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Effects of alternate partial root-zone irrigation on the utilization and movement of nitrates in soil by tomato plants

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ABSTRACT

Alternate partial root-zone irrigation (APRI) can greatly affect water conservation and yield stabilization *via* its physiological regulation of plants. However, most studies have not distinguished the fate of residual nitrogen in specific soil layers, and little attention has been paid to the utilization and fate of residual nitrogen in different soil layers under APRI. The aim of this study is to evaluate the fate of nitrate accumulated in different soil profiles and its potential for utilization by crops under APRI. The ^{15}N tracer technique and simulated soil column method were used to study the effects of APRI on the movement and utilization of residual nitrate. The results showed that, compared to conventional irrigation, APRI could save 38.8% irrigation water without significant effects on tomato yield, even though the total plant biomass significantly decreased. APRI improved the absorption of residual nitrate and facilitated the transfer of nitrogen from the stems and leaves to the fruits. Compared to residual nitrate (labeled by ^{15}N) in the upper layer (10–20 cm), nitrate in the lower layer (40–50 cm) showed less potential for absorption by tomato plants and a diminished leaching distance, corresponding to a significantly increase loss (rate). Under APRI, the ^{15}N loss rate significantly decreased, but the utilization did not significantly decrease, compared to conventional irrigation. Moreover, APRI promoted root development, especially fine root growth, and reduced the leaching of residual nitrate in different soil layers.

1. Introduction

In recent years, partial root-zone irrigation (PRI) has been studied and practiced intensively in China as well as other countries. PRI includes alternate PRI (APRI) and fixed PRI (FPRI) (Bravdo, 2005; Dodd et al., 2006; Loveys et al., 2000). In APRI, approximately half of the root system is exposed to drying soil, while the remaining half is sufficiently irrigated. The wetted and dried sides of the root system are alternated in a frequency according to the crop types, growing stages, and soil water balance (Li et al., 2007). Thus, APRI can divert water stress alternatively to different root parts, promote compensatory growth in the root system, and enhance overall root function (Skinner et al., 1999). Moreover, root-sourced signaling can considerably reduce both the stomatal aperture and the transpiration rate of plants without significant reductions in photosynthesis (Wei et al., 2016). Thus, APRI offers remarkable advantages in saving irrigation water with little adverse influence on crop yields (de Lima et al., 2015; Dodd et al., 2015; Du et al., 2006; Kang and Zhang, 2004; Li et al., 2011). Not surprisingly, APRI has been applied to a wide range of crops, such as soybeans, chilis, apples, potatoes, tomatoes, cotton, and grapes (Kang and Zhang, 2004; Sepaskhah and Ahmadi, 2010).

Additionally, because nitrogen fertilizers have been heavily applied in China, nitrate pollution of groundwater has become a major issue in agricultural areas (Nie et al., 2012). If accumulated nitrogen is not absorbed by crops, it moves into the deeper soil profile and beyond the root zone, causing a reduction in bioavailability, accumulation of nitrate nitrogen in deep soil, and pollution of underground water (Ju et al., 2006; Zhang et al., 1996). One effective way to mitigate this pollution is enhanced plant absorption of nitrate nitrogen from different soil layers (Gathumbi et al., 2003; Ju et al., 2007; Kumar and Goh, 2002; Macdonald et al., 2002). Numerous studies have shown that APRI can decrease the deep percolation of water, which could reduce the leaching of nitrate nitrogen to increase its accumulation in the soil, thus increasing its probability of eventually being absorbed by crops (Skinner et al., 1998; Wang et al., 2014). However, most of these studies have not distinguished the fate of residual nitrogen in specific soil

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Table 1
Basic physicochemical of the experimental soil.

Soil layers (cm)	pH	O.M. (g kg^{-1})	Total N (g kg^{-1})	NH_4^+-N (mg kg^{-1})	NO_3^--N (mg kg^{-1})	Available P (mg kg^{-1})	Available K (mg kg^{-1})	Bulk soil density (g cm^{-3})	Soil texture (%)
0–20	7.32	12.6	0.71	20.6	141.2	8.30	80.7	1.55	29/68/3
20–40	7.69	6.91	0.16	22.9	70.5	1.75	41.8	1.56	40/59/1
40–80	7.87	5.84	0.24	20.4	52.8	1.68	29.6	1.56	50/47/3
80–120	7.89	4.31	0.18	23.9	27.9	0.08	21.3	1.44	54/44/2

The soil texture is expressed as the percentage of “sand/loam/clay” in soil.

layers. Generally, the movement and utilization of residual nitrogen in different soil layers can vary considerably (Zhang et al., 2005, 2007).

In the present study, tomatoes (a popular cultured vegetable in the local area) were chosen as the study material for such an evaluation. To perform this study, the ^{15}N tracer technique and simulated soil column method were used. The outcome of this research is crucial for efficiently using irrigation water and fertilizer and for reducing nitrogen contamination in the environment.

2. Materials and methods

2.1. Experimental site

The experiment was carried out in a steel-framed greenhouse in the Pangwang Demonstration Garden (E116°46′, N33°58′), a vegetable base in Huaibei city in eastern China. This area is characterized by a typical warm, temperate, humid climate with a mean annual air temperature of 14.4 °C, a relative humidity of 71%, a frost-free-period of 202 days, and total sunshine hours of 2315.8 h. The air temperature ranged from 15 °C to 30 °C during the experiment. The basic physicochemical properties of the experimental soil are summarized in Table 1.

2.2. Experimental design

The experiment was performed with a simulated soil column. Two ditches were dug in the experimental field, and soil layers from depths of 0–20, 20–40, 40–80, and 80–120-cm were separately removed. A homemade cylindrical aluminum barrel without a bottom with a height of 120 cm and a diameter of 45 cm was used as a mold (Fig. 1). An agricultural polyethylene film (0.15 mm thick) was first applied closely to the inner wall of the barrel, and then, the mold was placed at a designated site in the ditch. Mixed and sieved soils (passed through a 2-mm sieve) from the different original layers were filled into the aluminum barrel at corresponding layers to a depth of 120 cm. Once each soil layer was filled, the soil was watered to 90% of its field water capacity (Zhang et al., 2014).

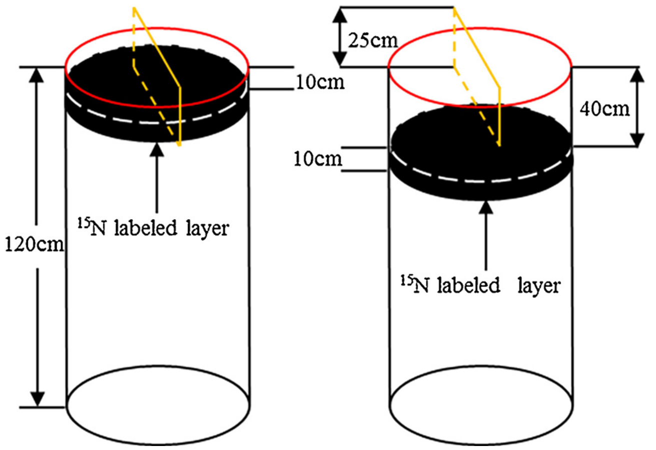

Fig. 1. Sketch map of soil column and ^{15}N labeled layers.

While filling the soil column, the ditch outside was simultaneously filled with soil in a layer-by-layer manner. The mold was gently removed while filling, leaving the film intact. In this way, a soil column with a depth of 0–120 cm was formed by the leftover polyethylene film separating the inner soil from the surrounding soil. A 45-cm-long and 0.15-mm-thickness polyethylene film was set in the middle of the soil column at a depth of 0–20 cm with 5 cm protruding from the soil surface to form two equal root compartments. A 5-cm × 5-cm hole was formed in the center of the polyethylene film for tomato transplanting. The soil column did not have a bottom to enable the exchange of water and nutrients between the soil column and the deeper soil.

During the soil filling, exogenous ^{15}N was labeled to a corresponding soil layer at a depth of either 10–20 cm or 40–50 cm according to the experimental design (Fig. 1). The dose of exogenous ^{15}N consisted of NO_3^- accumulated within the specific soil layer (Zhang et al., 2005). The proportion of ^{15}N in $K^{15}NO_3$ (supplied by the Shanghai Research Institute of Chemical Industry) was 10.28%. During labeling, 14.5 g of $K^{15}NO_3$ was thoroughly mixed with the soil of the corresponding layer before filling for each column. After making all the soil columns, 60-day-old tomato seedlings selected for uniform size, together with their seedling containers, were transplanted into the center hole of the film in the soil columns. This film divided the soil column into two even root-zone compartments to prevent irrigated water from moving to the opposite root zone. The tomato seedlings were transplanted with one seedling per soil column.

The utilized tomato variety was *Jiafen No.1*, which was provided by the Beijing Vegetable Research Center and is widely planted in local areas. Two factors were set in the experiment: irrigation mode and ^{15}N-labeled layer in the soil profile (each with two levels). Irrigation mode included conventional sufficient irrigation (CI, included in treatments CI15 and CI45; Table 2) and APRI (included in treatments APRI15 and APRI45; Table 2); ^{15}N was labeled in the soil profile at two depth levels, 10–20 cm and 40–50 cm. A total of four treatments (2 × 2) were applied in the experiment, each with four replicates (Table 2).

Sixteen ^{15}N-labeled soil columns were positioned 15 cm apart in the greenhouse in two rows. In addition, two soil columns without ^{15}N were set as a reference for CI and APRI; other conditions were identical to the columns with ^{15}N. To monitor and record soil moisture changes, time-domain reflectometer (TDR) instruments (TRIME-PICO-IPH-TDR, IMKO, Germany) were buried in the reference columns at a depth of 0–200 cm. Thus, a total of 20 soil columns were prepared this way and used in the experiment. The experimental layout is illustrated in Fig. 2.

2.3. Fertilization and field management

The fertilization regime approximated the usage by local farmers, *i.e.*, nitrogen fertilizer was applied at 100 mg kg^{-1} N as ammonium sulfate ($(NH_4)_2SO_4$), 100 mg kg^{-1} P_2O_5 as monopotassium phosphate (K_2HPO_4), and 100 mg kg^{-1} K_2O as potassium sulfate (K_2SO_4). These fertilizers were of analytical reagent quality. The fertilizer dose was calculated based on the air-dried weight of the 0–20 cm soil layer. To prevent any mixture of ^{15}N and the fertilizers, the fertilizers were mixed into the 0–10 cm soil layer. Two-thirds of the nitrogen fertilizer was supplied as a basal nutrient, with the remainder supplied as topdressings.