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Managing salinity for sustainable agricultural production in salt-affected soils of irrigated drylands

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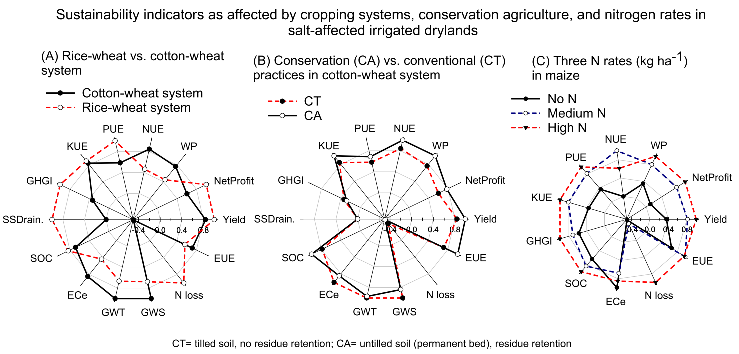
HIGHLIGHTS

- Declining water quantity and quality are leading to increasing soil salinity and threatening sustainability of salt-affected irrigated drylands
- Experiments, simulation, and multi-criteria trade-off used for assessing sustainability of predominant crops and technologies
- Accounting multiple approaches, cotton-wheat system has better environmental indicators than rice-wheat system
- Increased irrigation water salinity and soil evaporation can increase salinity by 78% in rice-wheat and by 66% in cotton-wheat
- Conservation agriculture combined with efficient irrigation and optimal nitrogen rate has potential to improve sustainability of cotton-wheat system

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Declining water quantity and quality and poor land, water, and crop management practices are leading to increasing soil salinity, land degradation, desertification, and threatening the overall sustainability of the crop production system in irrigated drylands. Assessments of salinity dynamics and sustainability indicators under alternative agricultural practices are needed to identify the right combination of practices that improve sustainability while minimizing land and environmental degradation.

OBJECTIVE: The objective of this study was to assess the potential of conservation agriculture (CA)-based practices, water-saving irrigation, water quality, and nitrogen (N) fertilizer rates for improving the sustainability of rice-wheat (RWS) and cotton-wheat (CWS) systems in salt-affected irrigated drylands.

METHODS: The study included mixed-method approaches of two years of field experiments, soil profile and groundwater salinity simulation using Hydrus-1D model, and multi-criteria trade-off analysis for the holistic

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assessment of alternative innovations in RWS and CWS. The treatments in experiments were composed of a combination of CA-based practices, water-saving irrigation and N rates. Fourteen sustainability indicators computed from experiments and simulation were compared to evaluate the sustainability of those cropping systems and to reveal the potential of those practices for improving sustainability.

RESULTS AND CONCLUSIONS: Compared to the initial conditions, the soil salinity decreased in both cropping systems, while the reduction rate was much higher in RWS than CWS (by 28%). In RWS, the conventional treatment had the lowest salinity level, while in CWS, CA (permeant bed + residue retention) had the lowest. RWS raised the groundwater table by 25% compared to CWS. The long-term scenario analysis with Hydrus-1D demonstrated that, with increased irrigation water salinity and soil evaporation rates, soil profile salinity increases by 78% in RWS and 66% in CWS. RWS had a higher net profit (+81%) and soil organic carbon (SOC) (-15%), but lower water productivity (WP) (−147%), nitrogen, and energy use efficiency (EUE) (−46%) than CWS. The CA-based practices in CWS improved sustainability indicators with higher yield and net profit (+20%), WP (+26%), SOC (+456%), and EUE (36%) with decreased soil salinity than in the conventional system.

SIGNIFICANCE: The study attempts to assess the effectiveness of resource conservation technologies such as choice of crop species and cropping systems, and tillage and water and fertilizer management practices for improving sustainability. This study showed the significance of agronomic, soil, and water management practices for minimizing soil salinity. Further, the findings from this study strongly demonstrated the role of CA in sustainable agricultural production particularly under CWS in salt-affected irrigated dryland.

1. Introduction

Soil salinization is a global problem that has affected 833 million ha of agricultural land in over 100 countries (Zaman et al., 2018). Globally, 833 million ha of soils are salt-affected (FAO, 2021). Approximately 20% of the world's cultivated lands and 33% of irrigated lands are salt-affected (Machado and Serralheiro, 2017). Soil salinization is spreading at the rate of 1–2 million ha year^{-1} globally, affecting a significant portion of crop production and making land unsuitable for cultivation (Hopmans et al., 2021; Abbas et al., 2013).

Irrigated agriculture plays a vital role in global food security, contributing to more than 40% of global food production (World Bank, 2021). To meet increasing food demand, the irrigated area needs to be expanded from current 202 million ha to 242 million ha in 2030 (Bruinsma, 2009; FAO News, 2021; Faurès et al., 2002). Moreover, the demand for irrigation is greater in arid- and semi-arid regions, where more than 90% of agriculture depends on irrigation. Also, these regions are more vulnerable to soil salinity and land degradation (Brady et al., 2008). In irrigated drylands, several factors, either in combination or independently, cause human-induced secondary soil salinization (Cuevas et al., 2019; Daliakopoulos et al., 2016; Qureshi et al., 2008). Prevalent improper land, water, and crop management practices include excessive use of poor quality (saline) irrigation water and poor drainage system (Wichelns and Qadir, 2015); inefficient use of chemical inputs (Gabriel et al., 2014); imbalance between rainfall, temperature, evapotranspiration, and water inputs (Minhas et al., 2020; Soni et al., 2021); intensive soil tillage, residue removal, and mono-cropping system (Abrol et al., 1988; Sarkar et al., 2020; Yang et al., 2006); and declining soil organic carbon and degrading soil health (SOC) (Lal, 2015; Cuevas et al., 2019).

Situated in Central Asia and part of the Aral Sea Basin, Uzbekistan is one of the world's most seriously affected countries in terms of land-degradation, desertification, and abandonment (Hopmans et al., 2021). Here, more than 65% of arable land (Nkonya et al., 2012; Robinson, 2016; UNEP/GRID-Arendal, 2005) and more than 90% of the total irrigated land (Akramkhanov et al., 2018) is currently affected by various levels of salinization. About 20,000 ha of irrigated lands are lost due to salinity and invariably abandoned every year (Toderich et al., 2008). Cotton (*Gossypium hirsutum* L.), wheat (*Triticum aestivum* L.), rice (*Oryza sativa*), and maize (*Zea mays* L) are the predominant crops grown in 1.2, 1.4, 0.4, and 0.42 million ha areas, respectively (FAOSTAT, 2021). These crops are mostly grown under the RWS and CWS (Devkota, 2011a, 2011b). As reported elsewhere, poor land and improper water management are the most important factors threatening the productivity and sustainability of those crops in Uzbekistan. Farmers in the country apply large quantities of irrigation water (>50,000 m^3 for rice and > 5000 m^3 ha^{-1} for each cotton, maize, and wheat) (Devkota, 2011a, 2011b) with salinity ranging from 1 to 15 dS m^{-1}. Excessive use of irrigation water raises groundwater tables (GWT), which has led to increasing secondary soil salinization, where 67% of the fields have GWT above the threshold level, which induces secondary salinization (Forkutsa et al., 2009; Ibrakhimov et al., 2007). Therefore, proper soil and water management strategies have been needed for sustaining crop production in such areas.

In recent years, many attempts have been made from different sectors to prevent and manage soil salinity and rehabilitate the degrading land. Sustainable land and water management practices, such as CA practices (minimal soil disturbance, proper crop rotation, and the optimal amount of crop residues retention) combined with efficient irrigation water management, minimize the adverse effect of conventional practices (CT) (Devkota et al., 2015a, 2015b, 2015c; Ondrasek et al., 2014; Sayre and Hobbs, 2004). CA-based practices counterbalance and combat soil salinity (Carrijo et al., 2017). However, soil salinity dynamics differ under different cropping systems, types of crop grown, amount and quality of irrigation water application, and adopted cultivation practices (Chen et al., 2010; Zhang et al., 2012).

Hydrological models can provide a useful complement to the experimental results. The hydrological model, Hydrus-1/2/3D (Šimůnek et al., 2013) has been used extensively in a wide range of irrigation management applications (furrow, surface, and subsurface pressurized irrigations). It has been applied in the evaluation of soil hydraulic properties, boundary condition, irrigation frequency, amount and discharge rate, water quality/salinity, the timing of nutrient application, drainage system, and crop type for optimizing soil and water management practices (Ajdary et al., 2007; Egea et al., 2016; Hopmans, 2008; Hopmans et al., 2006; Jian-jun et al., 2015; Ramos et al., 2012; Rezaei et al., 2016, 2017, 2021; Selim et al., 2018). It can be used to quantify the long-term impacts of several agronomic innovations on soil and water productivity and sustainability.

Sustainability is improvement in economic, environmental, social and institutional indicators (Corsin et al., 2007) for "meeting society's present needs without compromising the ability of future generations to meet their own needs" (Bell and Morse, 2012; Ghelichkhan et al., 2018). Maintaining and improving the sustainability of degrading irrigated drylands is important for achieving Sustainable Development Goals (SDG) (UNDP, 2017). The advantages of agronomic innovations for improving individual indicators have been reported (Devkota et al., 2013a, 2013b, 2015b, 2015c). However, as soil salinity impacts soils, plants, and the environment, the holistic assessment of the innovations/technologies is essential to assess their potential to improve the sustainability of crop production (Hopmans et al., 2021). Systematic quantification and comparison of multiple sustainability indicators, comparing different cropping systems, crops, and agronomic management practices, provide adaptation guidelines and ways-forward to improve the sustainability of degrading irrigated drylands. In addition, in many circumstances, coupling experimental, simulation, and multi-criteria approaches are needed to improve sustainability. Thus, the objective of this study was to determine the potential of CA-based practices (no-tillage, crop rotations, and residue retention) coupled with water-saving alternative-wet and dry (AWD) irrigation, and N fertilizer rates for improving sustainability of crop production in salt-affected irrigated drylands of Central Asia.

2. Materials and methods

2.1. Climate and soil

The study was conducted at a field in the Khorezm region, south of the Aral Sea in Uzbekistan (60.05°- 61.39° N and 41.13°-42.02° E, 100 m asl), an area representative of the degrading saline irrigated arid and semi-arid region. The region has an arid continental climate, with an average annual precipitation of less than 100 mm, and the potential evapotranspiration always greatly exceeds precipitation (Forkutsa, 2006). The soil of the experimental site had Calcaric Gleysols “Meadow soil”, which corresponds to Xerosols and anthropogenic Fluvisols according to USDA classification (Vlek et al., 2001), and is characterized by a shallow GWT often with elevated groundwater salinity (GWS), and salinization in the upper soil profile. During the crop growing period from March to October, the groundwater table rises up to 1.2–1.4 m and drops to about 1.8 m, and this rise in groundwater increases soil salinity by adding 3.5–14 t salt ha^{-1} y^{-1} (Ibragimov et al., 2007). The inherent soil organic carbon and fertility of Khorezmian soil is rather low. The experimental field had medium to high soil mineral nitrogen (N), NH$_4$-N ranging from 4.4–6.5 and NO$_3$-N 3.4–5.3 mg kg^{-1}, low total soil N (0.04–0.05%), low SOC (0.30–0.36%), and a moderate range of available phosphorus 23.9–27.9 mg kg^{-1} and exchangeable potassium (76.8–98.5 mg kg^{-1}). Soil salinity in the region corresponds to the electrical conductivity of saturated soil extract (ECe) of 6–16 dS m^{-1} at the top 30 cm soil profile.

2.2. Experimental study

2.2.1. Experimental design and treatments

Experiments in RWS and CWS were conducted during 2008–2010 at Cotton Research Institute (CRI), Urgench, in the Khorezm region of Uzbekistan. All abbreviations used in this manuscript are described in Table SI1.

2.2.1.1. RWS. The experiment in this system was implemented with seven treatments in 2008 and eight treatments in 2009 using a randomized complete block design (Fig. SI1; Table 1). The treatments for RWS were from the combination of irrigation methods, i.e., AWD and continuous flood irrigation (FI); and three tillage methods, for example, raised permanent bed (PB) and zero tillage (ZT) planting on flat land with three levels of crop residue retention, i.e., residue harvested (R0), 50% residue retention (R50) and 100% residue retention (R100) (Table 1). In the conventional practice (third tillage method), previous crop residue was removed, then the soil was levelled after dry then wet soil ploughing (puddling). In WSR-FI, 24-h soaked and 48-h incubated pre-germinated seed was directly broadcast seeded into 5–10 cm standing water and, after rice emergence, FI keeping 5–15 cm standing water throughout the growing season (as in the farmers’ practice) was applied. In the other six treatments, i.e., PB and ZT with three residue rates, rice was dry direct-seeded (DSR) using no-till seeder and AWD irrigation was applied (collectively called DSR-AWD (or CA) for those 6 treatments). In treatments of DSR-AWD, rice was flood-irrigated when the average soil matric potential at 20 cm depth was 20 kPa, which corresponds with the volumetric soil water content 5–10% below the field capacity. In RWS, surface-seeded wheat (SSW; broadcasting of sprouted wheat into the standing rice field 25 days before rice harvest) was grown in all treatments. Experimental details have been presented in Devkota et al. (2013b, 2015a).

Table 1

Description of the treatments in rice-wheat and cotton-wheat system experiments 2008–2010.

		Rice-wheat system
SN	**Treatment**	**Description**
1	DSR-PB-R0	Dry seeded rice (DSR) grown on permanent bed (PB), no residue retention, alternate wet and dry (AWD) irrigation in rice followed by surface seeded wheat (SSW) with no residue retention
2	DSR-PB-R50	DSR grown on bed, 50% residue retention, AWD irrigation in rice followed by SSW with 50% residue retention
3	DSR-PB-R100	DSR grown on bed, 100% residue retention, AWD irrigation in rice, followed by SSW with 100% residue retention
4	DSR-ZT-R0	DSR grown on flat, no residue retention, AWD irrigation in rice followed by SSW with no residue retention
5	DSR-ZT-R50	DSR grown on flat, 50% residue retention, AWD irrigation in rice, followed by SSW with 50% residue retention
6	DSR-ZT-R100	DSR grown on flat, 100% residue retention, AWD irrigation in rice followed by SSW with 100% residue retention
7	WSR-FI	Wet-direct-seeded rice (WSR) grown on flat, no residue retention, conventional tillage and flood irrigation (FI) in rice followed by SSW with no residue retention
8	WSR-AWD	WSR grown on flat, no residue retention, conventional tillage and AWD irrigation in rice followed by SSW with no residue retention (2nd year)

Cotton-wheat system			
	Cotton	**Wheat**	**Maize**
1	PB (CA)-R0-N0	PB (CA)-R0-N0	PB (CA)-R0-N0
2	PB (CA)-R0-N125	PB (CA)-R0-N100	PB (CA)-R0-N100
3	PB (CA)-R0-N250	PB (CA)-R0-N200	PB (CA)-R0-N200
4	PB (CA)-R100-N0	PB (CA)-R100-N0	PB (CA)-R100-N0
5	PB (CA)-R100-N125	PB (CA)-R100-N100	PB (CA)-R100-N100
6	PB (CA)-R100-N250	PB (CA)-R100-N200	PB (CA)-R100-N200
7	CT-R0-N0	CT-R0-N0	CT-R0-N0
8	CT-R0-N125	CT-R0-N100	CT-R0-N100
8	CT-R0-N250	CT-R0-N200	CT-R0-N200
10	CT-R100-N0	CT-R100-N0	CT-R100-N0
11	CT-R100-N125	CT-R100-N100	CT-R100-N100
12	CT-R100-N250	CT-R100-N200	CT-R100-N200

¶Note: PB=Permanent bed also called conservation agriculture (CA), CT = conventional practices, R0 = no residue retention, R100 = maximum possible amount of residue retention; N = Nitrogen rate (kg ha^{-1}).

2.2.1.2. CWS. Twelve treatments – (Fig. SI1, Table 1) in each crop (cotton, wheat, and maize in rotation) from the combination of two tillage methods, i.e., permanent bed, PB (also called CA), and CT; two residue levels (residue retained, R100, and residue harvested, R0) and three N application rates (no N application (N0), and 50% less than and 50% more than the recommended rates) (Table 1) – were evaluated. The CA practices include raised permanent bed planting, crop planted/seeded using a tractor-drawn seed drill machine under untilled conditions and residue retention. The experiments were implemented in a split-plot design with tillage methods in the main plot and six treatments from a factorial combination of three N and two residue rates randomized in sub-plot (Devkota et al., 2013c, 2015b, 2015c). In the residue retained treatments (R100), 3 t ha^{-1} wheat residues from an external source (initial external application), 6.6 t ha^{-1} cotton residues, and 6.88 t ha^{-1} wheat residues were retained during the cotton, wheat, and maize seasons, respectively (Table 2). In all residue harvested (R0) treatments, residues were removed from the field as per farmers' practice in both CA and CT plots. In CT plots, the soil was ploughed 2–3 times before seeding, crops were harvested from the base, and all residues were removed.

Experiments were conducted in four replications, with an operational plot size of 480 m^2 for RWS and 550 m^2 for CWS. The RWS experiment was implemented for two seasons of each crop (2 years) and cotton-wheat-maize in CWS three crops. Once established in 2008, DSR-AWD treatments in RWS and CA treatments in CWS were permanently adopted.

2.2.2. Crop management practices

All crops were seeded using standard and recommended crop management practices. Rice variety Nukus-2, wheat Krasnodar-99, cotton Khorezm-127, and maize Maldoshki (hybrid) were used. The crop growing duration was June–October for rice; wheat October–May; cotton May–October; and maize June–September. Crop management practices adopted for both RWS and CWS are presented in Table 2, and details of these are explained in Devkota et al. (2015a) and (Devkota et al., 2013a, 2013b) for RWS, and Devkota et al. (2013c, 2015b, 2015c) for CWS.

Table 2

Crop management practices and input use in rice-wheat and cotton-wheat systems 2008–2010.

Rice-wheat system	Rice 2008	Wheat 2009	Rice 2009	Wheat 2010
Variety	Nukus-2	Krasnodar-99	Nukus-2	Krasnodar-99
Seeding date	18 June	23 September 2008	21 June	1 October 2009
Harvesting date	8 October	13 June	22 October	22 June
Seed rate (kg ha^{-1})	140	200	140	200
Fertilizer rate (NPK kg ha^{-1})	257:120:80	124:100:70	250:120:80	233:140:70
Residue amount in R50 (kg ha^{-1})	1500	2922	4146	2926
Residue amount in R100 (kg ha^{-1})	3000	4657	6689	3139

Cotton-wheat system	**Cotton 2008**	**Wheat 2009**	**Maize 2009**
Variety	Khorezm-127	Krasnodar-99	Maldoshki
Seeding	6 May	October 2008	28 June 2009
Harvesting	October	Mid-June	Sept-2009
Seed rate (kg ha^{-1})	60	200	40
Fertilizer rate ($N:P_2O_5:K_2O$ kg ha^{-1})	0, 125, 250 kg ha^{-1}N; 140:100 kg $P_2O_5:K_2O$	0, 100, 200 kg N ha^{-1}; 160:70 kg $P_2O_5:K_2O$ ha^{-1}	0, 100, 200 kg N ha^{-1}; 160:70 kg $P_2O_5:K_2O$ ha^{-1}
Residue amount in R100 (kg ha^{-1})	3000	6600	6880

2.2.3. Measurements

2.2.3.1. Water application. In both experiments, the amount of irrigation water applied was measured using standard Trapezoidal Cipolletti weirs (0.5 m crest width) with automated data loggers (Divers) for level measurement (DL/N-70), which measured the water level above the Chipolletti crest at a 1-min interval. The rate of water discharged (in m^3 s^{-1}) from the respective Cipolletti crest was calculated based on the equation provided by Kraatz and Mahajan (1975).

2.2.3.2. Soil profile salinity. To assess the salt dynamics in the soil profile, soil samples were collected from the pre-determined sampling points for each plot (six points were fixed in each plot) during the entire crop rotation cycle in both systems.

2.2.3.2.1. RWS. Soil samples were collected at 19 different dates from a rice field in 2008, 11 times from a wheat field in 2009, and 27 times from a rice field in 2009. Soil samples were collected from 0 to 10, 10–20, 20–30, 30–50, and 50–80 cm depths before irrigation using a tube augur-sized 3 cm in diameter.

2.2.3.2.2. CWS. Samples were collected from 0 to 10, 10–20, 20–30, 30–60, and 60–90 cm soil depths one day before irrigation and at each crop harvest. The samples were collected at 11 dates each during cotton and wheat season and 7 dates during maize season. In the PB system in both cropping systems, soil samples were collected from both tops of the bed and the center of the furrow to obtain the average salinity of the bed system.

A total of 6083 soil samples in RWS and 4749 samples in CWS were analyzed. In both systems, the collected soil samples were analyzed for gravimetric soil moisture content and electrical conductivity (EC_p), which is the EC of 1:1 water: soil paste. The measured EC_p was converted to the international standard EC value of the saturated soil extract (ECe; Rhoades et al., 1999), and derived from the equation as provided by Akramkhanov et al. (2009):

$$EC_e\left(ds\ m^{-1}\right) = \left(2.02\ x\ EC_p\right) + 0.14 \tag{1}$$

2.2.3.3. Groundwater salinity and depth. To measure GWS and GWT, nine piezometers, i.e., six in the section of DSR-AWD irrigation and three in the WSR-FI, were installed (Fig. SI1), and 32 observations during rice 2008, 62 during wheat and 109 during rice 2009, were taken in RWS. In CWS, across the experimental field, 20 piezometers were randomly installed up to 2.75 m depth and 16, 20, and 21 observations were collected during cotton, wheat, and maize growing season, respectively. Groundwater measurement was not available during the freezing period (November to March) when the GWT depth dropped below the depth of the piezometers. Water samples were collected from each piezometer before and after irrigation in both RWS and CWS. GWT was measured using a hand-operated sounding apparatus with acoustic and light signals (Eijkelkamp Co.) and the groundwater was analyzed for ECe with a Hanna instrument (HI-98312 EC) in dS m^{-1}.

2.3. Simulating soil water content, soil and groundwater salinity dynamics

2.3.1. Hydrological model description

Simulation of water flow and solute transport which are assumed to be in the vertical direction in the vadose zone, was carried out for three crop seasons in both systems using Hydrus-1D version 4.17. The model uses the 1-D Richards equation (Eq. 2) for vertical water flow:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h(\theta)}{\partial z} + 1\right)\right] - S(h) \tag{2}$$

Where, θ is the volumetric water content (L^3L^{-3}), t is time (T), z is the radial and vertical space coordinate taken positive downward (L), $K(h)$ is the unsaturated hydraulic conductivity function (LT^{-1}), h is the pressure head (L), and *S(h)* represents a sink term ($L^3L^{-3}\ T^{-1}$), defined as the volume of water removed from a unit volume of soil per unit time.

The model computes the solute transport using standard Hydrus solute transport module in a variably-saturated rigid porous medium in the liquid phase with root nutrient uptake as:

$$\frac{\partial \theta c_k}{\partial t} + \rho_b \frac{\partial \overline{c_k}}{\partial t} = \frac{\partial}{\partial z}\left(\theta D \frac{\partial c_k}{\partial z}\right) - \frac{\partial q c_k}{\partial z} - S c_{r,k} \tag{3}$$

where θ is the volumetric water content (L^3L^{-3}), c, $\overline{c}$ and c_r are solute concentration in the liquid phase ($M\ L^{-3}$), solid phase ($M\ M^{-3}$) and sink term ($M\ L^{-3}$), respectively, t is time (T), z is the radial and vertical space coordinate taken positive downward (L), ρ_b is the soil bulk density ($M\ L^{-3}$), q is the volumetric flux density (LT^{-1}), the subscript k represents chemical species of major ions, and D represents the hydrodynamic dispersion coefficient (L^2T^{-1}). The standard module takes into account the interaction between the liquid and solid phases of EC (Ramos et al., 2011).

2.3.2. Modeling framework

Due to the high fluctuation of GWT, the simulated soil profile in the model extended to 200 cm depth and was divided into two functional layers (0–60 and 60–200 cm). To solve Richards' equation (Eq. 2), the Brooks-Corey soil hydraulic model was used. The initial values of hydraulic properties were obtained from a neural network prediction implemented into the model based on soil texture and bulk density. The hydrodynamic dispersion coefficient was imposed as one-tenth of soil profile depth, i.e., 20 $cm^2 day^{-1}$ (Ramos et al., 2011). The initial soil water content distribution was adjusted uniformly and set to 0.20 $cm^3\ cm^{-3}$ through all soil profiles. The EC of soil was used as the initial condition of solute concentrations of each layer. The upper boundary condition for water flow and solute transport were imposed from measured data of rainfall, applied irrigation water, potential evapotranspiration (ET_o), leaf area index (LAI), EC of applied water (cTop), and EC of groundwater (cBot). The meteorological data were obtained from the experimental station. ET_o was calculated based on the FAO Penman-Monteith equation on a daily basis (Allen et al., 1998) using meteorological data. LAI was derived from the measured data from Devkota (2011a, 2011b). The variable pressure head bottom boundary was imposed by setting measured groundwater table data. The Feddes' model (Feddes et al., 1978) as the sink term of Richards' equation Eq. (2), *S(h)* was used for the quantification of potential root water uptake and water stress as:

$$S(h) = w(h)R(x)T_p \tag{4}$$

Where, $R(x)$ is the root distribution function (cm), T_p is potential transpiration ($cm\ h^{-1}$), and $w_{(h)}$ is the water stress response function ($0 \leq w_{(h)} \leq 1$) which prescribes the reduction in uptake that occurs due to drought/salinity stress. Crop-specific values of this reduction function were chosen from the default Hydrus data set.

2.3.3. Model calibration and validation

2.3.3.1. Model calibration. For accurate parameter estimation, a long period with several drying and wetting events was selected (from May 2008 to October 2009), i.e., two growing seasons as suggested by Rezaei et al. (2016). The model was calibrated for both RWS (480 days) and CWS (532 days). Time series observed data, i.e., 392 soil water content and EC records for RWS and 156 records for CWS, were used for four observation points/depths (as data for inverse solution). In the calibration, we optimized all hydraulic parameters as well as the hydrodynamic dispersion coefficient for one CA treatment in each cropping system. Finally, the best performing parameter set – based on performance criteria, non-uniqueness of the parameter sets, and the visual inspection of simulated and observed soil-water content and EC data – was selected for validation using independent data from conventional practice treatment.

2.3.3.2. Model evaluation and statistical analysis. The performance of Hydrus-1D in simulating water content and EC from the different cultivation systems was evaluated graphically (Rezaei et al., 2016) and a variety of statistics (Neuman et al., 2003). The root-mean-square errors (RMSE), mean absolute error (MAE), and coefficient of determination (R^2) are popular and were used to evaluate the difference between observed and simulated values.

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i - \overline{O})(S_i - \overline{S})}{\sqrt{\sum_{i=1}^{n}(S_i - \overline{S})^2 \sum_{i=1}^{n}(O_i - \overline{O})^2}}\right)^2 \tag{5}$$

$$MAE = \frac{\sum_i^n |O_i - S_i|}{n} = \frac{\sum_i^n |e_i|}{n} \tag{6}$$

$$RMSE = \sqrt{\frac{\sum_i^n (O_i - S_i)^2}{n}} \tag{7}$$

Where, O and S are observed and simulated values at time/place i, respectively. $|e_i|$ is an arithmetic average of the absolute errors.

2.3.3.3. Scenario analysis. In both systems, the model was run to analyze the impact of quantity and quality of irrigation water on soil salinity.

2.3.3.3.1. RWS. The model was run for six different scenarios:

- Current conventional method of flood irrigation (WSR-FI)
- Current DSR-AWD
- Current WSR-FI, but with 50% less water in rice
- DSR-AWD with double irrigation water salinity
- Current WSR-FI with double irrigation water salinity
- Current DSR-AWD with 50% reduced irrigation water quantity but with doubled irrigation water salinity.

2.3.3.3.2. CWS. Four different scenarios were analyzed to evaluate sustainability and identify the most influential factor on soil EC in future. The comprised:

- Current irrigation amount and irrigation water salinity
- Double irrigation water salinity
- Increasing ETo by 1.2 times
- Increasing EC of water by 2 times and ETo by 1.2 times of observed/current data.

2.4. Sustainability assessment using multi-criteria assessment

To assess the broad-based sustainability of two cropping systems, four different crops, an alternative CA-based system with water-saving irrigation and N rates, and 14 sustainability indicators from economic, environmental and soil health and resilience were assessed (Fig. SI2). Those indicators include: 1. grain yield; 2. net profit; (3–5) nitrogen-, phosphorus-, and potassium-use efficiencies (NUE, PUE, and KUE); 6. water productivity (WP); 7. SOC sequestration; 8. soil salinity (ECe); 9. yield scaled greenhouse gas (GHG) emission intensity (GHGI); 10. GWT depth; 11. GWS; 12. drainage loss of irrigation water; 13. energy use efficiency (EUE); and 14. mineral nitrogen balance, were computed. The detail of the computation methods of all these indicators has been explained in Supplementary Information Appendix I.

The GHGI was computed for all four crops and all treatments considering three components of GHG emission: (I) CO_2-equivalent methane emission (in rice only), (II) direct CO_2-equivalent emission from applied N, P, and K fertilizers; and (III) indirect CO_2-equivalent emissions from N_2O emission, N-volatilization, and N-leaching from applied N fertilizers (Supplementary Information Appendix I). The results expressed in GHGI (kg CO_2 equivalent emissions t^{-1} grain or seed cotton) as suggested by Pittelkow et al. (2014), Sainju et al. (2014) and Snyder et al. (2009).

$$\text{Greenhouse gas emisison intensity (GHGI)} = \frac{\text{Total } CO_2 \text{ equivalent emission (kg)}}{\text{Grain or seed cotton yield (t)}} \tag{8}$$

The EUE was computed for all four crops and both cropping systems, as the ratio of energy output from grain or seed cotton and straw/stover divided by the total energy input in all production operations.

$$\text{Energy use efficiency (EUE)} = \frac{\text{Total energy output}}{\text{Total agronomic energy input}} \tag{9}$$

Partial mineral N balance was computed from the difference between output (uptake + mineral N left at harvest) and input (initial mineral N + N applied from fertilizers), the positive value indicates N loss. The amount of N fertilizers applied, initial and after crop harvest soil N content, and crop N uptake were measured in all crops in both cropping systems. The detail computation procedure of mineral N balance has been explained in Devkota et al. (2013a).

2.5. *Data analysis*

Repeated measure analysis of variance (ANOVA) was conducted for salinity measured over time during the crop growing period using R version 4.03. Linear regression was used to quantify the difference in soil salinity over time on different crops, cropping systems, CA-based practices, and irrigation management. The daily soil salinity and volumetric water content at 0–90 cm soil depth, and GWS and GWT dynamics as affected by CA-based practices, were simulated for CWS, and affected by water management practices (WSR-FI vs. DSR-AWD) were simulated for RWS. Multi-criteria trade-off analysis among sustainability indicators was used for the broad-based assessment of different cropping systems, crops, CA-based practices, water management methods, and N fertilizer rates for their potential for managing salinity in degrading irrigated drylands.

3. Results

3.1. *Soil salinity as affected by cropping systems*

Soil salinity varied across the sampling time in both cropping systems (Table SI2). The initial soil salinity at the top 30 cm soil depth decreased by 22% after leaching and laser-guided land leveling (just before the start of the experiment) (Fig. 1A). Compared to the initial level (3.28 dS m^{-1}), the soil salinity decreased in both cropping systems, while the reduction rate was higher in RWS (by 28%) than CWS. In RWS, the significant crop x treatment x sampling time, indicating salinity among the treatments, varied significantly with time and crops grown. In conventional practices (WSR-FI), compared to the initial condition (after leaching and before rice seeding), the salinity decreased by 48% in first rice and by 16% from wheat to second rice. In CWS, soil salinity was the highest ($p < 0.05$) in cotton, followed by wheat and then lowest in

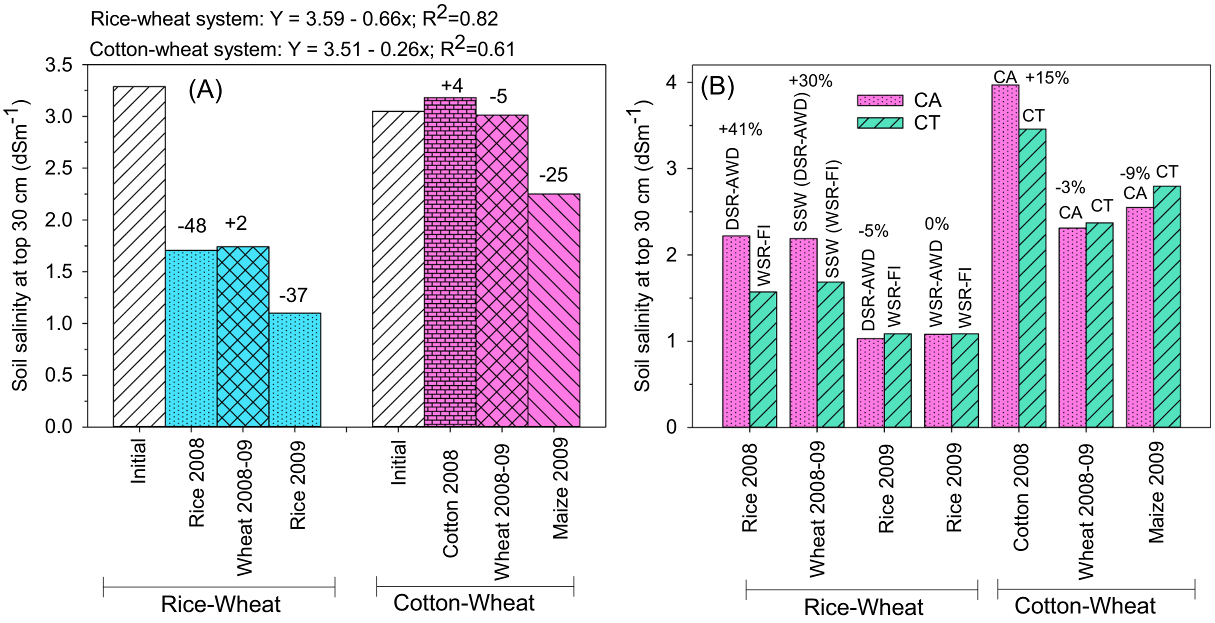

Fig. 1. Soil salinity (at crop harvest compared to the initial in conventional treatments) under rice-wheat and cotton-wheat systems (A); and salinity as affected by conservation and conventional practices in rice-wheat and cotton-wheat systems (B). DSR = dry-direct seeded rice; WSR = conventional wet-direct seeded rice; SSW = surface seeded wheat; AWD = alternate wet and dry irrigation; CA = conservation agriculture; CT = conventional practices. The values on the top are changes in soil salinity under different cropping systems over initial in Fig. (A), and changes in soil salinity with conservation agriculture (CA)-based practices over conventional (CT)-based practices (B).

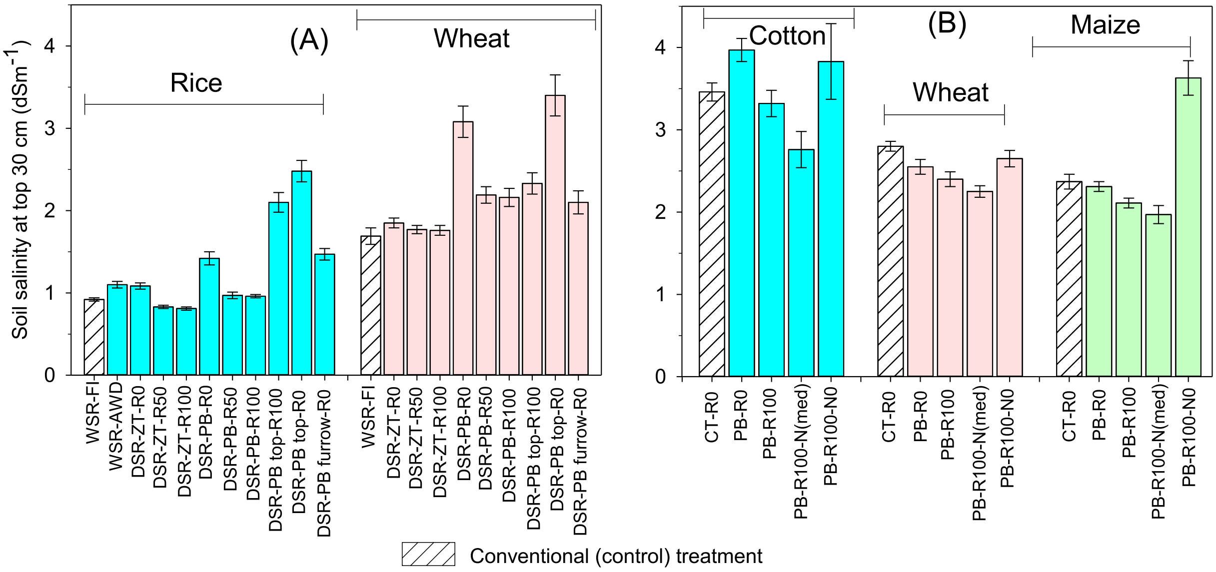

Fig. 2. Soil salinity dynamics as affected by different water management, tillage and residue treatments in rice-wheat (A) and cotton-wheat system (B). WSR-FI = wet-direct seeded rice with continuous flood irrigation; WSR-AWD = wet-direct seeded rice (puddled) with alternate wet and dry irrigation; ZT = zero tillage flat planting; PB = permanent bed; R0 = residue removed; R50 = 50% residue retention; R100 = 100% residue retention; SSW = surface-seeded wheat, all wheat in RWS was SSW after rice; CA = conservation agriculture; CT = conventional practices. N(med)= medium N rate. The 1st bar (with slanting lines) in each panel are the conventional (control treatment).

maize, where, compared to the initial level, it increased by 4% in first cotton, but decreased by 25% from wheat to maize. In CWS, CT had significantly higher salinity than CA and residue retention (R100) had significantly low salinity than residue removal (R0).

3.2. *Soil salinity as affected by CA-based practices*

In RWS, salinity was lower in the WSR-FI based system than under DSR-AWD, while in CWS, except in cotton, it was lower in the CA-based system than under CT (Fig. 1B). In RWS, compared to WSR-FI, an average of DSR-AWD (6 treatments) had higher salinity by 41% in rice season and 30% in wheat season. In 2009, WSR-AWD comparison with treatments of DSR-AWD showed salinity levels in those treatments were similar. In CWS, after three crops, CA practice (PB + residue retention) reduced salinity level by 3% in wheat and by 9% in maize compared to CT. The PB system without residue retention (R0) had a higher (+17 to +66%) soil salinity on the top of the bed than CT. Salinity level on the top of the bed increased by (+62 to +69%) than in the furrow when crop residues were removed. However, the bed system with residue retention reduced salinity by 15–31% compared to residue harvest (Fig. 2A). Similarly, in CA-based CWS, salinity level was reduced by 28–46% under N-applied treatments compared to the treatment without N application (Fig. 2B).

Table 4
Calculated performance criteria showing the correspondence of simulated and observed data of two cultivation systems. RMSE, R^2 and MAE are the root-mean-square deviation, coefficient of determination and mean weighted absolute error (cm^3cm^{-3}).

Cropping system	RMSE	R^2	MAE
Model calibration			
Rice-wheat system	0.340	0.750	0.192
Cotton-wheat system	0.068	0.711	0.051
Model validation			
Rice-wheat system	0.345	0.883	0.224
Cotton-wheat system	0.452	0.823	0.299

3.3. *Simulated soil water content, groundwater and soil salinity dynamics*

3.3.1. *Model calibration and validation*

As the soil profile was divided into two layers, all the soil hydraulic parameters and the hydrodynamic dispersion coefficient of each layer were optimized (Table 3). The results of parameters optimized and its performance are shown in Tables 3, 4. There was a close matching of

Table 3
Initial and optimized values of hydraulic properties and the hydrodynamic dispersion coefficient *(D)* of RWS and CWS rotation systems. θ_r, θ_s are residual and saturated water content, respectively; α and n are shape parameters for the Brooks and Corey equation. K_s and L denote the saturated hydraulic conductivity and Tortuosity parameter in the conductivity function respectively.

Parameters	θ_r (cm^3cm^{-3})	θ_s (cm^3cm^{-3})	α (cm^{-1})	n	K_s (cm d^{-1})	L	D (cm^2 d^{-1})
Rice-wheat system							
Initial values, 1st layer	0.006	0.391	0.100	0.200	150.20	1.00	20
Initial values, 2nd layer	0.0042	0.349	0.001	0.200	124.36	1.00	20.00
Optimized values, 1st layer	0.045	0.438	0.045	0.141	149.11	0.745	19.769
Optimized values, 2nd layer	0.0196	0.553	0.0736	0.151	183.27	0.0029	50.463
Cotton-wheat system							
Initial values, 1st layer	0.041	0.453	0.068	0.322	62.16	1.00	20.00
Initial values, 2nd layer	0.041	0.453	0.068	0.322	62.16	1.00	20.00
Optimized values, 1st layer	0.001	0.390	0.040	0.330	192.22	0.388	11.271
Optimized values, 2nd layer	0.005	0.628	0.034	0.367	125.96	0.005	32.762

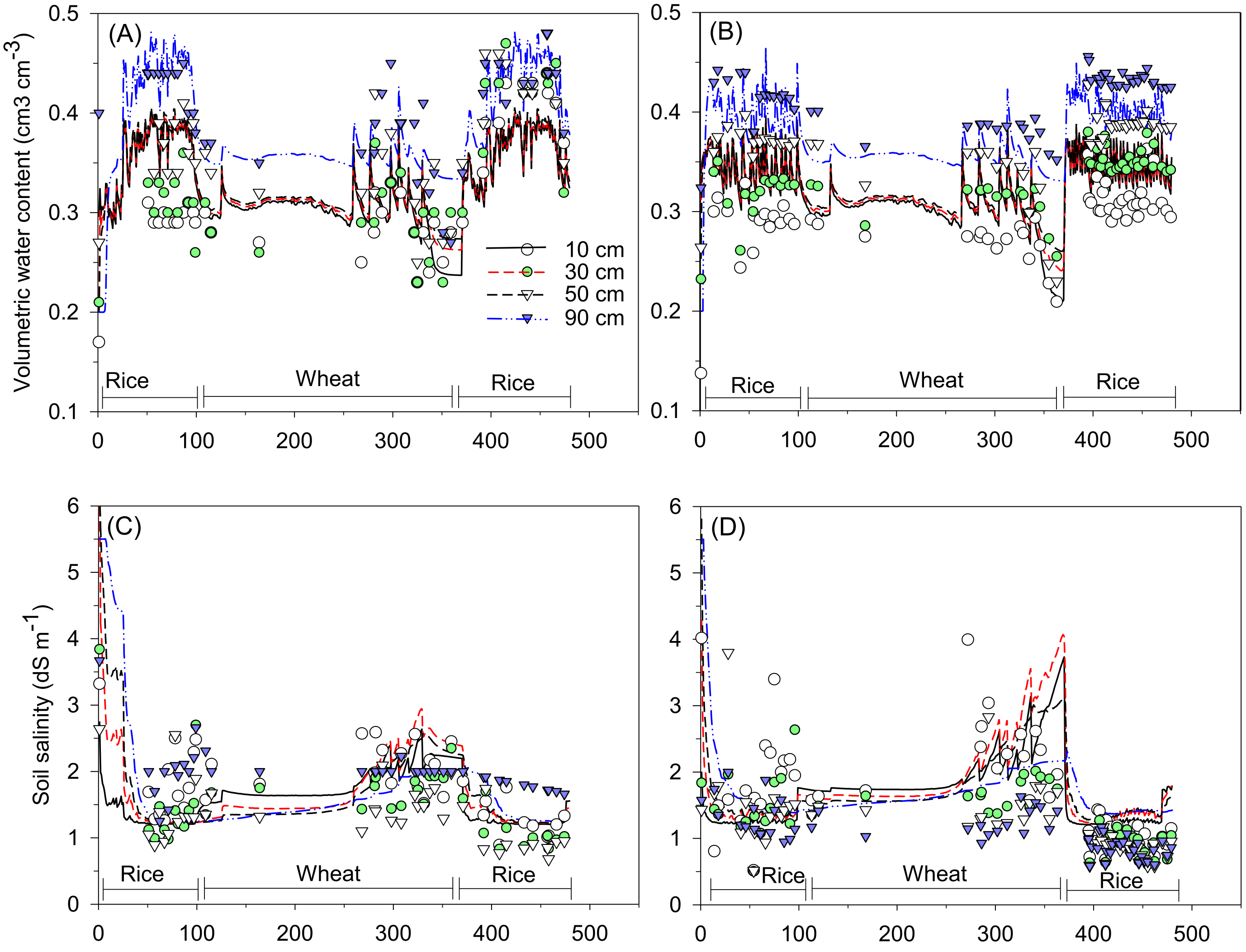

Fig. 3. Measured and simulated soil moisture dynamics at 10, 30, 50 and 90 cm soil depths in wet-direct seeded rice with flood irrigation (WSR-FI: A); dry-direct seeded rice with alternate wet and dry irrigation (DSR-AWD: B) and soil salinity in WSR-FI (C) and DSR-AWD (D) in rice-wheat system. (*Left side*) calibration (*right side*) validation.

simulated and measured soil profile salinity values in all four crops (rice, wheat, maize, and cotton). This suggests the model performed satisfactorily and predicted well for the soil salinity level and water content (Figs. 3, 4); however, some fluctuation can be observed. Larger differences in simulated and observed EC can be seen in RWS compared to CWS. That is logical due to puddling where the soil was always close to saturation in rice field. In RWS, soil salinity was increased at the end of the wheat season (Fig. 3). In CWS, soil salinity was increased as soil water content decreased during the cotton season, but it was reduced significantly during wheat and maize seasons. Overall, the model performs well for the upper layer and its observation depths where the plant roots are concentrated, which is consequently the most critical in terms of irrigation and nutrition management.

The validation results, using the optimized hydraulic parameters and hydrodynamic dispersion coefficient values (Table 3) of the calibration under different upper (rainfall and water supply, ET_o, LAI) and lower (groundwater depth) boundary conditions, are shown in Figures 3 and 4. The results of parameter optimization performance, according to performance criteria, are shown in Table 5. Similar to Rezaei et al. (2016), model performance during the calibration was superior to the validation at all observation depths, particularly in RWS. The model underpredicted soil water content and consequently overpredicted soil EC in CWS, while soil water content was overpredicted and EC was underpredicted in RWS. These differences may be attributed to a large number of optimized parameters, different parameters values in the calibration and evaluation data, and also seasonal changes in soil hydraulic properties.

3.3.2. *Measured and simulated groundwater table depth and salinity*

During the entire crop growing period, GWT was shallower (1.14 m) by 25% in RWS than in CWS (1.52 m) (Fig. 5A). In crop comparison, GWT was 23% shallower in rice than in cotton during the summer season, while during the winter season, wheat in RWS had 7% shallower GWT than wheat in CWS. The coefficient of variation (CV) for GWT was higher in rice (37%) than in other crops (11–12%). In rice, variation in GWT was higher in DSR-AWD by 8% than in WSR-FI. Both simulated and measured results showed that GWT and GWS in rice were affected due to water management practices, where DSR-AWD had deeper GWT and higher GWS.

Groundwater salinity was decreased with an increase in irrigation amount, where it was higher in CWS by 1.16 dS m^{-1} (64%) than in RWS (1.83 dS m^{-1}) (Fig. 5B). Similar to GWT, variation in GWS was higher in RWS (CV-27%) than in CWS (CV-16%). Simulation results confirmed a significant increment in GWT and GWS in wheat after rice in RWS than in wheat after cotton in CWS.

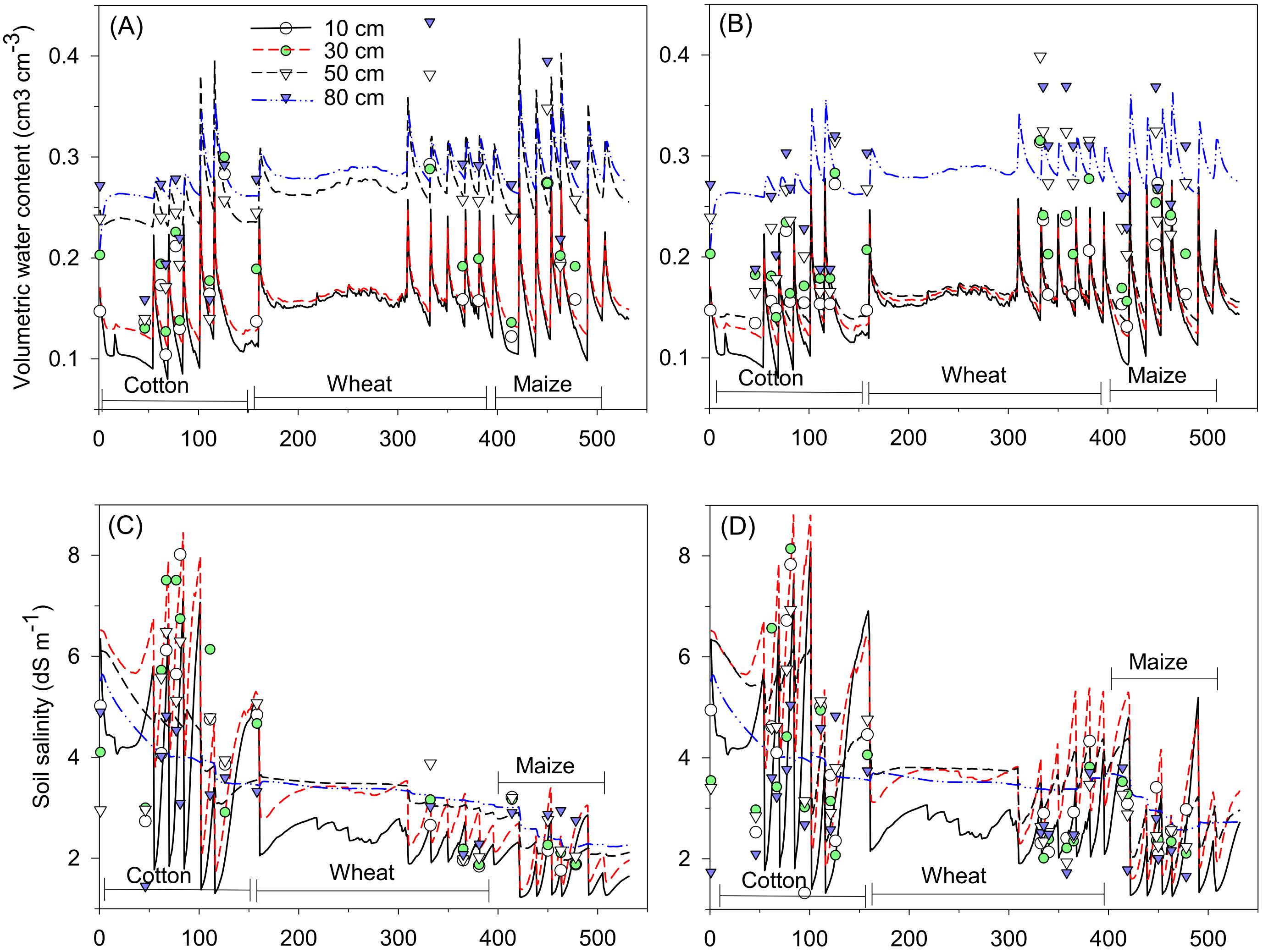

Fig. 4. Measured and simulated soil moisture dynamics at 10, 30, 50 and 90 cm soil depths in conventional practices (CT) without residue retention (A) and conservation agriculture (permanent bed planting with residue retention (CA) (B) and soil salinity dynamics in CT (C) and CA (D) in cotton-wheat system. Calibration (*Left side*), validation (*right side*).

3.3.3. *Measured and simulated soil salinity dynamics at different soil profiles*

Irrespective of the treatment effect, both measured and simulated results found that soil salinity at the top 30 cm soil profile was higher (by 81%; 2.86 dS m^{-1}) in CWS than RWS (1.58 dS m^{-1}). Across the soil depth, soil salinity was higher by 73% at the top 10 cm, 92% at 20 cm, 81% at 30 cm, 8% at transition zone (80–90 cm) in CWS than in RWS (Figs. 3, 4). During the crop growing period, salinity level at all soil layers, including transition zone and at groundwater, was highest in cotton – followed by wheat and maize in CWS and the lowest in rice in RWS. The simulated result clearly proved that DSR-AWD rice had a higher salinity than WSR-FI at all soil depths. As the model does not have the option to simulate salt dynamics due to bed configuration and residue retention, we did not simulate the effect of CA on salinity dynamics.

3.3.4. *Simulated water balance in rice- and cotton-based systems*

Results from daily water balance simulation (Fig. SI3) showed that a measurable amount of water input (irrigation + rainfall) was lost through sub-surface drainage, where 74% of total water input was drained from RWS (a significant amount of water was lost from WSR-FI (92%) followed by DSR-AWD treatments (65%), and no loss from wheat), while no drainage losses occurred from CWS (all three crops). The root water uptake in RWS was 794 mm in WSR-FI and 768 mm in DSR-AWD, while it was 1067 mm in CWS, across three crops in both systems (Fig. SI3).

3.4. *Simulated long-term soil salinity dynamics as affected by irrigation amount and quality*

Results of different scenarios of the modeling approaches are shown in Fig. SI4 (for RWS) and Fig. SI5 (for CWS). With the current situation and conditions (same upper and bottom boundary conditions) – i.e., scenario 1, when the model ran for 10 crop rotations –unsurprisingly no significant changes in water content and soil EC can be seen in both cultivation systems. In RWS, when water application was reduced by half, the soil EC did not change significantly (only increased slightly). However, the quality of irrigation water has a significant consequence on predicted EC values when it is doubled (scenario 4). It can be noted that increasing ETo and decreasing water quality increased soil EC, especially in the upper layer. Similar results can be seen for CWS. Significant differences in changing soil EC by varying irrigation water quality and ETo are obvious in RWS compared to CWS. Overall, results of the scenario assessment indicate that soil salinity can be increased by 78% and 66% in RWS and CWS respectively when doubling irrigation water salinity and increasing ETo by 20% (Figs. SI4 and SI5).

Table 5

Averaged values of measured performance indicators under conservation (CA) and conventional (CT)-based practices in rice- and cotton-based systems.

Performance indicators in two cropping systems	Rice-wheat system												Cotton-wheat system					
	Rice						Wheat¶						Cotton		Maize		Wheat	
	WSR-FI		PB (DSR-AWD)		ZT (DSR-AWD)		WSR-FI		PB (DSR-AWD)		ZT (DSR-AWD)		CT	CA	CT	CA	CT	CA
	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009	2008	2008	2009	2009	2008	2008
Yield (kg ha^{-1}) (seed cotton and grain	7230	6900	5398	3494	5099	4354	7007	7804	7632	7010	6932	7349	4150	4120	4298	6480	8577	10,151
Net profit (USD ha^{-1})	2066	2289	1318	921	1340	1366	1264	1392	1270	1118	1253	1263	916	945	526	1048	1659	2005
Water productivity (kg grain m^{-3} water)	0.11	0.12	0.31	0.20	0.25	0.21	1.12	1.25	1.66	1.52	1.26	1.34	1.20	1.20	0.53	1.03	1.59	2.13
Nitrogen use efficiency (PFP-N, kg grain kg^{-1} elemental N)	29	28	22	14	20	17	39	43	42	39	39	41	33	33	43	65	86	102
Phosphorus use efficiency (PFP-P; kg grain kg^{-1} elemental P)	137	130	103	66	96	82	160	178	174	160	158	167	69	66	62	94	124	144
Potassium use efficiency (PFP-K; kg grain kg^{-1} elemental K)	87	83	65	42	61	53	120	134	131	120	119	126	51	49	73	112	148	175
GHG Emission Intensity (GHGI) (kg CO_2 emission t^{-1} grain)	1066	1117	1249	2004	998	1161	279	256	256	287	285	271	329	324	296	182	144	120
Sub-surface drainage loss of irrigation water (mm)	6260	5361	1045	1236	1293	1499	0	0	0	0	0	0	0	2	23	0	0	0
Carbon sequestration (kg SOC ha^{-1})	350	502	700	968	253	501	431	384	1104	1000	435	326	323	336	225	1484	445	2180
Soil salinity in top 30 cm depth at harvest (ECe; dS m^{-1})	1.71	1.10	1.79	1.07	1.51	1.05	1.64	–	1.93	–	1.77	–	3.85	3.29	1.73	1.63	3.75	3.22
Groundwater table (GWT) depth (m)	0.98	0.76	1.15	0.93	1.15	0.93	1.63	–	1.77	–	1.77	–	1.78	1.78	1.17	1.17	2.09	2.09
Groundwater salinity (GWS; dS m^{-1})	1.72	1.68	1.72	1.44	2.43	1.44	1.35	–	2.16	–	2.04	–	3.03	3.03	3.23	2.22	2.69	2.45
Energy use efficiency (EUE)	2.48	2.71	4.07	3.47	3.47	4.15	9.24	9.08	10.37	9.44	9.51	8.37	7.22	8.58	4.29	8.08	10.27	13.69
Loss of mineral N (kg ha^{-1})	129	141	148	161	140	174	12	−58	8	−70	−5	−76	−68	−65	30	−30	−42	−94

¶Note: All treatments in wheat was surface seeded. In rice-wheat system, PB = permanent bed plating without residue (R0); ZT = zero tillage planting in flat without residue (R0). In cotton-wheat system, CT = no residue, and medium N rate; CA = with residue, bed planting, and medium N rate.

3.5. *Sustainability of rice- and cotton-based cropping systems in salt-affected soil*

3.5.1. *Trade-off among sustainability indicators as affected by CA practices*

Under CT systems, the comparison of three crop seasons (two rice and one wheat in RWS, and cotton, wheat, and maize in CWS) showed that RWS had a higher equivalent yield (+23%), net profit (82%), SOC sequestration (+15%), and lower soil salinity (−72%), with the trade-off of lower water productivity (−150%), NUE (−41%), EUE (−31%) with higher GHGI emission (+223%) than in CWS (Fig. 6A; Table 5). Also, a significant amount of irrigation water drained out from the rice field which raised the GWT to a shallow level. Rice had the highest net profit followed by wheat (CWS), wheat (RWS), cotton, and the lowest in maize. CA practices (no-tillage bed planting with residue retention) with medium N rate had significantly higher positive sustainability indicators in CWS, where CA had high yield (+19%), net profit (+20%), WP (+27%), NUE (+20%), PUE (+18%), KUE (+20%), SOC (+456%), and EUE (+35%), with 7% low soil salinity and 12% lower GHGI than under CT (Fig. 6C). Also, the trade-offs among different indicators in different resource-saving practices in rice observed that WSR-FI had a trade-off for higher yield and profit with the lowest WP (−51%), GHGI (−48%), and EUE (−24%) lower than DSR-AWD (Fig. 6D). In contrast to CWS, the CA-based practices in RWS (i.e., DSR-AWD-R100) had the lowest yield, N-, P-, and K-use efficiency, and profitability, but the highest amount of SOC sequestration with the highest GHGI.

3.5.2. *Trade-off among sustainability indicators across three N rates in cotton-wheat system*

The trade-off among different sustainability indicators across three N rates in cotton, wheat, and maize crops showed an appropriate N rate is key for improving the sustainability indicators – wherein all three crops majority of the sustainability indicators were at the lowest level without N fertilizer application (0 kg ha^{-1} N), but indicators improved with the application of high N rates. The response of N fertilizer rate was higher in CA-based practices than under CT. The highest N rate improved most of the sustainability indicators in wheat and maize crops, while the medium N rate (except carbon sequestration) improved in cotton (Fig. 7). In all three crops in both establishment methods, medium N rate had the highest NUE, while the highest N rate had the highest PUE and KUE and SOC sequestration potential, indicating increasing N application improved yield and biomass production through the better uptake and utilization of P and K. In all three crops and both establishment methods, medium N rate had consistently the lowest salinity while the lowest N rate had the highest salinity. Residue retention did not have an effect in cotton (might be due to transition season from CT to CA), while in wheat and maize, it increased yield (+10%), WP (+10%), SOC sequestration (+355%), and EUE (+16%), while reducing soil salinity (−16%) and GHGI (−15%). Even without residue retention, wheat and maize crops with PB increased yield (+18%), SOC sequestration (+22%), NUE, PUE, and KUE (+ from 18 to 22%), EUE (+38%) with reduced GHGI (−18%), but with an increment of salinity (+20%) compared to CT.

4. Discussion

Our results from the mixed-method approach clearly indicated that the sustainability of salt-affected irrigated drylands can be improved through the combination of a better choice of crop and cropping system, crop-specific adoption of CA-based management, optimal use of irrigation water (amount and quality), and optimal N fertilizer management. These practices not only reduced soil salinity but also increased yield, profitability, and SOC sequestration (Figs. 6, 7). In the irrigated drylands, improving sustainability with better soil salinity management is vital for achieving SDG goals, such as #2, 6, 13, and 15 (Singh, 2021; UNDP, 2017). To meet increasing food demand, these drylands need to be managed while balancing gains in economic, environmental and soil

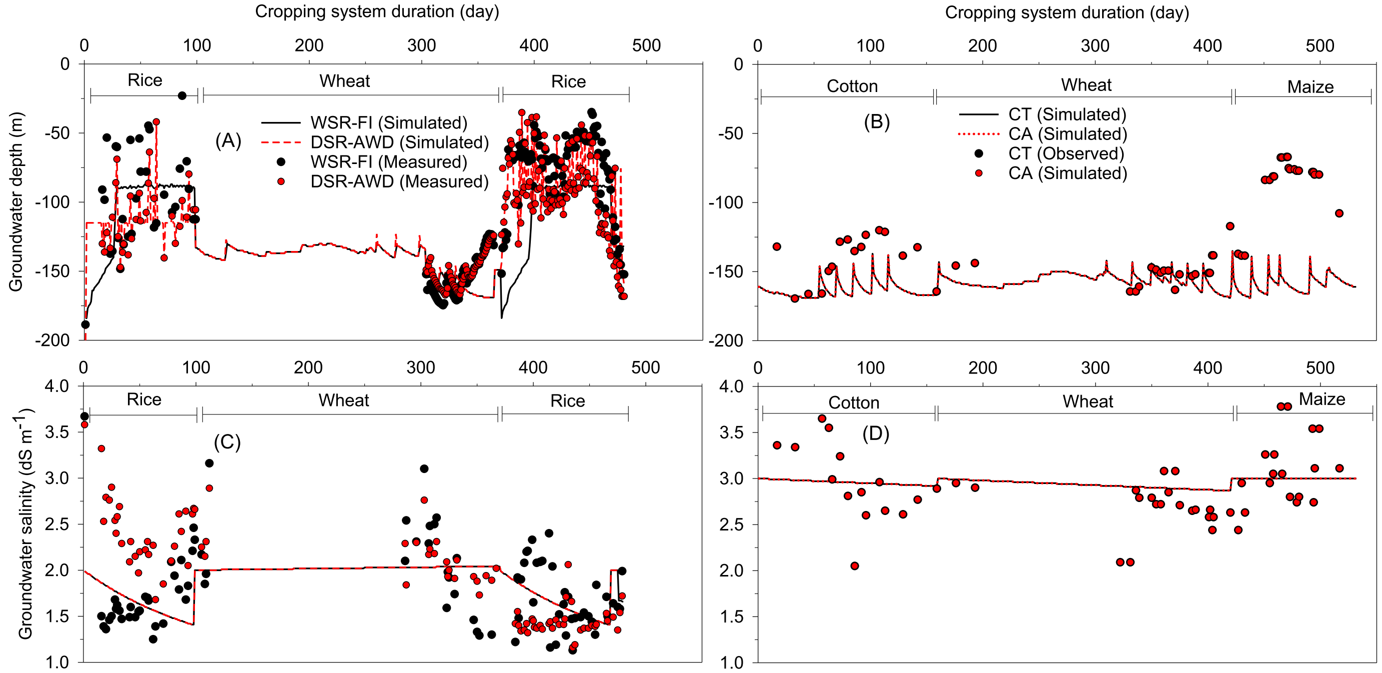

Fig. 5. Measured and simulated (Hydrus-1D) groundwater table (m) in rice-wheat system (A), cotton-wheat system (B) and groundwater salinity (dS m^{-1}) in rice-wheat system (C) and cotton-wheat system (D) in 2008–2009. WSR-FI = wet-direct seeded rice with flood irrigation; DSR-AWD = dry-direct seeded rice with alternate wet and dry irrigation; CT = conventional practices. The GWT depth is the averaged value from 6 piezometers in the DSR-AWD and from 3 piezometers in the WSR-FI in RWS and from 20 piezometers in CWS.

health and resilience indicators. Our findings help in improving sustainability through prevention and management of degrading soil in irrigated drylands.

4.1. Soil and groundwater salinity dynamics under different innovations

Soil salinity has been reduced through the optimization of irrigation water (quantity and quality) (Figs. SI4 and SI5) and the adoption of CA-based practices (minimum soil disturbance + residue retention) (Figs. 1, 2). Reduced water application lowered GWT depth (Fig. 5) and decreased sub-surface drainage loss of water (Fig. SI3). Similarly, permanent soil cover under CA minimized the increasing soil salinity level by reducing evaporation loss of water from the soil surface and minimized secondary soil salinization (Devkota et al., 2015a; Hasan et al., 2015; Kienzler et al., 2012). Reduced irrigation application (Nassah et al., 2018; Wang et al., 2019), decreased evaporative loss of water (Hou et al., 2016; Wang et al., 2019), and controlled GWT depth and GWS level (Soppe and Ayars, 2003), have been reported as the sustainable and rehabilitating technologies for salt-affected irrigated drylands.

Lower soil salinity in RWS than in CWS in this study is mostly due to the high amount of water application (irrigation water salinity 1.2 to 2.4 dS m^{-1}). However, a high amount of water application shallowed GWT depth (Fig. 5) and increased sub-surface drainage loss (Fig. SI3), which enhances secondary soil salinization. The shallow GWT (Fig. 5) showed both systems might worsen secondary salinization, while the chance of worsening GWT is higher with RWS. Salt accumulation by soil evaporation and transpiration is generally higher when the GWT is less than 1.5 m below the soil surface (Hopmans et al., 2021). Furthermore, RWS had a lower irrigation water use efficiency (mainly in rice; 7% in WSR-FI and 23% in DSR-AWD) (Table 5), with a significant amount of water loss through sub-surface drainage (Fig. SI3) than in CWS. Also, in long-term simulation (Fig. SI4), RWS is considered an unsustainable system as it enhances soil profile and groundwater salinity if continuously practiced >10 years with current production practices. All these findings indicated that RWS is more vulnerable to salinization by enhancing secondary salinization compared to CWS.

The water-saving method of rice cultivation (DSR-AWD) helped to reduce irrigation amount and sub-surface drainage loss by more than one-third (Fig. SI3) and increased water productivity, but had a trade-off with soil salinity, productivity, and profitability (Fig. 6D). A significant amount of water loss from the DSR-AWD (PB and ZT) also suggests the proposed alternative establishment method (DSR) and the water-saving irrigation (AWD) is inefficient in improving irrigation efficiency in rice. However, as DSR-AWD is cost-saving technology, upon the availability of suitable salt-tolerant aerobic rice varieties, it can be an alternative option in a water-scarce environment with low drained soil (Radanielson et al., 2018). Bed planting without retaining the crop residue as surface mulch increased soil salinity level in both RWS and CWS (Fig. 2). This could be due to the reduction in surface evaporation with surface mulch in residue retained treatment, whereas in RWS, residue retention reduced surface evaporation by 123 and 53 mm during rice and wheat seasons, respectively, compared to residue harvest.

The simulated long-term scenario results (6 scenarios in RWS and 4 scenarios in CWS) demonstrated that irrigation water salinity (both canal and groundwater) and amount are key for the long-term sustainability of the irrigated drylands for minimizing salinization and land degradation. The simulation results, while doubling salinity of water input and increased evapotranspiration (Figs. SI4, SI5), showed climate change, global warming, and human-induced activities (over fertilizer/solute application, mismanagement in irrigation amount and quality, and improper cropping systems) can further worsen soil salinization. Irrigation using groundwater or surface water with salinity levels higher than the soil salinity is risky, and a policy on the threshold of irrigation water salinity and restriction in the application of higher salinity irrigation water than soil salinity is required.

The trends of declining freshwater availability, increasing salinity of fresh and groundwater, raising water table, and worsening drainage systems are increasing in irrigated drylands of the Aral Sea Basin (Kulmatov et al., 2020; Stavi et al., 2021), South Asia (Bhatt et al., 2021; Timsina and Connor, 2001), India (Singh, 2009), China (Huang et al., 2016; Li et al., 2014; Siyu et al., 1996), Vietnam (Nguyen et al., 2014),

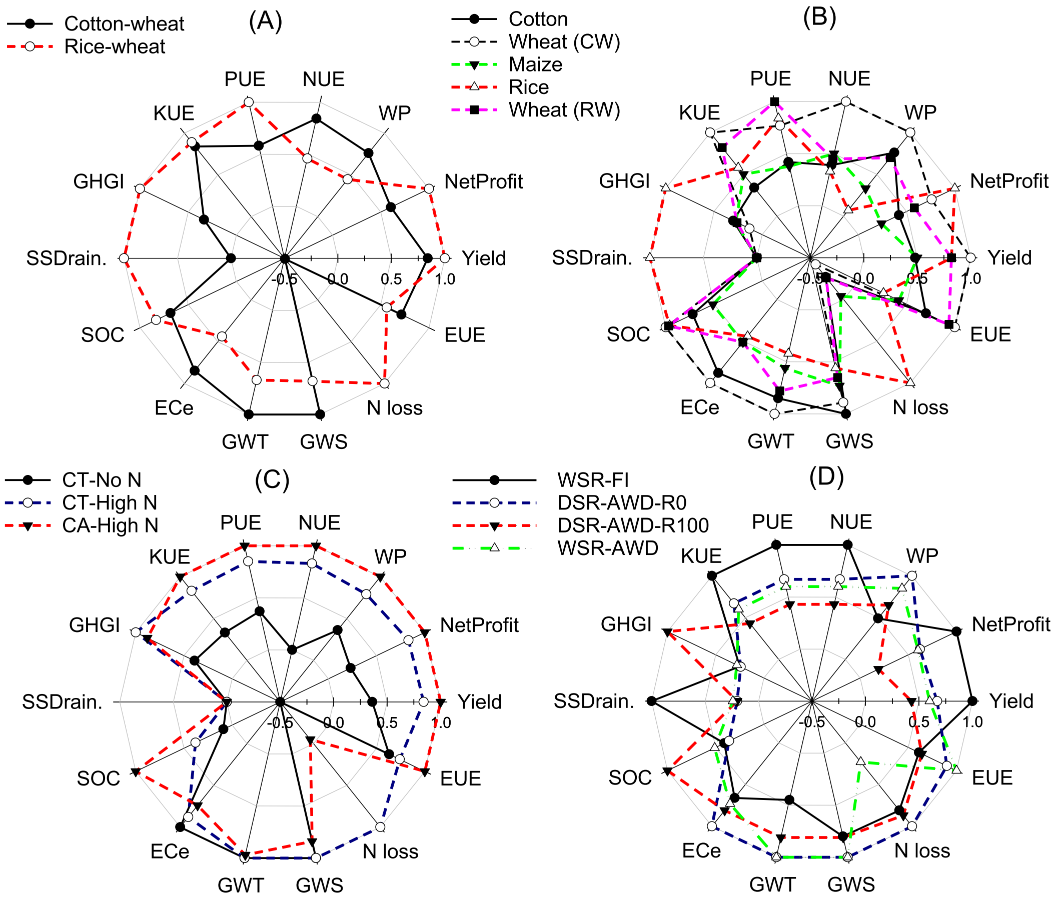

Fig. 6. Trade-offs among sustainability indicators between RWS and CWS (A), among different crops (B), among conventional (CT) and conservation agriculture (CA)-based practices in cotton-wheat system at low and high N rates (C), and among the conventional (wet-direct seeded) method of crop establishment and flood irrigation (WSR-FI), dry-direct seeded with water-saving irrigation (DSR-AWD) with two residue rates (0 and 100%), and conventional method of crop establishment but with water-saving irrigation (WSR-AWD) in rice in rice-wheat system (D). Data combined over three crops (cotton, wheat, and maize in cotton-wheat and for two years in rice-wheat system. WP = water productivity; NUE = Nitrogen use efficiency; PUE = Phosphorus use efficiency; KUE = Potassium use efficiency; GHGI = GHG emission intensity (kg CO_2 t^{-1} grain); SSDrain. = Sub-surface drainage of the irrigation water; SOC=Soil organic carbon sequestration (kg C ha^{-1}); ECe = Soil Salinity (ECe dS m^{-1}); GWT = Groundwater table depth (m); GWS = Groundwater salinity (dS m^{-1}); EUE = Energy-use efficiency; and N loss = Loss of mineral N (kg ha^{-1}).

Pakistan (Syed et al., 2021), Mediterranean region (Shahid et al., 2018; Tomaz et al., 2020), and several other irrigated dryland region and countries (Hopmans et al., 2021). In those regions, excessive use of irrigation water with marginal quality, rising water table, increasing salinity of irrigation water, climate change and rainfall variability are increasing risk of crop production, and the findings from this study might offer a risk minimization opportunities in those areas. In such conditions, secondary salinization can be minimized by: (i) AWD irrigation with a further reduced volume of irrigation water using crop-demand based surface, sub-surface, drip, mulched drip or sprinkler irrigation (Hopmans et al., 2021); (ii) adaptation of alternative crops other than rice, which requires low irrigation water and tolerates salinity; (iii) adapting cropping systems with salt-tolerant crop species; (iv) developing efficient drainage schemes in drylands, as reported by Jafari-Talukolaee et al. (2016) in Northern Iran; (v) and an improved sub-surface drainage system coupled with improved agricultural water management ('integrated on-farm drainage management'), as reported by Hopmans et al. (2021) to reduce the rate of soil salinization in California, USA.

4.2. Potential for improving sustainability of crop production in salt-affected irrigated drylands

High productivity, profitability, and EUE with a reduced environmental footprint (GHGI) enhance sustainability in crop production (Devkota et al., 2020; Gathala et al., 2020). Fourteen performance indicators computed and compared in this study clearly showed the potential for improving sustainability through accelerated adoption of integrated soil, water and other agronomic practices. The increased system productivity, profitability, WP, NUE, PUE, KUE, SOC sequestration, and EUE with lower soil salinity (−7%) and yield scaled GHGI (−14%) than in CT practice (Fig. 6C), indicates that sustainability of existing CWS can be improved with the adoption of CA-based practices. In RWS, DSR with AWD improved water productivity, reduced water input, improved EUE and SOC sequestration, and lowered GWT depth. However, it could not prove superior to WSR-FI in yield and profitability, indicating WSR-FI still can be the choice if water is available as a free gift. However, in light of predicted future conditions regarding declining water resources in the Aral Sea Basin, rice cultivation with flood irrigation cannot be advised. Under the water-scarce conditions, low water productivity (−147%); NUE (−70%); EUE (−46%) but with high GHGI (+220%), and increased GWT by 25% in RWS than in CWS (Fig. 6A), might offset the positive benefits from RWS, i.e., higher profitability with reduced salinity. In the drylands, long-term sustainability is more important than short-term economic benefit (e.g., rice production) (Schwilch et al., 2014). The high profitability of RWS was due to the higher yield and price of rice than cotton. A higher amount of SOC-sequestration in RWS was due to a higher amount of residue/straw

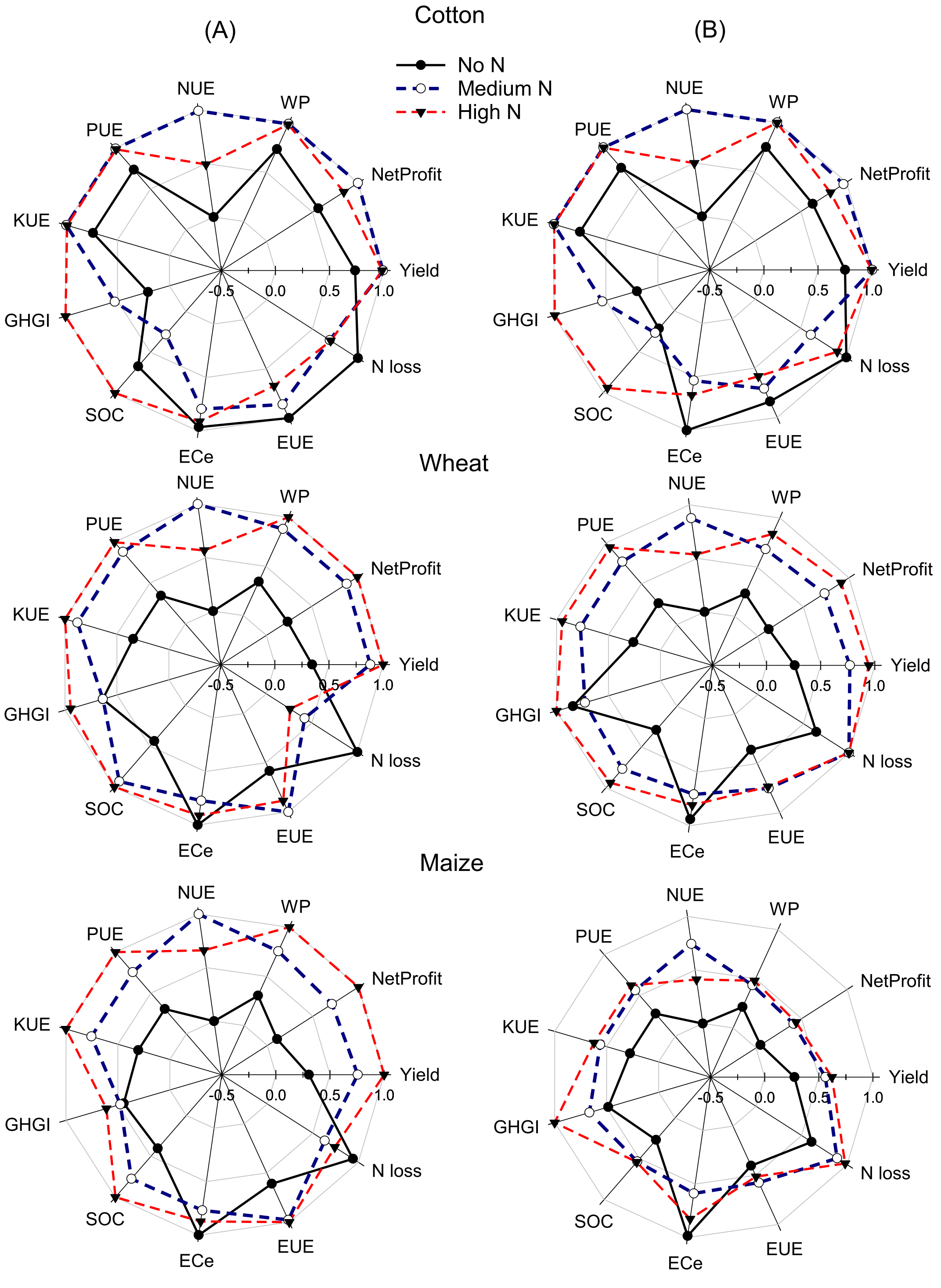

Fig. 7. Trade-offs among sustainability indicators across three N (no, medium, and high N rates) in cotton, wheat and maize crops under conservation agriculture (CA; A) and conventional practices (CT; B) practices in cotton, wheat and maize crops in cotton-wheat system in Khorezm region of Uzbekistan. Sub-surface drainage, groundwater table depth and groundwater salinity were not plotted as these indicators were not measured across three N rates. For the description of the figure symbols, Fig. 6.

production by the rice crop than cotton. Although SOC is the major indicator of soil health (Giongo et al., 2020; Hopmans et al., 2021), higher SOC-sequestration through rice requires at least 3 times higher water input than in cotton (Devkota et al., 2013b, 2013c).

In crop-wise comparison (Fig. 6B), wheat (winter season) crop had the highest number (6) of positive indicators (yield, WP, NUE, KUE, SOC-sequestration, EUE) with the lowest GHGI, indicating its better resilience. Water productivity is the key indicator for crop production in the drylands, and it will further be important in the context of future climate change (Shi et al., 2021). Among the three summer crops (rice, cotton, and maize), rice had the highest profitability but lower value among other indicators. On the other hand, maize had the lowest value for the majority of sustainability indicators, suggesting cotton is still the best among the three crops. However, in comparison to other crops, an increase in soil salinity was seen with an increase in cotton cultivation (Figs. 1, SI5). Therefore, technologies mitigating salinity problems, for instance, CA with residue retention, or alternate-skip-furrow irrigation (Devkota et al., 2015c), are suggested for the sustainability of cotton planting in the region. Similar findings on the improvement of sustainability with a reduced environmental footprint (GHGI) using CA-based management practices were also reported by Jat et al. (2020) in the Indo-Gangetic Plains. Further, lower GHGI or yield-scaled emissions with high EUE with CA-based practices in CWS indicated gains in agricultural productivity is also possible.

NUE in rice remained critically low compared to other crops (Fig. 7), indicating the need for better N management for improving sustainability. In CWS, the optimal N rate increased many of the sustainability indicators and helped minimize the soil salinity (Fig. 7). However, under the highest N rate, 83 and 35 kg ha^{-1} mineral N was lost from cotton and maize fields (Fig. 6; Table 5) and higher GHGI in CWS indicated that the N rate should be optimized based on the crop demand. A higher N rate alleviated the negative effects induced by salinity stress and helped to improve plant growth and yield by maintaining the integrity of the photosynthesis and chlorophyll inflorescence processes in oat plants in salt-affected areas of Ontario, Canada (Song et al., 2019). It was also reported that N fertilization improved salinity tolerance of cotton (Chen et al., 2010) and wheat (Elgharably et al., 2010), as N plays both nutritional and osmotic roles in saline conditions. The combinations of treatments comprising different cropping systems, crop species, level of irrigation, residue applications, and N fertilizer showed farmers can adopt all practices as a package for better sustainability, or either practice, considering possible trade-offs as well as affordability and acceptability. However, under resource-constrained conditions, the choice of crops and cropping systems using CA-based practices, followed by optimal water and nitrogen management, might be the technologies for consideration for saline conditions.

5. Conclusions

The sustainability of crop production in salt-affected irrigated drylands is becoming challenging and further exacerbated by poor soil, water, and nutrient management. This study sought to understand how CA-based practices, coupled with adaptive management practices such as choice of crop and cropping system, water, and fertilizer management impact the sustainability of crop production in these conditions using mixed-method approaches (field experiments, simulation, and the multi-criteria analysis). Soil salinity dynamics differ with crop and cropping systems: RWS had a lower salinity than CWS. Significantly low WP, EUE, and NUE with high GHGI and a greater sub-surface drainage loss of water input, raised GWT depth and increased the probability of secondary salinization under RWS – indicating that CWS has a higher sustainability index over RWS. In rice, adoption of DSR-AWD technology saved water input, doubled the WP and SOC sequestration, improved EUE, and decreased the probability of secondary salinization, compared to WSR-FI – hence it can be an alternative under the water-scarce condition if RWS is the dominant system. Residue retention was found to be beneficial in the irrigated drylands in both RWS and CWS, where SOC content increased by more than 300%, offering the opportunity to improve soil health. In CWS, CA-based practices (no-tillage and residue retention) reduced salinity level, while CA with optimal N ha^{-1} has the greatest potential for improving sustainability with resilience. A better choice of crops and cropping systems, CA-based management practices, appropriate N application rate, and water-saving irrigation, are critical to improving the sustainability of the agricultural production system in the salt-affected degrading irrigated drylands of Central Asia and the regions with similar conditions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2022.103390.

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