Agricultural Water Management 177 (2016) 248–263

Contents lists available at ScienceDirect

Agricultural Water Management

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

Towards modeling soil texture-specific sensitivity of wheat yield and water balance to climatic changes

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ARTICLE INFO

Article history:
Received 24 December 2015
Received in revised form 23 July 2016
Accepted 27 July 2016

Keywords:
Crop-climate interactions
CSM-CERES-Wheat
Global warming
MarkSimGCM
Soil texture

ABSTRACT

Climate change has significant influences on agricultural water management particularly in arid and semi-arid regions. Increased water scarcity and consecutive droughts in these regions must be extensively taken into considerations in any water management scheme dealing with agricultural production. This study was aimed to find out climate changes impacts on soil water balance components and rainfed wheat yield, phenology and failure across eight different soil textural classes over 2070–2099. In order to project the future conditions, outputs of five climate models under RCP-4.5 and RCP-8.5 downscaled by MarkSimGCM were used to drive the CSM-CERES-Wheat v4.6 model. Results indicated that crop-growing season will be shorter by 10.7–21.6 days under RCP-4.5 and 25.8–45.5 days under RCP-8.5. Averaged across all investigated soils, the crop yield would decline in four studied large areas mainly due to drought and inappropriate planting date. Yield loss, averaged across all sites, are likely to be higher in finer-texture soils. More frequent harvest failure can occur over the 2080s particularly in the finer-textured soils at most studied sites. Deep drainage and runoff are expected to drop in almost all soils due to rainfall deficit. Decline of evaporation appears likely as a consequence of drought, shorter growing period and change of evapotranspiration partitioning. The crop model projected larger reduction in drainage and evaporation for coarse soils and in runoff for finer-textured soils. Higher transpiration, averaged over all sites, in coarser soils can be attributed to considerable decline of nitrogen leaching and higher subsoil water content. Furthermore, there would be an increase in soil water storage under most soil-climate simulation runs particularly in heavy-textured soils. In general, soil texture as an inherent static property highly conditions crop-climate interactions in changing climates. Furthermore, rainfed wheat production would likely be more sustainable on coarser soil textures under climate changes.

1. Introduction

Agricultural productions and food security in water-limited systems are highly impacted by water scarcity and non-water limiting factors such as poor nutrition and salinity (Rockström et al., 2010; Saadat and Homaee, 2015). In arid and semi arid regions, both water scarcity (Homaee et al., 2002a, 2002d) and salinity (Homaee et al., 2002b, 2002c; Homaee and Schmidhalter, 2008) are the two main important challenges for agricultural water management. Since pre-industrial period, rising atmospheric concentration of greenhouse gases and aerosols mainly as a result of fossil fuel overuse, land use/cover changes and agricultural activities have triggered anthropogenic global warming and climate change (CC) (IPCC, 2013). Drought exhibited upward trend since 1950 and was projected to be more severe and widespread in the future due to climatic changes, namely decreased precipitation and/or higher atmospheric evaporative demand (Dai, 2011, 2013). In the eastern Middle East including west of Iran, meteorological drought would also be more frequent and severe due to declined storm track activity (Evans, 2009). In other words, the already drought prone and water limited regions such as Iran are likely to be more liable to CC-related drought (Li et al., 2009).

The average rates of reduction in major crop yields linked to drought disaster will likely be more than 50 and 90% in 2050 and 2100, respectively, over the globe (Li et al., 2009). This drought-induced yield decrease associated with increased food demand due to westernization of diet and growing population will likely result in food insecurity in water-limited developing countries

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http://dx.doi.org/10.1016/j.agwat.2016.07.025

such as Iran (Tai et al., 2014). Therefore, it seems that more knowledge related to planning and managing water resources under climate changes is required to avoid harvest failure and food shortage in water-controlled environments. Meteorological drought and global warming would influence the components of soil water balance through affecting soil water-temperature and soil water-precipitation feedbacks (Seneviratne et al., 2010). The mathematical expression of root zone water balance can be written as (Hillel, 1998):

$$\overbrace{(P+I)}^{Gains}-(\overbrace{E+T+D+R}^{losses})=\overbrace{\Delta S}^{Storage\ \ change} \quad (1)$$

$$S=\sum_{i=1}^{n}\theta_i * \Delta Z_i \quad (2)$$

where P denotes precipitation, I irrigation (included in irrigated lands), E soil evaporation, T plant transpiration, D deep downward drainage (deep percolation or leakage), R surface runoff, ΔS change in root zone water storage, θ volumetric soil moisture ($cm^3\ cm^{-3}$), Z soil horizons depth and n the number of soil layers. The components are expressed in terms of volume of water per unit soil area (i.e. equivalent depth of water) during specific time interval.

Considering heavy dependence of agricultural production on soil moisture storage particularly under rainfed condition (Bannayan et al., 2011), change of water balance is expected to greatly impact crop production under CC (Yang et al., 2015; Yang et al., 2014). Assessing climatic changes impacts on soil water balance components can therefore shed light on crop-climate interactions in the future (Eitzinger et al., 2003; Jalota et al., 2014). Soil texture also controls some ecological and hydrological processes such as water retention, aeration and nutrition availability (Hillel, 1998; Rodríguez-Iturbe and Porporato, 2005). Hence, the crop response to CC and variability is expected to vary with soil texture (He et al., 2014). Moreover, different scenarios and features of future climatic changes appear to influence crop yield differently depending on soil texture. van Ittersum et al. (2003) predicted an increase and a decline of wheat yield in a sandy soil under drier (decline of precipitation by 25%) and warmer (increase of temperature up to 3 °C) scenarios, respectively, in western Australia. On the contrary, compared with the sandy soil, the inverse changes were simulated for yield on a clay soil under above-mentioned scenarios. As a result, appropriate adaptation strategy may differ with soil types. Ludwig and Asseng (2006) concluded that wheat production on an acid sandy loam soil would likely be less vulnerable to drier and warmer climatic condition compared with a clay soil in western Australia. El Chami and Daccache (2015) also projected that climatic changes are likely to more negatively influence rainfed wheat grown on a silty clay loam (heavy-textured) soil with respect to that on a sandy loam (lighter-textured) soil in the east of England. These findings illustrate that yield response to CC will be largely impacted by soil texture. Using virtual soil profiles, Bormann (2012) found that soil texture greatly affects sensitivity of soil moisture storage changes to global warming. Yang et al. (2014) concluded that crop response to CC markedly varies with soil type. Yang et al. (2015) also studied the likely climatic changes effects on water balance components of 12 soil types under wheat in southeastern Australia. They used all soils for all surveyed sites to establish a broad range of soil types with different available water capacity. P, E and T were predicted to descend in 2021–2040 as the growth period will be shortened, while R and D would less likely be changed significantly. Further, they pointed out that spatial analyses of yield response to CC can be less uncertain and confounding if a broad range of soil types (not only a representative soil profile) are considered. The method (i.e. considering different soils for a site) used by Yang et al. (2014) can be helpful for deepening our understanding of uncertainties associated with spatial variability of soil physical properties which has been poorly addressed in the climate change literature.

To our knowledge, no research has been carried out to date to directly assess the CC influences on crop yield and water budget across a broad range of soil textures. Therefore, this study was aimed to find the CC impacts on soil water balance components, and rainfed wheat yield, growing season length and failure during the 2080s (2070–2099) relative to the baseline (1961–1990) under RCP-4.5 and RCP-8.5 over eight different textural classes in the west of Iran.

2. Materials and methods

2.1. Study area

Iran has a wide range of climatic conditions which includes 9 out of 30 climate types based on updated Köppen-Geiger climate classification (Peel et al., 2007) mainly due to the existence of the Alborz and the Zagros mountain ranges. Rain producing air masses predominantly enter from the west and northwest of Iran and cause above-average rainfall (around 300–500 mm precipitation per year) in the western half of the country owing to the Zagros mountain chain geographical location (Sadeghi et al., 2002). Consequently, semi-arid Mediterranean climate mostly dominates in the west and northwest of Iran. According to the results of some works conducted to analyze trend of precipitation (Tabari and Talaee, 2011b), temperature (Tabari et al., 2011; Tabari and Talaee, 2011a) and reference crop evapotranspiration (Talaee et al., 2014) during recent five decades, there was a shift towards drier and warmer climatic condition in Iran. The study area and location of surveyed sites are depicted in Fig. 1. Geographic and climatic characteristics of all stations are also given in Table 1.

2.2. Data

2.2.1. Climatic data

In this study, MarkSimGCM was employed to downscale coarse-scale GCMs (General Circulation Models) outputs to a 0.5° × 0.5° latitude/longitude grid resolution using stochastic downscaling and climate typing techniques (Jones and Thornton, 2013). MarkSimGCM generates rainfall based on third-Markov stochastic model and daily temperature (minimum and maximum) as well as solar radiation using Richardson (1981) approach. The model collects the baseline period climate data (1961–1990) from the WorldClim database. In this study, an ensemble mean of five GCMs participating in the fifth phase of Coupled Model Intercomparison Project (CMIP5) (IPCC, 2013), i.e. BCC-CSM 1.1(m) (Beijing Climate Center, Climate System Model, version 1.1 (moderate resolution), 2.81° × 2.81° latitude/longitude) (Wu, 2012), FIO-ESM (First Institute of Oceanography-Earth System Model, 2.81° × 2.81° latitude/longitude) (Song et al., 2012), GFDL-ESM2M (Geophysical Fluid Dynamics Laboratory Earth System Model with MOM, version 4 component, 2° × 2.5° latitude/longitude) (Dunne et al., 2012), (Institut Pierre-Simon Laplace Coupled Model, version 5A, low resolution, 1.87° × 3.75° latitude/longitude) (Dufresne et al., 2013) and MIROC-ESM-CHEM (Model for Interdisciplinary Research on Climate, Earth System Model, Chemistry Coupled, 2.81° × 2.81° latitude/longitude) (Watanabe et al., 2011) under RCP-4.5 and RCP-8.5 (Representative Concentration Pathways) were used for future climate condition. It should be noted that combining GCMs outputs enhances the skill, reliability and consistency of climate model forecasts (Donat et al., 2010; Tebaldi and Knutti, 2007) and reduces the bias of simulations (Fu et al., 2005). Cantelaube and Terres (2005)