UC Riverside
UC Riverside Previously Published Works

Title

Two-dimensional modeling of nitrogen and water dynamics for various N-managed water-saving irrigation strategies using HYDRUS

Permalink

https://escholarship.org/uc/item/46k3s4p0

Journal

Agricultural Water Management, 193(C)

ISSN

0378-3774

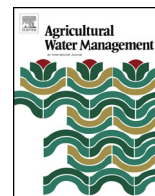**Authors**

Karandish, Fatemeh
Šimůnek, Jiří

Publication Date

2017-11-01

DOI

10.1016/j.agwat.2017.07.023

Peer reviewed

Two-dimensional modeling of nitrogen and water dynamics for various N-managed water-saving irrigation strategies using HYDRUS

Fatemeh Karandish [a],[*], Jiří Šimůnek [b]

[a] Water Engineering Department, University of Zabol, Zabol, Iran
[b] Department of Environmental Sciences, University of California Riverside, Riverside, CA 92521, USA

ABSTRACT

Nitrate losses are the dominant cause of the non-point source pollution under agricultural fields. In this study, the HYDRUS-2D model was first calibrated and validated using data collected during a two-year field investigation in a drip-irrigated maize field and then applied to evaluate the influence of 176 different N-managed water-saving irrigation scenarios on water and N dynamics and maize grain yield. Various scenarios were defined by combining 11 irrigation levels (IL = 0–100% with a 10% interval), 8 N fertilization rates (NR = 0–400 kg ha^{-1} with a 50 kg ha^{-1} interval) and two water-saving irrigation strategies: deficit irrigation (DI) and partial root-zone drying (PRD). Reliable estimates of soil NO_3^--N concentrations (RMSE = 0.39–10.9 mg l^{-1} and MBE = −8.9–8.4 mg l^{-1}), crop N uptake (RMSE = 3.9–8.9 kg ha^{-1} and MBE = −5.3–6.25 kg ha^{-1}), and soil water contents (RMSE = 2.3–5.11 mm and MBE = 1.63–4.93 mm) were provided by HYDRUS-2D. Based on the simulated results, the fertigation strategy with NR = 200 kg ha^{-1} is an optimum strategy. For the higher fertigation rates (NR ≥ 250 kg ha^{-1}), the NO_3^--N leaching out of the surface layers (0–20 cm) increased by 0.1–183% while N uptake was enhanced by only 0.3–15%. On the other hand, reducing NR below this level would have resulted in severe economic losses. A 30% reduction in IL at NR = 200 kg ha^{-1} shows an enormous potential in lowering N leaching below different soil layers (12–99%) while reducing crop N uptake by only 5.4%. In addition, higher crop yield by 0.2–20.2% can be expected under PRD since crop N uptake is enhanced by more water available in the surface layers. While on the one hand, PRD ensures environmentally safer fertilizer applications, on the other hand, the economic objectives are met more easily under PRD than under DI. Additionally, it could be concluded that the HYDRUS-2D model, instead of labor- and time-consuming and expensive field investigations, could be reliably used for determining the optimal scenarios under both the DI and PRD strategies.

© 2017 Published by Elsevier B.V.

1. Introduction

Nitrogen (N) is well known to be an essential crop nutrient, which highly affects crop growth and yield (Jia et a1., 2014; Wienhold et al., 1995). As a result, farmers are usually encouraged to apply N-fertilizers especially to high-yield crops, such as maize, which require large amounts of N for achieving their optimal yield. Unfortunately, the lack of comprehensive management guidelines causes most farmers to apply N fertilizers based on their own experience and without considering subsequences for the environment (Wei et al., 2009). Excessive unmanaged applications of N-fertilizers above optimal amounts and without considering the crops N requirements lead to the pollution of water resources as a byproduct of N leaching out of the root zone, which is well documented for irrigated agricultural lands in many parts of the world (Zhu et al., 2005; Thompson et al., 2007; Dudley et al., 2008; Burow et al., 2010; Dahan et al., 2014; Karandish et al., 2017). A low recovery of N fertilizers by crops may be more hazardous in humid regions where the N residual in the soil could be freely leached to the groundwater due to off-season precipitions. In irrigated agriculture, water draining below the root-zone due to excessive irrigation is the dominant factor controlling NO_3^--N leaching (Tamini and Mermoud, 2002).

Organic N, ammonia (NH_4) and nitrate (NO_3) are the common forms of N in soils. Among these forms, NO_3 is the largest contributor to groundwater pollution (Li et al., 2007; Hu et al., 2009; Wang et al., 2010) due to its high mobility and leachability. A close correlation was reported between the amount of applied water and NO_3 leached below the root zone as well as between the N

fertilization rate and the leaching fraction under sprinkler irrigation (Gheysari et al., 2009). Therefore, using an efficient irrigation scheduling as well as an optimal management of N-fertilizer applications may reduce NO_3 losses from irrigated lands. In this regard, various water-saving irrigation strategies may be highly beneficial. Previous research focused mainly on finding an optimal combination of the N-fertilization rate and the amount of applied water under a regular deficit irrigation (DI) strategy (e.g., Haverkort et al., 2003; Daudén et al., 2004; Alva et al., 2006; Barton et al., 2006; Hutton et al., 2008; Wei et al., 2009; Gheysari et al., 2009; Jia et a., 2014). However, while using DI when less irrigation water is applied than potential crop evapotranspiration may indeed reduce deep percolation and NO_3 losses, it may also reduce crop yield and crop N uptake (Hu et al., 2009; Sepaskhah and Ahmadi, 2010; Wang et al., 2012). Under such circumstances, it can be expected that farmers will be reluctant to adopt DI since their economic interests will be threatened due to significant yield losses.

During the past few decades, a water-saving irrigation strategy called partial root-zone drying (PRD), in which one-half of the root zone is irrigated while the other half is allowed to dry out, has been developed (Dry and Loveys, 1998). The irrigated and dry sides are periodically switched (Karandish and Šimůnek, 2016a). A numerous studies have been carried out on the possible effects of this irrigation strategy on quantitative and qualitative properties of different crops, most of which agreed that there is a significant increase in the water use efficiency under PRD (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, 2016a). The results of these studies demonstrated that PRD can greatly induce the initiation and growth of secondary roots, which improve both water and nutrient uptake. Kirda et al. (2005) reported that PRD resulted in a better N-fertilizer recovery with less mineral N residual left in the soil after maize harvest. Despite focusing on the effects of PRD on yield and crop physiological response, and to a lesser extent on the crop N recovery, these studies have never attempted to find out the optimal combination of N fertilization rates and applied water levels under PRD with respect to both economic and environmental factors.

These goals can be achieved using laborious and time-consuming, and therefore expensive, field investigations. On the one hand, it is still challenging to directly quantify water and N losses at the field scale because of uncertainties in measured deep percolation and NO_3 concentrations in the leachate, even under well-managed conditions (Phogat et al., 2013). On the other hand, the inability of carrying out such research in the field at a low cost represents a restriction on the direct measurement of water and nutrient dynamics under different management scenarios. Modeling could be an alternative approach for identifying optimal conditions for PRD, especially when it may be economically or technically impossible to carry out the project in the field (Li and Liu, 2011).

Among different available models, HYDRUS-2D (Šimůnek et al., 2008, 2016) has been extensively and successfully used to simulate water and nutrient transport in soils even for complicated problems. Having both the flexibility to accommodate different types of boundary conditions for water flow and solute transport calculations and the capability to simultaneously consider root uptake of water and nutrients compared to other similar models (Li et al., 2015), the HYDRUS model can simulate soil water and solute dynamics in the fields under different water and solute management practices. The HYDRUS use is also greatly facilitated by its sophisticated, graphical, user-friendly interface. There are numerous studies in which the possible influence of soil physical properties (e.g., soil hydraulic properties, soil layering) as well as the effects of different field managements (e.g., the rate of dripper discharge, irrigation frequency, and quality, and timing

of nutrient applications) on water and nutrient dynamics have been investigated using HYDRUS-2D (Cote et al., 2003; Gärdenäs et al., 2005; Assouline et al., 2006; Hanson et al., 2006; Ajdary et al., 2007; Patel and Rajput, 2008; Šimůnek and Hopmans, 2009; Phogat et al., 2013; Li and Liu, 2011; Ramos et al., 2012, Karandish and Šimůnek, 2016a,b). All these studies concluded that HYDRUS-2D is an effective tool to carry out such investigations and that the simulation results are reliable. Therefore, using experimental results from a two-year field investigation, the following objectives will be addressed in this manuscript: (i) to calibrate and validate HYDRUS-2D for simulating soil water and N dynamics under different water-saving irrigation strategies and (ii) to find the optimal combination of the N-fertilizer rate and the applied irrigation water level for the DI and PRD conditions with respect to both economic and environmental factors.

2. Materials and methods

2.1. Experimental setup

During 2009–2010, a two-year field investigation was carried out in an 825 m^2 (15 × 55 m) maize field at the Sari Agricultural Sciences and Natural Resources University, Sari, Iran. According to daily weather data, 2010 was a warmer year, with 0.1–7.8 °C higher daily mean air temperatures (T) than in 2011. Vapor pressure deficits and net radiation were also higher in 2010 compared to 2011. Although there was precipitation of 8 and 40 mm during the growing seasons of 2010 and 2011, respectively, no rainfall occurred 55 and 45 days after sowing (DAS), respectively. Soil texture at 0–20 cm and 20–100 cm soil depths was sandy clay loam and clay loam, respectively. The surface layer (0–20 cm) contained 1.22% of organic matter and had an initial EC of 1.64 dS m-1. The measured soil pH varied in the range of 6.8–7.5 and 6.7–7.3 in 2010 and 2011. Our daily observations showed that the groundwater depth was 122 cm at the beginning of the cropping cycle of 2010 and it continued falling to a depth of 211 cm at harvest. In 2011, the groundwater depth fluctuated in the range of 115–221 cm. Soil properties are summarized in Table 1. For each soil layer (i.e., every 20 cm soil depths), we collected a total of 45 soil samples, 3 soil samples per each replicate of a treatment. Hence, we had 225 soil samples for the 5 soil layers. While we had soil properties for all 5 soil layers and for all treatment, we report in Table 1 only the average values. For each treatment, less than 5% deviations were observed among measured soil properties of each soil layer. Hence, such results confirmed the uniformity of the soil in the field both vertically and horizontally. Soil hydraulic properties were also determined for different soil layers. More detailed description of soil properties can be found in Karandish and Šimůnek (2016a,b).

The field experiment consisted of five irrigation treatments that included a full irrigation (FI) treatment, two partial root-zone drying (PRD) treatments (PRD$_{75}$ and PRD$_{55}$), and two deficit irrigation (DI) treatments (DI$_{75}$ and DI$_{55}$)], each in three replicates, which were carried out in a complete block design. Initial soil samples were collected every 20 cm down to a depth of 80 cm for all treatments to measure retention curves and initial NO_3 and the total N content. Thereafter, a surface drip irrigation system was installed, in which drip lines were placed on the soil surface 75 cm apart, with emitters 20 cm apart, and an emitter discharge rate of 2 L hr^{-1} (Fig. 1a).

Five 100 cm long TDR tubes (Trime FM; IMKO; Germany) were installed for each treatment to continuously monitor the soil water content (SWC) (i.e., 25 TDR tubes were installed in the study area; 5 probes * 5 treatments) (Fig. 1). The accuracy of SWCs measured using TDRs was compared with SWCs simultaneous measured using the gravimetric method. With an index of agreement of 95%, a

Table 1
Soil properties at the experimental site.

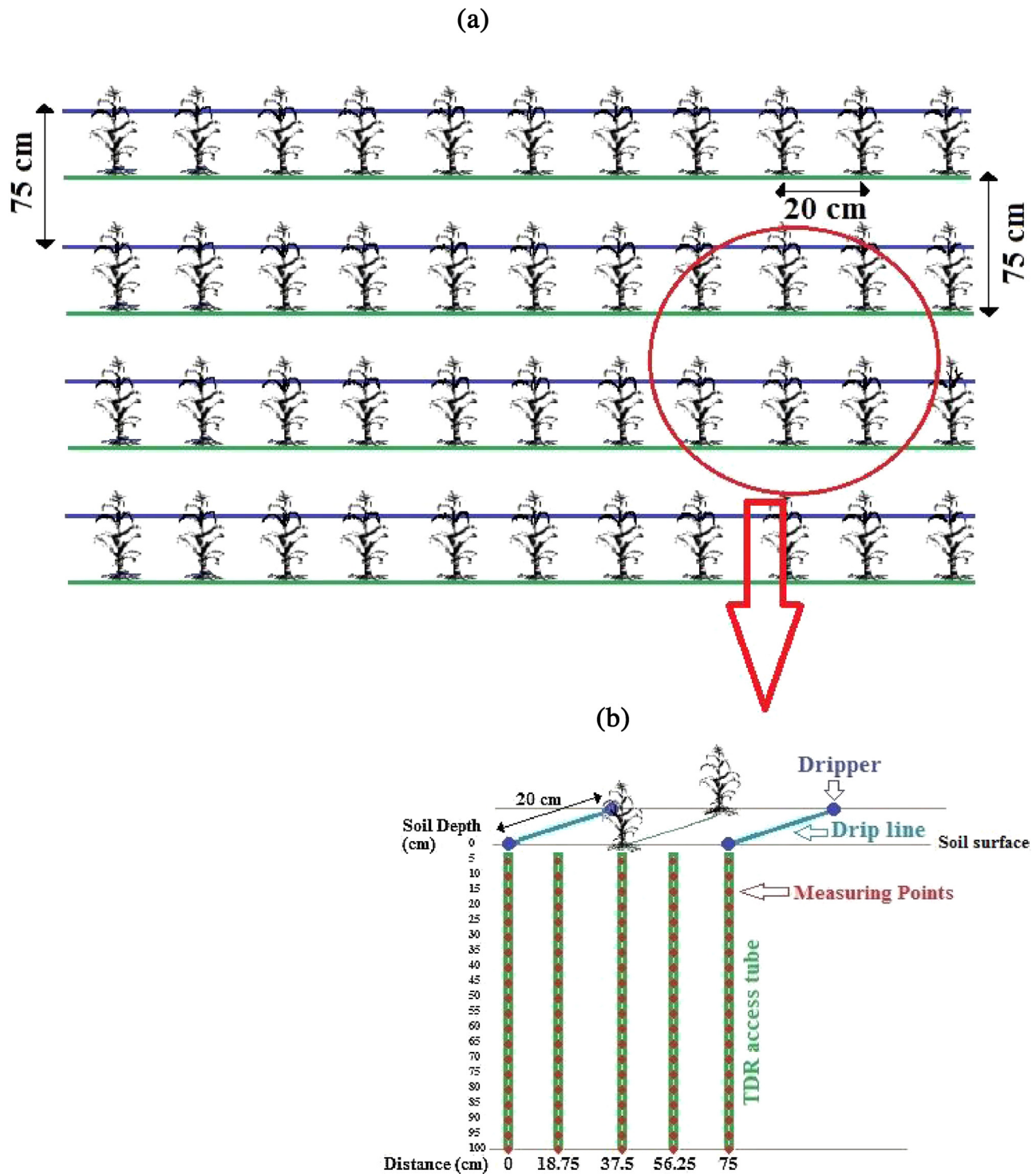| Depth (cm)	Soil texture	Sand (%)	Silt (%)	Clay (%)	Field capacity (%)	Wilting point (%)	Bulk density (g cm^{-3})
0–20	Sandy clay loam	49	22	27	30	15	1.40
20–40	Clay loam	40	25	35	32	14	1.38
40–60	Clay loam	30	36	34	32	14	1.35
60–80	Clay loam	37	30	33	32	14	1.37
80–100	Clay loam	36	28	34	32	14	1.37

Fig 1. Schematic of the field experimental site. Horizontal locations of laterals, drippers, and plants in the experimental field (a) and locations of TDR tubes in the maize root zone (b).

good agreement was found between SWCs data measured by these two methods, confirming the acceptability of the measured SWCs data by TDRs. TDR tubes were then used at least two times a day to measure SWCs at depths of every 5 cm during both growing seasons. Moreover, the movement of the wetting front was observed for at least 10 irrigation events for each treatment during each growing season (Karandish and Šimůnek, 2016a).

On May 26 in both 2010 and 2011, maize single-cross hybrid 704 was sown 5 cm deep, with 75 cm × 20 cm crop row and crop spacing, between and parallel to the drip lines. With an irrigation interval of two days, 53 and 55 irrigation events were applied using the surface drip irrigation system in the 2010 and 2011 growing seasons, respectively. For each irrigation event, the NO_3^--N concentration in irrigation water was measured.

Irrigation in the FI treatment was scheduled to refill the pore space in the rooting zone to the field capacity. The irrigation requirement (in mm) for the FI treatment was calculated using Eq. (1) for each irrigation event:

$$[I_n]_{FI} = \sum_{i=1}^{m} \left\{ \left[\theta_{FCi} - (\theta_{Bli})_{FI} \right] D_i \right\} \tag{1}$$

where $[I_n]_{FI}$ is the net irrigation depth (mm) of the nth irrigation event for the FI treatment, θ_{FCi} is the volumetric SWC at field capacity (FC, %) of the ith soil layer, $(\theta_{Bli})_{FI}$ is the average volumetric SWC of the ith soil layer (%) before irrigation in the FI treatment, D_i is the soil layer thickness (50 mm), i is the soil layer, and m refers to the number of soil layers down to a specific soil depth ($m = 16$), for which $[I_n]_{FI}$ is calculated. $(\theta_{Bli})_{FI}$ was measured using TDR tubes before each irrigation event.

The same amount of irrigation water was applied in all treatments (i.e., FI, DI, and PRD treatments) during the first 55 days after sowing (DAS) in 2010 and during 45 DAS in 2011. During the stress period (i.e., during 55–107 DAS in 2010 and during 45–110 DAS in 2011), the water-saving treatments were scheduled to receive 55% (PRD_{55} and DI_{55}) and 75% (PRD_{75} and DI_{75}) of the FI treatment's irrigation amount at each irrigation event. While in the FI and DI treatments, both drip lines were operated simultaneously, in the PRD treatments during the PRD period, to ensure partial root-zone drying, just one of the drip lines was operated while the other was not during each irrigation event. Only half of the root zone was thus irrigated during the PRD period, while irrigation shifted between the two sides of the plants each week.

Prior to applying irrigation treatments (i.e., on 55 DAS in 2010 and 45 DAS in 2011), and once a week during the stress period (i.e., on 60, 66, 72, 78, 84, 90, 96, 102, and 106 DAS in 2010 and 52, 58, 64, 70, 76, 82, 88, 94, 100, 106, and 110 DAS in 2011), soil samples were collected for each treatment vertically every 20 cm to a depth of 80 cm and at five equal horizontal distances between two drip lines. At each sampling date, three soil samples for each 20-cm soil depth of each replicate of one treatment were collected at each of the five horizontal distances, leading to a total of 225 soil samples for one treatment. Soil samples were analyzed for total nitrogen (TN) (the semi-micro Kjeldhal method (Bremner and Mulvaney, 1982)) and the NO_3^--N concentration (with a spectrophotometer (DR/2500, Hack Co.) using a cadmium reduction method (APHA, 1992)). At the same dates, plants were also harvested (less often in 2010) to determine their total nitrogen uptake (the sum of measured N for stem, leaves, and yield) and a leaf area index. At each sampling time, three plants per plot were harvested. The oven-dried (at 70 °C) weight of each part of a plant (root, stem, leaves, and yield) was determined. The semi-micro Kjeldahl method was applied to determine N uptake. A laboratory leaf area meter (Delta-t Devices Ltd.) was used to measure the entire leaf area, which was converted to LAI by dividing it with the corresponding soil surface covered by the plants. Temporal variations of the horizontal and vertical root distributions were also determined at 55, 62, 69,

76, and 83 DAP in 2010 and at 40, 56, 63, 70, 77, and 90 DAP in 2011 for all treatments. While the maximum rooting depths were different in different treatments, they did not extend below the 80 cm soil depth (Karandish and Šimůnek, 2016a). At final harvest, the above-discussed parameters, as well as crop yield, were determined for each treatment. Plants were harvested on September 9, 2010 (107 DAS) and on September 12, 2011 (110 DAS). A list of performed agricultural activities is summarized in Table 2. More detailed description of all measurements during the field investigation is presented in Karandish and Šimůnek (2016a,b).

2.2. HYDRUS-2D simulation

Soil water and nitrogen dynamics were simulated using HYDRUS-2D (Šimůnek et al., 2008, 2016), which is a powerful software for simulating the transient, two-dimensional movement of water and nutrients in soils for a wide range of boundary conditions and soil heterogeneities. The Richards equation for water flow is used in HYDRUS-2D:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left(K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial z} \left(K_z \frac{\partial h}{\partial z} \right) - \frac{\partial K_z}{\partial z} - WU(h, x, z) \tag{2}$$

where θ is the volumetric SWC ($L^3 L^{-3}$), K is the unsaturated hydraulic conductivity function (LT^{-1}), h is the soil water pressure head (L), x is the lateral coordinate, z is the vertical coordinate (positive downwards), t is time (T), and $WU(h, x, z)$ denotes root water uptake (T^{-1}). The hydraulic conductivity K was assumed to be the same in different directions (i.e., $K_x = K_z$). The following equation is applied for quantifying WU:

$$WU(h, x, z) = \gamma(h) RDF(x, z) WT_{pot} \tag{3}$$

where $\gamma(h)$ is the soil water stress response function (dimensionless) of Feddes et al. (1978), RDF is the normalized root water uptake distribution [L^{-2}], T_{pot} is the potential transpiration rate [LT^{-1}], and W is the width of the soil surface [L] associated with the transpiration process. Details about how water uptake is quantified in this research can be found in Karandish and Šimůnek (2016a,b).

The advective-dispersive transport in the liquid phase and the diffusive transport in the gaseous phase is considered in the solute transport equation that is used in HYDRUS-2D. Only the solute transport in the liquid phase is considered in this study, which is suitable for a conservative solute such as NO_3^--N:

$$\frac{\partial \theta c}{\partial t} = \left\{ \frac{\partial}{\partial x} \left(\theta D_{xx} \frac{\partial c}{\partial x} + \theta D_{xz} \frac{\partial c}{\partial z} \right) + \frac{\partial}{\partial z} \left(\theta D_{zz} \frac{\partial c}{\partial z} + \theta D_{zx} \frac{\partial c}{\partial x} \right) \right\}$$
$$- \left(\frac{\partial q_x c}{\partial x} + \frac{\partial q_z c}{\partial z} \right) - S_c \tag{4}$$

where c is the NO_3^--N concentration of the solute in the liquid phase (ML^{-3}), q_x and q_z are the components of the volumetric flux density (LT^{-1}), D_{xx}, D_{zz}, and D_{xz} are the components of the dispersion tensor (L^2T^{-1}) (Bear, 1972), S_c is a sink term, which generally includes the local NO_3^--N uptake (through a passive process), mineralization, microbial immobilization, and denitrification ($ML^{-3}T^{-1}$). The first term on the right side of (4) is the solute flux due to dispersion, the second term is the solute flux due to convection with flowing water and the third term is nutrient uptake by roots, which is a function of space and time and is computed from water uptake values as follows:

$$S_c = C_s . WU(x, z, h) \tag{5}$$

where C_s is the NO_3^--N concentration taken up by roots (ML^{-3}), which is a function of the soil NO_3^--N concentration and the maximum NO_3^--N concentration of root nitrogen uptake ($C_{s,max}$) (Ajdary et al., 2007; Tafteh and Sepaskhah, 2012).

Table 2
Agricultural activities during the growing seasons of 2010 and 2011.

Date	Agricultural activities and fertilization	Remarks
May 26 in 2010 and 2011	Planting and fertilization	150 kg ha^{-1} triple superphosphate was banded in crop rows prior to sowing date
June 12, 2010 and June 5, 2011 (18 and 11 DASs, respectively)	Fertilization	65 kg ha^{-1} urea and 50 kg ha^{-1} potassium sulfate was applied via irrigation (fertigation).
July 14, 2010 and July 4, 2011 (50 and 40 DAS, respectively)	Fertilization	135 kg ha^{-1} urea and 100 kg ha^{-1} potassium sulfate was applied via irrigation (fertigation).
July 19, 2010 and July 9, 2011 (55 and 45 DAS, respectively)	Onset of PRD treatments	
September 9, 2010 and September 12, 2011 (107 and 110 DAS, respectively)	Harvest	

Mineralization gains and denitrification losses were neglected in this study, similarly as done in many other studies (e.g., Ajdary et al., 2007; Wang et al., 2010; Tafteh and Sepaskhah, 2012). Mineralization (N supply) and immobilization (N removal from the mineral N pool) (M&I) are highly dependent on the soil organic matter (OM) and the amount of clay in a soil. Soils with less than 3% of OM in the upper horizon, as in our study, are classified as mineral soils (Huang et al., 2009), in which the M&I processes are often limited due to the lack of OMs (Wijanarko, 2015; Deenik, 2006; Herrmann, 2003; Li et al., 2003). Moreover, mineralization tends to be greater in coarse-textured soils with the low clay content and smaller as the soil clay content increases. Finally, textured soils with the high clay content, as in our current research, are often abundant in micropores, in which organic matter can find a physical protection from microbial decomposition and, consequently, from M&I (Deenik, 2006).

Denitrification losses were neglected due to the following reasons. First, the process of denitrification occurs predominantly in the saturated soil horizons (Laher and Avnimelech, 1980). Maintaining soil water contents in the optimal range for plant growth, i.e., under unsaturated aerobic conditions, stimulates microbial activity and, consequently, enhances the nitrification rate (Vale et al., 2007). Similarly as Ajdary et al. (2007), who applied HYDRUS-2D for simulating the soil water and N dynamics in the onion field under surface drip irrigation (in similar conditions as in the current research), we assumed that denitrification loss around the emitters may be ignored since an aerobic conditions are not reached here. Second, although denitrification is reported as a notable feature of alkaline soils with high pH values (Harris, 1978; Lundquist et al., 1999; Deenik, 2006; Vale et al., 2007; Tafteh and Sepaskhah, 2012), our temporal measurements showed low soil pH during both cropping cycles. The measured pH varied in the range of 6.8–7.5 and 6.7–7.3 in 2010 and 2011, respectively. Third, soil temperature plays a key role in controlling the denitrification rate. While denitrification occurs at high soil temperatures, nitrification is reported to take place mainly in the temperature range of 30–40 °C. Our previous research demonstrated that both DI and PRD strategies control soil temperatures at lower values and within the considered range (Karandish and Shahnazari, 2016).

NO$_3$$^-$-N concentrations tend to be significantly higher than NH$_4$$^+$-N concentrations under favorable conditions for the nitrification process (Sepaskhah and Yousefi, 2007). Marschner (1995) reported that average annual NH$_4$$^+$-N concentrations are often 10–1000 times lower than NO$_3$$^-$-N concentrations in well-aerated agricultural soils. Our weekly measurements (simultaneously measured soil NH$_4$$^+$-N and NO$_3$$^-$-N concentrations) demonstrated that NO$_3$$^-$-N concentrations were 38–352 times higher than NH$_4$$^+$-N concentrations. Since NO$_3$$^-$-N concentrations are significantly higher than NH$_4$$^+$-N concentrations, only the transport of NO$_3$$^-$-N is considered in our study and the model assumes that the input of fertilizers in the form of urea and NH$_4$$^+$-N is instantaneously nitrified into NO$_3$$^-$-N. A similar assumption has been used by other researchers (e.g., Ajdary et al., 2007; Tafteh and Sepaskhah, 2012), considering the fact that nitrification is fast compared to other pro-

cess and it takes only a few days (Havlin et al., 2006) to nitrify urea and NH$_4$$^+$-N into NO$_3$$^-$-N.

In fact, the nitrification process is supposed to be stimulated under low pH, low temperature, inorganic, and unsaturated conditions in finely textured soils with the high clay content, all of which cause higher NO$_3$$^-$-N availability for root uptake. Nitrate has been reported to be the most common N-source used by agricultural crops while ammonium plays a major role in crop N uptake for forest species and paddy rice, especially for low-pH saturated soils with high temperature (Tischner, 2000). Many other researchers indicated that agricultural crops often increase nitrate availability by stimulating nitrification process since they prefer to uptake N in the form of NO$_3$$^-$-N rather than NH$_4$$^+$-N (Lata et al., 2000; Hawkes et al., 2005). Additionally, the higher mobility of NO$_3$$^-$-N leads to a more rapid diffusion to roots and thus to an easier access for plants to it rather than to NH$_4$$^+$-N (Boudsocq et al., 2012). Our results also demonstrated that N uptake could be accurately estimated by HYDRUS-2D (RMSE=3.96-8.96 kg ha^{-1}) when the maximum NO$_3$$^-$-N concentration of root nitrogen uptake (i.e., $C_{s,max}$ in Eq. (5)) is well calibrated and validated.

Simulating complex processes of the rhizosphere dynamics of water and nutrient uptake requires differentiating between passive and active N uptake (Šimůnek and Hopmans, 2009), N mineralization, and denitrification (Bar-Yosef, 1999). To avoid such complications, we assumed that N uptake by plant roots is strictly passive, similarly as done in many other studies (e.g., Hanson et al., 2006; Ajdary et al., 2007; Tafteh and Sepaskhah, 2012). This simplification leads to the assumption that other mechanisms than those implicitly considered either do not occur or can be neglected (Hanson et al., 2006). N uptake can then be calculated by simply multiplying the soil N concentration and root water uptake (Eq. (5)).

The two-dimensional transport domain was defined using a rectangle 75 cm wide (between two neighboring emitters on either side of one plant) and 80 cm deep (i.e., the maximum observed rooting depth). Since the emitter spacing (20 cm) along drip lines was relatively small, drip lines were considered to be infinite line sources. A non-uniform finite element mesh (FEM) with finite element sizes gradually increasing with distance from the emitters' line was generated by HYDRUS-2D. In order to accurately model large spatial gradients in soil water pressure heads caused by infiltrating water, a high nodal density is required in the immediate vicinity of the emitters (Kandelous et al., 2011). Since no significant differences were observed between soil hydraulic properties of soil layers below the 20 cm depth, only two soil horizons with different soil hydraulic properties for the 0–20 cm and 20–80 cm soil depths were defined in the HYDRUS model.

Initial conditions were defined using the observed water and NO$_3$$^-$-N contents in different soil layers within the flow domain. The time-variable and atmospheric boundary conditions were specified at both emitters and at the soil surface, respectively, to represent drip irrigation and to apply precipitation, evaporation, and transpiration fluxes, respectively. A free drainage boundary

condition was applied along the bottom boundary, allowing for downward drainage. Solute was applied with irrigation water and a third-type Cauchy boundary condition was used to describe the concentration flux at the top boundary. In the case of drip fertigation, the solute flux is the product of water infiltration and the dissolved nitrate concentration. Cumulative nitrate leaching below the root zone (i.e., the lower boundary of the flow domain) is controlled by the nitrate concentration and the corresponding water flux at the bottom boundary. All other remaining boundaries were assigned a no-flow boundary condition.

The HYDRUS-2D model was then calibrated and validated for soil hydraulic and solute transport properties using the experimental data. The inverse solution option of the HYDRUS-2D model was used to optimize the solute transport parameters, i.e., the longitudinal (D_L, L) and transverse (D_T, L) dispersivities, as well as the soil hydraulic parameters, i.e., the saturated hydraulic conductivity (K_s), the saturated soil water content (θ_s), and the residual soil water content (θ_r). Soil water contents and soil NO_3^--N concentrations measured in 2010 were used to calibrate the model. The adjusted values of optimized parameters were then used to validate the model using the data collected in 2011. The initial value of the longitudinal dispersivity (D_L) was set to be one tenth of the soil depth and the initial value of the transverse dispersivity (D_T) was set to be one tenth of D_L (Ramos et al., 2012). Moreover, $C_{s,max}$ was obtained by comparing the simulated and observed values of crop N uptake. The molecular diffusion coefficient was always set equal to zero since molecular diffusion in soils can be usually neglected (Radcliffe and Šimůnek, 2010). Detailed information about the calibration and validation process for the soil hydraulic properties can be found in Karandish and Šimůnek (2016a).

2.3. Scenario analysis

Once HYDRUS-2D was calibrated and validated, it was applied to simulate the water and N dynamics under different management scenarios. In this regard, the two water-saving irrigation strategies DI and PRD were selected. In each scenario, the amount of applied irrigation water (IL) was considered to change from 0 to 100% of FI, with a 10% interval. For each considered irrigation water level, we also considered different N-fertilization rates (NR) between 0 and 400 kg ha^{-1}, with a 50 kg ha^{-1} interval. A total of 176 scenarios was defined by combining 11 ILs, 8 NRs, and two water-saving irrigation strategies. Each scenario is denoted IS$_{IL-NR}$, where IS refers to the irrigation strategy (DI or PRD), IL denotes the irrigation level (from 0% to 100%), and NR denotes the fertilization rate (from 0 to 400 kg ha^{-1}). For each scenario (i.e., for each combination of an irrigation level and a fertigation rate), a relative change in crop evapotranspiration ($rc=ET_{ca}/ET_{cp}$), seasonal crop N uptake (NU), and water and NO_3^--N leached below the 20, 40, 60, and 80 cm depths were simulated using HYDRUS-2D. The simulated results were then used to assess the integrated influence of different irrigation schemes and N managements on the N dynamics.

3. Results and discussions

3.1. Efficiency of HYDRUS-2D

The results reported in Karandish and Šimůnek (2016a,b) indicated that HYDRUS-2D was able to capture temporal and spatial trends in soil water contents (amounts of water in a soil layer) with the Model Efficiency (EF) ranging from 0.893 to 0.998 and with the Root Mean Square Error (RMSE) values ranging from 2.3 to 5.11 mm. Small differences between observed and HYDRUS-2D simulated soil water contents were likely due to the fact that the model reported point values (Phogat et al., 2014), whereas measured val-

ues were averaged over a certain soil volume, in which, due to irrigation, the gradient of soil water contents may not be linear and can be quite high, especially around the emitters (Mguidiche et al., 2015). Karandish and Šimůnek (2016a) demonstrated that HYDRUS-2D can be used to develop water-saving irrigation strategies by proposing both optimal irrigation scheduling and an optimal reduction of irrigation water without dramatically decreasing crop yield. The high accuracy of HYDRUS-2D is mainly due to the use of a deterministic approach for simulating soil water movement based on the Richards equation (Doltra and Munoz, 2010). Earlier research has also demonstrated the high potential of HYDRUS-2D for simulating soil water contents under full and deficit irrigation conditions (Cote et al., 2003; Ajdary et al., 2007; Crevoisier et al., 2008; Siyal and Skaggs, 2009; Mubarak, 2009; Tafteh and Sepaskhah, 2012) as well as under pressurized irrigation systems (Assouline et al., 2006; Ramos et al., 2012; Phoghat et al., 2013).

Using the soil hydraulic parameters optimized by Karandish and Šimůnek (2016a,b), HYDRUS-2D was further calibrated for solute transport based on data collected during the 2010 growing season (i.e., measured NO_3^--N concentrations in different soil layers as well as crop N uptake). The calibrated values of D_L and D_T were 5.0 cm and 0.42 cm for the 0–20 cm soil depth, respectively, and 4.8 cm and 0.51 cm for the 20–80 cm soil depth, respectively. A wide range of dispersivities, due to their dependence on soil properties and dimensional scales, has been reported in the literature. Dispersivities D_L and D_T have been set to 0.1 cm and 0.01 cm by Cote et al. (2003), to 5 cm and 0.5 cm by Gardenas et al. (2005) and Hanson et al. (2006), to 0.3 cm and 0.03 cm by Ajdary et al. (2007), to 5 cm and 0.5 cm by Phogat et al. (2013), and to 20 cm and 2 cm by Wang et al. (2014), respectively. Additionally, the longitudinal dispersivity D_L has been set to 12.2-25.8 cm by Ramos et al. (2012), and to 2 cm by Tafteh and Sepaskhah. (2012).

The agreement between observed and simulated soil water content and N data during the calibration period was quantitatively assessed using the RMSE and the Mean Bias Error (MBE) statistics (Table 3), in addition to the visual inspection (Fig. 2). With respect to NO_3^--N concentrations, the RMSE values during the calibration process ranged from 4.2–10.9 mg l^{-1} for the 0–20 cm soil depth, from 3.6–8.0 mg l^{-1} for the 20–40 cm soil depth, from 1.2–9.7 mg l^{-1} for the 40–60 cm soil depth, and from 0.38–0.55 mg l^{-1} for the 60–80 cm soil depth. Regardless of the treatment, lower deviations between measured and modeled NO_3^--N were observed for the 60–80 cm soil layer, which could probably be attributed to lower changes in the NO_3^--N concentrations at greater depths during the calibration process.

Higher variations in NO_3^--N concentrations in the surface layers under drip irrigation were detected by Alva et al. (2006) and Hutton et al. (2008). This was confirmed in this study in which higher deviations in NO_3^--N were observed in the surface layers (0–40 cm soil depth), where NO_3^--N variations were higher due to irrigation, nitrate leaching, and/or N uptake. Phogat et al. (2014) also reported that the mean absolute error (MAE) at the 25 cm soil depth was higher (MAE=21.3 mg l^{-1}) than at deeper soil depths (MAE=8.8–10.3 mg l^{-1}) when simulating the NO_3^--N distribution over a 150 cm soil profile with HYDRUS-2D under field cropped condition. A similar match between simulated and measured NO_3^--N distributions was reported in other studies as well (Tournebize et al., 2012; Ramos et al., 2012; Ajdary et al., 2007). Deviations between observed and simulated data may be due to the fact that the model assumed a homogeneous soil environment while the field may be far more heterogeneous and anisotropic. In addition, only the two-dimensional movement of NO_3^--N was considered by the model while more complex nitrate processes were not taken into account (Phogat et al., 2014). Numerous factors affect the agreement between observed and simulated soil water contents and solute concentrations in the soil under a pres-

Table 3
Model performance criteria at different soil depths for the calibration (2010) and validation (2011) datasets. RMSE and MBE are the root mean squared and mean biased errors, respectively, and SW is the amount of water in a soil layer.

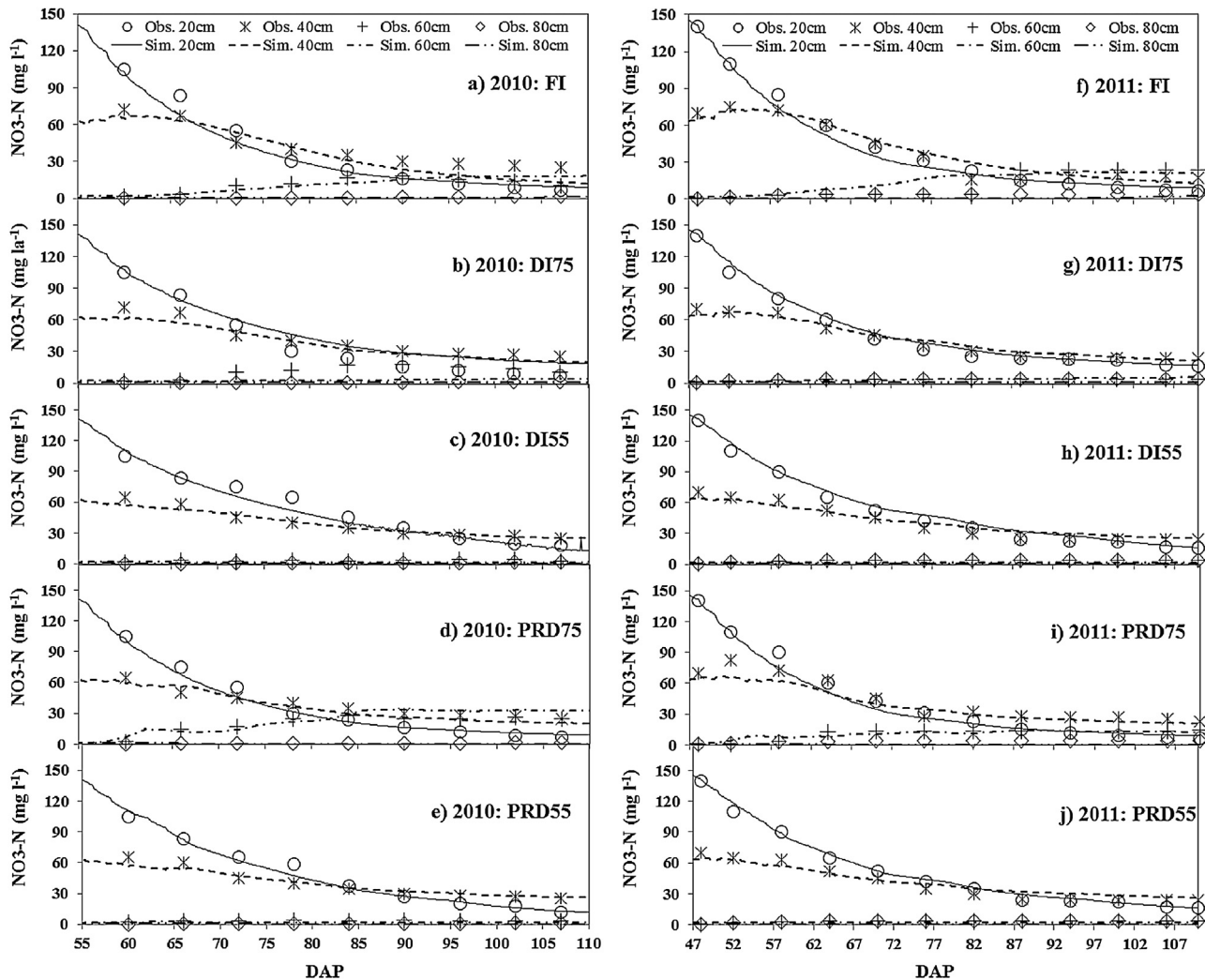| Year	Parameter	Soil Depth (cm)	FI			PRD$_{75}$			PRD$_{55}$			DI$_{75}$			DI$_{55}$		
			RMSE	MBE	EF	RMSE	MBE	EF	RMSE	MBE	EF	RMSE	MBE	EF	RMSE	MBE	EF
2010	NO$_3{}^-$-N (mg l^{-1})	0–20	6.17	2.31	0.86	4.20	1.40	0.95	4.60	1.19	0.94	10.89	−8.97	0.81	6.24	3.11	0.89
		20–40	7.95	4.91	0.85	4.56	3.01	0.94	3.72	0.56	0.96	5.98	3.99	0.96	3.59	0.84	0.96
		40–60	3.79	−0.23	0.96	5.70	−3.21	0.95	1.22	1.11	0.97	9.73	8.40	0.95	1.67	1.50	0.97
		60–80	0.38	0.05	0.98	0.55	0.16	0.98	0.55	0.16	0.98	0.55	0.16	0.94	0.55	0.16	0.98
	SW (mm)	0–20	0.8	1.1	0.93	0.73	0.93	0.94	0.83	0.83	0.92	0.43	0.53	0.99	0.71	0.81	0.97
		20–40	0.85	1.2	0.90	0.73	0.91	0.97	0.79	0.85	0.95	0.44	0.58	0.99	0.70	0.92	0.97
		40–60	0.78	0.85	0.94	0.64	0.87	0.98	0.81	0.69	0.93	0.51	0.7	0.98	0.60	0.70	0.95
		60–80	0.28	0.48	0.99	3.69	10	0.87	5.84	5.5	0.83	1.9	3.0	0.89	2.50	3.50	0.89
	N uptake (kg ha^{-1})	–	8.96	−5.32	0.96	7.52	−4.85	0.96	8.21	−4.85	0.93	8.15	−4.25	0.94	6.13	−2.43	0.96
2011	NO$_3{}^-$-N (mg l-1)	0–20	4.82	1.90	0.95	5.83	2.32	0.93	3.33	−1.96	0.96	4.55	−3.09	0.94	4.84	−3.81	0.91
		20–40	5.66	−0.26	0.93	7.73	5.13	0.85	4.72	−1.04	0.94	3.69	−0.30	0.95	4.53	−0.99	0.90
		40–60	6.61	−2.57	0.88	2.62	0.61	0.98	1.44	1.05	0.99	1.07	−0.43	0.99	1.90	1.50	0.99
		60–80	2.51	2.25	0.99	2.86	2.63	0.97	2.85	2.62	0.98	2.85	2.62	0.98	2.85	2.62	0.98
	SW (mm)	0–20	1.18	0.89	0.88	0.82	1.4	0.90	0.35	0.45	0.99	1.18	2.5	0.88	2.1	4.2	0.84
		20–40	0.38	1.2	0.99	0.78	0.95	0.93	0.72	0.82	0.94	0.38	0.58	0.99	0.48	0.55	0.97
		40–60	0.48	0.8	0.96	0.8	1.2	0.90	0.6	0.7	0.95	0.48	0.68	0.97	0.43	0.63	0.97
		60–80	0.41	0.75	0.96	0.87	0.97	0.89	0.51	0.65	0.95	0.41	0.52	0.98	0.63	0.85	0.95
	N uptake (kg ha^{-1})	–	3.96	1.86	0.99	7.58	2.27	0.97	7.97	6.25	0.91	6.82	5.13	0.94	6.89	2.65	0.97

Fig. 2. Observed and simulated NO$_3{}^-$-N during the 2010 (a through e, the calibration dataset) and 2011 (f through j, the validation dataset) growing seasons for different irrigation treatments (FI (a,f), PRD$_{75}$ (b,g), PRD$_{55}$ (c,h), DI$_{75}$ (d,i), and DI$_{55}$ (e,j)).

surized drip irrigation system (Ramos et al., 2012). These factors may explain simulation errors related to NO_3^--N concentrations in the current study as well. Nevertheless, low values of RMSEs and MBEs for all treatments (RMSE=0.38–10.89 mg l^{-1} and MBE=-8.97–8.40 mg l^{-1}) indicate that the model represents well NO_3^--N concentrations in different soil layers during the calibration process. Moreover, the RMSE values ranged from 6.13 (for the DI$_{55}$ treatment) to 8.96 ka ha^{-1} (for the FI treatment) among various irrigation treatments when considering crop N uptake, indicating a good agreement between simulated and measured N uptake during the 2010 growing season. Model performance criteria for different locations with different horizontal distances from the dripper also indicate the high accuracy of HYDRUS-2D when modeling soil nitrogen dynamics on a two-dimensional scale.

HYDRUS-2D was then validated using data collected during the 2011 growing season. Fig. 2 compares the temporal variations of the simulated and observed NO_3^--N concentrations in different soil layers for various irrigation treatments during the cropping cycles of 2010 (the calibration dataset) and 2011 (the validation dataset) to illustrate the capability of HYDRUS-2D of capturing the temporal trends of NO_3^--N. Generally, the simulated NO_3^--N concentrations agreed well with the observed values, with the RMSE ranging from 1.07–7.73 mg l^{-1} and the MBE ranging from −3.81–5.13 mg l^{-1}. A close match between simulated and observed NO_3^--N concentrations, as well as their seasonal trends, was also obtained in other studies for various soils and crops under pressurized irrigation conditions (Cote et al., 2003; Gärdenäs et al., 2005; Hanson et al., 2006; Ajdary et al., 2007; Šimůnek and Hopmans, 2009; Phogat et al., 2013; Li and Liu, 2011; Ramos et al., 2012). Moreover, a comparison between simulated and measured values of N uptake shown in Fig. 3 indicates that HYDRUS-2D can be successfully used to predict temporal variations of N uptake for both deficit irrigation and partial root-zone drying strategies, as well as for full irrigation during both calibration (2010) and validation (2011) periods. The results of the quantitative assessment reported in Tables 3 and 4 agrees well with the visual inspection of the results displayed in Figs. 2 and 3 for both soil NO_3^--N concentrations and N uptake, respectively. A close match of both water contents and solute concentrations indicates that HYDRUS-2D can be successfully used for predicting the results of hypothetical scenarios considered in this current study and discussed below.

3.2. Scenario analysis

The results of the HYDRUS simulations for the defined scenarios are discussed in the following sections with respect to both environmental and economic factors, including the effects on crop evapotranspiration, deep percolation, crop N uptake, NO_3^--N leaching, soil N residual, and crop yield.

3.2.1. Water dynamics

Fig. 4 displays the ratio of actual (ET_a) and potential (ET_p) crop evapotranspiration, irrigation (*In*), as well as water moved below the 20 (*DP*-20) and 40 cm (*DP*-40) soil depths for various irrigation scenarios. For example, for 70% ≤ IL ≤ 100%, the ET_a/ET_p ratio under PRD was 10–13% higher than under DI, reflecting a considerable increase in the soil water extraction capacity by roots under PRD. A better use of soil water for IL ≥ 70% under PRD is also obvious when temporal variations of *DP* below the surface layer (0–40 cm) is considered. While the irrigation volume at one dripper line was increased by 40, 60, 80, and 100% in the PRD$_{70-NR}$, PRD$_{80-NR}$, PRD$_{90-NR}$, and PRD$_{100-NR}$ scenarios, respectively, the other dripper line was alternatively not used at all. Therefore, higher *DP* can be expected under these scenarios since half of the root zone receives more irrigation water than the corresponding side under the FI treatment. However, simulated water fluxes out of the 20 cm

and 40 cm soil depths indicate that *DP*-20 and *DP*-40 for the PRD scenarios under IL ≥ 70% were considerably lower than those for the corresponding FI and DI scenarios. *DP*-20 for DI was 13–33% of the total applied water volume during the stress period while it was only 11–30% for PRD. In addition, *DP*-40 for DI was 1.5–3.3 time higher than for PRD when IL ≥ 70%. This result demonstrated that the soil water content at the wetted side of the row of the PRD plants was depleted more rapidly than at the same side of the control (FI) plants, indicating that the root system can partially compensate for the increasingly limited water availability at the dry side of the row (Kang et al., 2002).

These results are in agreement with the findings of other studies. For example, Sepaskhah and Ahmadi (2010) reported that the root system can partially compensate for a decreasing water availability on the non-irrigated side of PRD due to an increase in the root hydraulic conductivity. Liu et al. (2006) reported that soil water depletion was higher under PRD than under other deficit irrigation strategies due to a higher root hydraulic conductivity. Karandish and Šimůnek (2016a) reported that higher ET_c under PRD$_{75}$, despite a lower mean *BAW* (i.e., the relative Before-irrigation Available soil Water) during the stress period, may indicate that there is a lower available soil water threshold, below which actual *ET* in other water-saving treatments is reduced compared to its maximum value in the PRD$_{75}$ treatment. Nagore et al. (2014) also reported a lower water content threshold for the *ET* reduction for a new maize hybrid than for the older species. Nevertheless, the simulated results indicate that the reduction in the irrigation level under the PRD scenarios is a key factor for maintaining ET_a at a favorable level. Fig. 4 shows that for IL < 70%, no considerable differences were observed between the PRD and DI strategies regarding the ET_a/ET_c ratio while both *DP*-20 and *DP*-40 under the PRD scenarios were higher than under the DI scenarios. Previous studies have also stressed the importance of the reduction in the irrigation level for sustaining the positive effects of PRD (Liu et al., 2006; Karandish and Shahnazari, 2016; Karandish and Šimůnek, 2016a,b).

3.2.2. N uptake

N uptake was affected by both ILs and NRs (Fig. 5). Regardless of the irrigation strategy (DI or PRD) and the irrigation level (0–100%), crop N uptake increased in response to an increase in the application of N fertilizer from 0 to 200 kg ha^{-1} (i.e., NR ≤ 200 kg ha^{-1}). An increase in NR from 200 kg ha^{-1} to 250 kg ha^{-1} caused only a slight increase of 0.27–5.9% in crop N uptake, while there was no considerable increase in crop N uptake when NR increased from 250 kg ha^{-1} to 400 kg ha^{-1} for all ILs. In other words, crop N uptake is limited when the soil NO_3^--N concentration increases above $C_{s,max}$ (Eq. (5)). Therefore, an additional application of N fertilizer beyond 200 kg ha^{-1} may lead to a negative environmental impact since more N will be left in the soil at final harvest. In addition, while increasing IL beyond 70% did not produce a corresponding increase in crop N uptake for all NRs, increasing IL from 0 to 70% had a positive effect on crop N uptake due to enhanced root water uptake. Such results may be attributed to the lower N availability in the surface layer as a result of increased N leaching under enhanced IL (Figs. 5 and 6). These results are in agreement with the findings of Gheysari et al. (2009) who reported the negative effect of increasing irrigation levels for different amounts of N fertilization rates.

Different water-saving irrigation strategies (DI and PRD) did not perform similarly under various scenarios. Fig. 5 shows that for NR ≥ 150 kg ha^{-1}, N uptake under the DI scenarios did not considerably increase for IL ≥ 60%, while it continued growing for IL up to IL=70% under the PRD scenarios. Moreover, when IL ≥ 70% and regardless of NRs, N uptake under PRD was considerably higher than under DI, indicating an increased N use efficiency under the PRD scenarios. This difference was more obvious for NR ≥ 150 kg ha^{-1}. For example, when NR=100 kg ha^{-1}, N uptake
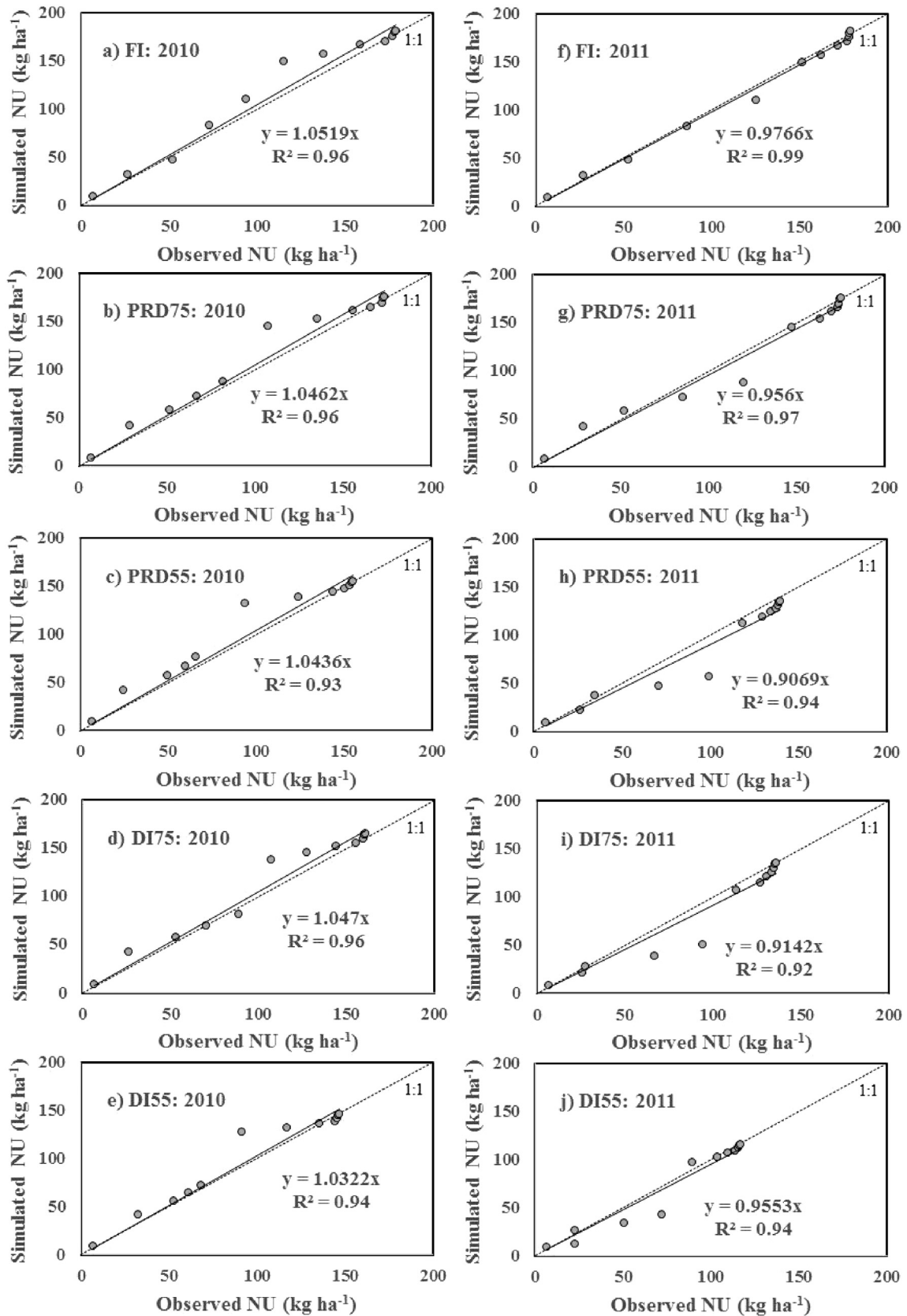
Fig. 3. Scatter plots between observed and HYDRUS-simulated N uptake (NU) during 2010 (a through e, the calibration dataset) and 2011 (f through j, the validation dataset) growing seasons for different irrigation treatments) (FI (a,f), PRD$_{75}$ (b,g), PRD$_{55}$ (c,h), DI$_{75}$ (d,i), and DI$_{55}$ (e,j)).

Table 4
Model performance criteria at different locations with different horizontal distances from the dripper for the calibration (2010) and validation (2011) datasets. RMSE and MBE are the root mean squared and mean biased errors, respectively.

Growing season	Treatment	Position[a]									
		A		B		C		D		E	
		RMSE[b]	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE
2010	FI	4.75	1.96	4.62	1.69	3.69	1.70	4.55	1.49	4.80	1.82
	PRD$_{75}$	3.80	2.03	3.95	2.61	3.89	1.36	3.83	1.52	3.91	2.12
	PRD$_{55}$	3.75	1.11	3.73	1.64	3.12	0.36	3.65	1.43	4.18	1.55
	DI$_{75}$	7.28	5.78	6.75	5.64	5.22	−2.35	6.92	5.43	7.10	5.95
	DI$_{55}$	3.12	1.96	2.85	1.68	2.65	1.43	3.10	1.41	3.25	1.72
2011	FI	4.95	2.23	4.32	−1.57	4.12	−1.31	4.65	−1.38	5.12	2.40
	PRD$_{75}$	5.20	2.72	4.75	2.47	4.60	2.44	4.68	2.32	4.95	3.12
	PRD$_{55}$	3.32	2.12	3.20	−1.67	2.95	−1.41	3.35	−1.65	3.80	2.08
	DI$_{75}$	3.22	2.66	3.00	−1.57	2.80	−1.34	3.11	−1.41	3.60	2.58
	DI$_{55}$	4.12	2.50	3.75	−1.45	3.13	−1.42	3.45	−2.10	3.68	2.65

[a] A: below the first dripper (Fig. 2), B, C, D and E are 18.75, 37.5, 56.25, and 75 cm away from the first dripper, respectively.

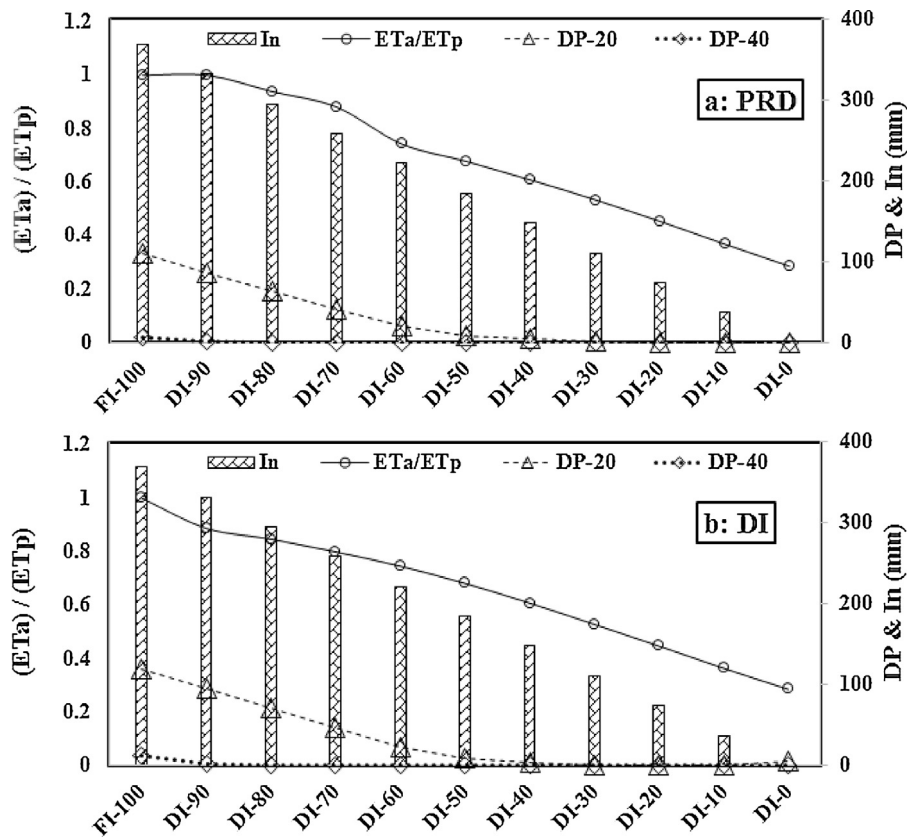[b] RMSE is the root mean square error and MBE is the mean bias error. Units for both RMSE and MBE are "mg l^{-1}".

Fig. 4. The ratio of actual (ET_a) and potential (ET_p) crop evapotranspiration (ET_a/ET_p, the left axis), and irrigation and water moved below the 20 (DP-20) and 40 cm (DP-40) soil depths (the right axis) for various irrigation scenarios.

under PRD for IL=70, 80, 90, and 100% was 3.9, 7.6, 13.6, and 13.6% higher, respectively, than the corresponding values under the DI scenarios. For NR=200 kg ha^{-1}, N uptake under PRD for IL=70, 80, 90, and 100% was 17.4, 19.3, 25, and 26.1% higher, respectively, than the corresponded values under the DI scenarios. Improved N uptake under PRD may be better understood when considering N uptake from the surface soil layers, especially from the 0–20 cm soil depth. For a specific NR, the amount of N taken up by roots from the 0–20 cm soil depth under the PRD scenarios was 5.9–31.2% higher than under the DI scenarios when IL ≥ 70%. In addition, 5.6–12.8% more N was taken up by roots from the 0–20 cm soil depth under the PRD scenarios when IL=60% although total N uptake from the 0–80 cm soil depth under PRD was slightly higher than under DI;

accounting for 0.5–5.3%. It can also be seen from Fig. 5 that for a specific NR, N uptake from the 0–20 cm soil layer considerably decreased under DI when IL > 50% while this downward slope was smaller under PRD. The trend in N uptake from the 20–40 cm depth was the same as from the 0–80 cm soil depths.

Overall, our results demonstrated that for IL ≥ 70%, PRD performed substantially better than DI for all NRs with respect to seasonal crop N uptake. Increased N uptake under the PRD scenarios could be ascribed to an increase in available N in the soil. It is plausible to state that more root water uptake under the PRD scenarios for IL ≥ 70% led to a considerable reduction in DP below the surface soil layer (a 0–40 cm soil depth), which consequently led to a significant reduction in NO$_3^-$-N leaching below the sur-
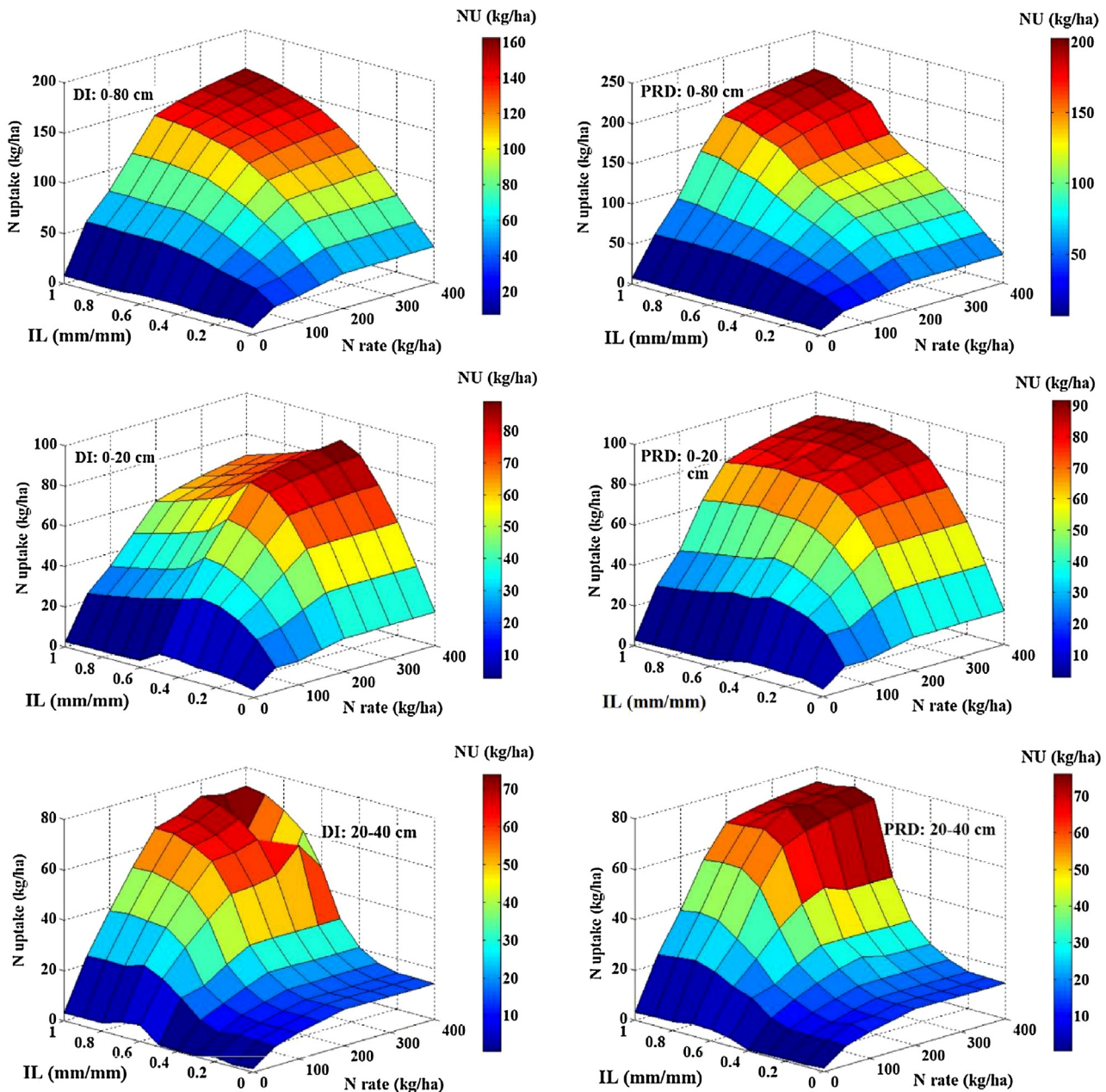
Fig. 5. Crop N uptake from the entire rooting zone and from the 0–20 cm and 20–40 cm soil depths for the DI (*left*) and PRD (*right*) scenarios. NU is N uptake (kg/ha), N rate is the N fertilization (kg/ha), and IL is irrigation level.

face layers (Figs. 4 and 6). A reduction in N leaching resulted in more available N in the 0–40 cm soil depth, which subsequently caused more N uptake under the PRD scenarios for IL ≥ 70%. This is in agreement with findings of other researchers who believed that more frequent wetting and drying cycles under PRD would increase the N availability and, consequently, N uptake (Nourbakhsh and Karimian Eghbal., 1997; Vale et al., 2007; Wang et al., 2010). Some other researchers also observed that the root systems extend to deeper layers under PRD, which induces the initiation and growth of secondary roots, which improves the ability of the plant to absorb both water and nutrients (Fort et al., 1997; Sepaskhah and Kamgar-Haghighi, 1997; Liang et al., 1996; Poni et al., 1992).

Despite the lower movement of both water and NO_3^-N below the surface soil layers when IL is decreased to 70% (Fig. 6), plant N uptake under DI was considerably lower than under PRD when 70 ≤ IL ≤ 100 (Fig. 5). Hu et al. (2009) reported that both mass flow

and diffusion rates were significantly reduced under water deficit irrigations, which decreased nitrogen availability and its transport to the roots. Water deficits under DI were additionally reported to significantly limit root growth (Sepaskhah and Ahmadi, 2010). These results are in agreement with several studies that reported a significant reduction in plant N uptake under DI (Shahnazari et al., 2008; Hu et al., 2009; Wang et al., 2012).

3.2.3. NO_3^--N leaching

Temporal variations of NO_3^--N leaching below the 20, 40, 60, and 80 cm soil depths were simulated for various scenarios (data not shown). The HYDRUS-simulated results showed that higher ILs along with higher NRs resulted in the higher NO_3^--N content in the top soil layers during the early maize growth stages while the NO_3^--N content in the deeper soil layers increased gradually as the season progressed. Deep percolation and NO_3^--N leaching
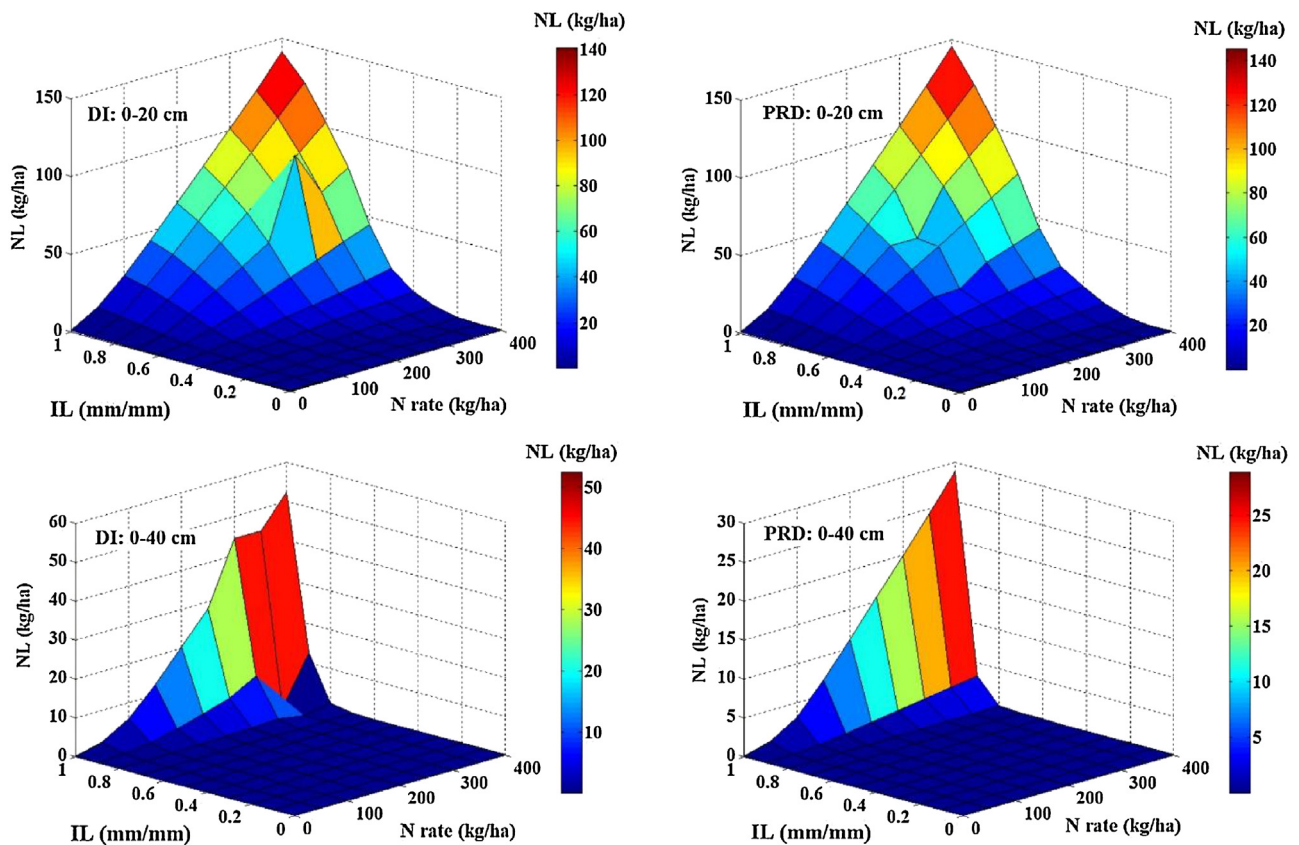
Fig. 6. The total N lost due to leaching of NO_3^--N below the 20 and 40 cm soil depths under the DI (*left*) and PRD (*right*) scenarios. NL is NO_3^--N leaching (kg/ha), N rate is the N fertilization (kg/ha), and IL is irrigation level.

were always observed immediately after an irrigation event. For all scenarios, most NO_3^--N leaching below the rooting zone (at the 0–80 cm soil depth) occurred before 63 DAS, while NO_3^--N leaching below the 20 or 40 cm continued untill the end of the simulation period. NO_3^--N leaching out of the root zone accounted for only a small part of the total applied N and was correlated with deep percolation. Nevertheless, NO_3^--N leaching out of the 0–20 cm soil depth, which is the most important soil layer regarding crop N uptake, had the highest contribution to the leaching fraction, ranging from 0.02–35.3% of the total N applied for DI and 0.04–36.4% for PRD. Chuan et al. (2010) also indicated that the soil depth is a key factor determining the amount of N losses under a certain IL and NR.

Lower NO_3^--N leaching at the 80 cm soil depth may have been a consequence of improved irrigation management by using a pressurized drip irrigation system under which the water use efficiency is improved due to lower deep percolation and evaporation losses (Phoghat et al., 2013; Wang et al., 2014). Barton and Colmer (2006) also showed that the N use efficiency is strongly influenced by the irrigation efficiency. Similarly, lower deep percolation of both water and NO_3^--N was also observed by Tarkalson et al. (2006) when an adequate irrigation scheduling technique was used. Such results ensure environmentally safer applications of fertilizer compared to other irrigation systems (Mmolawa and Or, 2003).

N leaching from the surface layer is important because the sufficiently high concentrations of N in the top soil layers enable continued uptake by roots (Phogat et al., 2013). Therefore, seasonal NO_3^--N leaching from the 0–20 and 0–40 cm soil depths were simulated for various scenarios and the results are presented in Fig. 6. It is obvious that as more water and N were applied, more water moved below the 20 and 40 cm soil depths occurred, eventually increasing NO_3^--N leaching. This is consistent with the findings of

Jia et al. (2014) who reported that NO_3^--N leaching was significantly affected by both irrigation and N levels as well as by the type of fertilizer and by the mutual interactions between these three factors. Other studies also concluded that the application of high levels of irrigation and N fertilizers result in higher NO_3^--N leaching from the soil, greatly exceeding the crop N requirement and thus leading to the lower fertilizer use efficiency (Daudén and Quilez, 2004; Gasser et al., 2002; Mosier et al., 2002; Kumar et al., 1993).

It is evident from Fig. 6 that both water movement and NO_3^--N leaching could be reduced by adopting an appropriate irrigation and fertilization management. It is worth noting that a reduction in NR is a suitable agro-hydrological strategy. For example, Kurtzman et al. (2013) reported that under different environmental conditions a 25% reduction in the application of the N fertilizer resulted in a 50% lower nitrate flux to the groundwater. Nevertheless, the appropriate NR should be selected with caution since plant N uptake is highly dependent on the N availability in the soil. Therefore, we further analyzed possible consequences of various considered scenarios on both N leaching (Fig. 6) and plant N uptake (Fig. 5). For IL=100%, reducing NR from 400 to 250 kg ha^{-1} will considerably diminish NO_3^--N leaching below the 20 and 40 cm soil depths by 12.4–56.4% and 12.3–46.1%, respectively (Fig. 6), while only slightly reducing crop N uptake by 0.2–8.7% in (Fig. 5). However, lower NO_3^--N leaching below 20 cm for PRD were up to 13.3% higher than for DI. Although N uptake was reduced by only 0.3–5.9%, lowering NR from 250 kg ha^{-1} to 200 kg ha^{-1} produced savings of 19.7–24.6% and 19.6–28.5% of NO_3^--N in the 0–20 and 0–40 cm soil layers, respectively. However, when the NR reduction is larger (i.e., when NR $\leq$ 150 kg ha^{-1}), the negative effects on N uptake will overshadow the positive consequences with respect to N leaching from the surface layers. As shown in Fig. 6, while an additional 25% reduction in NR (i.e., NR=150 kg ha^{-1} at IL=100%) results in
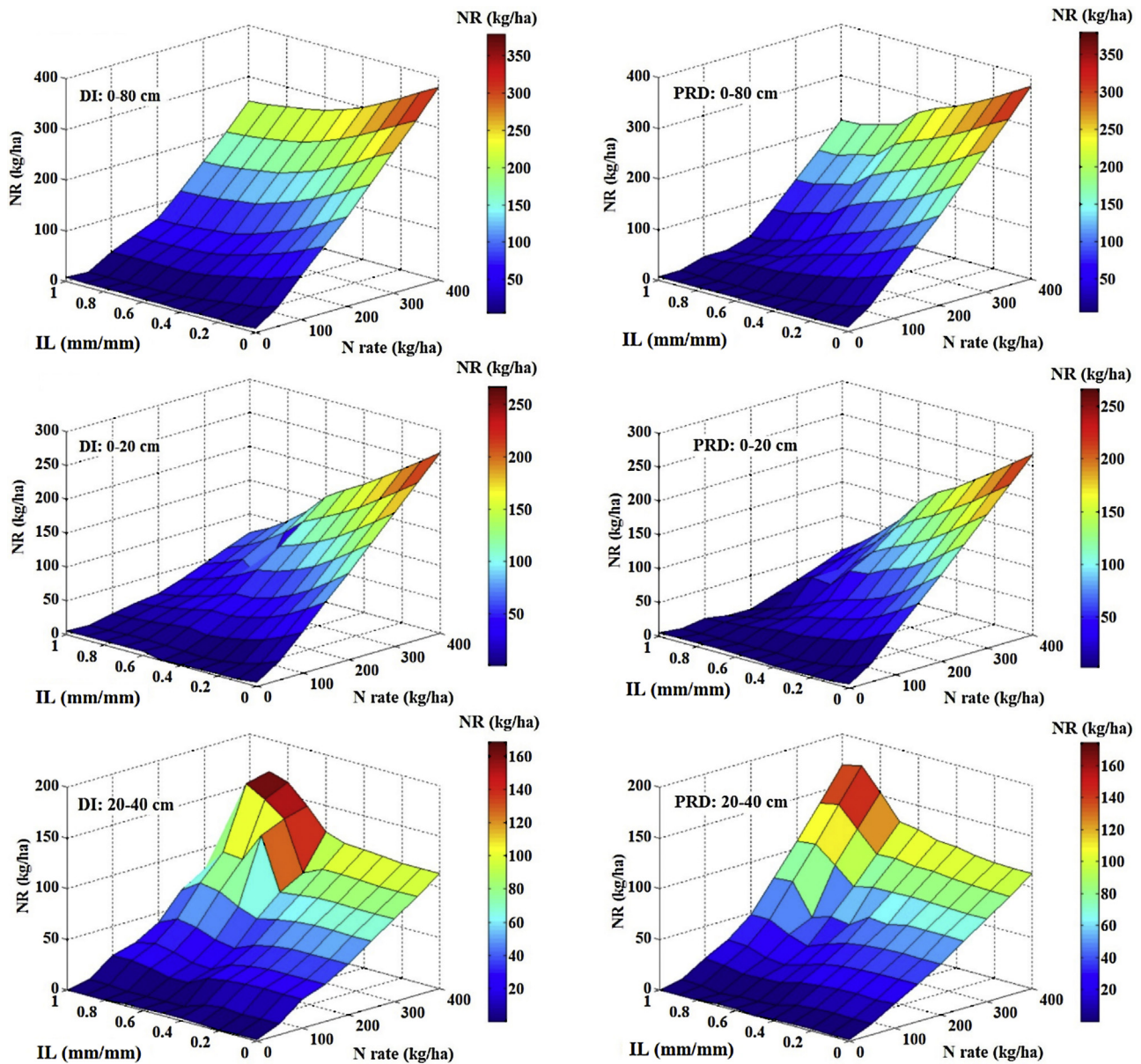
Fig. 7. Residual NO_3^--N at 0–80, 0–20 and 20–40 cm soil depths under the DI (left) and PRD (right) scenarios. NR is NO_3^--N residual in soil (kg/ha), N rate is the N fertilization (kg/ha), and IL is irrigation level.

a pronounced decrease in NO_3^--N leaching below depths of 20 (24.5% for DI and 31.5% for PRD) and 40 cm (24.4% for DI and 38.6% for PRD), the corresponding reduction in plant N uptake is much higher, 15–22% compared to NR=200 kg ha^{-1} (Fig. 5). When NR is reduced even more by 50% (NR=100 kg ha^{-1} at IL=100%) and 75% (NR=50 kg ha^{-1} at IL=100%), plant N uptake is reduced by 28.8–50% and 37.4–70%, respectively, compared to NR=200 kg ha^{-1}. There are very small NO_3^--N leaching from the surface layer for these low NR scenarios. Such results suggest that reducing NRs is not a viable option. A significant reduction in plant N uptake would adversely affect plant growth and yield, resulting in negative impacts on the sustainability of the expensive irrigation system.

It is worth noting that when NR=200–250 kg ha^{-1}, decreasing IL seems to be a better proposition to sustain plant N uptake. A 30% reduction in IL (i.e., lowering IL from 100% to 70%) at NR=250 kg ha^{-1} shows an enormous potential for reducing N leaching below the 20 (45.7% and 48.7% for DI and PRD, respectively) and 40 cm (99.5% and 99.7% for DI and PRD, respectively) soil depths

while plant N uptake remains at a favorable rate (i.e., about 7% less than when plants are fully irrigated). Similarly, plant N uptake is slightly reduced (i.e., by less than 6%) when IL is lowered to 70% at NR=200 kg ha^{-1}. Nevertheless, reducing IL more will adversely affect plant N uptake although it may produce a desirable control on NO_3^--N leaching out of the 20 and 40 cm soil depths. For example, lowering IL to 50% at NR=200 kg ha^{-1} produced a pronounced reduction in NO_3^--N leaching by 84–99.8% below the surface layers, but it also resulted in a considerable decrease in plant N uptake by up to 32.3% compared to full irrigation (IL=100%), which is due to a significant reduction in root water uptake under the soil water stress. The mismatch between NR and plant N uptake ultimately increases when IL is lower than 50%. Such results suggest that the excessive water and N leaching from the surface layer and maintaining N uptake at a favorable rate may be controlled by modifying both irrigation and fertilization scheduling.

Moreover, Fig. 6 well confirms that when IL ≥ 70%, NO_3^--N leaching to deeper soil layers are lower under PRD compared to

those under DI while plant N uptake is considerably higher. This result is consistent with our findings for *DP* and plant N uptake under PRD. In other words, PRD may ensure environmentally safer fertilizer applications compared to DI. While higher root water uptake and less *DP* below the surface layers reduces the downward movement of NO_3^--N, a considerable reduction in NO_3^--N leaching causes more N to be available in the surface layer for plat N uptake.

3.2.4. N residual

The HYDRUS-2D simulation results showed that the storage of NO_3^--N in different soil layers varied greatly among different scenarios (Fig. 7). For the 0–80 cm soil depth, the lower amounts of irrigation combined with the higher amounts of fertilizer resulted, as expected, in the higher mass of NO_3^--N left in the root zone after final harvest. The higher amount of NO_3^--N remaining in the soil indicates that the plant was not able to take up all nitrogen added through fertilization and that nitrogen will thus build up in the soil over time. A higher level of residual NO_3^--N in the soil at the end of the growing season is unwelcomed since it could be easily leached by offseason rainfall and potential pollute water body. It could also flow into stream and rivers and pollute water resources which may be used for drinking or irrigation. These results are in agreement with the findings of Barlow et al. (2009) and Correll et al. (2010) who reported high NO_3^- concentrations in drainage water under drip and furrow fertigation irrigation systems.

For a specific NR, the NO_3^--N content in the deeper soil layers was higher when higher IL was applied since more water infiltrated downwards after irrigation events. Similarly, the higher amount of NR (i.e., NR $\geq$ 200 kg ha^{-1}) for a specific IL led to similar results. This is in agreement with the findings of Jia et al. (2014) who suggested that the application of a large amount of N fertilizer and irrigation led to the enrichment of deeper soil layers by NO_3^--N and to much greater overall N losses due to leaching. Nevertheless, the PRD scenarios retained less N in the soil at final harvest, suggesting that the vulnerability to offseason N losses may be reduced if the irrigation strategy is modified. In agreement with the results of hypothetical scenarios, our field data also revealed that of all water-saving treatments (PRD$_{75}$, PRD$_{55}$, DI$_{75}$, and DI$_{55}$), the PRD$_{75}$ treatment had the lowest residual nitrogen in the root zone at final harvest (data not shown). This is in accordance with the findings that the PRD$_{75}$ plants absorbed more N compared to the DI and PRD$_{55}$ plants.

3.2.5. Grain yield

From the farmers' point of view, grain yield (*Y*) is a key factor for adopting a new technology since they expect to achieve an adequate economic return (Paredes et al., 2014; Karandish, 2016). Therefore, based on the observed data, a linear equation was developed to describe the relationship between the amount of N uptake and maize grain yield (an index of agreement=85%) (Fig. 8). While agronomist may focus on finding the relationship between GY and fertilization rate (NR), such relationship may be of high interest when only fertilizer management scenarios are analyzed. Irrigation water depth (IL) may also affect GY other that NR, as is demonstrated by other researchers. Hence, the relation between GY and NR may not be sufficient when analyzing the combined influence of both ILs and NRs. N uptake, which is demonstrated to significantly affect GY (Lifen et al., 2016), is highly depended on both ILs and NRs (Gheysari et al., 2009). Hence, we extracted the relationship between GY and NU rather than between GY and NR in our research.

Increased N uptake increases grain yield, which was also reported by others (Shahnazari et al., 2008; Karandish and Shahnazari, 2016). As confirmed by our results (Fig. 5) and those reported by the other researchers (Van Dijk and Brouwer, 1998; Montemurro et al., 2006; Gheysari et al., 2009), NU may not increase
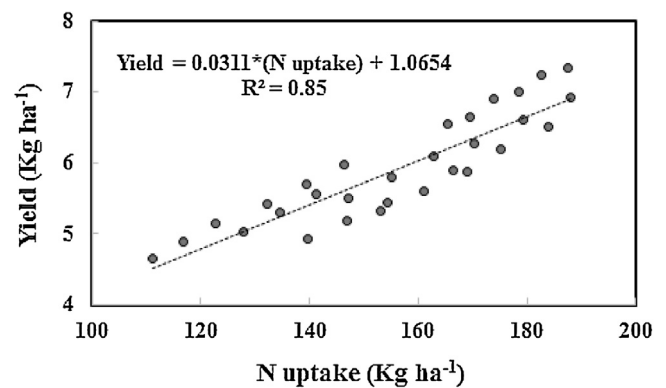

Fig. 8. The linear relationship between maize grain yield and crop N uptake.

after a special amount of NR. As a consequent result, the relationship between GY and NR tend not to be linear when NR exceeds the maximum rate since GY is significantly correlated with NU (Biswas and Ma, 2016; Gheysari et al., 2009). Nevertheless, linear relationship may be found when considering this relationship between NU and GY (Sheoran et al., 2016) rather than between NR and GY

The yield equation was then used to calculate maize grain yield for different scenarios and the results are presented in Fig. 9 for the DI and PRD scenarios. Regardless of the irrigation strategy (i.e., PRD or DI), increased IL and NR led to higher yield, which is in agreement with findings of Jia et al. (2014) who reported that maize grain yield was affected by both the amount of irrigation and the N application level. The highest yield of 7.5 t ha^{-1} was obtained for IL=100% and NR=400 kg ha^{-1} under PRD, which was about 20% higher than for the same conditions under DI (6.3 t ha^{-1}). Nevertheless, there was not a considerable increase in grain yield when IL varied between 70 and 100% or when NR varied from 200 to 400 kg ha^{-1} under both PRD and DI.

When IL $\geq$ 70%, maize grain yield under PRD is considerably higher (by 0.2–20.2%) than under DI for all NRs, while for IL $\leq$ 60% a no considerable difference was observed between yields obtained for the PRD or DI scenarios. These results are in agreement with our 2-years field data (Karandish and Šimůnek, 2016a), for which the statistical analysis revealed that the water stress led to a significant reduction in *Y* for the PRD$_{55}$, DI$_{75}$, and DI$_{55}$ treatments compared to the FI treatment, while it caused no significant reduction in *Y* for the PRD$_{75}$ treatment. On the other hand, increased NR above 200 kg ha^{-1} did not affect considerably crop yield under the PRD or DI scenarios, although yield was higher for the PRD than DI scenarios. Such results indicate that both ILs and NRs are important for adopting PRD since they both determine the yield efficiency. In other words, PRD may lead to better results with respect to both economic (maize grain yield) and environmental issues (N dynamics) compared to DI when a favorable IL and NR are adopted.

A large body of evidence shows that PRD can significantly improve yield (Dry et al., 2000; Kang and Zhang 2004; Kirda et al., 2004; Tang et al., 2005; Shao et al., 2008; Wang et al., 2012; Karandish, 2016; Karandish and Šimůnek, 2016a). Higher availability of N increases the duration of the vegetation growth and postpones leaf senesce due to more N nutrition in leaves (Haverkort et al., 2003). In agreement with this, our field data revealed that the leaf nitrogen in PRD$_{75}$ was significantly higher than that for other treatments (data not shown). A better N nutrition in the leaves and more N accumulated in plants in the PRD scenarios result in an increase in grain yield by maintaining a greater photosynthesis rate in the PRD scenarios (Varvel et al., 1997; Gianquinto et al., 2003).
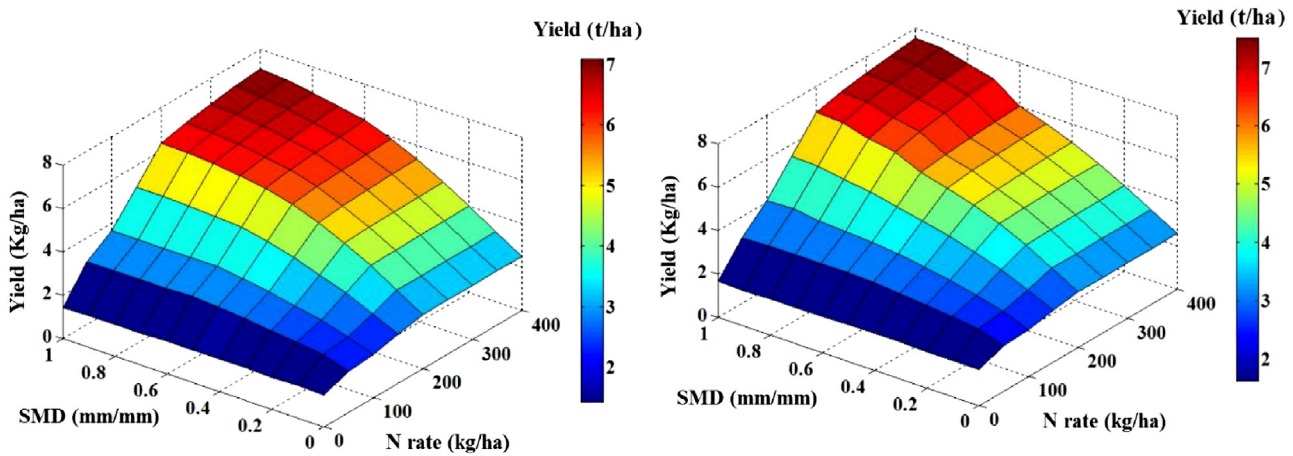
Fig. 9. Maize grain yield for various hypothetical scenarios under the DI (left) and PRD (right) scenarios. N rate is the N fertilization (kg/ha), and IL is irrigation level.

4. Conclusions

We have conducted a combined field and model investigations involving a drip-irrigated maize field to evaluate the influence of various N and water managed scenarios under deficit irrigation (DI) and partial root-zone drying (PRD) on water and N dynamics. The quantitative analysis indicated the capability of the HYDRUS-2D model to simulate soil water contents, soil NO_3^--N concentrations, and crop N uptake, and their temporal trends for all treatments. Simulated results reflected well the effects of the irrigation and fertilization managements on water and N dynamics as well as on grain yield. The simulated results indicate that when there are restrictions on water applications, NR needs to be adjusted depending on IL in order to alleviate the mismatch between the N application and uptake to prevent environmental damage. Furthermore, IL also requires an adjustment depending on a particular NR to ensure a desirable N use efficiency. On the other hand, both IL and NR need to be optimized to prevent economic losses while preventing environmental damage. Reducing the amount of irrigation water by 30% and applying NR=200 kg ha^{-1} seems to be the optimum scenario for which both economic and environmental objectives are satisfied. Additionally, our results demonstrated that PRD, by increasing crop N uptake, ensures environmentally safer fertilizer applications compared to DI. Moreover, the use of PRD results in 0.2–20.2% higher yield compared to DI under various scenarios. The combination of IL=70% and NR=200 kg ha^{-1} under PRD is thus the most efficient N-managed water-saving irrigation strategy for the maize cultivation in the study area. Additionally, it could be concluded that the HYDRUS-2D model, instead of labor- and time-consuming and expensive field investigations, could be reliably used for determining the optimal scenarios under both DI and PRD strategies.

References

Šimůnek, J., Hopmans, J.W., 2009. Modeling compensated root water and nutrient uptake. Ecol. Model 220, 505–521.

Šimůnek, J., van Genuchten, M.Th., Šejna, M., 2008. Development and applications of the HYDRUS and STANMOD software packages and related codes. Vadose Zone J. 7 (2), 587–600, http://dx.doi.org/10.2136/vzj2007.0077.

Šimůnek, J., van Genuchten, M.Th., Šejna, M., 2016. Recent developments and applications of the HYDRUS computer software packages. Vadose Zone J. 15 (7), 25, http://dx.doi.org/10.2136/vzj2016.04.0033.

American Public Health Association (APHA), 1992. Standard Methods for the Examination of Water and Wastewater, 18th edition. APHA, Washington, DC.

Ajdary, K., Singh, D.K., Singh, A.K., Khanna, M., 2007. Modelling of nitrogen leaching from experimental onion field under drip fertigation. Agric. Water Manage. 89, 15–28.

Alva, A.K., Paramasivam, S., Obreza, T.A., Schumann, A.W., 2006. Nitrogen best management practice for citrus trees I. Fruit yield quality, and leaf nutritional status. Sci. Horti. 107, 233–244.

Assouline, S., Moller, M., Cohen, S., Ben-Hur, M., Grava, A., Narkis, K., Silber, A., 2006. Soil–plant system response to pulsed drip irrigation and salinity: bell pepper-case study. Soil Sci. Soc. Am. J. 70, 1556–1568.

Bar-Yosef, B., 1999. Advances in fertigation. Adv. Agron. 65, 1–75.

Barlow, K., Bond, W., Holzapfel, B., Smith, J., Hutton, R., 2009. Nitrogen concentrations in soil solution and surface run-off on irrigated vineyards in Australia. Aust. J. Grape Wine Res. 15, 131–143.

Barton, L., Colmer, T.D., 2006. Irrigation and fertilizer strategies for minimizing nitrogen leaching from turfgrass. Agric. Water Manage. 80, 160–175.

Bear, J., 1972. Dynamics of Fluid in Porous Media. Elsevier, New York, NY.

Biswas, K.D., Ma, B.L., 2016. Effect of nitrogen rate and fertilizer nitrogen source on physiology yield, grain quality, and nitrogen use efficiency in corn. Can. J. Plant Sci. 96, 392–403.

Boudsocq, S., Niboyet, A., Lata, J.C., Raynaud, X., Loeuille, N., Mathieu, J., Blouin, M., Abbadie, L., Barot, S., 2012. Plant preference for ammonium versus nitrate: a neglected determinant of ecosystem functioning? Am. Nat. 180, 60–69.

Bremner, J.M., Mulvaney, C.S., et al., 1982. Nitrogen: total. In: Page, A.L. (Ed.), Methods of Soil Analysis: Part 2. , 2nd ed. Agronomy Monograph 9, ASA, SSSA, Madison, WI, pp. 595–641.

Burow, K.R., Nolan, B.T., Rupert, M.G., Dubrovsky, N.M., 2010. Nitrate in groundwater of the United States, 1991–2003. Environ. Sci. Technol. 44, 4988–4997.

Chuan, L.M., Zhao, T.K., An, Z.Z., Du, L.F., Li, S.J., Ma, L., 2010. Research advancement in nitrate leaching and nitrogen use in soils. Chin. Agric. Sci. Bull. 26, 200–205.

Correll, R., Smith, L., Waller, T., Zandona, R., Christen, E., Kookana, R., 2010. Managing root zone water quality. In: Project Report. CSIRO Land and Water, CSIRO, Australia.

Cote, C.M., Bristow, K.L., Charlesworth, P.B., Cook, F.J., Thorburn, P.J., 2003. Analysis of soil wetting and solute transport in subsurface trickle irrigation. Irrig. Sci. 22, 143–156.

Crevoisier, D., Popova, Z., Mailhol, J.C., Ruelle, P., 2008. Assessment and simulation of water and nitrogen transfer under furrow irrigation. Agric. Water Manage. 95 (4), 354–366.

Dahan, O., Babad, A., Lazarovitch, N., Russak, E.E., Kurtzman, D., 2014. Nitrate leaching from intensive organic farms to groundwater. Hydrol. Earth Syst. Sci. 18, 333–341.

Daudén, A., Quilez, D., 2004. Pig slurry versus mineral fertilization on corn yield and nitrate leaching in a Mediterranean irrigated environment. Eur. J. Agron. 21, 7–19.

Doltra, J., Munoz, P., 2010. Simulation of nitrogen leaching from a fertigated crop rotation in a Mediterranean climate using the EU-Rotate N and Hydrus-2D models. Agric. Water Manage. 97, 277–285.

Dry, P.R., Loveys, B.R., 1998. Factors influencing grapevine vigor and the potential for control with partial root zone drying. Aust. J. Grape Wine Res. 4, 140–148.

Dudley, L.M., Ben-Gal, A., Lazarovitch, N., 2008. Drainage water reuse: biological, physical, and technological considerations for system management. J. Environ. Qual. 37, 25–35.

Feddes, R.A., Kowalik, P.J., Zaradny, H., 1978. Simulation of field water use and crop yield. In: Simulation Monographs. Pudoc, Wageningen.

Fort, C., Fauveau, M.L., Muller, F., Label, P., Granier, A., Dreyer, E., 1997. Stomatal conductance, growth and root signaling in young oak seedlings subjected to partial soil drying. Tree Physiol. 17, 281–289.

Gärdenäs, A.I., Hopman, J.W., Hanson, B.R., Šimůnek, J., 2005. Two-dimensional modeling of nitrate leahing for various fertigation scenarios under micro-irrigation. Agric. Water Manage. 74 (3), 219–242.

Gasser, M.O., Laverdiere, M.R., Lagace Caron, R.J., 2002. Impact of potato-cereal rotation and slurry applications on nitrate leaching and nitrogen balance in sandy soils. Can. J. Soil Sci. 82, 469–479.

Gheysari, M., Mirlatifi, S.M., Homaee, M., Asadi, M.E., Hoogenboom, G., 2009. Nitrate leaching in a silage maize field under different irrigation and nitrogen fertilizer rates. Agric. Water Manage. 96 (6), 946–954.

Gianquinto, G., Sambo, P., Pimpini, F., 2003. The use of SPAD-502 chlorophyll meter for dynamically optimising the nitrogen supply in potato crop. Acta Hortic. 627, 225–230.

Hanson, B.R., Šimůnek, J., Hopmans, J.W., 2006. Evaluation of urea-ammonium-nitrate fertigation with drip irrigation using numerical modeling. Agric. Water Manage. 86, 102–113.

Harris, P.M., 1978. Mineral nutrition. In: Harris, P.M. (Ed.), The Potato Crop: The Scientific Basis for Improvement. Chapman and Hall, New York, pp. 195–243.

Haverkort, A.J., Vos, J., Booij, R., 2003. Precision management of nitrogen and water in potato production through monitoring and modeling. In: Proceedings of the XXVI International Horticultural Congress: Potatoes, Healthy Food for Humanity: International Developments in Breeding, Production, Protection and Utilization, Toronto, Canada.

Havlin, J.L., Beaton, J.D., Tisdale, S.L., Nelson, W.L., 2006. Soil Fertility and Fertilizers, 7th ed. Prentice Hall of India, New Delhi.

Hawkes, C.V., Wren, I.F., Herman, D.J., Firestone, M.K., 2005. Plant invasion alters nitrogen cycling by modifying the soil nitrifying community. Ecol. Lett. 8, 976–985.

Herrmann, A., 2003. Predicting Nitrogen Mineralization from Soil Organic Matter – a Chimera? Swedish University of Agricultural Sciences.

Hu, T., Kang, H., Li, F., Zhang, J., 2009. Effects of partial root-zone irrigation on the nitrogen absorption and utilization of maize. Agric. Water Manage. 96, 208–214.

Huang, P.T., Palet, M., Santagata, M.C., Bobet, A., 2009. Classification of Organic Soils. Purdue University, pp. 195.

Hutton, R., Holzapfel, B., Smith, J., Hutchinson, P., Barlow, K., Bond, W., 2008. Influence of irrigation and fertilizer management on the movement of water and nutrients within and below rootzone of vines for sustainable grape production. CRC for Viticulture Report S2.3.6.

Jia, X., Shao, L., Liu, P., Zhao, B., Gu, L., Dong Sh Bing, S.H., Zhang, J., Zhao, B., 2014. Effect of different nitrogen and irrigation treatments on yield and nitrate leaching of summer maize (Zea mays L.) under lysimeter conditions. Agric. Water Manage. 137 (2014), 92–103.

Kandelous, M.M., Šimůnek, J., van Genuchten, M.Th., Malek, K., 2011. Soil water content distribution between two emitters of a subsurface drip irrigation system. Soil Sci. Soc. Am. J. 75 (2), 488–497.

Kang, S., Zhang, J., 2004. Controlled alternate partial root- Zone irrigation: its physiological consequences and impact on water use efficiency. J. Exp. Bot. 55, 2437–2446.

Kang, S.Z., Hu, X., Goodwin, I., Jerie, P., 2002. Soil water distribution, water use, and yield response to partial root zone drying under a shallow groundwater table condition in a pear orchard. Sci. Hortic. 92, 277–291.

Karandish, F., Šimůnek, J., 2016a. A field-modeling study for assessing temporal variations of soil-water-crop interactions under water-saving irrigation strategies. Agric. Water Manage. 178, 291–303, http://dx.doi.org/10.1016/j.agwat.2016.10.009.

Karandish, F., Šimůnek, J., 2016b. Numerical and machine-learning modeling of soil water content for sustainable water management in agriculture under water stress. J. Hydrol. 543, 892–909, http://dx.doi.org/10.1016/j.jhydrol.2016.11.007b.

Karandish, F., Shahnazari, A., 2016. Soil temperature and maize nitrogen uptake improvement under partial root zone drying. Pedosphere 26 (6), 872–886.

Karandish, F., Darzi-Naftchali, A., Asgari, A., 2017. Application of machine-learning models for diagnosing health hazard of nitrate toxicity in shallow aquifers. Paddy Water Environ. 15 (1), 201–215, http://dx.doi.org/10.1007/s10333-016-0542-2.

Karandish, F., 2016. Improved soil-plant water dynamics and economic water use efficiency in a maize field under locally water stress. Arch. Agron. Soil Sci. 62 (9), 1311–1323, http://dx.doi.org/10.1080/03650340.2015.1135326.

Kirda, C., Cetin, M., Dasgan, Y., Topcu, S., Kaman, H., Ekici, B., Derici, M.R., Ozguven, A.I., 2004. Yield response of greenhouse grown tomato to partial root drying and conventional deficit irrigation. Agric. Water Manage. 69, 191–201.

Kirda, C., Topcu, S., Kaman, H., Ulger, A.C., Yazici, A., Cetin, M., Derici, M.R., 2005. Grain yield response and N-fertiliser recovery of maize under deficit irrigation. Field Crops Res. 93, 132–141.

Kumar, K., Prihar, S.S., Gajri, P.R., 1993. Determination of root distribution of wheat by auger sampling. Plant Soil 149, 245–253.

Kurtzman, D., Shapira, R.H., Bar-Tal, A., Fine, P., Russo, D., 2013. Nitrate fluxes to groundwater under citrus orchards in a Mediterranean climate: observation, calibrated models, simulations and agro-hydrological conclusions. J. Contam. Hydrol. 151, 93–104.

Laher, M., Avnimelech, Y., 1980. Nitrification inhabitation in drip irrigation systems. Plant Soil 55, 35–42.

Lata, J.-C., Guillaume, K., Degrange, V., Abbadie, L., Lensi, R., 2000. Relationships between root density of the African grass *Hyparrhenia diplandra* and nitrification at the decimetric scale: an inhibition-stimulation balance hypothesis. Proc. R. Soc. B: Biol. Sci. 267, 595–600.

Li, J., Liu, Y., 2011. Water and nitrate distributions as affected by layered-textural soil and buried dripline depth under subsurface drip fertigation. Irrig. Sci. 29, 469–478.

Li, H., Han, Y., Cai, Z., 2003. Nitrogen mineralization in paddy soils of the Taihu Region of China under anaerobic conditions: dynamics and model fitting. Geoderma 115, 161–175.

Li, F., Liang, J., Kang, S.H., Zhang, J., 2007. Benefits of alternate partial root-zone irrigation on growth, water and nitrogen use efficiencies modified by fertilization and soil water status in maize. J. Plant Soil 295, 279–291.

Li, Y., Šimůnek, J., Zhang, Z., Jing, L., Ni, L., 2015. Evaluation of nitrogen balance in a direct-seeded-rice field experiment using Hydrus-1D. Agric. Water Manage. 148, 213–222.

Liang, J., Zhang, J., Wong, M.H., 1996. Effects of air-filled soil porosity and aeration on the initiation and growth of secondary roots of maize (Zea mays). J. Plant Soil 186, 245–254.

Lifen, H., Jun, Y.U., Jie, Y., Rong, Z., Yanchao, B.A.I., Chengming, S., Hengyang, Z., 2016. Relationships between yield, quality and nitrogen uptake and utilization of organically grown rice varieties. Pedosphere 26 (1), 85–97.

Liu, F., Shahnazari, A., Andersen, M.N., Jacobsen, S.E., Jensen, C.R., 2006. Effects of deficit irrigation (DI) and partial root drying (PRD) on gas exchange, biomass partitioning, and water use efficiency in potato. Sci. Hortic. 109, 113–117.

Lundquist, E., Jackson, L., Scow, K., 1999. Wet–dry cycles affect dissolved organic carbon in two California agricultural soils. Soil Biol. Biochem. 31, 1031–1038.

Marschner, H., 1995. Mineral Nutrition of Higher Plants. Academic Press/Harcourt Brace and Company, London.

Mguidiche, A., Provenzano, G., Douh, B., Khila, S., Rallo, G., Boujelben, A., 2015. Assessing HYDRUS-2D to simulate soil water content (SWC) and salt accumulation under an SDI system: application to a potato crop in a semi-arid area of central Tunisia. Irrig. Drain. 64, 263–274.

Mmolawa, K., Or, D., 2003. Experimental and numerical evaluation of analytical volume balance model for soil water dynamics under drip irrigation. Soil Sci. Soc. Am. J. 67, 1657–1671.

Montemurro, F., Maiorana, M., Ferri, D., Convertini, G., 2006. Nitrogen indicators: uptake and utilization efficiency in a maize and barley rotation cropped at different levels and sources of N fertilization. Field Crop Res. 99, 114–124.

Mosier, A.R., Bleken, M.A., Chaiwanakupt, P., Ellis, E.C., Freney, J.R., Howarth, R.B., Matson, P.A., Minami, K., Naylor, R., Weeks, K.N., Zhu, Z.L., 2002. Policy implications of human-accelerated nitrogen cycling. Biogeochemistry 57, 477–516.

Mubarak, I., 2009. Effect of temporal variability in soil hydraulic properties on simulated water transfer under high-frequency drip irrigation. Agric. Water Manage. 96 (11), 1547–1559.

Nagore, M.L., Echarte, L., Andrade, F.H., Maggiora, A.D., 2014. Crop evapotranspiration in Argentina maize hybrids released. Field Crop Res. 155, 23–29.

Nourbakhsh, F., Karimian Eghbal, M., 1997. <EDN></EDN>. In: Soil Fertility, first edition. Entesharat Ghazal, Isfahan, pp. 312 (In Farsi).

Paredes, P., Rodrigues, G.C., Alves, I., Pereira, L.S., 2014. Partitioning evapotranspiration, yield prediction and economic returns of maize under various irrigation management strategies. Agric. Water Manage. 135, 27–39.

Patel, N., Rajput, T.B.S., 2008. Dynamics and modeling of soil water under subsurface drip irrigated onion. Agric. Water Manage. 95 (12), 1335–1349.

Phogat, V., Skewes, M.A., Cox, G., Alam, J., Grigson, G., Šimůnek, J., 2013. Evaluation of water movement and nitrate dynamics in a lysimeter planted with an orange tree. Agric. Water Manage. 127 (2013), 74–84.

Phogat, V., Skewes, M.A., Cox, J.W., Sanderson, G., Alam, J., Šimůnek, J., 2014. Seasonal simulation of water, salinity and nitrate dynamics under drip irrigated mandarin (Citrus reticulata) and assessing management options for drainage and nitrate leaching. J. Hydrol. 513 (2014), 504–516.

Poni, S., Tagliavini, M., Neri, D., Scudellari, D., Toselli, M., 1992. Influence of root pruning and water stress on growth and physiological factors of potted apple, grape, peach and pear trees. Sci. Hortic. 52, 223–226.

Radcliffe, D., Šimůnek, J., 2010. Pp. In: Soil Physics with HYDRUS: Modeling and Applications. CRC Press, Taylor & Francis Group, Boca Raton, FL, pp. 373 (2010, ISBN: 978-1-4200-7380-5).

Ramos, T.B., Šimůnek, J., Goncalves, M.C., Martins, J.C., Prazeres, A., Pereira, L.S., 2012. Two-dimensional modeling of water and nitrogen fate from sweet sorghum irrigated with fresh and blended saline waters. Agric. Water Manage. 111, 87–104.

Sepaskhah, A.R., Ahmadi, S.H., 2010. A review on partial root-zone drying irrigation. Int. J. Plant Product. 4 (4), 241–258.

Sepaskhah, A.R., Kamgar-Haghighi, A.A., 1997. Water use and yields of sugar beet grown under every-otherfurrow irrigation with different irrigation intervals. Agric. Water Manage. 34, 71–79.

Sepaskhah, A.R., Yousefi, F., 2007. The effects of zeolite application on nitrate and ammonium retention of a loamy soil under saturated conditions. Aust. J. Soil Res. 45, 368–373.

Shahnazari, A., Ahmadi, S.H., Lærke, P.E., Liu, F., Plauborg, F., Jacobsen, S.E., Jensen, C.R., Andersen, M.N., 2008. Nitrogen dynamics in the soil-plant system under deficit and partial root-zone drying irrigation strategies in potatoes. Eur. J. Agron. 28, 65–73.

Shao, G.C., Zhang, Z.Y., Liu, N., Yu, S.E., Xing, W.G., 2008. Comparative effects of deficit irrigation (DI) and partial rootzone drying (PRD) on soil water distribution water use, growth and yield in greenhouse grown hot pepper. Sci. Hortic. 119 (1), 11–16.

Sheoran, P., Sardana, V., Singh, S., Kumar, A., Mann, A., Sharma, P., 2016. Agronomic and physiological assessment of nitrogen use, uptake and acquisition in sunflower. Agric. Water Manage. Int. J. Plant Product. 10 (2), 109–121.

Siyal, A.A., Skaggs, T.H., 2009. Measured and simulated soil wetting patterns under porous clay pipe sub-surface irrigation. Agric. Water Manage. 96 (6), 893–904.

Tafteh, A., Sepaskhah, A.R., 2012. Application of HYDRUS-1D model for simulating water and nitrate leaching from continuous and alternate furrow irrigated rapeseed and maize fields. Agric. Water Manage. 113, 19–29.

Tamini, T., Mermoud, A., 2002. Water and nitrogen dynamics under irrigation onion in a semi-arid area. Irrig. Drain. 51, 77–86.

Tang, L.S., Li, Y., Zhang, J., 2005. Physiological and yield responses of cotton under partial root-zone irrigation. Field Crop Res. 94, 214–223.

Tarkalson, D.D., Payero, J.O., Ensley, S.M., Shapiro, C.A., 2006. Nitrate accumulation and movement under deficit irrigation in soil receiving cattle manure and commercial fertilizer. Agric. Water Manage. 85, 201–210.

Thompson, A.J., Andrews, J., Mulholland, B.J., McKee, J.M.T., Hilton, H.W., Horridge, J.S., Farquhar, G.D., Smeeton, R.C., Smillie, I.R.A., Black, C.R., Taylor, I.B., 2007. Overproduction of Abscisic acid in tomato increases transpiration efficiency and root hydraulic conductivity and influences leaf expansion. Plant Physiol. 143, 1905–1917.

Tischner, R., 2000. Nitrate uptake and reduction in higher and lower plants. Plant Soil Environ. 23 (10), 1005–1024.

Tournebize, J., Gregoire, C., Coupe, R.H., Ackerer, P., 2012. Modelling nitrate transport under row intercropping system: vines and grass cover. J. Hydrol. 440-441, 14–25.

Vale, M., Mary, B., Justes, E., 2007. Irrigation practices may affect denitrification more than nitrogen mineralization in warm climatic conditions. Biol. Fertil. Soils 43, 641–651.

Van Dijk, W., Brouwer, G., 1998. Nitrogen recovery and dry matter production of silage maize (Zea mays L.) as affected by subsurface band application of mineral nitrogen fertilizer. Neth. J. Agric. Sci. 46, 139–155.

Varvel, G.E., Schepers, J.S., Francis, D.D., 1997. Ability for in-season correction of nitrogen deficiency in corn using chlorophyll meters. Soil Sci. Soc. Am. J. 61, 1233–1239.

Wang, H., Liu, F., Andersen, M.N., Jensen, C.R., 2009. Comparative effects of partial root-zone drying and deficit irrigation on nitrogen uptake in potatoes (Solanum tuberosum L.). Irrig. Sci. J. 27, 443–448.

Wang, H., Ju, X., Wei, Y., Li, B., Zhao, L., Hu, K., 2010. Simulation of bromide and nitrate leaching under heavy rainfall and high-intensity irrigation rates in North China Plain. Agric. Water Manag. 97, 1646–1654.

Wang, Z., Liu, F., Kang, Sh., Jensen, C.R., 2012. Alternate partial root-zone drying irrigation improves nitrogen nutrition in maize (Zea mays L.) leaves. J. Environ. Exp. Bot. 75, 36–40.

Wang, Z., Li, J., Li, Y., 2014. Simulation of nitrate leaching under varying drip system uniformities and precipitation patterns during the growing season of maize in the North China Plain. Agric. Water Manage. 142, 19–28.

Wei, Y.P., Chen, D.L., Hu, K.L., Willett, I.R., Langford, J., 2009. Policy incentives for reducing nitrate leaching from intensive agriculture in desert oases of Alxa, InnerMongolia, China. Agric. Water Manage. 96, 1114–1119.

Wienhold, B.J., Trooien, T.P., Reichman, G.A., 1995. Yield and nitrogen use efficiency of irrigated corn in the northern Great Plains. Agron. J. 87 (5), 842–846.

Wijanarko, A., 2015. Effect of organic matter and soil fertility on nitrogen mineralization and uptake by Cassava (Manihot esculenta Crantz) in a typic hapludults. J. Exp. Biol. Agric. Sci. 3 (3), 232–240.

Zhu, J.H., Li, X.L., Christie, P., Li, J.L., 2005. Environmental implications of low nitro-gen use efficiency in excessively fertilized hot pepper (Capsicum frutescens L.) cropping systems. Agric. Ecosyst. Environ. 111, 70–80.