Science Press

Journal of Arid Land

2012, 4(3): 320–329

doi: 10.3724/SP.J.1227.2012.00320

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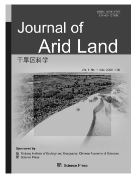

The fate of fertilizer N applied to cotton in relation to irrigation methods and N dosage in arid area

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Abstract: Quantitative information on the fate and efficiency of nitrogen (N) fertilizer applied to coarse textured calcareous soils in arid farming systems is scarce but, as systems intensify, is essential to support sustainable agronomic management decisions. A mesh house study was undertaken to trace the fate of N fertilizer applied to cotton (*Gossypium hirsutum* L. cv., Huiyuan701) growing on a reconstructed profile (0–100 cm) of a calcareous (>15% $CaCO_3$) sandy loam soil. Two irrigation methods (drip irrigation, DI; and furrow irrigation, FI) and four N application rates (0, 240, 360 and 480 kg/hm^2, abbreviated as N_0, N_{240}, N_{360}, and N_{480}, respectively) were applied. ^{15}N-labelled urea fertilizer was applied in a split application. DI enhanced the biomass of whole plant and all parts of the plant, except for root; more fertilizer N was taken up and mostly stored in vegetative parts; N utilization efficiency (NUE) was significantly greater than in FI. N utilization efficiency (NUE) decreased from 52.59% in N_{240} to 36.44% in N_{480}. N residue in soil and plant N uptake increased with increased N dosage, but recovery rate decreased consistently both in DI and FI. Plant N uptake and soil N residue were greater in DI than in FI. N residue mainly stayed within 0–40 cm depth in DI but within 40–80 cm depth in FI. FI showed 17.89% of N leached out, but no N leaching occurred in DI. N recovery rate in the soil-plant system was 75.82% in DI, which was markedly greater than the 55.97% in FI. DI exhibited greater NUE, greater residual N in the soil profile and therefore greater N recovery rate than in FI; also, N distribution in soil profile shallowed in DI, resulting in a reduced risk of N leaching compared to FI; and enhanced shoot growth and reduced root growth in DI is beneficial for more economic yield formation. Compared to furrow irrigation, drip irrigation is an irrigation method where N movement favors the prevention of N from being lost in the plant-soil system and benefits a more efficient use of N.

Keywords: drip irrigation; furrow irrigation; N application rate; N utilization efficiency; N recovery; *Gossypium hirsutum*

Water and nutrient supply are the main factors controlling productivity in irrigated agriculture. Improving the efficient use of these factors becomes crucial in arid regions where water resources are limited and is the target of agronomic management. In addition, in irrigated agriculture, N becomes the most limiting factor in crop productivity. In the traditional furrow irrigation, the utilization efficiency of both irrigation water and N fertilization is often low and depends largely on methods of application (Bondada *et al*., 2001; Norton *et al*., 2007; Clawson *et al*., 2008). Drip irrigation is considered to be one of the most efficient irrigation methods, which can distribute water uniformly, control the irrigation quota precisely, and reduce evaporation and deeper percolation (Stikic *et al*., 2003; Badr *et al*., 2010). Also, it can greatly improve the utilization of N because both timing and dosage of nutrients can be controlled to meet the requirements of crop at the whole growth stage (Sammis *et al*., 1980; Sharmasarkar *et al*., 2001).

Xinjiang is the largest cotton (*Gossipium hirsutum* L.) production area in China, and cotton is a leading cash crop in this region. The area of cotton cultivation has been expanding rapidly since the 1990s after the introduction of a new cultivation system characterized by DI, plastic film mulching, high planting density,

Received 2011-12-17; accepted 2012-04-26

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and with most of N fertilizer applied by fertigation. These changes have led to an increase in cotton yield from around 1,350 kg/hm^2 to 2,100 kg/hm^2 (Wang *et al*., 2004). Although it is well acknowledged that DI significantly increased N utilization efficiency (NUE) (Starck *et al*., 1993; Muchow and Sinclair, 1994; Phene *et al*., 1995; Mohammad *et al*., 1999), detailed researches on related mechanism, for example, N allocation in different parts of plant, and N residual quantity in soil profile, N losses in the plant-soil system, are not adequate. Although considerable researches have been conducted to study NUE and water utilization efficiency (WUE) both in traditional irrigation methods and DI, these studies have often been performed separately, and the results drawn are not comparable. Extensive fertigation researches on many crops are available (Quiñones *et al*., 2005; Badr *et al*., 2010; Hancock *et al*., 2011). However, few studies have been conducted on cotton. Besides, the use of ^{15}N labeled fertilizers provides accurate tools to evaluate N utilization efficiency (Zapata, 1990). The objectives of this study are to evaluate N distribution in whole plant and different plant parts, in soil profile and leaching liquid by using ^{15}N labeled tracer method, to quantify the fate of N both in DI and FI based on an identical soil and crop management. Additional objectives for this study are to reveal plant growth response to different irrigation methods and N application rates, and to present some useful information to support sustainable agronomic management decisions.

1 Materials and methods

1.1 Study area

This experiment was conducted at the Agricultural Experiment Station at Shihezi University, Shihezi, Xinjiang, China in 2009. The research site is located in northern Xinjiang (86°02'E, 44°18'N) with an elevation of 440 m above sea level. The average maximum and minimum temperatures during crop growing seasons were 37ºC and 17ºC, respectively, and relative humidity ranged from 40% to 59%. The average annual precipitation is 200 mm, much lower than in agriculture areas with self-sufficient precipitation, so agricultural activity must be aided with irrigation in this area. The soil is calcareous with alkaline and is poor in organic matter, N and P. Available K is rich for normal plant growth. Texture of soil in this area is coarse from sandy to loam.

1.2 Experimental design

Three distinct soil layers, 0–20 cm, 20–40 cm and 40–100 cm, were collected from the Agricultural Experimental Station, Shihezi University. After being dried on a plastic sheet, soil was sieved to pass through an 8-mm mesh, and sub-samples were collected to determine soil water content. Soil was then packed in a PVC cylinder of 110 cm in height and 25 cm in diameter by 10-cm increments up to 100 cm. Bulk density of soil was set at 1.3 t/m^3 in the top 0–40 cm and 1.45 t/m^3 in 40–100 cm, so the weight of soil in each 10-cm increment could be scaled by considering soil water content. All P and K fertilizers were applied in the 0–20 cm soil layer. Before soil was filled in the cylinder, some irregular-shaped tiles were set at the bottom of the cylinder to make sure water could freely flow to the bottom of the cylinder, and at the immediate bottom of the cylinder, a hole of 10 mm in diameter was drilled to allow leaching liquid to be collected by a connecting plastic tube. After filling the cylinder with soil, 9.7 L of water was added in the cylinder to adjust the soil water content to about 70% field water capacity. The top of the cylinder was covered with a plastic film to prevent water from evaporating and ensure water being redistributed to the whole soil profile, and in this way, soil was naturally deposited and soil properties was kept stable. The soil column was left undisturbed for 25 days. The soil's basic properties are shown in Table 1.

The experimental design was a 2×4 factorial with two irrigation methods and four N application rates. N application rates were 0, 240, 360 and 480 kg/hm^2

Table 1 Chemical properties of the soil used in the experiment

Soil property	Mean value
pH	7.90
Organic matter (OM, g/kg)	19.90
Total nitrogen (N, g/kg)	1.08
Available phosphorus (Olsen-P, mg/kg)	17.95
Available potassium (K, mg/kg)	1,340.00
$CaCO_3$ (%)	18.62

(abbreviated as N_0, N_{240}, N_{360}, N_{480}, respectively). The area of the cylinder was 0.049 m^2, so the dosage of N for each treatment was 0, 1.178, 1.767 and 2.356 g/cylinder, respectively. To fully meet the nutrient requirement of the cotton plants, 105 kg P_2O_5/hm^2 and 75 kg K_2O/hm^2 were also applied uniformly as base fertilizers in the 0–20 cm soil layer. Irrigation amount was 4,500 m^3/hm^2 in DI and 6,500 m^3/hm^2 in FI, or 22.1 L/cylinder in DI and 31.9 L/cylinder in FI, close to local farmers' quota of irrigation. Irrigation water was split to 12 increments for DI and 6 increments for FI. In addition, each cylinder received 4.0 L of water for seed germination and seedling establishment both in DI and FI (Table 2). In DI treatment, nitrogen fertilizer was applied through a simulated DI system during cotton growth period. ^{15}N-labeled urea (10% atom enrichment) was adopted and applied in eight equal splits in DI. In FI treatment, 1/3 of ^{15}N-labeled urea was applied in the budding stage and the rest 2/3 was applied in the flowering-bolling stage. The experiment was established in a completely randomized design with 4 replicates (2×4×4=32 cylinders). Cotton (*Gossypium hirsutum* L. cv., Huiyuan701) was planted in PVC cylinders on 12 May, 2009. The growing season was from May to September. After emergence, the cotton plants were thinned to 2 plants per cylinder at the growth stage of three true leaves.

1.3 Methods

At harvesting, cotton plants were cut at their cotyledon nodes and separated into leaves, stems/branches, boll shells, seed cotton parts and roots. Falling buds and flowers were carefully collected and combined with boll shells as parts of the reproductive organs. The soil cylinder was cut into five parts in 20-cm increments (0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm). Soil contained in each increment was fully mixed and cotton roots were picked out by hand. Soil samples were collected simultaneously. Plant components were then washed with distilled water, oven dried at 80ºC for 72 h, and weighed. Oven-dried plant samples were ground to pass through a 1-mm screen. Soil cores were air-dried, and sub-samples were ground with a mortar and pestle.

^{15}N concentrations in sub-samples of plant and soil samples were analyzed at the Institute for Application of Atomic Energy, Chinese Academy of Agricultural Science, China, using a mass spectrometer (ANCA-SL, Europe Scientific, Crewe, UK).

The percentage of plant N derived from fertilizer (NDFF) was calculated as follows (Wienhold *et al*., 1995; Allen *et al*., 2004):

$$\text{NDFF}=(a-b)/(c-d)\times 100\%. \quad (1)$$

Where, a is the atom % ^{15}N abundance in fertilized cotton; b is the atom % ^{15}N abundance in non-fertilized cotton; c is the atom % ^{15}N abundance in the fertilizer; and d is natural atom % ^{15}N abundance in the atmosphere.

Percentage of NUE was calculated as follows (Wienhold *et al*., 1995; Barber *et al*., 1996; Allen *et al*., 2004):

$$\text{NUE} = (\text{NDFF}\times S)/R\times 100\%. \quad (2)$$

Where, S is the content of N in cotton plant (g/cylinder); and R is the total amount of N applied (g/cylinder).

Residual fertilizer ^{15}N in the soil was determined by using the following equation (Allen *et al*., 2004):

$$\text{Residual fertilizer } ^{15}\text{N in the soil} = ((a-c)/(b-c))\times(\text{Np}/\text{Nf})\times 100\%. \quad (3)$$

Where, Np is the total amount of N in soil (g/cylinder); and Nf is the total amount of ^{15}N applied to the soil as labeled fertilizer (g/cylinder).

Table 2 Timing and amounts of irrigation and fertilizer

		9 May[1]	5 Jun	21 Jun	27 Jun	1 Jul	8 Jul	12 Jul	15 Jul	22 Jul	27 Jul	29 Jul	5 Aug	12 Aug	19 Aug	1 Sep	Total
DI[2]	Irri. Water (L/cylinder)	4	1.5	2.4	1	1.5	1.5		2	2		2	2	2	2	2.2	22.1
	N application			♦[4]		♦	♦		♦	♦			♦	♦			
FI[3]	Irri. Water (L/cylinder)	4	1.5	2.4		4		6			7			7		4	31.9
	N application			×[5]				×[6]									

Note: [1] irrigation water for germination is not included for water consumption in the growth period; [2] drip irrigation; [3] furrow irrigation; [4] N fertilizer applied: N dosage is 0.1473, 0.2209, 0.2945 g/cylinder for treatments N_{240}, N_{360} and N_{480}, respectively; [5] N fertilizer applied: N dosage is 0.3927, 0.5890, 0.7853 g/cylinder for treatments N_{240}, N_{360} and N_{480}, respectively; [6] N fertilizer applied: N dosage is 0.7853, 1.1789, 1.5707 g/cylinder for treatments N_{240}, N_{360} and N_{480}, respectively.

1.4 Data analysis

A two-way analysis of variance (ANOVA) was used to test the differences between factors. When *F* value was significant, a multiple mean comparison was performed using the least significant difference test (LSD) at the 0.05 or 0.01 probability level. Statistical analysis was performed with SPSS statistical program (v. 11.0, SPSS Inc., 1996).

2 Results

2.1 Biomass under different irrigation methods and N application rates

The biomass of whole plant markedly enhanced with the increase of N application rate up to 360 kg/hm^2, and no further increase was observed at 480 kg/hm^2. Similar trends were observed in the biomass of all parts of cotton plants except for seed cotton yield, which declined when N application rate was 480 kg/hm^2, significantly smaller than at 360 kg/hm^2. N dosage at 360 kg/hm^2 produced the highest seed cotton yield with an increase by 35.1% as compared to 0 and 480 kg/hm^2, and 240 kg/hm^2 produced intermediated seed cotton yield with no significant difference (Table 3).

Irrigation methods strongly influenced the growth of cotton plants. Across all N treatments, there was an 18.9% increase in the biomass of whole plant and a 22% increase in seed cotton yield in DI relative to FI. Similarly, biomass of leaf, stem, bud and boll and seed cotton was significantly greater in DI than in FI, with the exception of roots, whose biomass was greater in FI than in DI.

2.2 Uptake of fertilizer and NUE

With the increase in the rate of N application, NDFF increased as well; and the highest and the lowest NDFF was found in seed cotton and root, respectively. All vegetative parts exhibited an increase in NDFF with the increase of fertilizer N input, whereas in reproductive parts NDFF showed no significant difference with the increase of N application rates. NDFF even showed a decreasing trend in bud and boll when paired to N input. Two-way ANOVA showed that NDFF was significantly greater in all parts in DI than in FI except for seed cotton yield, suggesting that plants rely more heavily on the supply of fertilizer nutrition in DI than in FI (Table 4).

N application rate had a highly significant (P<0.001) effect on the whole plant NUE. With the increase of N application, NUE decreased sharply, both in DI and FI. NUE ranked the highest (52.59%) in N_{240}, and the smallest (36.44%) in N_{480}, with a relatively decrease of 44.32% (Tables 5, 6).

NUE was significantly greater in DI than in FI in all parts and whole plant, across all rates of N application. Average NUE was 49.60% in DI and 36.46% in FI, a relative increase of 36.04%. Seed cotton showed a

Table 3 Biomass accumulation in different plant parts and in the whole plant under different irrigation methods and N application rates

	Leaf	Stem	Bud and boll	Seed cotton	Root	Whole plant
			(g/plant)			
N_0	11.51^{B1}	7.92^{C}	6.88^{C}	15.05^{C}	4.66^{B}	45.94^{C}
N_{240}	14.12^{A}	9.79^{B}	7.86^{BC}	18.50^{B}	5.26^{AB}	58.17^{B}
N_{360}	14.62^{A}	11.16^{A}	8.29^{AB}	20.33^{A}	5.63^{A}	62.32^{A}
N_{480}	14.94^{A}	11.58^{A}	9.09^{A}	17.99^{B}	6.21^{A}	63.56^{A}
DI[2]	14.58^{A}	11.55^{A}	8.13^{A}	19.74^{A}	5.17^{B}	62.46^{A}
FI[3]	13.16^{B}	8.68^{B}	7.92^{A}	16.18^{B}	6.17^{A}	52.54^{B}
			F value			
N rate	17.66^{**}	161.16^{**}	13.19^{**}	25.68^{**}	17.09^{**}	39.97^{**}
Irri.	21.87^{**}	53.18^{**}	0.72	67.03^{**}	45.68^{**}	60.89^{**}
N rate × Irri.	2.98	15.47^{**}	5.07^{*}	4.15^{*}	3.39^{*}	5.85^{**}

Note: [1] within-dimention values followed by the same capital letter are not significantly different at P<0.01 (LSD test); [2] drip irrigation; [3] furrow irrigation; * and ** mean significance at 0.05 and 0.01 level, respectively.

Table 4 Two-way ANOVA of NDFF variation under different irrigation methods and N application rates

	Leaf	Stem	Bud and boll	Seed cotton	Root	Whole plant
				(%)		
N_{240}	39.70^{B1}	42.41^{B}	43.80^{A}	48.86^{A}	30.77^{B}	36.00^{B}
N_{360}	45.13^{A}	47.16^{A}	43.50^{A}	48.52^{A}	33.47^{B}	44.94^{A}
N_{480}	46.45^{A}	46.69^{A}	42.18^{A}	50.77^{A}	39.25^{A}	44.94^{A}
DI^{2}	47.94^{A}	48.90^{A}	46.27^{A}	49.63^{A}	38.25^{B}	45.34^{A}
FI^{3}	39.58^{B}	41.94^{B}	38.72^{B}	47.80^{A}	30.74^{A}	38.58^{B}
				F value		
N rate	9.09^{**}	12.86^{**}	1.54	2.91	26.83^{**}	7.40^{**}
Irri.	37.20^{**}	15.16^{**}	16.25^{**}	1.91	60.52^{**}	9.52^{**}
N rate × Irri.	1.65	3.57	2.41	0.57	2.52	0.25

Note: [1] within-dimension values followed by the same capital letter are not significantly different at P<0.01 (LSD test); [2] drip irrigation; [3] furrow irrigation; * and ** mean significance at 0.05 and 0.01 level, respectively.

bigger increase of NUE in DI than in FI, with a relative increase of 37.58% (Tables 5, 6).

2.3 Fertilizer N residue in the soil

N residue in the soil profile was significantly influenced by N application rates and irrigation methods. With the increase of N rate, N residue increased in both DI and FI (Fig. 1). Residual fertilizer N contents in whole soil profile in N_{240}, N_{360}, and N_{480} in DI were 16%, 17% and 18% greater than in FI with the same N application, respectively. N residue in the 0–40 cm soil layer accounted for 75.97% of N residue in DI, which showed that most of N is retained in the shallowest layer of soil. In FI, N residue mainly stayed in the 40–80 cm depth, accounting for over 60% of the residual N in the profile, which showed that N was driven by irrigation water to a deeper layer of soil. N residue increased by 48.1% in the 0–100 cm depth for N_{360}, and increased by 129.3% for N_{480} when compared to N_{240}, showing that excessive N fertilizer application leads to a huge amount of N accumulation in the soil profile.

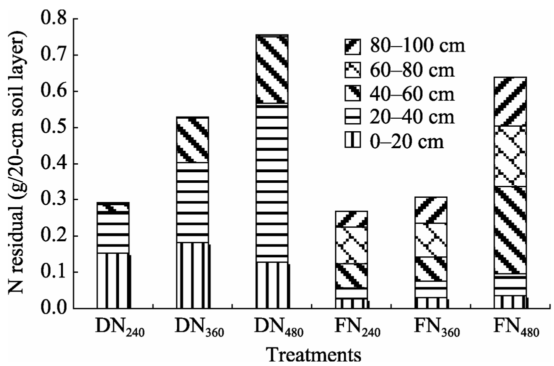

Fig. 1 N residual in soil profile as affected by irrigation methods and N fertilizer application rates. DN_{240}, DN_{360} and DN_{480} represent N level of 240, 360 and 480 kg/hm^2, respectively, and irrigation method is drip irrigation; FN_{240}, FN_{360} and FN_{480} represent N level of 240, 360 and 480 kg/hm^2, respectively, and irrigation method is furrow irrigation.

Two-way ANOVA showed that N residue in the soil profile exhibited a significant difference between DI and FI. The amount of residual N was greater in DI than in FI (a relative 24.8% increase). Residual N significantly differed among the five soil depths. The greatest layer of residual N was in the 60–80 cm soil depth and the smallest was in the 0–20 cm in FI. The layer with the greatest N residue was found in the 20–40 cm layer and the least N residual was detected in the 80–100 cm in DI (Table 7).

2.4 Fertilizer N fate as affected by irrigation methods and N application rates

During the growth period, no leaching liquid was collected in DI treatments, so N leaching in DI was zero. N leaching occurred in FI treatments. The amount of N leaching in N_{240}, N_{360} and N_{480} in FI was 0.1238, 0.3378 and 0.5608 g/cylinder, respectively. Correspondingly, the percentage of N leaching in N_{240}, N_{360} and N_{480} in FI was respectively 10.8%, 19.1% and 23.8% of total N application amount (Table 8), which showed a significant increase with increased N application rates.

With the increase of N application rates, plant N uptake increased significantly (Table 9), but the plant

Table 5 N uptake and allocation in cotton plant organs under different irrigation methods and N application rates

	Leaf	Stem	Bud and boll	Seed cotton	Root	Whole plant
	(g/cylinder)					
N_{240}	0.1284^{B1}	0.0871^{B}	0.0554^{b}	0.3034^{B}	0.0443^{C}	0.6186^{C}
N_{360}	0.1413^{B}	0.0872^{B}	0.0523^{b}	0.4390^{A}	0.0551^{B}	0.7749^{B}
N_{480}	0.1852^{A}	0.1027^{A}	0.0659^{a}	0.4789^{A}	0.0843^{A}	0.917^{A}
DI^{2}	0.1861^{A}	0.1080^{A}	0.0709^{A}	0.4838^{A}	0.0622	0.911^{A}
FI^{3}	0.1172^{B}	0.0766^{B}	0.0447^{B}	0.3304^{B}	0.0602	0.6291^{B}
	F value					
N rate	16.75**	8.29**	5.88*	22.25**	41.00**	31.05**
Irri.	67.30**	75.76**	59.58**	46.43**	0.29	62.68**
N rate × Irri.	7.30**	7.43**	2.42	10.58**	0.44	7.06**

Note: [1] within-dimension values followed by the same capital letter are not significantly different at $P<0.01$ (LSD test), by the same low case letter are not significantly different at $P<0.05$ (LSD test); [2] drip irrigation; [3] furrow irrigation; [4] percentage of total plant N uptake; * and ** mean significance at 0.05 and 0.01 level, respectively.

Table 6 Percentage of total plant N uptake under different irrigation methods and N application rates

	Leaf	Stem	Bud and boll	Seed cotton	Root	Whole plant
	(%)					
N_{240}	10.33^{A}	6.73^{A}	4.45^{A}	27.26^{A}	3.83^{A}	52.59^{A}
N_{360}	7.97^{B}	4.66^{B}	2.78^{B}	21.47^{B}	3.17^{B}	40.05^{B}
N_{480}	7.37^{B}	4.33^{B}	2.64^{B}	18.98^{C}	3.12^{B}	36.44^{C}
DI^{2}	10.00^{A}	6.03^{A}	3.94^{A}	26.14^{A}	3.49^{a}	49.60^{A}
FI^{3}	7.10^{B}	4.45^{B}	2.64^{B}	19.00^{B}	3.26^{b}	36.46^{B}
	F value					
N rate	69.03**	193.27**	117.06**	59.52**	18.62**	161.93**
Irri.	177.68**	212.41**	148.67**	125.85**	4.65*	291.75**
N rate × Irri.	2.14	3.61	9.03*	1.98	10.80**	2.56

Note: [1] within-dimension values followed by the same capital letter are not significantly different at $P<0.01$ (LSD test), by the same low case letter are not significantly different at $P<0.05$ (LSD test); [2] drip irrigation; [3] furrow irrigation; [4] percentage of total plant N uptake; * and ** mean significance at 0.05 and 0.01 level, respectively.

recovery rate decreased significantly as well. Soil N residue increased with the increase in the level of N application, and the recovery rate showed a trend similar with the plant recovery rate. Totally, recovered N increase was consistent with the increase of N application rate, but recovery rate decreased from 70.03% for N_{240} to 62.36% for N_{480}.

N recovery was also significantly influenced by irrigation methods. N recovery rate was 75.82% in DI, markedly greater than the 55.97% in FI. Both plant recovery rates and soil N residual rates were significantly greater in DI than in FI. Considering 17.89% of N leached in FI while no N leaching occurred in DI, this is an important reason to explain why N recovery amount and rate were markedly lower in FI than in DI.

3 Discussion

3.1 DI maintained more fertilizer N in the soil profile, especially in the upper layers

This study has added new information on the common perception that fertigation makes crop utilize more fertilizer N in the soil, hence residual N in soil is less than in FI. Our results indicated that N residue in soil is greater in DI than in FI when N application is identical, especially in the upper soil layer (Table 8). The reason is that DI reduced N leaching, though the crop absorbed a greater amount of N in the soil (Table 5), so that more N accumulated in the soil profile. Another possible reason is that N application in this study is highly consistent with farmer's N fertilization rates.

Table 7 Two-way ANOVA of N residual in the soil profile under different irrigation methods and N application rates

	0–20 cm	20–40 cm	40–60 cm	60–80 cm	80–100 cm	0–100 cm
	(N g/soil core)					
N_{240}	0.0787^{C1}	0.0855^{B}	0.0394^{C}	0.0542^{B}	0.0206^{C}	0.2785^{C}
N_{360}	0.0872^{B}	0.1468^{B}	0.0915^{B}	0.0459^{C}	0.0360^{B}	0.4125^{B}
N_{480}	0.0922^{A}	0.2137^{A}	0.1763^{A}	0.0952^{A}	0.0663^{A}	0.6387^{A}
DI[2]	0.1439^{A}	0.2483^{A}	0.0957^{B}	0.0024^{B}	0.0017^{B}	0.4921^{A}
FI[3]	0.0328^{B}	0.0445^{B}	0.1090^{A}	0.1279^{A}	0.0801^{A}	0.3943^{B}
	F value					
N rate	7.72**	9.85**	17.47**	461.97**	9.24**	69.8**
Irri.	59.82**	61.50**	46.97**	78.08**	11.04**	15.8**
N rate × Irri.	1.77	5.11*	145.72**	4.59*	1.89	7.3**

Note: [1] within-dimension values followed by the same capital letter are not significantly different at P<0.01 (LSD test); [2] drip irrigation; [3] furrow irrigation; * and ** mean significance at 0.05 and 0.01 level, respectively.

Table 8 Amount of N leaching under different irrigation methods and N application rates

Irrigation method	Fertilization (N kg/hm^2)	N leach (g/cylinder)
DI[2]	N_{240}	0
DI	N_{360}	0
DI	N_{480}	0
FI[3]	N_{240}	0.1268^{C1}
FI	N_{360}	0.3378^{B}
FI	N_{480}	0.5608^{A}

Note: [1] values followed by the same capital letter are not significantly different at P<0.01 (LSD test); [2] drip irrigation; [3] furrow irrigation.

Excessive application of N led to greater N accumulation, and if N rate is not so high, the trend may reverse. This implies a possibility to reduce N application in the research region for cotton production. Chinese agriculture is characterized by a high chemical N fertilizer input with a relatively low yield. It led to a low NUE (30%–40%) with serious N loss (40%–60%) (Zhu *et al*., 2002; Cui *et al*., 2010). It also contributes to some environmental concerns such as non-point source of N pollution (Hagin and Lowengart, 1996; Xing *et al*., 2001). So DI can be an option to increase fertilizer efficiency and reduce fertilizer input.

3.2 More fertilizer N was leached beyond the root zone in FI

We define N that moves to deeper than 100 cm in the soil profile as N leaching loss. This definition is reasonable, because the soil depth is around 100–160 cm in the study area. We did not observe N leaching in DI, while in FI leached liquid was collected below the 100-cm depth and N content in leaching liquid was respectively 0.1268, 0.3378 and 0.5608 g/cylinder, accounting for 10.8%, 19.1% and 23.8% of the total N applied, which implied that N was leached beyond the cotton root zone. Considering irrigation water was applied to soil in FI (for a slow penetration speed) for 7 individual times, irrigation amount in each operation was less than in real field practice, so we can deduce that in real agricultural practice N leaching could be more serious than in this research. The soil column density was set at 1.45 t/m^3 in 40–100 cm, where the soil was more compact. High compactness

Table 9 Recovery of fertilizer N in soil-plant system

	Plant		Soil		Leaching		Total recovery	
	N uptake (g/pot)	%[4]	N residual (g/pot)	%	N residual (g/pot)	%	N residual (g/pot)	%
N_{240}	0.5400^{c1}	52.59^{A}	0.2851^{C}	24.20^{B}	0.0634^{C}	5.83^{B}	0.8251^{A}	70.03^{a}
N_{360}	0.7421^{B}	40.05^{B}	0.4117^{B}	23.30^{B}	0.1689^{B}	9.56^{A}	1.1538^{B}	65.29^{ab}
N_{480}	0.8455^{A}	36.44^{C}	0.6238^{A}	26.48^{A}	0.2804^{A}	11.90^{A}	1.4693^{A}	62.36^{b}
DI[2]	0.8367^{A}	49.60^{A}	0.4946^{A}	27.83^{A}	0.0000^{B}	0.00^{B}	1.3313^{A}	75.82^{A}
FI[3]	0.5817^{B}	36.46^{B}	0.3858^{B}	21.49^{B}	0.3418^{A}	17.89^{A}	0.9675^{B}	55.97^{B}

Note: [1] within-dimension values followed by the same capital letter are not significantly different at P<0.01 (LSD test), and within-dimension values followed by the same low case letter are not significantly different at P<0.05 (LSD test); [2] drip irrigation; [3] furrow irrigation; [4] percentage of total N applied in soil.

also prevented water from leaching, which also implied a higher potential of N leaching loss in the real field.

3.3 More shoot parts and less root system were produced in DI

Our experimental results indicated that irrigation methods significantly influenced the biomass and fertilizer N uptake of cotton plants. Biomass of leaf, stem, bud and boll, and seed cotton was significantly greater in DI than in FI, but root biomass was significantly less in DI than in FI. This suggests that a more even soil moisture distribution in DI was beneficial for shoot growth and reduced root growth, while FI caused an extended dry period and induced bigger root growth (Davidson *et al*., 1969; Mackay *et al*., 1985). This biomass distribution pattern is beneficial for the improvement of cotton seed yield, while it also means a weaker capacity for stress-tolerance in DI.

3.4 Cotton acquired more N from fertilizer in DI than in FI

We observed a significant increase of NDFF in the vegetative parts (leaf, stem and root) of cotton plant with the increase in N application rate. While in the reproductive parts (seed cotton and bud and boll), fertilization did not cause any significant change in NDFF (Table 4). This seems to imply that cotton plant tends to uptake more N nutrition if N in the soil becomes more abundant and stores N in vegetative organs, but reproductive organs are more closely related to their inherit potential, so their NDFFs are not influenced significantly by N application levels.

3.5 NUE is highly associated with N fertilizer application rates

N application rate had a highly significant (P<0.001) effect on the NUE of the whole plant. With the increase in N application, NUE decreased sharply. NUE is 52.59% for N_{240} and only 36.44% for N_{480}, with a relative decrease of 44.32% (Table 6). This result agrees with the findings of other researchers (Hou *et al*., 2007; Zhang *et al*., 2008). Our study confirmed that DI could greatly enhance N efficiency compared to FI, the reason of which might lie in better water regime (Papadopoulos *et al*., 1988), higher frequency fertigation, and better plant growth (Mmolawa *et al*., 2000).

3.6 N gaseous loss is similar in DI and FI

Recovery of N in the plant-soil system accounted for 75.82% of applied N in DI and 55.94% in FI (Table 9). This means that 24.18% of N in DI and 44.03% in FI escaped from the soil-plant system. Considering that N loss from leaching accounted for 17.89% in FI but no N loss was observed in DI, N loss by ammonia volatilization/denitrification would be 24.18% in DI and 26.14% in FI. Some researchers reported that in calcareous soil, N volatilization is very limited, especially in drip irrigation (Chua *et al*., 2003). Xu *et al*. (2009) reported that the ammonia volatilization ratio in calcareous soil in Xinjiang is only 0.39%–1.23% of total N applied (Xu *et al*., 2009), so most of gaseous loss is by way of denitrification. Researchers suggested that higher irrigation frequency in drip irrigation makes a relatively wet zone, therefore resulting in a stronger denitrification rate compared to furrow irrigation (Mahmood *et al*., 2000; Thompson *et al*., 2000; Chua *et al*., 2003). Freney *et al*. (1993) reported that 43%–63% of the N loss was due to denitrification for irrigated cotton fields in Australia. Our study indicated that 24.18% of N loss in DI and 26.14% in FI were due to denitrification, no big difference for the two treatments.

4 Conclusions

We observed that DI enhanced whole plant biomass and the biomass of different plant parts in cotton more than FI did, except for the decrease in root biomass due to a beneficial water regime and nutritional state in drip irrigation. We also found that cotton plants uptake more N and seem to store it in vegetative parts in DI. Correspondingly, NUE was also significantly greater in DI than in FI. N dosage showed a highly significant effect on NUE. With the increase of N application, NUE decreased sharply from 52.59% for N_{240} to 36.44% for N_{480}.

N residue in soil and plant N uptake increased with increased N dosage, but recovery rate decreased consistently. N residue mainly stayed in the 0–40 cm soil layer in DI, while N residue in FI mainly stayed in the

40–80 cm soil layer, showing N mainly distributes in shallow layers in DI but in deeper layers in FI. N recovery rate was 75.82% in DI, markedly higher than the 55.97% in FI. Soil N residual was significantly greater in DI than in FI. FI showed 17.89% N leaching, while no N leaching occurred in DI.

From these findings, it can be concluded that DI offers the following advantages: greater NUE in plant, greater residual N in the soil profile and therefore a greater N recovery rate; Zero N leaching and shallow N distribution in soil profile result in reduced risk of N leaching; enhanced shoot growth and reduced root growth are all beneficial for more economic yield.

Acknowledgements

This study was financed by the Special Fund for Agro-scientific Research in the Public Interest (201103003), the National Natural Science Foundation of China (31060276), and the National High Technology Research and Development Program of China (2011AA100508). Thanks also go to Dr. Long LI in China Agriculture University, China, Dr. XinPing YANG in Nanjing Agriculture University, China, and Mr. Ivan MALKOC in Shihezi University, China.

References

Allen S C, Jose S, Nair P K R, *et al.* 2004. Competition for ^{15}N-labeled fertilizer in apecan (*Carya illinoensis* K. Koch)-cotton (*Gossypium hirsutum* L.) alley cropping system in the southern United States. Plant and Soil, 263: 151–164.

Badr M A, Abou Hussein S D, El-Tohamy W A, *et al.* 2010. Nutrient uptake and yield of tomato under various methods of fertilizer application and levels of fertigation in arid lands. Healthy Plants, 62(1): 11–19.

Barber L D, Joern B C, Volenec J J, *et al.* 1996. Supplemental nitrogen effects on alfalfa regrowth and nitrogen mobilization from roots. Crop Science, 36: 1217–1223.

Bondada B R, Oosterhuis D M. 2001. Canopy photosynthesis, specific leaf weight, and yield components of cotton under varying nitrogen supply. Journal of Plant Nutrition and Soil Science, 24: 469–477.

Chua T T, Bronson K F, Booker J D, *et al.* 2003. In-season nitrogen status sensing in irrigated cotton: I. yields and nitrogen-15 recovery. Soil Science Society of America Journal, 67: 1428–1438.

Clawson E L, Cothren J T, Blouin D C, *et al.* 2008. Timing of maturity in ultra narrow and conventional row cotton as affected by nitrogen fertilizer rate. Agronomy Journal, 100: 421–431.

Cui Z L, Chen X P, Zhang F S. 2010. Current nitrogen management status and measures to improve the intensive wheat–maize system in China. Ambio, 39: 376–384.

Davidson R L. 1969. Effects of soil nutrients and moisture on root/shoot ratios in *Lolium perenne* L. and *Trifolium repens* L. Annals of Botany, 33(3): 571–577.

Freney J R, Chen D L, Mosier A R, *et al.* 1993. Use of nitrification inhibitors to increase fertilizer nitrogen recovery and lint yield in irrigated cotton. Nutrient Cycling in Agroecosystems, 34: 37–44.

Hagin J, Lowengart A. 1996. Fertigation for minimizing environmental pollution by fertilizers. Fertilizer Research, 43: 5–7.

Hancock J M, McNeill A M, McDonald G K, *et al.* 2011. Fate of fertiliser N applied to wheat on a coarse textured highly calcareous soil under simulated semi-arid conditions. Plant and Soil, 348: 139–153.

Hou Z A, Li P F, Li B G, *et al*. 2007. Effects of fertigation scheme on N uptake and N use efficiency in cotton. Plant and Soil, 290: 115–126.

Mackay A D, Barber S A. 1985. Soil moisture effects on root growth and phosphorus uptake by corn. Agronomy Journal, 77(4): 519–523.

Mahmood T, Ali R, Sajjad M I, *et al.* 2000. Denitrification and total fertilizer-N losses from an irrigated cotton field. Biology and Fertility of Soils, 31: 270–278.

Mmolawa K, Or D. 2000. Root zone solute dynamics under drip irrigation: a review. Plant and Soil, 222: 163–190.

Mohammad M J, Zuraiqi S, Quasmeh W, *et al.* 1999. Yield response and nitrogen utilization efficiency by drip irrigated potato. Nutrient Cycling in Agroecosystems, 54: 243–249.

Mohammad M J. 2004. Utilization of applied fertilizer nitrogen and irrigation water by drip-fertigated squash as determined by nuclear and traditional techniques. Nutrient Cycling in Agroecosystems, 68: 1–11.

Norton E R, Silvertooth J C. 2007. Evaluation of added nitrogen interaction effects on recovery efficiency in irrigated cotton. Soil Science, 172: 983–991.

Papadopoulos I. 1988. N fertigation of trickle-irrigated potato. Fertilizer Research, 16: 157–167.

Phene C J. 1995. The most economical method of irrigation. Irrigation and Drainage, 14(1): 50–52.

Quiñones A, Bañuls J, Primo-Millo E, *et al.* 2005. Recovery of the ^{15}N-labelled fertiliser in citrus trees in relation with timing of application and irrigation system. Plant and Soil, 268: 367–376.

Sammis T W. 1980. Comparison of sprinkler, trickle, subsurface and furrow irrigation methods for row crops. Agronomy Journal, 72: 701–704.

Sharmasarkar F C, Sharmasarkar S, Miller S D, *et al.* 2001. Assessment of drip and flood irrigation on water and fertilizer use efficiencies for sugarbeets. Agricultural Water Management, 46: 241–251.

Starck J, McCann C, Westermann I R, *et al.* 1993. Potato response to split N timing with varying amount of excessive irrigation. American Potato Journal, 70: 765–777.

Stikic R, Popovic S, Srdic M, *et al.* 2003. Partial root drying (PRD): a new technique for growing plants that saves water and improves the quality of fruit. Bulgarian Journal of Plant Physiology (Special issue): 164–171.

Thompson T L, Doerge T A, Godin R E. 2000. Nitrogen and water interactions in subsurface drip-irrigated cauliflower: II. Agronomic, economic, and environmental outcomes. Soil Science Society of America Journal, 64: 412–418.

Wang C, Isoda A, Wang P. 2004. Growth and yield performance of some cotton cultivars in Xinjiang, China, an arid area with short growing period. Journal of Agronomy and Crop Science, 190: 177–183.

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

Xing G X, Gao Y C, Shi S L. 2001. N pollution sources and denitrification in water bodies in Taihu Lake region. Science in China: Series B, 44(3): 304–314.

Xu W L, Liu H, Zhang Y S, *et al.* 2009. *In situ* monitoring of ammonia volatilization from grey desert soil under different fertilizers in Xinjiang. Acta Ecologica Sinica, 29(8): 4565–4571.

Zapata F. 1990. Isotope techniques in soil fertility and plant nutrition studies. In: Hardarson G. Use of Nuclear Techniques in Studies of Soil–Plant Relationships. Vienna: International Atomic Energy Agency, 61–128.

Zhang L, Spiertz J H J, Zhang S, *et al.* 2008. Nitrogen economy in relay intercropping systems of wheat and cotton. Plant and Soil, 303: 55–68.

Zhu Z L, Chen D L. 2002. Nitrogen fertilizer use in China – contributions to food production, impacts on the environment and best management strategies. Nutrient Cycling in Agroecosystems, 63: 117–127.