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An application of the water footprint assessment to optimize production of crops irrigated with saline water: A scenario assessment with HYDRUS

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ABSTRACT

Agriculture, due to a growing scarcity of fresh water resources, often uses low-quality waters for irrigation, such as saline waters. However, unmanaged applications of such waters may have negative environmental and economic consequences. Based on the concept of the water footprint (*WF*), a measure of the consumptive and degradative water use, the field-calibrated and validated HYDRUS (2D/3D) model was applied to find optimal management scenarios (from 1980 different evaluated scenarios). These scenarios were defined as a combination of different salinity rates (SR), irrigation levels (IL, the ratio of an actual irrigation water deth and a full irrigation water depth), nitrogen fertilization rates (NR), and two water-saving irrigation strategies, deficit irrigation (DI) and partial root-zone drying (PRD). The consumptive *WF* was defined as the crop water consumption divided by the crop yield. The grey *WF* was calculated for the N fertilizer and defined as the volume of freshwater required to dilute nitrogen (N) in recharge so as to meet ambient water quality standards. Simulated components of water and solute dynamics were used to calculate criteria indices, which were divided into two groups: (a) environmental indices, including the degradative grey water footprint (*GWF*) and the apparent N recovery rate efficiency (*ARE*), and (b) economic indices, including economic water (*EWP*) and land (*ELP*) productivities. While significant improvements of 3.9–59.2%, 0.1–165.8%, and 0.01–166.5% in *ARE*, *EWP*, and *ELP*, respectively, were obtained when NR varied within the range of 0–200 $\mathrm{kg\,ha^{-1}}$, changes in these indices were relatively minor when NR was higher than 200 $\mathrm{kg\,ha^{-1}}$. At a given NR, *GWF* tends to increase considerably by up to 180% when DI-crops are subject to low-intermediate salt ($\mathrm{SR} < 7\,\mathrm{dS\,m^{-1}}$) and water ($\mathrm{IL} > 70\%$) stresses. This is at the expense of up to a 55% reduction in *ELP* and up to a 120% increase in *EWP*. With N uptake 0.2–17.3% higher, PRD seems to be a more viable agro-hydrological option than DI in reducing a pollutant load into regional aquifers as well as in sustaining farm economics. The entire analysis reveals that the PRD strategy with N-fertilization rates of 100-200 $\mathrm{kg\,ha^{-1}}$, a moderate salinity stress ($\mathrm{SR} < 5\,\mathrm{dS\,m^{-1}}$), and irrigation levels of 60–90% represents the best management scenario. It can be concluded that, while there is a substantial need for rescheduling irrigation and fertilization managements when crops are irrigated with saline waters, HYDRUS modeling may be a reliable alternative to extensive field investigations when determining the optimal agricultural management practices.

1. Introduction

It has been well documented that groundwater pollution induced by the agricultural sector poses a serious and widespread environmental threat to Iran (e.g., Karandish et al., 2016), California (e.g., Harter and Lund, 2012), and many other countries. In Iran, after the 1979 Islamic revolution, the government implemented several new agricultural policies aimed at achieving national food security through increased domestic productivity and self-sufficiency of staple crops (Karandish and Hoekstra, 2017). The construction of irrigation and drainage networks and enhanced applications of organic/inorganic fertilizers were among these policies. While Iran's policy on agricultural self-sufficiency satisfied growing demands for food and raw materials, ill-thought-out agricultural practices resulted in adverse environmental consequences. The alteration of the balance of soil N compounds through excessive uncontrolled applications of N-fertilizers above optimal amounts and without considering crops N requirements led to significant groundwater pollution (Zhu et al., 2005; Thompson et al., 2007; Dudley et al., 2008; Burow et al., 2010; Dahan et al., 2014; Karandish et al., 2016).

Nitrate vulnerability may be of particular interest in water-scarce

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regions where crops need to be produced with minimal fresh water. In these regions, there is room for savings of fresh water if crops receive less irrigation water during their growing season (Karandish and Šimůnek, 2016a). In this regard, many researchers have investigated the economic and environmental consequences of applying deficit irrigation (DI) (Payero et al., 2006; Klocke et al., 2004; Stone, 2003) or partial root-zone drying (PRD) (Dry and Loveys, 1998; Kang and Zhang, 2004; Kirda et al., 2004; Shao et al., 2008; Tang et al., 2005; Karandish and Šimůnek, 2016a, 2016b). They mostly concluded that, while significant economic losses could be expected under DI, PRD may produce water savings without a significant decrease in yields. While crops are exposed to the water stress under both DI and PRD, the way the stress is applied under PRD may produce better results. A regular alternation of irrigated and non-irrigated sides of the crop under PRD results in the secretion of root-generated Abscisic Acid (ABA) (Schachtman and Goodger, 2008), which is transported to shoot regulating stomata of the leaves. Such regulation reduces crop water losses through stomata, while maintaining crop CO_2 adsorption at the favorable level (Kang and Zhang, 2004), which consequently results in a higher crop water use efficiency compared to DI, or even FI (Karandish and Šimůnek, 2016a).

Although irrigation with saline waters may be another alternative to using fresh water in the agricultural sector (Pereira et al., 1995), this may lead to serious economic and environmental losses if not managed properly (Yurtseven and Sönmez, 1992; Mer et al., 2000; Zhu et al., 2005; Thompson et al., 2007; Corwin et al., 2007; Dudley et al., 2008; Roberts et al., 2009; Burow et al., 2010; Dahan et al., 2014). Water or salinity stresses may reduce crop N uptake (Karandish and Šimůnek, 2017; Ramos et al., 2012) and lead to higher nutrient loads into aquifers as a byproduct of N leaching out of the root zone (Zhu et al., 2005; Thompson et al., 2007; Dudley et al., 2008; Burow et al., 2010; Dahan et al., 2014; Karandish et al., 2016). If fresh water is applied, N leaching may be lower under PRD than under DI due to a higher crop N recovery (Kang and Zhang, 2004; Kirda et al., 2005; Li et al., 2007; Wang et al., 2009; Hu et al., 2009; Wang et al., 2012; Karandish and Šimůnek, 2017), which could translate into lower groundwater contamination. Even so, no earlier studies have ever attempted to find the optimal combination of N fertilization rates and applied water levels under PRD irrigated with saline water.

The degradative grey water footprint (*GWF*) may be an appropriate measure to assess new adjustments to the N fertilization rate under combined water and salinity stress conditions. Considered an indicator of the pollution assimilative capacity (Chukalla et al., 2017), the *GWF* is defined as the volume of freshwater required to dilute a load of pollutants so as to meet ambient water quality standards (Hoekstra et al., 2011). The *GWF* of the crop production represents the volume of water needed to sufficiently lower nitrogen concentrations that reach the water systems due to leaching or runoff, given an ambient $NO_3{}^-N$ concentration of 10 mg l^{-1}, which corresponds to 44 mg l^{-1} of NO_3- (Self and Waskom, 2013, Shyns and Hoekstra, 2013). Increased N application rates beyond the optimal rate may significantly increase the *GWF*. On the other hand, a low N application rate can potentially hamper plant growth and result in a low crop yield (Raun et al., 2002) even though water pollution per hectare may still be small (Chukalla et al., 2017). Instead of carrying out laborious, time-consuming, and thus expensive field investigations with a limited number of treatments, an optimal N application rate can be estimated using a modeling approach (Karandish and Šimůnek, 2016a, 2016b, 2017). This may be especially advantageous in situations where it may be economically or technically impossible to carry out the project in the field (Li and Liu, 2011). Among a large number of analytical and numerical models simulating soil water and solute dynamics (e.g., Johnsson et al., 1987; Hutson and Wagenet, 1991; Ma et al., 2001; Šimůnek et al., 2008, 2016; Doltra and Munoz, 2010), the HYDRUS (2D/3D) model (Šimůnek et al., 2008, 2016) is among the most powerful models for evaluating sound agricultural practices due to its flexibility in accommodating different types of boundary conditions for water flow and solute transport, its ability to simultaneously consider root uptake of water and nutrients, and its sophisticated graphical user interface (Li et al., 2015; Karandish and Šimůnek, 2017).

The literature review reveals that there are many research gaps in this field of research. (i) Almost no research has been done on the use of the HYDRUS model to analyze soil-water-crop relationships under PRD. The concept behind PRD is different than behind DI and thus soil-water-crop relationships may be affected by these differences. While the HYDRUS model has been previously used to simulate soil water and nutrient dynamics under PRD (Karandish and Šimůnek, 2016a, 2016b, 2017), this has not yet been done while taking into account simultaneously both water and salinity stresses and their effects on soil-water-crop relationships. (ii) Similarly, little research has been carried out to find optimal management strategies with respect to both economic and environmental factors. While some limited work has been done with respect to finding an optimal combination of water-salinity-fertility levels for DI (Azizianand Sepaskhah, 2014a, 2014b), no similar work has been done for PRD. No research has considered simultaneously both environmental and economic indices when finding optimal management strategies for the DI or PRD strategies. (iii) Finally, no research has been carried out at the field scale to assess the total and grey water footprints under different combinations of water, fertility, and salinity stress (for both DI and PRD). While developing benchmark levels of the water footprint (*WF*) is still in its infancy, none of the previous studies have addressed the salinity stress in their analysis when benchmarking *WF*. In addition, the economic benefits associated with a more efficient water consumption due to benchmarking have not been quantified before.

Hence, the current study aims to advance the field of *WF* benchmarking by (i) developing field-specific benchmark levels for both total and grey *WF*s for various water-salinity-fertility scenarios and (ii) comparing the economic water productivities of the current crop production with productivities if *WF*s were reduced to benchmark levels. Therefore, the water footprint concept is applied in this study to provide the best 10% and 25% combinations of N-application rates and irrigation levels for different salinity rates under two water-saving irrigation strategies of DI and PRD with respect to both environmental and economic indices. The HYDRUS (2D/3D) model (its 2D level) is first calibrated and validated using a two-year field dataset and then used to analyze the soil-water-crop interactions for a large number of scenarios involving different combinations of N fertilizer rates, irrigation water levels, and salinity levels of the irrigation water under the DI and PRD conditions. The simulated results are then used (i) to calculate both consumptive and degradative *grey WF* related to crop production for various scenarios, (ii) to economically analyze the probable consequences of the defined scenarios, and, finally, (iii) to find the optimal management strategies with respect to both economic and environmental factors.

2. Materials and methods

2.1. Data collection

During the 2010 and 2011 cropping cycles, a two-year field investigation was carried out in the 825 m^2 (15 × 55 m) maize field at the Sari Agricultural Sciences and Natural Resources University in Sari, Iran. Daily weather data were collected at the weather station near the experimental field. Soil textures at 0–20 cm and 20–100 cm soil depths were sandy clay loam and clay loam, respectively. The randomized complete block design with five irrigation treatments (full irrigation [FI], two partial root-zone drying [PRD] treatments [PRD_{75} and PRD_{55}], and two deficit irrigation [DI] treatments [DI_{75} and DI_{55}]; the PRD and DI treatments were scheduled to receive 55% (PRD_{55} and DI_{55}) or 75% (PRD_{75} and DI_{75}) of the calculated irrigation volume of the FI treatment during each irrigation event) in three replicates was used in the field trial. The dimension of each treatment (i.e., the total land