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Fate of urea-^{15}N as influenced by different irrigation modes

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Fertilizer nitrogen (N) is a main pollutant in the agricultural ecosystem, while the fate of fertilizer N influenced by different irrigation modes is not well comparatively investigated. In this study, the distribution of fertilizer N in soil layers and tomato organs as well as its loss under drip, spray and flood irrigation with different quotas of 140, 180 and 220 m^3 ha^{-1} were evaluated quantitatively by using nitrogen-15 (^{15}N) labeled urea (abundance of 19.6%) as fertilizer source. The results showed that the plant ^{15}N, soil ^{15}N and ^{15}N loss accounted for 27.9–47.8%, 38.8–54.0% and 10.3–21.9% of the total applied ^{15}N, respectively. The amount of ^{15}N absorbed by plants was significantly ($p < 0.05$) higher under drip and spray irrigation in comparison to flood irrigation with the same irrigation quota. The maximum ^{15}N use efficiency and the minimum ^{15}N residual were detected under drip irrigation with quota of 180 m^3 ha^{-1}, indicating that the supply and demand of urea-^{15}N was more synchronized under such an irrigation mode. The ^{15}N loss increased obviously as irrigation quota increased. Moreover, the correlation analysis between ^{15}N loss and the possible impact factors indicated that the soil mineral ^{15}N content after irrigation was one important factor influencing the ^{15}N loss. Among the three irrigation modes, spray irrigation caused the lowest ^{15}N loss of 10.3–13.1% when using the same irrigation quota. It was concluded that the irrigation modes have profound impacts on the fate of urea-^{15}N. Irrigation could be used as a regulation pathway of plant N absorption and agricultural N output.

Introduction

Water-saving irrigation has achieved great success in Israel, The Netherlands, the United States, Japan, *etc.*[1–5] In China, for a long time, most greenhouses have adopted the traditional furrow irrigation with low water use efficiency of only 40%.[1] After the start of the 1990s, China began to attach importance to the agricultural water-saving irrigation with increasing investment. Agricultural demonstration areas or points for water-saving irrigation were set up in various places, which promoted the popularization and application of drip irrigation and micro spray irrigation in China.[2] The only difference between spray irrigation and drip irrigation is the emitter (sprayer or dripper). The dripper consumes the residual pressure of the capillary by its own structure, while the micro sprayer consumes energy by direct spraying.[3] The wetted area of spray irrigation is greater than that of drip irrigation, this is beneficial for eliminating the water saturation zone and improving the ventilation conditions around the crop roots, but spray irrigation increases the water loss through evaporation from the soil surface.[4] Compared to spray irrigation, drip irrigation results in higher crop water use efficiency, while excessive irrigation water under drip irrigation may cause water saturation in the root zone that leads to root anoxia.[5,6] Therefore, it is of great importance to choose a suitable irrigation method according to the actual production situation.

Nitrogen (N) is the key nutrient element for plant growth. Water is the carrier of N transport in SPAC system.[7] Many studies have shown that there is a coupling effect between water and N.[13,14] The mechanism of water and N coupling in the research by Kim[8] shows: (1) the response of plants to water and N occurs simultaneously; (2) N application can increase water use efficiency; (3) water improves the ability of crops to absorb soil N and fertilizer N. Under sufficient water supply, the crop N use efficiency is higher due to the increased crop growth and evapotranspiration and the enhanced movement of N towards to root system along with water. The mode of water supply affects the crop utilization of N through changing the soil water condition. Early study[9] shows that the drip irrigation increases the N use efficiency by the tomato plants in the spring-summer season by 8.4% compared with the traditional furrow irrigation.

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N is not only a fertilizer resource, but one of the pollutants.[10] The environmental problems caused by N are particularly prominent, such as the migration of nitrous oxide to atmosphere that increasing the greenhouse effect and disturbing the ozone layer; the migration of N oxide to rivers and ground water that polluting the drinking water and causing the eutrophication of water bodies; the deposited ammonia and N oxide from atmosphere to land that affecting the function of forest ecosystem.[18–21] According to survey, 82% of China's 532 rivers are polluted by different degrees of N. The result by Zhu indicated that 92% of the N entering into Yangtze River and 88% into Yellow River each year are sourced from agriculture, and 50% of these agricultural N is from chemical fertilizer.[22] Irrigation water is the carrier of N for its movement and transformation. Early results show that drip irrigation and other water-saving irrigation modes can change the distribution of N in soil profile. Besides, the fate of N is also influenced by irrigation amount. A higher N loss was observed from furrow or drip irrigation with full irrigation.[11]

However, although many studies have investigated the movement and utilization of N under water regulation, there is still a lack of comparative researches on the fate of N under different irrigation modes. Moreover, few related studies have distinguished soil N from fertilizer N. To improve the fertilizer N use efficiency and reduce the fertilizer N loss are of great significance for the ecological environment protection in modern agriculture. In this study, tomato was employed as plant material, and ^{15}N isotope tracer was used to conduct the experiment under a plastic shed. The experiment included different irrigation modes and quotas. The objective of this study was: (1) to understand the distribution of fertilizer ^{15}N (urea-^{15}N) in tomato organs and soil layers under different irrigation modes; (2) to determine the amount of ^{15}N loss and to find out the possible influencing factors.

Material and method

Experimental site

The experiment was carried out from May to October in 2018 at the modern agricultural park of Rudong County, Nantong City, Jiangsu Province of China. Rudong belongs to the area with a subtropical marine monsoon climate, where is affected by obvious ocean regulation and monsoon circulation. Rudong is very close to the ocean, and it has a mild climate, abundant precipitation, sufficient light and distinct four seasons (Table 1). In Rudong, the rainfall from June to September accounts for 55–80% of the total annual rainfall, which is unevenly distributed within the year. The annual dominant wind direction is southeast. The experiment was carried out under plastic shed. The plastic shed was 30 m in length and 8 m in width. The soil in the experimental area was loam with particle size of 0.02–0.2 mm, salt content of 2.47 g kg^{-1}, bulk density of 1.35 g cm^{-3}, field capacity of 24.6%, available N content was 163.4 mg kg^{-1}, available P content of 15.2 mg kg^{-1}, and available K of 138.1 mg kg^{-1}.

Experimental design

The experiment covers an area of 120 m^2. The tomato variety "Dahongbao" (*Lycopersicon esculentum* Mill) was employed as plant material. The tomato seedlings were transplanted when they had six leaves. The transplant date was May 16. The tomato seedlings were planted in soil ridges. Each soil ridge had the height of 5 cm, length of 3.2 m and width of 55 cm. A distance of 20 cm was left between two adjacent ridges. Two rows of tomatoes were planted in one ridge, with row-to-row spacing of 30 cm and plant-to-plant spacing of 40 cm (Fig. 1a). The 16 tomato plants in the two rows of one ridge were formed as one treatment (Fig. 1). Plastic impervious membrane was installed between adjacent treatments with a depth of 60 cm to prevent the lateral seepage of water and fertilizer nutrients. The urea (N of 46%), calcium superphosphate (P_2O_5 of 16%) and potassium sulfate (K_2O of 50%) were used as fertilizer. The fertilization amount was 180 kg ha^{-1} N, 90 kg ha^{-1} P_2O_5 and 54 kg ha^{-1} K_2O assigned according to the basic fertilizer: the first ear fruit: the second ear fruit = 1 : 1 : 1. The 4 tomato plants (Fig. 1b) in the middle of each treatment were applied with ^{15}N labeled urea (abundance of 19.6%, produced by Shanghai Zhenzhun Biotechnology Co., Ltd) instead of common urea, while applications of P and K were the same as those of other tomatoes. It should be noted that only fertilizer (urea) was labeled with ^{15}N, therefore the observed plant ^{15}N was sourced from the labeled fertilizer. The total plant N minus plant ^{15}N was the plant N sourcing from soil. The weeding and pest control of different treatments were consistent and carried out in accordance with local habits.

The experiment contained three irrigation quotas of 140, 180 and 220 m^3 ha^{-1}, and three irrigation modes of spray irrigation, drip irrigation and flood irrigation, in a total of $3 \times 3 = 9$ treatments. Each treatment repeated three times. The irrigation amounts were controlled using the water meters. Spray irrigation used the plastic rotary sprinkler with pressure of 0.25 MPa and flow rate of 20 L h^{-1} (produced by Shandong Yuchen Water Saving Equipment Co., Ltd). The drip irrigation employed the PVC inlaid cylindrical pipe with 30 cm distance between two adjacent drippers, an inner diameter of 8 mm, a flow rate of 2 L h^{-1} and a working pressure of 0.3 MPa (produced by Shandong Yuchen Water Saving Equipment Co., Ltd). The flood irrigation adopted the manually hand irrigation. In practice, the hand

Table 1 The climate information in the experimental site

Experimental site	Average temperature (°C)	Average rainfall (mm)	Wind speed (m s^{-1})	Frost-free duration (days)	Annual sunshine hours (h)
Rudong	15	1042	3.5	223	1786

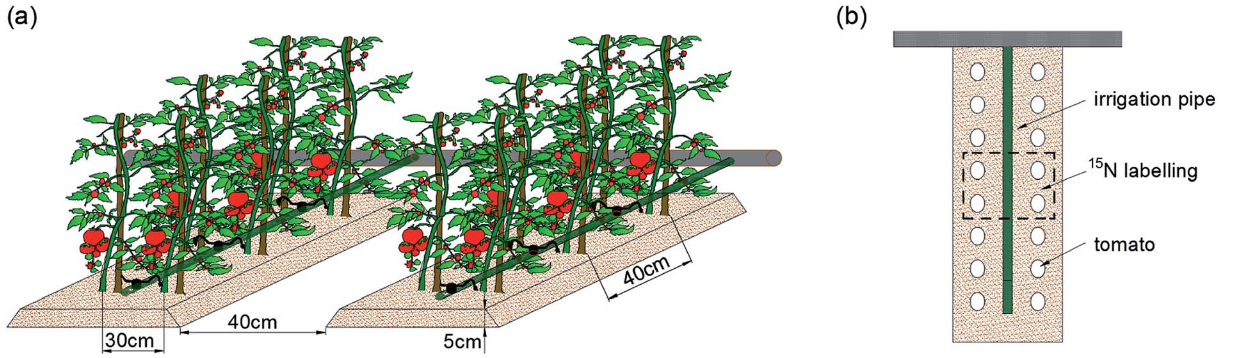

Fig. 1 Arrangement of tomato plants.

irrigation was conducted near the plant roots without formation of runoff. For the experimental site, as well as many other vegetable cultivated areas in China, one fixed pump was used to irrigate various crops simultaneously. The pump was easy to be damaged if it was used to irrigate only one crop in a small area, due to the huge difference of flow between the inlet and outlet of the pump. Therefore, as local habits, the interval duration between two irrigations was 6 days, 21 times of irrigation were conducted during the whole growth stage of tomato. The plastic shed was well ventilated. No additional light, CO_2, *etc.* were provided.

Sampling and measurement

Tomato fruits were harvested in batches from the end of July, and finished harvest on October 2. Three ^{15}N-labeled tomato plants were randomly selected for each repetition in each treatment. The roots, leaves and fruits of these plants were separated, laid into an oven at 105 °C to be killed, and then dried at 70 °C to constant weight for measurement. The biomass of the different organs were weighed and recorded.

On a typical date in vigorous growth stage of tomato (July 5, the second day after irrigation), a soil drill was used to collect the soil samples in 0–20 and 20–40 cm soil layers for measuring soil mineral ^{15}N and organic ^{15}N contents. At the end of the experiment, on October 2, soil samples were collected with 10 cm increment in depth using a soil drill to investigate the distribution of ^{15}N in soil profile. The soil samples were divided into two parts, one part was directly used for measurement, and the other part was air dried naturally. After air dried, the soil samples were grinded and passed through a 0.15 mm sieve.

The mineral N in fresh soil samples was extracted using 2 M KCl and distilled using micro Kjeldahl apparatus, in the presence of MgO and Devarda alloy. The ^{15}N atom percentage excess in soil or plant samples was measured by mass spectrometer (Finniga-Mat-251, Mass-Spectrometers, Finnigan, Germany). Inside the mass spectrometer, the soil samples were vaporized and ionized into ion beams and then passed through electromagnetic field, different mass ions were deflected differently by the field and focused in different positions, so as to obtain the mass spectra of ^{15}N isotope.

The crop use efficiency of urea-^{15}N (^{15}NUE) was calculated as:

$$N_{\rm dff} = C_{\rm s} \times \frac{E_{\rm s}}{E_{\rm f}}$$

$$^{15}{\rm NUE} = \left(\frac{N_{\rm dff}}{M_{\rm f}}\right) \times 100\%$$

where, $N_{\rm dff}$ is the total ^{15}N absorbed by tomato (kg ha^{-1}), $C_{\rm s}$ is the total N in tomato (kg ha^{-1}), $E_{\rm s}$ is the ^{15}N atom percentage excess in tomato (%), $E_{\rm f}$ is the ^{15}N atom percentage excess in the ^{15}N labeled urea (%), and $M_{\rm f}$ is the application amount of ^{15}N (kg ha^{-1}). Both $E_{\rm s}$ and $E_{\rm f}$ were measured using the mass spectrometer.

The ^{15}N recovery was the sum of plant ^{15}N absorption and soil ^{15}N residue in 0–80 cm soil layer. The ^{15}N loss is the differential value between total applied ^{15}N and recovered ^{15}N.

Data analysis

The SPSS 17.0 software was used for the significance analysis according to Duncan's multiple range test.[12]

Results

The accumulation of ^{15}N in tomato organs and ^{15}N use efficiency

In general, under the same irrigation mode, the increased irrigation quota promoted the ^{15}N accumulation in different organs of tomato plants except that the tomato under drip irrigation with 180 m^3 ha^{-1} irrigation quota accumulated more ^{15}N in leaves, stems and fruits, compared to other irrigation quotas (Table 2). Irrigation mode had a significant ($p < 0.01$) effect on ^{15}N accumulation in the organs. The drip irrigation obviously increased the accumulation of ^{15}N in all the organs compared with irrigation and spray irrigation. There was a significant ($p < 0.05$) coupling effect from irrigation mode and quota on ^{15}N accumulation amount in stem or fruit. The fruit ^{15}N contributed most greatly to the whole plant ^{15}N, accounting for about half of the total ^{15}N absorbed by tomato plant. The highest fruit ^{15}N of 44.0 kg ha^{-1} was obtained under 180 m^3

Table 2 The effects of experimental treatments on the distribution of ^{15}N-urea in different organs of tomato[a]

Irrigation mode	Irrigation quota (m^3 ha^{-1})	Leaf (kg ha^{-1})	Stem (kg ha^{-1})	Root (kg ha^{-1})	Fruit (kg ha^{-1})
Spray	140	27.6 ± 1.02 c	6.12 ± 0.24 d	2.54 ± 0.08 a	32.4 ± 1.77 bc
	180	28.3 ± 1.03 bc	6.59 ± 0.24 bcd	2.31 ± 0.08 b	34.1 ± 0.41 b
	220	30.0 ± 0.57 abc	7.09 ± 0.22 ab	2.29 ± 0.13 b	34.1 ± 1.78 b
Drip	140	29.4 ± 1.10 abc	6.34 ± 0.18 cd	2.35 ± 0.11 ab	34.2 ± 2.65 b
	180	32.3 ± 3.13 a	7.45 ± 0.27 a	2.21 ± 0.09 bc	44.0 ± 5.59 a
	220	31.4 ± 1.11 ab	6.83 ± 0.31 bc	2.04 ± 0.12 cd	34.4 ± 0.44 b
Flood	140	20.3 ± 1.07 d	4.84 ± 0.28 e	1.82 ± 0.09 d	23.1 ± 0.98 d
	180	21.6 ± 1.57 d	5.24 ± 0.25 e	1.82 ± 0.11 d	25.7 ± 0.36 d
	220	23.4 ± 1.23 d	5.24 ± 0.18 e	1.86 ± 0.10 d	27.6 ± 2.5 cd
Irrigation mode	**	**	**	**	
Irrigation quota	*	**	*	*	
Mode × quota	ns	*	ns	*	

[a] In the same column, means followed by the same letter (a, b, c, d, e) do not differ significantly at 0.05 level, according to Duncan's multiple range test. *, ** and ns indicate that the experimental treatment has a significant (at 0.05 level) effect, an extremely significant (at 0.01 level) effect and no significant effect, respectively on the indicator.

ha^{-1} drip irrigation which significantly ($p < 0.05$) higher than that under other treatments.

The ^{15}N use efficiency was overall improved by the increased irrigation quota in addition to that under drip irrigation conditions (Fig. 2). Under the same irrigation quota, the ^{15}N use efficiency by tomato under drip irrigation or spray irrigation was significantly ($p < 0.05$) higher than that under flood irrigation. The lowest ^{15}N use efficiency was only 27.9% under 140 m^3 ha^{-1} flood irrigation treatment. Under 140 or 220 m^3 ha^{-1} irrigation quotas, there was no significant difference between drip irrigation and spay irrigation in tomato ^{15}N use efficiency while the efficiency was significantly ($p < 0.05$) higher with drip irrigation under the quota of 180 m^3 ha^{-1}, reaching 47.8%.

Distribution of ^{15}N in soil profile

The total ^{15}N in soil decreased with the deepening of soil layer (Fig. 3). The total amounts of ^{15}N in 0–10 and 10–20 cm soil layers were the highest under flood irrigation. However, below 20 cm layer, the amounts of soil ^{15}N under drip irrigation and spray irrigation were higher than that under flood irrigation, indicating that spray and drip irrigation were conducive to the migration of ^{15}N to the soil layer below 20 cm. The amount of detected soil ^{15}N below 60 cm was very low. Under the same irrigation mode, the decreased irrigation quota reserved more ^{15}N in the surface soil (0–10 cm and 10–20 cm). Under irrigation quota of 220 m^3 ha^{-1}, drip irrigation is more effective than spray irrigation in driving ^{15}N to move below 20 cm soil layer, but this rule was not found under the quotas of 140 or 180 m^3 ha^{-1}.

Mineral ^{15}N and organic ^{15}N after typical irrigation

The mineral ^{15}N content in 0–20 cm soil layer under drip irrigation was significantly ($p < 0.05$) higher than that under spray or flood irrigation, similar rule was more obvious in 20–40 cm soil layer. However, the comparative difference of soil organic ^{15}N was opposite to that of mineral ^{15}N. The soil organic ^{15}N content in 0–20 cm soil layer was significantly ($p < 0.05$) greater under flood irrigation compared to other irrigation modes with all irrigation quotas, while in 20–40 cm soil layer, the organic ^{15}N content was greater under flood irrigation only with 140 m^3 ha^{-1} quota. The key in the coupling effect of water and N is to promote the transformation of ^{15}N from fertilizer form to mineral form after water regulation. From this perspective, drip irrigation is more advantageous than the other two modes under the same irrigation quota.

The balance of ^{15}N

The plant ^{15}N, soil ^{15}N and ^{15}N loss accounted for 27.9–47.8%, 38.8–54.0% and 10.3–21.9% of the total applied ^{15}N, respectively (Table 3). The soil ^{15}N amount decreased with the increased irrigation quota except under drip irrigation. A higher ^{15}N residue in soil increased the risk of ^{15}N loss, and also

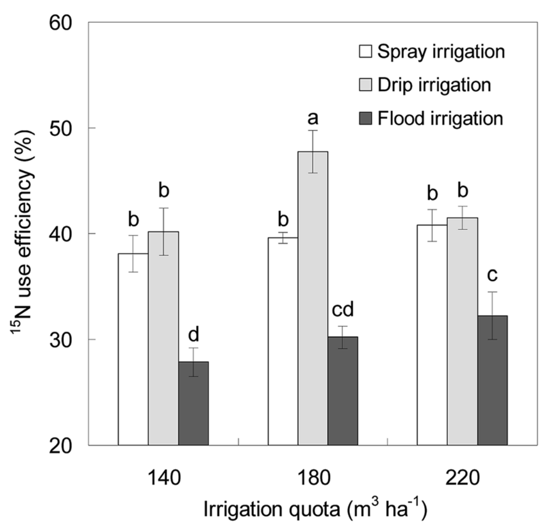

Fig. 2 The ^{15}N use efficiency under different irrigation treatments (values are means ± standard deviation. Means followed by the same letter (a, b, c, d) do not differ significantly at 0.05 level, according to Duncan's multiple range test. The ^{15}N was resourced from the ^{15}N-labelled urea with an abundance of 19.6%).

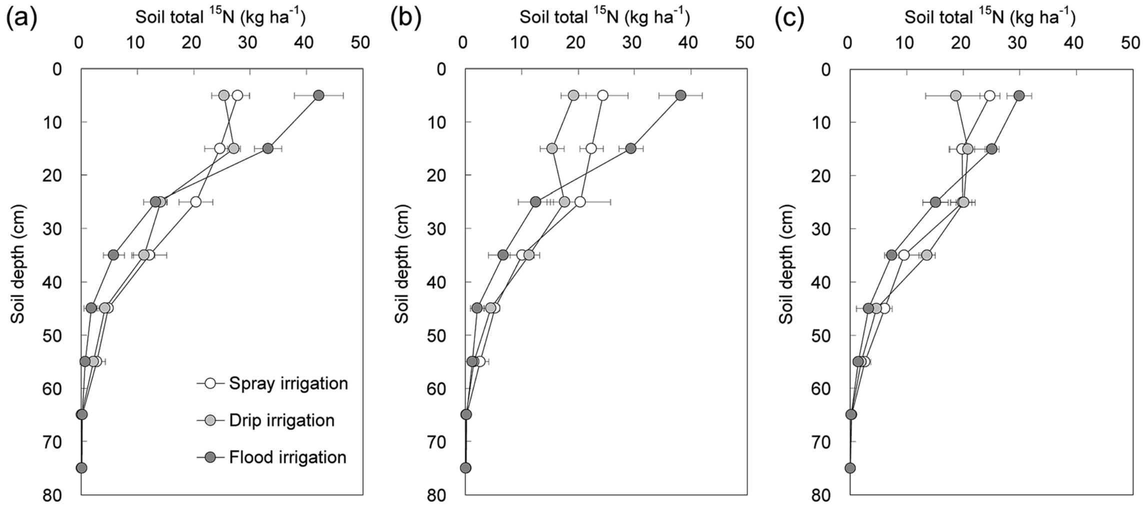

Fig. 3 The distribution of ^{15}N-urea in soil profile under different irrigation quotas of 140 (a), 180 (b) and 220 (c) m^3 ha^{-1} (values are means ± standard deviation).

indicated that the ^{15}N supply and demand was not harmony. Under drip irrigation with quota of 180 m^3 ha^{-1}, the soil residual ^{15}N was the lowest (69.8 kg ha^{-1}), whereas the plant ^{15}N was the greatest (86.0 kg ha^{-1}). The ^{15}N loss increased with the increased irrigation quota, the maximum ^{15}N loss of 39.5 kg ha^{-1} was detected under flood irrigation with the quota of 220 m^3 ha^{-1}, and the minimum ^{15}N loss of 18.6 kg ha^{-1} was found under spray irrigation with the quota of 140 m^3 ha^{-1}. The irrigation mode or quota had a significant ($p < 0.01$) effect on the fate of ^{15}N, but the combination of irrigation mode and quota only had the significant ($p < 0.05$) effect on plant ^{15}N.

The possible influencing factors for ^{15}N loss

Due to the constant total applied ^{15}N, the ^{15}N loss was negatively correlated with soil residual ^{15}N ($p < 0.05$) (Table 4), and the correlation coefficient reached −0.965 and −0.995 under spray and flood irrigation, respectively. Overall, the ^{15}N loss was positively correlated with the mineral ^{15}N content in 0–20 cm or 20–40 cm layer after irrigation, and the relationship was much significant ($p < 0.01$) and significant ($p < 0.05$) respectively under spray irrigation and flood irrigation. Under spray irrigation, there was a significant ($p < 0.01$) correlation between ^{15}N loss and organic ^{15}N content in both 0–20 cm and 20–40 cm layers, but this rule was not found under drip irrigation and flood irrigation.

Discussion

N is the "life element" for plant and contributes most to crop yield.[13] Urea contains a high N content of 46% with relatively stable property and low production cost, and is easy to be stored and transported.[14,15] The behavior of urea in soil not only has

Table 3 The balance of ^{15}N-urea[a]

Irrigation mode	Irrigation quota (m^3 ha^{-1})	Total ^{15}N (kg ha^{-1})	Plant ^{15}N (kg ha^{-1})	Soil ^{15}N (kg ha^{-1})	^{15}N loss (kg ha^{-1})
Spray	140	180	68.6 ± 3.11 b	92.8 ± 4.67 ab	18.6 ± 1.57 d
	180	180	71.2 ± 0.94 b	85.5 ± 2.94 bc	23.3 ± 2.00 cd
	220	180	73.4 ± 2.70 b	83.1 ± 4.45 bc	23.5 ± 1.76 cd
Drip	140	180	72.3 ± 4.05 b	84.4 ± 5.72 bc	23.2 ± 1.67 cd
	180	180	86.0 ± 3.60 a	69.8 ± 6.71 d	24.3 ± 3.11 c
	220	180	74.7 ± 1.96 b	80.1 ± 3.64 cd	25.2 ± 1.68 c
Flood	140	180	50.1 ± 2.41 d	97.3 ± 4.99 a	32.6 ± 2.58 b
	180	180	54.4 ± 1.92 cd	90.4 ± 3.84 abc	35.2 ± 1.92 ab
	220	180	58.0 ± 4.00 c	82.5 ± 6.78 bc	39.5 ± 2.78 a
Irrigation mode		ns	**	**	**
Irrigation quota		ns	**	**	**
Mode × quota		ns	*	ns	ns

[a] In the same column, means followed by the same letter (a, b, c, d) do not differ significantly at 0.05 level, according to Duncan's multiple range test. *, ** and ns indicate that the experimental treatment has a significant (at 0.05 level) effect, an extremely significant (at 0.01 level) effect and no significant effect, respectively on the indicator.

Table 4 Correlation analysis between ^{15}N loss and possible influencing factors[a]

	^{15}N loss	Soil total residual ^{15}N	Mineral ^{15}N (0–20 cm)	Mineral ^{15}N (20–40 cm)	Organic ^{15}N (0–20 cm)	Organic ^{15}N (20–40 cm)
Spray irrigation						
^{15}N loss	1	−0.965**	0.986**	0.962**	0.943**	0.940**
Soil total residual ^{15}N		1	−0.967**	−0.901**	−0.989**	−0.823**
Mineral ^{15}N (0–20 cm)			1	0.932**	0.943**	0.899**
Mineral ^{15}N (20–40 cm)				1	0.872**	0.957**
Organic ^{15}N (0–20 cm)					1	0.801**
Organic ^{15}N (20–40 cm)						1
Drip irrigation						
^{15}N loss	1	−0.694*	0.424	0.754*	0.244	0.875**
Soil total residual ^{15}N		1	−0.815**	−0.936**	−0.746*	−0.631
Mineral ^{15}N (0–20 cm)			1	0.843**	0.929**	0.259
Mineral ^{15}N (20–40 cm)				1	0.765*	0.641
Organic ^{15}N (0–20 cm)					1	0.026
Organic ^{15}N (20–40 cm)						1
Flood irrigation						
^{15}N loss	1	−0.995**	0.796*	0.768*	0.892**	0.261
Soil total residual ^{15}N		1	−0.799**	−0.791*	−0.911**	−0.199
Mineral ^{15}N (0–20 cm)			1	0.769*	0.728*	0.310
Mineral ^{15}N (20–40 cm)				1	0.872**	0.058
Organic ^{15}N (0–20 cm)					1	0.310
Organic ^{15}N (20–40 cm)						1

[a] *Represent significant correlation at 0.05 level, and **represent much significant correlation at 0.01 level. 0–20 cm and 20–40 cm represent the soil layer. The ^{15}N was resourced from ^{15}N-labelled urea with an abundance of 19.6%.

similarities with other fertilizers, but also has some differences.[16] Urea is a main solid N fertilizer that is widely used at present. In China's facility agriculture, urea is one of the main providers of N in the compound fertilizer. Applying urea has become the habit of Chinese farmers during agricultural production.[15]

Our study evaluated the effect of different irrigation modes on the fate of urea-^{15}N. The significant effect from irrigation modes on plant ^{15}N accumulation sourced from that the different modes enhanced the soil N metabolism and changed the plant absorption for water and ^{15}N in various degrees.[17] Under the same irrigation quota, the soil water moved laterally under flood irrigation and had invalid loss under spray irrigation, thus relatively, drip irrigation provided more water for crops which resulted in a higher ^{15}N use efficiency. This result was similar to the early study by Du[18] that the N use efficiency increased with more water supply in crop rhizosphere. Our result also verified the coupling effect between water and N by many previous studies.[19,20]

The higher mineral ^{15}N content in both 0–20 cm and 20–40 cm soil layers after drip irrigation (Fig. 4) suggested that drip irrigation had a better effect on promoting mineralization of fertilizer N. Previous study have shown that the amount and the rate of soil N mineralization present a positive feedback with soil water content within a certain threshold.[21] The lower soil moisture will restrict the growth of soil microorganisms and inhibit the N mineralization, while the higher soil moisture content enhances denitrification under anaerobic soil environment that causes a reduction on the rate of soil N mineralization.[22–24] In dryland, N mineralization is positively correlated with the soil water content which above the hygroscopic water content but below the optimum water content, under such range, the N mineralization amount increases linearly with the increased soil water content.[25] Therefore, concluding from previous studies and ours, it is inferred that drip irrigation creates the most suitable soil moisture conditions for urea-^{15}N mineralization, compared to spray and flood irrigation ratio under the three irrigation quotas in this study.

After experiment, 38.8–54.0% of the urea-^{15}N remained in the soil, which was lower than the previous result in the tobacco soil (72.1%) using ^{15}N double-labeled NH_4NO_3 as fertilizer source,[10] which likely due to that nitrate ions in the previous study are easier to enter into the soil layers below main root zone with irrigation water and are harder to be absorbed by crops, leading to a higher residue in soil. It is speculated that the loss of urea-^{15}N in this study is more related to urea hydrolysis reaction, since only small amount of ^{15}N was detected below 60 cm soil layer (Fig. 3). After being applied into the soil, the urea is hydrolyzed by the promotion of soil urease, this process produces NH_4^+ and the NH_4^+ transforms into NH_3, which results in the loss of urea-^{15}N.[26,27] Under flood irrigation, the more ^{15}N loss should be attributed to the lateral migration of ^{15}N. The surface soil has a lower bulk density and a higher porosity compared to the middle soil, the water supply in a short duration under flood irrigation limits the downward movement of irrigation water and promotes horizontal

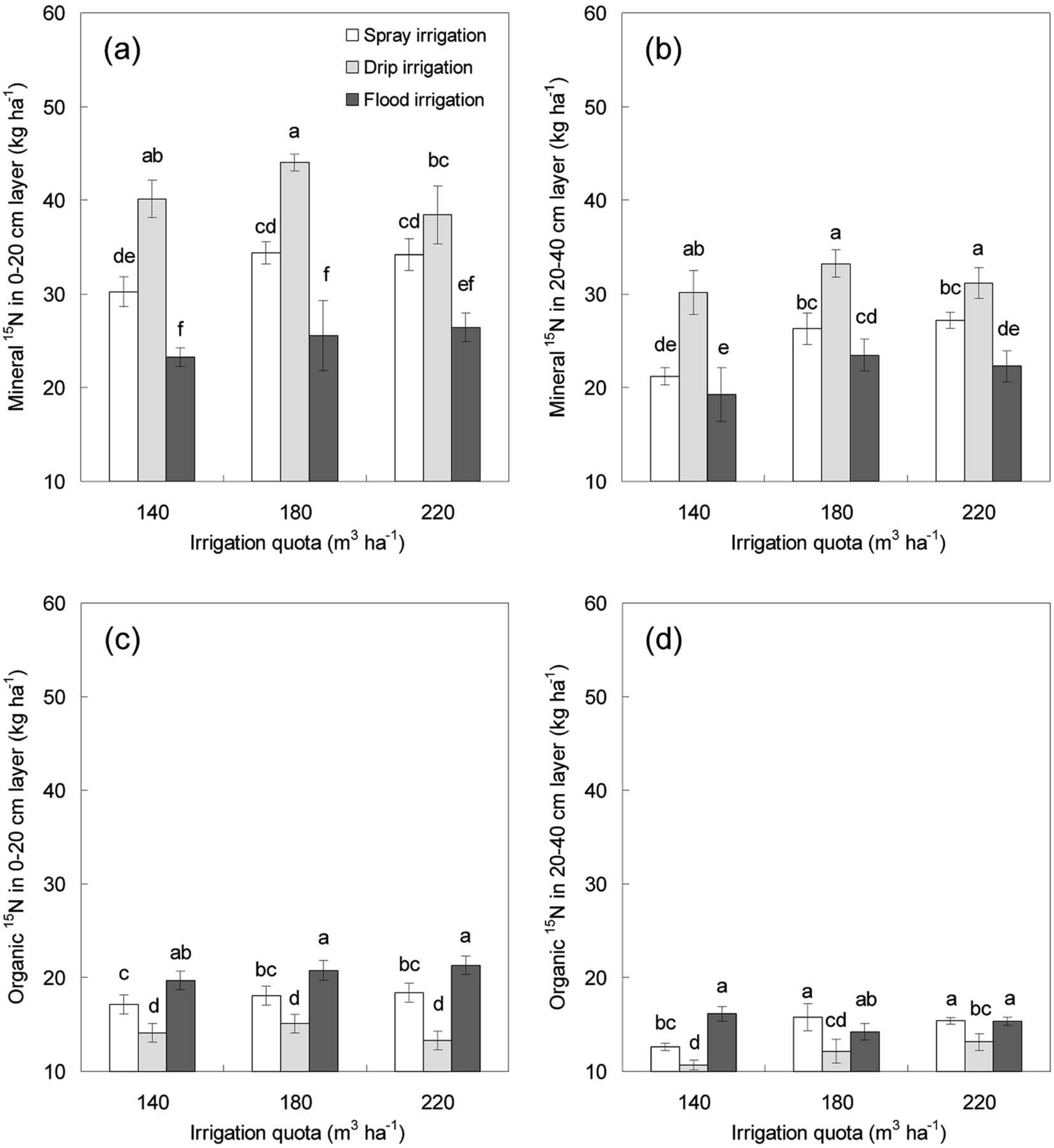

Fig. 4 Contents of mineral ^{15}N in 0–20 cm (a) and 20–40 cm (b) soil layer, and organic ^{15}N in 0–20 cm (c) and 20–40 cm (d) soil layer after one typical irrigation (The sampling date was July 5, the next day after irrigation in vigorous stage of tomato plant. Values are means ± standard deviation. Means followed by the same letter (a, b, c, d) do not differ significantly at 0.05 level, according to Duncan's multiple range test. The ^{15}N was resourced from the ^{15}N-labelled urea with an abundance of 19.6%).

movement of ^{15}N. Therefore, the lower ^{15}N detected in soil profile under flood irrigation leads to a higher calculated loss of ^{15}N compared to that under drip and spray irrigation. Our study detected a urea-^{15}N loss of 10.3–21.9%, which is similar to the early result of 25% including 15% ammonia volatilization, 9% leaching and 1% denitrification losses.[28] However, we only considered the total loss of ^{15}N calculating by total applied ^{15}N and recovered ^{15}N. The obvious pathways of total fertilizer N loss included NH_3, N_2 and N_2O to atmosphere, drainage and runoff of mineral N, which should be considered in future research.

The positive correlation between ^{15}N loss and soil mineral ^{15}N (Table 4) is due to that the soil mineral ^{15}N is easy to migrate and leach with the water and lost through ammonia volatilization. The presence of organic ^{15}N reflects the capacity of mineralizable ^{15}N, therefore there is also a positive correlation found between ^{15}N loss and soil organic ^{15}N, especially under spray irrigation. In addition, it should be noted that 220 $m^3\ ha^{-1}$ quota under drip irrigation increased the soil ^{15}N amount in 30, 40 and 50 cm soil layers (Fig. 3c), which will increase the risk of ^{15}N loss through leakage from deep soils. In general, ^{15}N loss under the spray irrigation in this study was the lowest, this confirms the study by Chen.[29] Our result proves that different irrigation modes have different influences on the fate of urea-^{15}N under the same irrigation quota, thus it is of great practical significance to select suitable irrigation mode according to the actual situation of production site. Moreover, when similar researches are conducted under field conditions, it should be noticed that the rainfall is an important indicator since it mainly influences the fate of fertilizer N *via* runoff and drainage. The crop water use under the different irrigation modes also needed to be further investigated since it was helpful to better understand the mechanism of crop ^{15}N utilization.

Conclusion

Under different treatments, the plant ^{15}N, soil ^{15}N and ^{15}N loss accounted for 27.9–47.8%, 38.8–54.0% and 10.3–21.9% of the total applied ^{15}N, respectively. The amount of ^{15}N absorbed by plants were significantly ($p < 0.05$) higher under drip and spray irrigation in comparison to flood irrigation with a same irrigation quota. Highest ^{15}N use efficiency but lowest ^{15}N residual was detected under 180 m^3 ha^{-1} drip irrigation, indicating that the supply and demand of urea-^{15}N was more synchronized under such irrigation. The ^{15}N loss increased obviously with increased irrigation quota. Moreover, correlation analysis between ^{15}N loss and the possible impact factors showed that the soil mineral ^{15}N content after irrigation might be one important factor that influencing ^{15}N loss. Among the three irrigation modes, the ^{15}N loss caused by spray irrigation was the lowest (10.3–13.1%), when with the same irrigation quota. The irrigation modes have profound impacts on the fate of urea-^{15}N. Irrigation could be used as regulation pathway of plant N absorption and agricultural N output.

Conflicts of interest

There are no conflicts to declare.

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