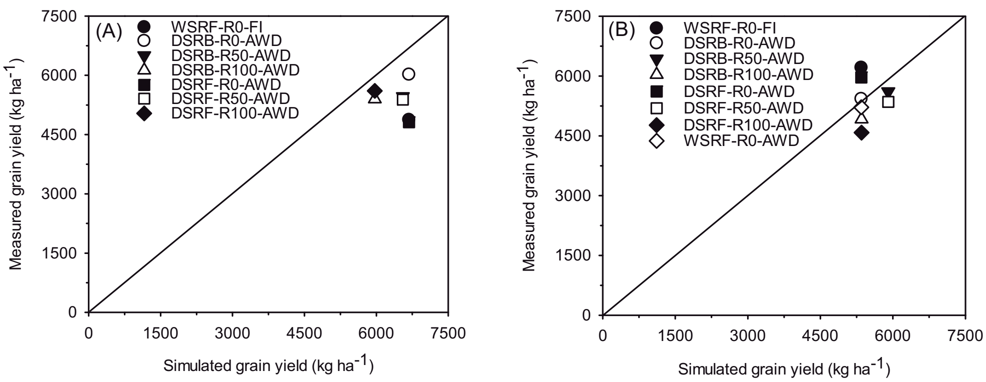

Fig. 4. Measured and simulated (A) grain yield of wheat (kg ha^{-1}) following parameterization with 2008 data and (B) validation with 2009 data Urgench, Uzbekistan. Details on the legend see Table 1.

total aboveground biomass accumulation differed by 0.5 t ha^{-1}, and grain yield by 0.4 t ha^{-1} (Table 5).

3.4. Soil mineral nitrogen in rice–wheat system

In rice, the measured and simulated results showed that NH_4–N is the dominant form of N in WSRF-R0-FI and NO_3–N in the DSR (Fig. 5). However, during wheat cultivation, NO_3–N remained the most dominant form of N rather than NH_4–N and at all growth stages the availability of NO_3–N was higher ($p < 0.05$) in the WSRF-R0-FI than in the DSR treatments. Also, during the wheat growing season, both the measured and simulated results showed that NH_4–N was not different between WSRF-R0-FI and DSR treatments.

3.5. Volumetric soil moisture content in rice–wheat system

No difference in volumetric soil moisture content between residue retention and removal occurred during rice cropping in both years. However, during wheat cultivation, volumetric moisture content was higher by 1–2% in R50 and by 3–4% in R100 treatments (data not shown). The RMSE value in both crops during all growing period indicated that the model was capable of satisfactory simulating the volumetric soil moisture content over time (Fig. 6).

3.6. Simulating the long-term impact of water saving irrigation and conservation agriculture practices in rice–wheat systems

3.6.1. Grain yield and soil organic carbon

The results of the multi-year simulation supported the two-year empirical findings confirming that yields of rice (5.6 t ha^{-1}) and wheat (6.8 t ha^{-1}) are consistent and highest under WSRF-R0-FI compared to all water saving irrigation and CA-practices. Inter-annual variability of AWD irrigated rice yield was higher than WSRF-R0-FI. However, the simulation results showed a trend of increasing grain yields for both crops and for all CA-practices (Fig. 7, Table 6). Whereas the positive effect of zero-tillage and residue retention on rice grain yields became visible after 13 years only, wheat yields increased virtually from the first season and for all remaining seasons. After 39 simulation years the impact of CA-practices, compared to the base year 1971, was evidenced in an increase in rice yield ranging from 32 to 64% and in wheat yield ranging from 3 to 15% for the DSR-AWD treatments. During the same period, yield increased only by 12 and 2% in rice and 14 and 5% in wheat for WSRF-R0-FI and WSRF-R0-AWD, respectively. Averaged across the residue levels, the yield of rice was higher under zero tillage flat (4.0 t ha^{-1}) than on beds (3.7 t ha^{-1}), while wheat yield was at par (6.0 t ha^{-1}) under both establishment methods. The lowest yield of rice (3.4 t ha^{-1}) occurred for the WSRF-R0-AWD and

Table 5
Evaluation results of CERES-Rice and CERES-Wheat simulation findings for growth, phenology and yield with the observation for the 2009 growing season.

Parameters	Mean		Ratio	Standard deviation		R^2	RMSE	d-Stat	Observations
	Measured	Simulated		Measured	Simulated				
I. Rice									
Phenological and final harvest parameters									
Anthesis (days)	72	70	0.97	4	3	0.75	3	0.80	8
Maturity (days)	115	119	1.03	4	7	0.83	5	0.80	8
TAGB accumulation (kg ha^{-1})	10,766	12,245	1.32	1713	1152	0.85	3010	0.76	8
Grain yield (kg ha^{-1})	3293	3263	0.99	1400	743	0.88	830	0.85	8
Grain N content (kg ha^{-1})	51	50	0.99	18	18	0.92	5	0.98	8
TAGB N content (kg ha^{-1})	96	115	1.23	28	30	0.87	22	0.87	8
Growth parameters									
Leaf weight (kg ha^{-1})	1227	1021	0.82	738	632	0.98	261	0.96	48
Stem weight (kg ha^{-1})	3062	2873	0.88	2444	2298	0.87	946	0.95	48
Grain weight (kg ha^{-1})	1836	1840	0.93	1117	1306	0.70	856	0.85	24
TAGB weight (kg ha^{-1})	5199	5225	0.91	4071	4377	0.95	1029	0.98	48
Leaf area index	1.71	1.63	0.93	0.54	0.64	0.86	0.30	0.93	40
II. Wheat									
Phenological and final harvest parameters									
Anthesis (days)	186	191	1.03	2	3	0.76	5	0.75	8
Maturity (days)	225	225	1.00	3	4	0.73	2	0.73	8
TAGB weight (kg ha^{-1})	12,966	12,417	0.96	770	588	0.72	1167	0.72	8
Grain yield (kg ha^{-1})	5411	5834	1.09	495	389	0.75	877	0.73	8
Tiller number (No. m^{-2}	580	608	1.05	33	44	0.60	62	0.59	8

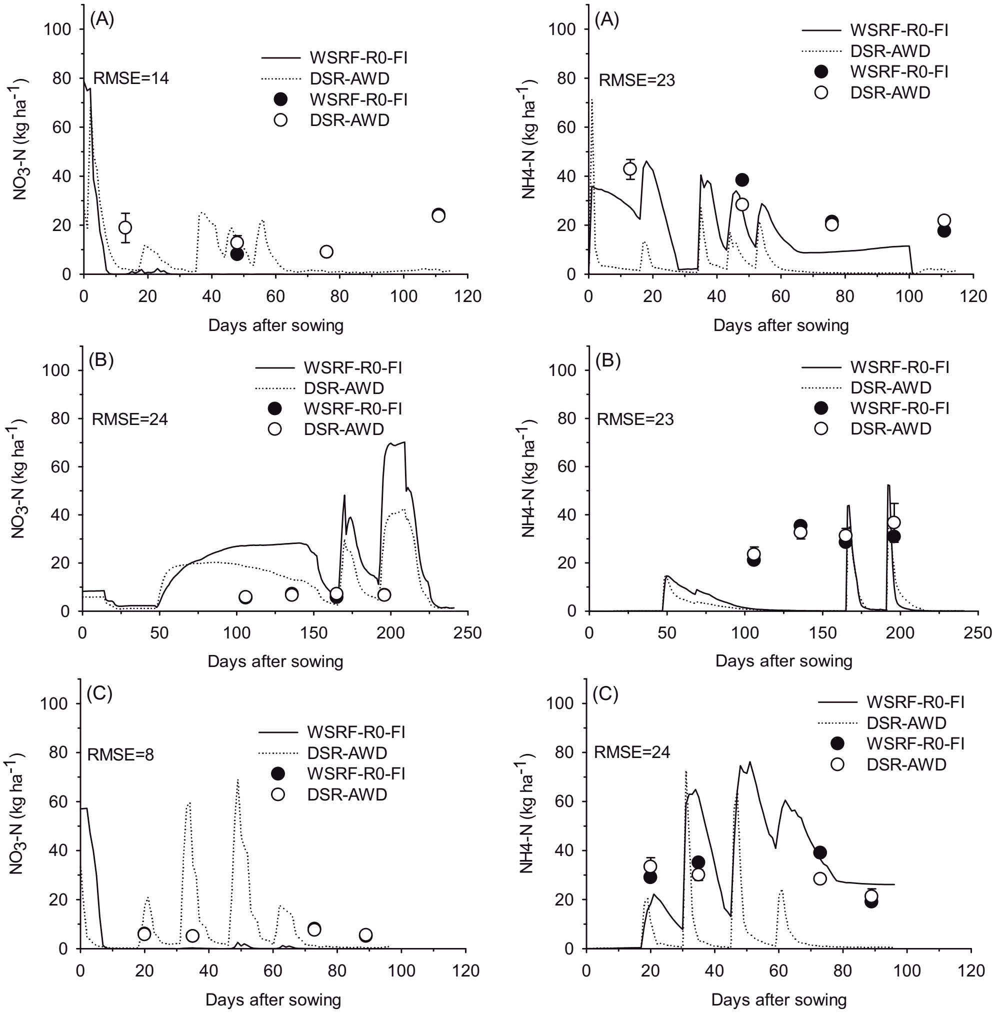

Fig. 5. (left) Simulated and measured nitrate (NO_3–N) and (right) ammonium (NH_4–N) dynamics in the top 20 cm of soil during (A) rice season 2008, (B) wheat 2008 and (C) rice 2009 under conventional method of crop establishment (WSRF-R0-FI) and alternative dry-seeded crop establishment method with alternate wet and dry irrigation (DSR-AWD) Urgench, Uzbekistan. The lines are simulated and the points with error bars are the measured values.

Table 6
Simulated mean grain yield, components of the water balance, and soil organic carbon (SOC) in rice–wheat rotation, 1971–2010. Details on the legend see Table 1.

SN	Simulation	Grain yield (kg ha^{-1})		Water applied (mm)		Water at the beginning of the growing season (mm)		Evapotranspiration (mm)		Drainage and runoff (mm)		Water at the end of the growing season (mm)		SOC (kg ha^{-1})	
		Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat
1	WSRF-R0-FI	5617	6859	5435	675	153	354	551	451	4685	385	353	193	44,755	43,740
2	DSRB-R0-AWD	3624	5658	1775	674	182	189	537	411	1231	268	190	185	36,040	35,933
3	DSRB-R50-AWD	3714	6107	1776	677	189	186	397	358	1383	312	186	193	46,998	47,192
4	DSRB-R100-AWD	3890	6298	1776	674	195	192	352	343	1426	326	192	197	54,248	54,706
5	DSRF-R0-AWD	3817	5590	2092	674	183	191	535	406	1548	273	191	186	36,079	35,999
6	DSRF-R50-AWD	3958	6119	2093	677	190	189	398	357	1696	316	189	193	47,513	47,738
7	DSRF-R100-AWD	4113	6307	2092	674	195	195	354	345	1737	328	195	197	55,022	55,521
8	WSRF-R0-AWD	3429	5656	2163	675	180	207	553	431	1582	269	208	182	34,057	33,965
9	WSRF-R0-AWD-Puddled	5632	6489	2161	675	201	339	547	447	1476	382	339	185	44,609	43,964
10	CT-DSR-AWD	3495	5624	2174	676	183	193	566	412	1598	271	193	185	34,800	34,499
11	CT-DSR-AWD-DPUS	3982	5754	2174	675	182	195	560	414	1600	271	195	185	38,429	38,075
	p value	<0.001	<0.001	<0.001	ns	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	LSD (0.05)	171	177	48	–	3.5	4.8	11	8.0	48	4.6	5.0	1.7	1730	1603
	Grand mean	4116	6044	2339	675	185	221	487	398	1816	309	221	189	42,939	42,827

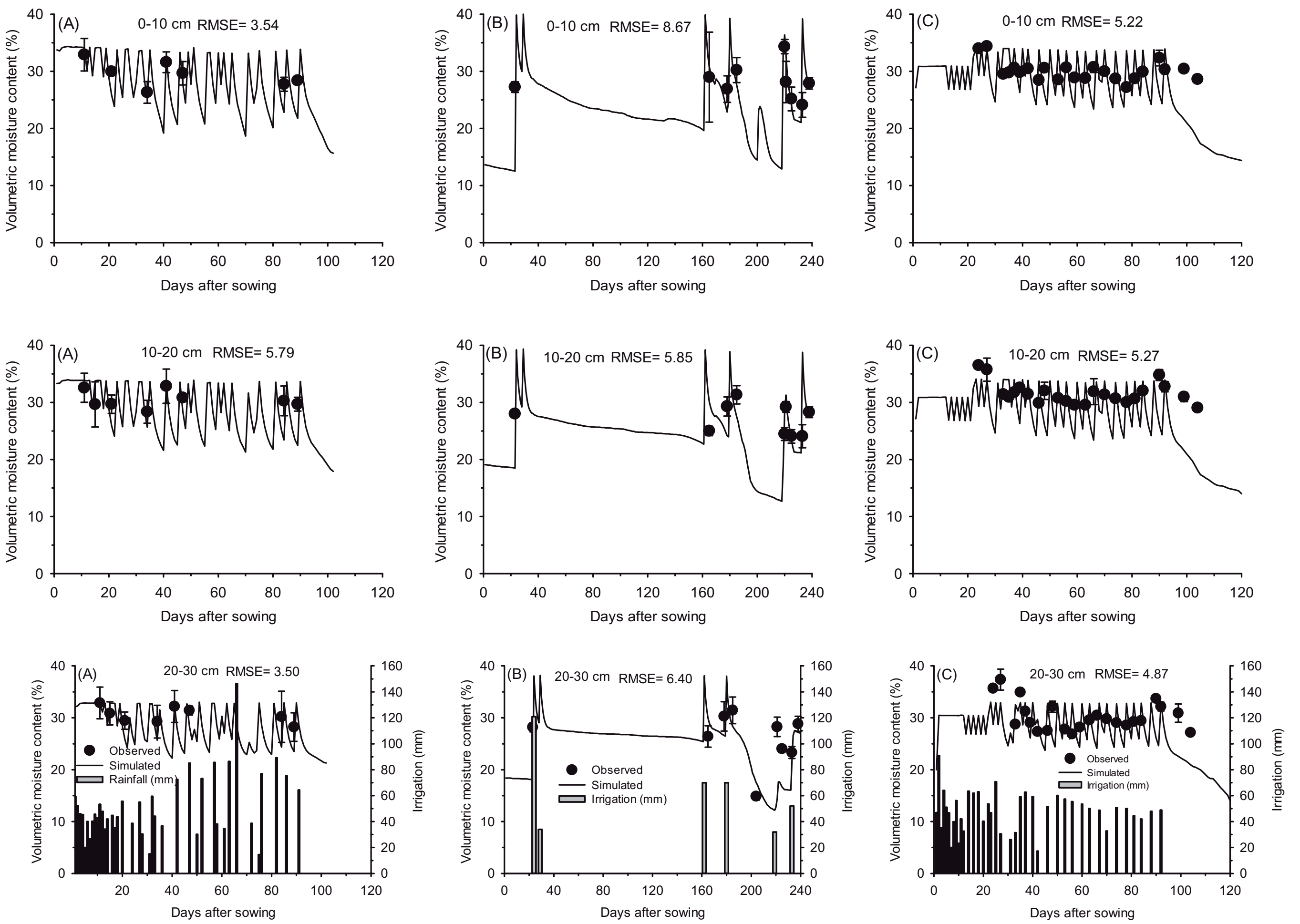

Fig. 6. Soil volumetric moisture dynamics in dry seeded rice in flat, no residue retention, alternate wet and dry irrigation (DSRF-R0-AWD) treatment in the top 0–10, 10–20 and 20–30 cm soil depths in (A) rice 2008, (B) wheat 2008 and (C) rice 2009 in Urgench, Uzbekistan. The lines are simulated and the points with error bars are the measured values.

for wheat under the no-tillage-R0 treatments of bed and flat plots. For both crops, residue retention had a noticeable impact on grain yield, where R100 increased yields of rice by 8% and for wheat by 12% compared to R0. For both crops, the highest simulated yields occurred for R100 followed by R50 and R0 for both bed and flat plots (Fig. 7, Table 6).

Among the three simulations used for the sensitivity analyses (Table 1), an equivalent grain yield of rice (5.6 t ha^{-1}) as obtained under WSRF-R0-AWD-Puddled compared with WSRF-R0-FI condition, resulted in more than 60% water saving potential while maintaining high yield potential. The simulations showed furthermore that CT-DSR-AWD rice followed by zero-tillage wheat cannot perform better than no-till DSR-AWD followed by zero tillage wheat. However, deeply placed urea super granules (CT-DSR-AWD-DPUS) can increase rice yield by 0.5 t ha^{-1} under CT-DSR-AWD. Also, the simulated results showed an increase of SOC over time for all simulations with the highest rate of increment for R100 followed by R50, WSRF-R0-RI, R0, and the lowest for the WSRF-R0-AWD treatment (Fig. 8, Table 6).

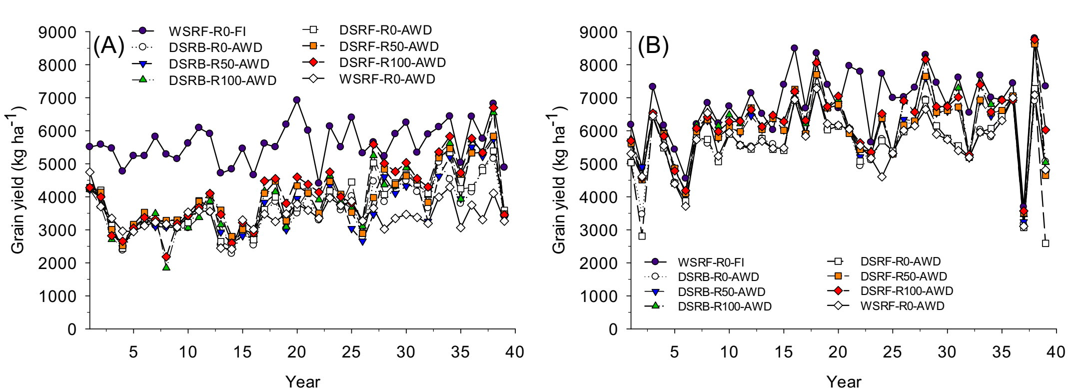

Fig. 7. Simulated grain yield of rice (A) and zero tillage wheat (B) under different water saving irrigation, crop establishment method and residue retention, 1971–2010. Details on the legend see Table 1.

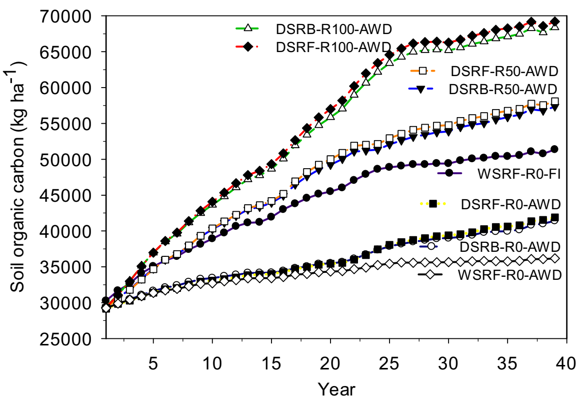

Fig. 8. Simulated soil organic carbon (kg ha^{-1}) dynamics in rice–wheat–fallow system, 1971–2010. Details on the legend see Table 1.

3.7. Soil water balance

The irrigation applications for the DSR treatments were three times lesser compared to the WSRF-R0-FI treatment (Fig. 9, Table 6). Yet, the simulation results showed more than 80% of water loss as seepage and percolation from all treatments but were highest for the WSRF-R0-FI treatment. Hence, during rice cultivation, the implementation of water saving irrigation could improve the water use efficiency already by reducing drainage and runoff losses (Fig. 9, Table 6). For both crops, the components of the water balance were significantly different between the treatments. The CA-based practices contributed substantially to the reduction of soil evaporation losses. During the entire rice growing season, total and extractable soil water were consistently higher for the WSRF-R0-FI treatments than for the CA-based practices. None of the AWD irrigation treatments showed water stress during any of the growth stages of rice for all years (data not shown). Given the amount of irrigation water (Table 6) actually applied, water stress was low to absent in all treatments in wheat.

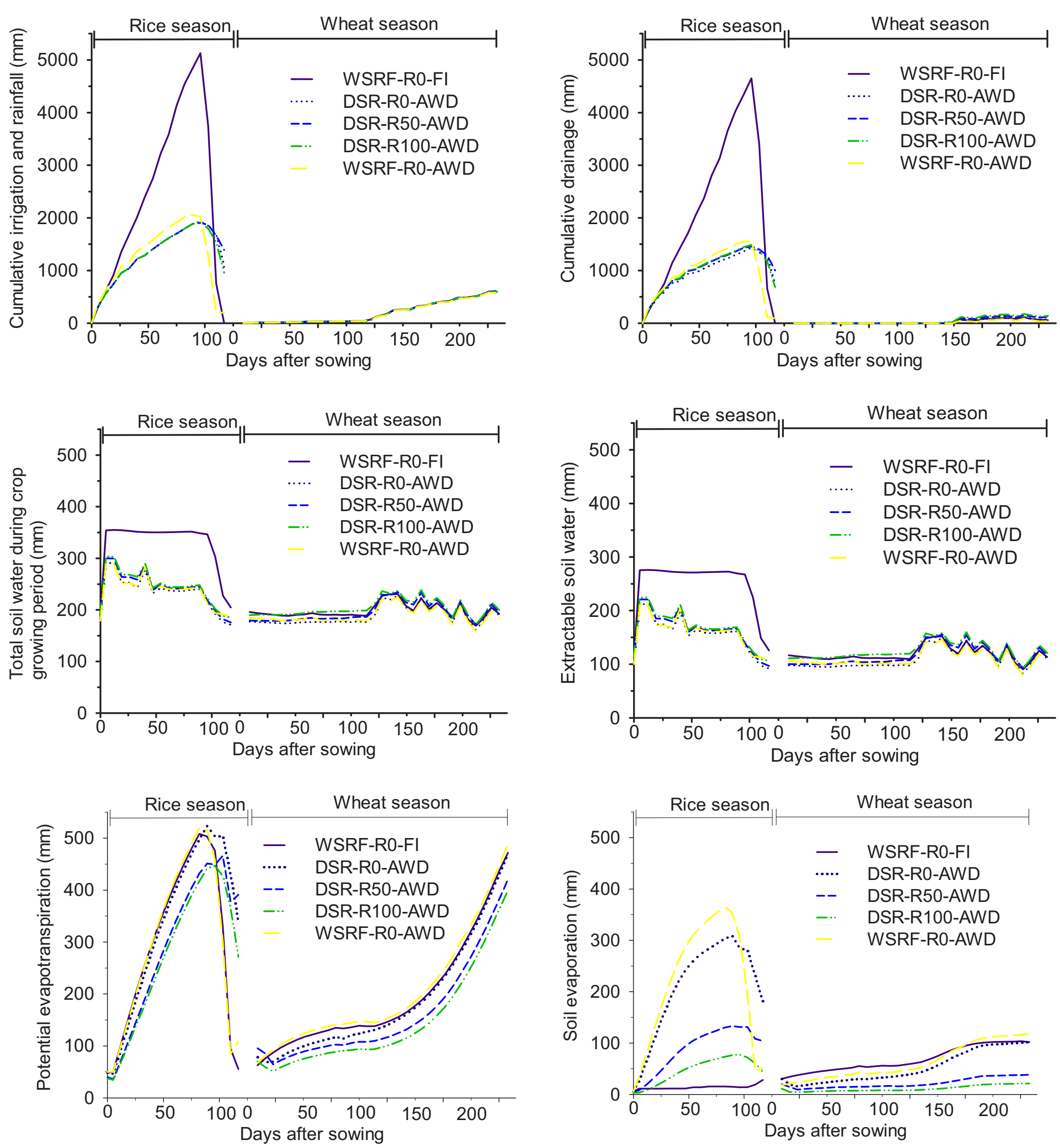

Fig. 9. Simulated daily components of water balance in rice–wheat system, 1971–2010. Between similar residues level of DSR treatments values are averaged across bed and flat treatments. WSRF-R0-FI: water seeded rice in flat, no residue retention, conventional tillage with continuous flood irrigation, DSR-R0-AWD: dry seeded rice, no residue retention, alternate wet and dry irrigation, DSR-R50-AWD: dry seeded rice, 50% residue retention, alternate wet and dry irrigation, DSR-R100-AWD: dry seeded rice, 100% residue retention, alternate wet and dry irrigation, and WSRF-R0-AWD: water seeded rice in flat, no residue retention, conventional tillage with alternate wet and dry irrigation.

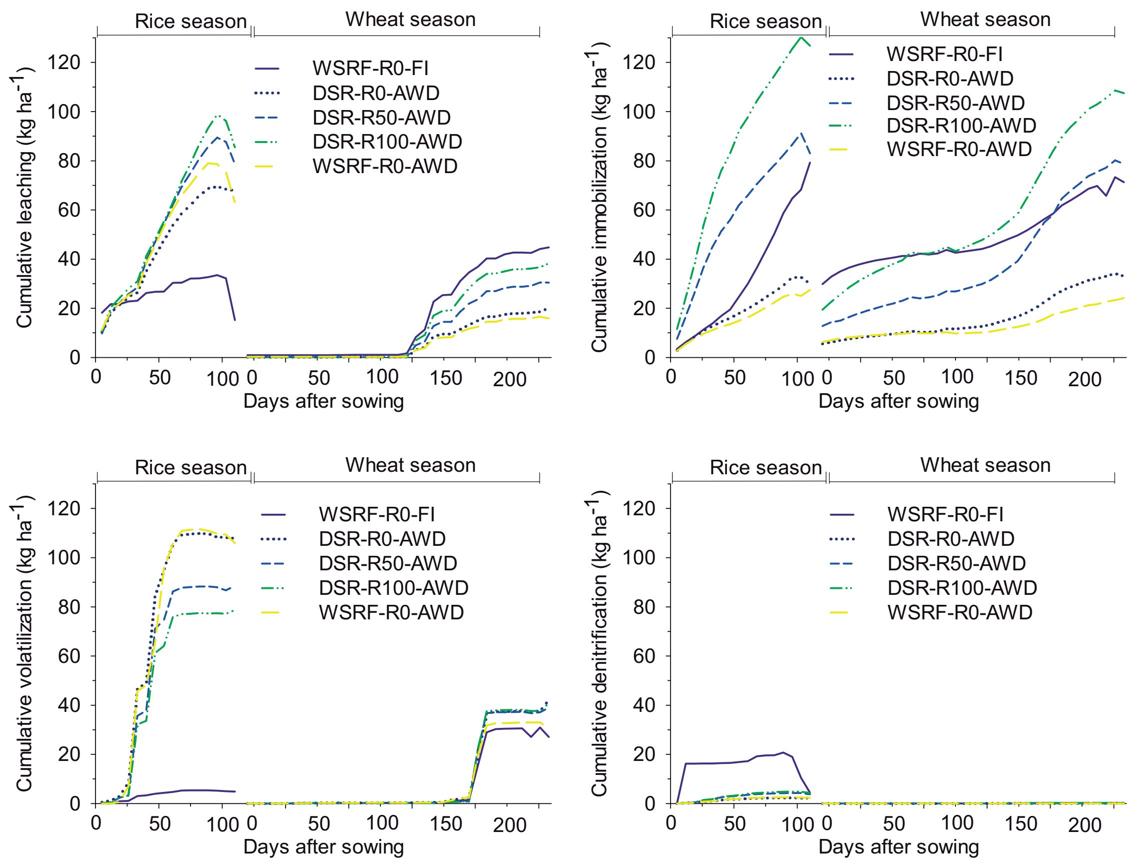

Fig. 10. Simulated daily average N losses (kg ha^{-1}) through different pathways during rice and wheat growing seasons as affected by different irrigation method and residue level (values are average of 39 years of rice–wheat simulation) at 0–80 cm soil depth. Details on the legend see Fig. 9.

3.8. Nitrogen dynamics in rice–wheat system

During the rice growing season, the long-term simulation results identified leaching, immobilization and volatilization as the major sources and pathways of N loss (Fig. 10, Table 7). Furthermore, total N losses were affected both by the irrigation method and residue levels and was highest (312 kg N ha^{-1}) for the R100 treatments of DSR followed by R50, WSRF-R0-AWD, and R0 and lowest (125 kg ha^{-1}) for WSRF-R0-FI (Fig. 10, Table 7). Ammonia volatilization loss was highest for the R0 treatments of DSR and the denitrification-driven N loss was highest ($p < 0.05$; 20 kg N ha^{-1}) for the WSRF-R0-AWD-Puddled followed by WSRF-R0-FI. Unlike water stress, in the simulation results of all treatments of AWD irrigation, N stress often appeared at many growth stages of rice in all years (data not shown).

For wheat cultivation, total N loss was half that of rice. During the wheat growing season, major N losses occurred due to immobilization followed by volatilization and leaching (Fig. 10; Table 7). Leaching and immobilization losses were mostly affected by residue levels evidenced by highest losses with the highest amounts of residue retention. Unlike in rice, N stress was less frequent and inconsistent in wheat.

4. Discussion

4.1. Performance of the simulation models

The parameterization of both the rice and wheat models was based on a comparison of simulated with measured data for phenological development (±1–3 days), grain yield (RMSE < 400 kg ha^{-1}, R^2 of >0.8, *d*-sat of >0.9), other model assessment values for various growth parameters, e.g., leaf area index, leaf N content, periodic and at final harvest (Table 4; Figs. 2 and 3). Similarly, there was a reasonable level of agreement between the simulated and measured parameters for the independent evaluation dataset, (e.g., phenological development RMSE ± 2–5 days, grain yield at harvest <900 kg ha^{-1}, R^2 of 0.8, *d*-sat of >0.8). The statistical values for several of the growth, leaf area index, and other periodic variables yield attributes at harvest (Table 5) indicated that model evaluation was also satisfactory (Figs. 3 and 4). Furthermore, the evaluation results of simulated and periodic measured volumetric moisture content and NH_4–N and NO_3–N dynamics indicate a reasonable RMSE. Thus, the goodness of fit between simulated and measured suggests that both models are able to accurately simulate phenological development, grain yield, N dynamics, and water balance of rice and wheat independently and in rotation under water saving irrigation combined with CA-practices for semi-arid climate conditions. The model parameterization and evaluation results are also comparable in terms of accuracy with previous studies (Liu et al., 2013; Singh et al., 2008a; Timsina et al., 2008).

Simulation result showed that, out of the 39 years simulated, in the 5 cold years (Devkota et al., 2013c), viz., 1974, 1985, 1989, 1994 and 2009, grain filling in rice was reduced. Hence, the increment in panicle weight between flowering and maturity was low (Fig. 3E, right sided). Another reason could be that up to panicle initiation (until rice attains certain height), the shading effect of the standing residue of the pre-rice crop (wheat) had impaired initial rice growth. Under residue retention, the slightly lower soil temperature (Devkota et al., 2013c) could have delayed phenological development and grain filling.

Table 7
Simulated N losses (kg ha^{-1}) through soil measuring 80 cm deep through different pathways during the rice and wheat growing seasons as affected by different irrigation and establishment methods and residue level. Based on 1971-2010 simulations. Details on the legend see Table 1.

SN	Simulation	Nitrogen applied (kg ha^{-1})		Inorganic N in soil at maturity (kg ha^{-1})		N uptake (kg ha^{-1})		N leached (kg ha^{-1})		N immobilized (kg ha^{-1})		NH_3 volatilization (kg ha^{-1})		NO_3 denitrification (kg ha^{-1})		N mineralized (kg ha^{-1})	
		Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat
1	WSRF-R0-FI	250	233	90	31	166	265	34	49	66	70	5	30	20	0.1	107	108
2	DSRB- R0-AWD	250	233	12	16	130	186	73	22	33	32	111	39	2	0.1	78	46
3	DSRB-R50-AWD	250	233	21	16	137	199	90	35	87	77	91	39	4	0.2	151	101
4	DSRB-R100-AWD	250	233	29	19	143	211	98	42	126	106	82	38	5	0.3	203	139
5	DSRF-R0-AWD	250	233	10	17	132	183	75	21	33	34	107	41	2	0.1	79	48
6	DSRF-R50-AWD	250	233	19	17	143	199	93	33	88	80	87	39	4	0.2	156	104
7	DSRF-R100-AWD	250	233	27	19	149	213	104	40	127	112	76	39	5	0.3	208	147
8	WSRF-R0-AWD	250	233	9	16	116	189	83	20	26	24	110	35	3	0.1	62	39
9	WSRF-R0-AWD-puddled	250	233	61	24	167	242	22	42	66	67	12	39	47	0.1	113	106
10	CT-DSR-AWD	250	233	9	18	123	184	83	20	28	28	108	37	3	0.1	69	41
11	CT-DSR-AWD-DPUS	250	233	17	20	144	196	168	30	42	39	0	36	5	0.1	91	63
	p value	–	–	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.01	<0.001	<0.001	<0.001	<0.001
	LSD (0.05)	–	–	2.7	2.8	6.5	6.4	5.6	3.6	6.4	5.3	4.1	5.3	5.1	0.03	9.1	8.3
	Grand mean	250	233	28	19	141	206	84	32	68	61	74	37	8	0.2	123	86

4.2. System yield and soil organic carbon dynamics

The long-term simulated grain yield of rice and wheat showed that the CA-practices can immediately be implemented for wheat (Fig. 7). Despite the inter-annual variability, all treatments are consistently yielding >5 t ha^{-1} grain of wheat under zero tillage conditions, whereas the national average yield of wheat under conventional method is 4.5 t ha^{-1} (FAOSTAT, 2014). However, the simulated result showed that yield penalties can initially be expected under DSR-AWD treatments of rice compared to WSRF-R0-FI (Bhushan et al., 2007; Choudhury et al., 2007). The major reasons for the yield penalty in the AWD treatments could be the N stress. This is consistent with the findings of Sudhir-Yadav et al. (2011) who stated that a safe AWD for DSR is 10 kPa at 15 cm soil depth. However, none of the AWD irrigated treatments showed water stress for the long-term simulations. Except for the WSRF-R0-AWD-Puddled treatment, all other AWD irrigated treatments often showed N stress in all years at different growth stages of the crop. Soil puddling reduced N losses through various pathways (Buresh and De Datta, 1991; Buresh and Haefele, 2010), improved water use efficiency and reduced water demands in rice from 5435 mm to 2161 mm (60% water saving) (Table 6). Also, the very high inter-annual variability in grain yield of rice in DSR treatments compared to WSRF-R0-FI, indicated that weather conditions are seldom favorable in arid and semi-arid regions for DSR-AWD. The simulated results showed furthermore that with the deep placement of urea N, grain yield of rice can be increased by 0.5 t ha^{-1}, while the conventional tillage dry seeded rice with AWD irrigation followed by zero-tillage wheat (CT-DSR-AWD) systems was found to be unproductive. Thus, for immediate water saving but combined with high yield potential, farmers can adopt WSRF-R0-AWD-Puddled or CT-DSR-AWD-DPUS whenever feasible. During initial years, the higher grain and biomass yield in rice under R0 compared to R100 could be due to a N immobilization as often reported by Singh et al. (2015). In rice, the long-term benefits from residue retention started after 13 years only. Yet, from than onwards a continuous build-up of SOC under CA-based practices was seen (Fig. 5; Table 6) as postulated before (Lal, 2015). The increase in SOC over time with non-till and retention of residues would provide more N through mineralization with successive cropping years (Table 7). This finding corresponds to those of Huang et al. (2013) in China and Gupta Choudhury et al. (2014) in India.

4.3. Nitrogen dynamics and water balance

The simulation results underlined the huge effect of water saving on the water balance (Table 6; Fig. 9) and N dynamics (Figs. 5 and 10; Table 7) for both the rice and wheat crop growing seasons. For all treatments of AWD irrigation, the overall moderate to high N stress (except WSRF-R0-AWD-Puddled and to a lower extent in CT-DSR-AWD-DPUS) at different growth stages and in the absence of an overall water stress indicated that the present water application rates can be reduced to at least the amount applied to the AWD treatments. The findings showed also that compared to conventional WSRF-R0-FI, DSR-AWD irrigation resulted in more than 60% water saving, but at the expense of large N losses, which in turn reduced grain yields. In arid dry lands, high temperatures combined with intensive soil tillage and over irrigation enhances the mineralization of soil N (Sainju et al., 2009), which increases N losses through leaching (Kienzler et al., 2012) and denitrification (Scheer et al., 2008) in the region. Under these conditions the development of integrated resource management strategies is needed (Gupta et al., 2009). However, the simulation results showed that even higher N losses under alternative resource conservation, i.e., DSR-AWD treatments during both cropping seasons (Fig. 10) at least compared to the flooded crop (WSRF-R0-FI) which had lower N leaching attributed to higher NH_4 content under flooded culture. This substantial N depletion can be explained by the increased porosity of the fields during DSR-AWD rice cultivation and the frequent irrigation which increased water use (Li et al., 2014) and accompanied N leaching (Devkota et al., 2013b). Also, under DSR volatilization is high (Xu et al., 2013) and there is immobilization of the crop residue material (Turmel et al., 2015) whilst no-tillage practices increase denitrification (Yao et al., 2009) losses. However, in the long-run, the increased soil organic C associated with residue retention and the reduced loss of SOC due to no-tillage (Fig. 8; Table 6), could mitigate most of these adverse effects and in turn lead to an increased organic N content, water holding capacity of the soil, improved soil quality and a higher crop yield (Bescansa et al., 2006; Zhang et al., 2014). CA-practices reduced soil evaporation during the growing period of both crops as suggested earlier (Lal, 2015). In addition, less evaporation loss occurred from the treatments that had a higher amount of residue retention (Bescansa et al., 2006).

4.4. Limitations and future research

The results from this study did not address the frequently reported negative effects of no-tillage and residue retention (Pittelkow et al., 2015), for example the built up of termite and nematode infestation, micro-nutrient deficiency, and weed infestation under no-tillage and residue retention conditions (Kumar and Ladha, 2011). Nevertheless, these reported challenges can potentially be managed through future research on puddling or the creation of a sub-surface during rice growing period, deep placement of urea fertilizer in DSR, residue chopping and uniform broadcasting, strip-tillage transplanting or direct seeding of rice and wheat (Devkota et al., 2015), and through the combined use of surface or sub-surface drip irrigation with CA-practices. Surface or sub-surface drip irrigation (Abalos et al., 2014) with CA-practices can significantly reduce percolation and seepage losses of water, increase N and other fertilizer use efficiency as it could provide option for precise fertilizer application through the irrigation water, reduce N fertilizer losses through various pathways, minimize nutrient deficiency, and can control termite and nematodes as it can provide the options for fertigation and chemigation (Freddie and Carl, 2007) whenever is needed. Addressing the limitations and issues through the abovementioned research issues, could provide a huge scope for a rapid and wide-scale spread of CA-practices as the alternative agriculture technology for the improvement of rice–wheat cropping systems in Central Asia.

5. Conclusions

This finding showed that the CERES-Rice and CERES-Wheat models are able to simulate irrigated rice–wheat crop rotations for semi-arid regions. For wheat, CA-practices are always remunerative caused by the effect on yield increases. For rice, the findings clarified CA-practices in irrigated rice to become beneficial after 13 years only. However, WSRF-R0-AWD-Puddled could yield the same as WSRF-R0-FI although using almost 3 times less irrigation water. However, since CA-practices reduce management costs (Devkota et al., 2015), require only 30% of the irrigation water, and provide a long-term positive impact on grain yield of both crops, these effects combined can justify efforts to increase the use of CA-practices in double, no-till rice–wheat cropping systems in the irrigated semi-arid drylands of Central Asia.

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