Agricultural and Forest Meteorology 214–215 (2015) 266–280

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

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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ARTICLE INFO

Article history:
Received 9 December 2014
Received in revised form 30 June 2015
Accepted 24 August 2015

Keywords:
DSSAT
CERES-Rice
CERES-Wheat
Alternate wet and dry (AWD) irrigation
Conservation agriculture (CA)

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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http://dx.doi.org/10.1016/j.agrformet.2015.08.264

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.