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Effects of drip irrigation frequency on soil wetting pattern and potato growth in North China Plain

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Abstract

The effect of irrigation frequency on soil water distribution, potato root distribution, potato tuber yield and water use efficiency was studied in 2001 and 2002 field experiments. Treatments consisted of six different drip irrigation frequencies: N1 (once every day), N2 (once every 2 days), N3 (once every 3 days), N4 (once every 4 days), N6 (once every 6 days) and N8 (once every 8 days), with total drip irrigation water equal for the different frequencies. The results indicated that drip irrigation frequency did affect soil water distribution, depending on potato growing stage, soil depth and distance from the emitter. Under treatment N1, soil matric potential (ψ_m) Variations at depths of 70 and 90 cm showed a larger wetted soil range than was initially expected. Potato root growth was also affected by drip irrigation frequency to some extent: the higher the frequency, the higher was the root length density (RLD) in 0–60 cm soil layer and the lower was the root length density (RWD) in 0–10 cm soil layer. On the other hand, potato roots were not limited in wetted soil volume even when the crop was irrigated at the highest frequency. High frequency irrigation enhanced potato tuber growth and water use efficiency (WUE). Reducing irrigation frequency from N1 to N8 resulted in significant yield reductions by 33.4 and 29.1% in 2001 and 2002,

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respectively. For total ET, little difference was found among the different irrigation frequency treatments.

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Keywords: Drip irrigation frequency; Potato; Soil water distribution; Root distribution

1. Introduction

Potatoes are one of the most important vegetables in the world. They are also quite sensitive to water stress. In Northern China, they are generally planted in raised beds and furrow-irrigated. Under traditional agronomic practices, a large amount of manure is added to the field prior to plowing and bedding. Typically, fertilizer is not applied to the field during the growing season. Because the roots are relatively shallow and concentrated within the raised bed, furrow irrigation often infiltrates under the root zone, while the topsoil of the raised bed is still dry. As such, water use efficiency is very low.

Drip irrigation is well suited for use with raised bed production cultures (Clark et al., 1995). Currently, because of water shortages, farmers have been encouraged to adopt drip irrigation by Chinese governments.

Irrigation frequency is one of the most important factors in drip irrigation scheduling. Due to the differences in soil moisture and wetting pattern, crop yields may be different when the same quantity of water is applied under different irrigation frequencies. Typically, the higher the irrigation frequency the smaller the wetted soil volume and the higher mean soil water content can be maintained in the wetted soil volume during a period when the total irrigation water is equal. High irrigation frequency might provide desirable conditions for water movement in soil and for uptake by roots (Segal et al., 2000). Several experiments have shown positive responses in some crops to high frequency drip irrigation (Freeman et al., 1976; Segal et al., 2000; Sharmasarkar et al., 2001). However, seeming inconsistencies as to what frequency might be optimum can also be found in the literature. Dalvi et al. (1999), found that the maximum yield was obtained at every second day frequency. Pitts et al. (1991) found that two drip irrigation frequencies (three times per day, one time per day) had no affect on tomato yield. However, root length density (total root length per soil volume) was significantly affected by irrigation treatment at the 0-0.15 m depth, with the more frequent irrigation treatment having less root length density. Meshkat et al. (2000) went one-step farther by pointing out that an irrigation regime with excessively high frequency could cause the soil surface to remain wet with first stage evaporation persisting most of the time resulting in a maximum rate of water loss. Evidence indicates that root systems under partial soil wetting are dominated by wetting patterns under the drippers (Clothier and Green, 1994; Coelho and Or, 1996). These limited root systems might not affect crop growth, however, when the main nutrients are applied through irrigation system. However, under such agronomic practices in Northern China, excessively limited wetting volume could possibly restrict the decomposition of manure and thus, result in crop nutrient stress.

Understanding soil water distribution, potato root distribution and water uptake patterns has become increasingly important in developing modern environmentally friendly drip irrigation practices. The purpose of this study was to determine what effects the frequency of irrigation has on soil water depletion and replenishment, root distribution, potato yields and water use efficiency.

2. Materials and methods

2.1. Experimental site

Field experiments were conducted at Luancheng Agro-ecosystem Station (LAES), Chinese Academy of Sciences, during the 2001 and 2002 growing seasons. LAES is located in Luancheng County, Hebei Province (latitude: $37^{\circ}53'$ N; longitude: $114^{\circ}41'$ E; 50 m above sea level). Annual precipitation is about 480 mm concentrated between July and September. Normally precipitation is very rare in the spring and early summer. The dominant soil type is loam, with an average bulk density of 1.53 g/cm³ for the upper 30 cm soil layer. The mineral content of the groundwater is less than 0.5 g/l, with the water table about 28 m below the surface.

2.2. Experimental design

There were six irrigation frequency treatments, each replicated three times: once every day (N1), once every 2 days (N2), once every 3 days (N3), once every 4 days (N4), once every 6 days (N6) and once every 8 days (N8). The total amount of irrigation water for the different treatments was equal. The drip irrigation system was installed after the experimental field was ploughed and bedded. Thin-wall drip tapes (Chapin Watermatics Inc.) with a flow rate of 3.72 l/m/h at 0.042 MPa were placed in the center of the raised beds (dripper spacing was 30 and 20 cm, respectively, in the 2001 and 2002 growing seasons). Each plot had one valve, one flow meter, and one pressure gauge to control the operating pressure and measure the irrigation quantity. In 2001, due to the lack of information on potato evapotranspiration under drip irrigation, N1 treatment was irrigated according to matric potential readings, weather broadcasts and visual observation of potato growth. In 2002, irrigation depth of N1 was the previous day ET measured by a lysimeter under a soil matric potential (-25 kPa) treatment conducted at the same site and time (Kang et al., 2004).

Irrigation water in the other treatments was taken as the cumulative value of N1 treatment. When it rained, effective rainwater was subtracted from irrigation application. Before the potatoes sprouted, all treatments plots were well irrigated with the same quantity of water at the same frequency in order to ensure a uniform germination rate. After that, each plot was irrigated according to prescribed frequency treatments.

2.3. Agronomic practices

Each plot was 5.6 m wide and 6.0 m long, with the potatoes planted every 20 cm in the center of the seven raised beds. Animal manure and fertilizer were applied uniformly to field before planting.

In 2001, the application of manure and N, P, K fertilizers were at 12 m³/ha, 105 kg/ha, 180 kg/ha and 130 kg/ha, respectively. The potatoes (*Solanum tuberosum*L.) were planted on 1 April, and emerged about three weeks later. They were harvested on 8 July.

In 2002, the applications of manure, plant ashes and N, P, K fertilizers were 12 m³/ha, 150, 105, 180 and 130 kg/ha, respectively. The crops (Favorita) were planted on 8 March, and emerged about four weeks later. They were harvested on 17 June.

2.4. Soil moisture measurement

In 2001, three sets of mercurial tensiometers (the size of the ceramic tip: inner diameter = 10 mm, outer diameter = 20 mm, length = 60 mm.) were installed in N1, N4 and N8 treatments. In 2002, six sets of tensiometers were installed in the six treatments. Every set of tensiometers had 30 sensors. Sensor placement is shown in Fig. 1.

Soil matric potential was measured at 8:00 every day following the emergence of the potatoes. To draw soil water retention curve, the gravimetric soil water content of different soil layers was measured frequently during some periods when the soil matric potential declined from the highest to the lowest, at a time interval of once every day or 2 days. The values were converted to a percentage volumetric basis by multiplying the respective values by the bulk density of the soil of the respective layer. Soil matric potentials were measured in a similar fashion.

2.5. Crop evapotranspiration estimation

Crop evapotranspiration was estimated using the following equation:

$$ET_c = I + P - \Delta S - R - D \tag{1}$$

where *I* is irrigation amount; *P* is precipitation; ΔS is the change of soil water storage; *R* is surface runoff; and *D* is downward flux below crop root zone.

To estimate ΔS , soil water contents in the soil profile (down to 90 cm) just before planting and harvesting were determined by gravimetric measurements. ΔS is the difference using the soil water storage before harvesting to subtract the soil water storage before planting. Because precipitation during the growing season was very small, surface runoff was ignored. Deep percolation was estimated according to Darcy's equation:

$$D = -K(\bar{\theta}) \left(\frac{\psi_{m2} - \psi_{m1}}{Z_2 - Z_1} + 1 \right)$$
(2)

where *D* is deep percolation (mm/day), ψ_{m2} and ψ_{m1} are the matric potentials at 90 cm and 70 cm, respectively, Z_1 and Z_2 are the soil depths under crop root zone ($Z_1 = 70$ cm, $Z_2 = 90$ cm); $\bar{\theta}$ is the mean soil moisture content at depths of of Z_1 and Z_2 . $K(\bar{\theta})$ is the unsaturated hydraulic conductivity (mm/day) estimated by the following empirical equation (Lei et al., 1988)

$$K(\theta) = K_{\rm s} \left(\frac{\theta}{\theta_{\rm s}}\right)^m \tag{3}$$

where K_s is saturated hydraulic conductivity, θ_s is saturated volumetric water content (both K_s and θ_s were measured in a method suggested by Lei et al. (1988) in the laboratory using



Fig. 1. Sensor placement of tensiometer.

original soil gotten at 80 cm depth from the field; they are equal to 0.713 (m/day) and 0.377, respectively; *m* is the regression coefficient, which was 27.74 in our experiment (unsaturated hydraulic conductivities were measured by a method suggested by Lei et al.



Fig. 2. Soil water characteristic curve.

(1988); and θ is volumetric water content derived from the soil water characteristic curve (Fig. 2) and expressed as

$$\theta = 0.3853 \mathrm{e}^{-0.01775\psi_{\mathrm{m}}} \tag{4}$$

where ψ_m is soil matric potential measured in the field as '-kPa' with range of -1 to -55 kPa.

2.6. Root sampling

Root sampling was carried out just before the harvesting day. A hollow auger with an internal diameter of 0.055 m was used to collect soil cores. Samples were collected at five points perpendicular to the drip line at 0, 10, 20, 30 and 40 cm such that the center of the standard potato crop was immediately under the dripper. In 2001, the samples were extracted at 10 cm intervals up to a depth of 60 cm. In 2002, the samples were extracted at 10 cm intervals up to a depth of 90 cm. The same process was repeated at three different locations in each treatment plot. Samples of the same depth and horizontal distance for the same treatment were mixed. The samples were steeped and flushed prior to measuring root length using a root scanner (CID201, CID Inc.) as suggested by Zhang (1999). Dry root weight was measured indoors after the root samples were oven-dried.

3. Results and discussion

3.1. Total water received

Irrigation quantities for N1 and precipitation after potato emergence are shown in Fig. 3. Irrigation total for each drip irrigation treatment was 192 and 142 mm during 2001, 2002 growing season, respectively. Rain total was 77 and 104 mm, respectively, for the two seasons.

3.2. Soil water distribution and changes

Fig. 4 illustrates the changes in ψ_m at depths of 10, 20, 30, 50, 70 and 90 cm at positions immediately under the drippers for N1, N4 and N8, respectively. The results indicate that



Fig. 3. Irrigations of treatment N1 and precipitations after potato emergence.

soil water in the upper soil layer changed more dramatically than in the lower layer. During the early growth period (20–50 days from planting), the $\psi_{\rm m}$ showed some change, but only at depths of 10 and 20 cm with no significant change occurring below 30 cm. The value of $\psi_{\rm m}$ at different depths varied from 0 to -40 kPa, and the tendencies for different treatments were similar, suggesting that ψ_m was not affected significantly by irrigation frequency during the period. However, with increases in air temperature, evapotranspiration increased, and ψ_m varied greatly within the soil profile. During the middle planting period (50–80 days from planting), $\psi_{\rm m}$ of the topsoil showed larger variations in the 0 to -60 kPa range, although there was little difference of $\psi_{\rm m}$ among different treatments at depths from 10 to 30 cm. At those depths below 30 cm, however, $\psi_{\rm m}$ variations increased as irrigation frequency decreased. During the late period (80–99 days from planting), variations in $\psi_{\rm m}$ for the three treatments were similar at depths from 10 to 50 cm. It is interesting to note that the $\psi_{\rm m}$ evolution for treatment N1 at the depths of 70 and 90 cm immediately under emitter fluctuates dramatically while the curves for treatments N4 and N8 were relatively smooth. The explanations of this phenomenon could be: (1) in a higher frequency treatment, the plane section area of wetted soil in the upper soil layer was always smaller (see Fig. 7), which means more water could move downward when the same amount of irrigation water was applied in a definite period, if $I > ET_c$. This can explain why ψ_m at these deeper positions for N1 was sometime higher than N4 and N8; (2) because the surrounding soil for these positions in N1 was much drier and soil water in the zone was very limited, soil water would be depleted more quickly because of evapotranspiration and horizontal movement, when $I < ET_c$ during the following days. This made ψ_m in N1 became smaller. In other words, the shortdated unbalance between water compensation (influx) and water depletion (outflux) in those soil zones resulted in the more dramatic fluctuation of ψ_m in a higher frequency treatment.

The evolution of ψ_m at different depths with a horizontal distance of 40 cm from the drip line was of great interest in this experiment, because they can reflect the range of wetted soil in the horizontal direction (see Fig. 5). It was showed that the ψ_m values at depths of 10,



Fig. 4. Soil water matric potential pattern at different depths immediately under emitter for treatments N1, N4 and N8.



Fig. 5. Soil water matric potential pattern at different depths at a horizontal distance of 40 cm to drip line for treatments N1, N4 and N8.

20, 30 and 50 cm for treatments N1, N4, N8 were all similar during the early growth period, suggesting that the irrigation frequencies had not significantly affected ψ_m at these depths. During later growing periods, the effects of irrigation frequency on ψ_m became clearer. It is interesting to note that the ψ_m value for treatment N8 showed a larger variation than the other two treatments at soil depths of 50–90 cm after the 65th day. This might be explained by two reasons. The longer duration of irrigations of N8 lead to larger range of wetted soil in the horizontal direction, on the hand, water in the wetted soil at these positions was depleted more quickly by root uptake because of more roots distributed in this zone than the other two treatments (see Fig. 8).

Further analysis of soil water distribution profile indicates that ψ_m values at soil depths of 70 and 90 cm became higher with less frequent treatments. This suggests that the irrigation water infiltrating to these depths had not been taken up commensurately as the irrigation amount increased.

Fig. 7 shows the soil moisture status of treatments N1, N4, and N8 just before irrigation and one day after irrigation at two stages (April and June). At the earlier stage, $\psi_{\rm m}$ of the three treatments was relatively high. For treatment N1, ψ_m was higher than -15 kPa throughout the 10–90 cm zone with only a relatively small slightly drier zone ($\psi_{\rm m}$ was between -15 kPa and -25 kPa) located close to the plant on treatments N4 and N8 before irrigation. As expected, this drier zone for treatment N8 was much bigger than that for treatment N4. After irrigation, ψ_m for all the treatments became higher than -15 kPa in all root zones. During the later stage, large dry zones appeared before irrigation for every treatment. The average $\psi_{\rm m}$ sequence in the 0–20 cm layer was N8 < N4 < N1. After irrigation, the wetted zone under a less frequency was larger than that under a higher one. Further, the larger wetted zone was found to have a longer duration (Fig. 6). The temporary dry zone just before irrigation may have caused water stress. The longer duration of a larger wetted zone also influenced soil aeration. These two factors might explain the reduction of potato yield under the less frequent treatment, since the ideal conditions for potato growth require high and nearly constant soil moisture potential and a high soil oxygen diffusion rate (Phene and Sanders, 1976).

3.3. Root distribution

Potato root distribution for the different irrigation treatments in 2001 season, is shown by means of root length density (RLD) and root weight density (RWD) in Tables 1 and 2. It

Root length density (cm/cm ³)										
Treatment	Soil layer									
	0-10 (cm)	10-20 (cm)	20-30 (cm)	30-40 (cm)	40-60 (cm)	0-60 (cm)				
N1	0.227	0.153	0.160	0.172	0.083	0.146				
N2	0.193	0.139	0.137	0.136	0.065	0.122				
N3	0.276	0.102	0.111	0.108	0.042	0.113				
N4	0.255	0.107	0.111	0.115	0.040	0.112				
N6	0.268	0.110	0.096	0.097	0.044	0.110				
N8	0.246	0.107	0.109	0.103	0.048	0.110				

Table 1 Root length density (cm/cm³)



Fig. 6. Evolution of ψ_m patterns with the depth and distance from emitter after irrigation for treatments N4 and N8, (*) irrigation day.



Fig. 7. Soil water matric potential distribution right before irrigation and one day after irrigation.

Root weight density (mg/cm ³)										
Treatment	Soil layer									
	0-10 (cm)	10-20 (cm)	20-30 (cm)	30-40 (cm)	40-60 (cm)	0-60 (cm)				
N1	0.883	0.178	0.109	0.154	0.043	0.235				
N2	1.030	0.108	0.099	0.087	0.081	0.248				
N3	1.486	0.237	0.186	0.150	0.072	0.367				
N4	1.614	0.132	0.097	0.122	0.051	0.345				
N6	1.924	0.166	0.127	0.074	0.029	0.392				
N8	2.175	0.221	0.125	0.106	0.090	0.468				

Table 2		
Root weight	density	(mg/cm^3)



Fig. 8. Root distributions of potato for different treatments.

can be seen from these tables that potato roots were concentrated in the 0–40 cm soil layer for all treatments. The highest root density appeared between 0 and 10 cm, where about 26–41 and 63–82% of the total roots concentrated based on RLD and RWD, respectively. Between 10 and 20 cm, 20 and 30 cm, and 30 and 40 cm, there were similar RLD values for each treatment with the exception of treatments N1 and N2 which had higher values. According to RLD values, when irrigation frequency is less than once every two days, root growth at these depths seemed to not be further affected by irrigation frequency. Mean RLD in the 0–60 cm layer was clearly affected by irrigation frequency, with the more frequent irrigation treatment having the higher RLD. In the 0–10 cm layer, RLD was not affected by irrigation treatment, however, RWD was clearly affected by irrigation frequency with the more frequent treatment having the lower RWD. This inconsistency between RLD and RWD has been reported previously (Plaut et al., 1996), causing some researchers to use RLD to characterize root systems (Coelho and Or, 1999). Nevertheless, it is clear that irrigation frequency does influence potato-rooting patterns to some extent.

The root length distributions for treatments N1, N4, N8 and CK (Fig. 8) show that the zones with densest roots appeared around the main roots in the 0-10 cm soil layer for every treatment. Among the different treatments, there was not much difference in RLD distributed horizontally except to at 40 cm where N8 had the biggest RLD among the three treatments. The denser root distribution at 40 cm might be caused by the larger dry zone before irrigation and the wider wetted zone after irrigation, since crop root systems under water stress have a tendency to develop elsewhere.

In the 2002 season, however, no clear rule was found in relation to the root distributions for the different treatments (Kang et al., 2004).

From the experimental results analyzed above, it seems that potato root systems are not limited to rather small wetting ranges as supposed, even when the crop was irrigated at the high frequency. This probably means that the soil profiles for all the treatments were not so dry as to restrain root growth during some critical period.

3.4. Crop evapotranspiration (ET_c)

The results of ΔS , D and ET_c estimated by Eq. (1) are listed in Table 5.

In 2001, ΔS of each treatment was negative, indicating that the soil became drier at the end of the growing season. In 2002, it was positive, suggesting that the soil became wetter.

However, no changing tendency of ΔS can be found for different treatments. In 2001, total soil water downward fluxes (D) for treatments N1, N4 and N8 through the 80 cm layer, estimated by Eq. (2), were 0.3, 4.4 and 4.9 mm, respectively. Since these values are very small, it is safe to conclude that the percolation loss of each treatment can be ignored. However, in 2002, the biggest D for treatment N8 was 12.0 mm, much higher than the other treatments. The 2-year results indicate that the least frequency treatment had the highest probability of more deep percolation. The average ET_c in 2001 was 74.4 mm higher than that in 2002, however, the ET_c for every treatment in both the two growing seasons suggests that the effect of irrigation frequency on total ET_c for potato was insignificant.

3.5. Potato tuber grade

The 2001 results of tuber grade analysis are listed in Table 3. It was found that although treatments N1, N2, N3, N4 and N6 had more tubers per plant than N8, the difference among the six treatments was not significant (F: P > 0.05). Analysis of mean tuber weight, the number of big tubers (W > 150 g), the number of medium tuber (100 g $\leq W < 150$ g), and the number of culls indicated there was little difference among the different drip frequency treatments. The difference in the number of small tubers among irrigation frequency treatments was significant (P < 0.05), but there was no significant difference between different treatments according to Duncan's test. There were significant differences in the number of marketable tubers among treatments, N2 had the most, N1 had the second, and N8 had the least. N1, N2, N3, N4 and N6 were significantly more than N8, however, the difference between any two treatments of N1, N2, N3, N4 and N6 was insignificant. The 2002 results of tuber grade analysis are listed in Table 4. The difference in marketable tuber number among the treatments was also highly significant (F: P < 0.05). N1 had the most marketable tubers, and significantly had more tubers than N4, N6 and N8 according to Duncan's test. N2 and N3 had very close marketable tuber, and N3 was significantly higher than N6. Significant difference in total tuber number per plant among the treatments was found, which was different from the 2001 result. It can be found, however, that N1 had the highest tuber number per plant in both the experimental years.

Treatment	Tuber number of 10 plants	Mean weight of single tuber (g)	Tuber number of different grade (10 plants)						
			$\frac{\text{Big}}{(W \ge 150 \text{ g})}$	Medium (100 g $\leq W$ < 15 0g)	Small (50 g $\leq W$ < 100 g)	Culls $(W < 50 \text{ g})$	Marketable $(W \ge 50 \text{ g})$		
N1	69.0 NS	52.2 NS	2.3 NS	7.3 NS	23.3 a	36 NS	33.0 ac SS [§]		
N2	66.6	55.4	2.3	5.7	26.7 a	31.9	34.7 a		
N3	60.3	54.0	2.3	6.3	18.3 a	33.4	26.9 ac		
N4	60.7	51.5	1.7	6.0	19.7 a	33.3	27.4 ac		
N6	65.7	46.8	0.7	6.0	19.3 a	39.7	26 ac		
N8	40	52.1	1	5.7	10.3 a	23.0	17 b		

Table 3 Potato tuber grading and its statistical analysis

NS: differences among frequency treatments are not significant by *F*-test (P > 0.05). SS: differences among frequency treatments are significant by *F*-test (P < 0.05).

[§] Values in a column with the same letter are statistically homogeneous by Duncan's test.

Treatment	Tuber number of 10 plants	Mean weight of single tuber (g)	Tuber number of different grade (10 plants)					
			$\frac{\text{Big}}{(W \ge 150 \text{ g})}$	Medium (100 g $\leq W$ < 150 g)	Small (50 g $\leq W$ < 100 g)	Culls $(W < 50 \text{ g})$	Marketable $(W \ge 50 \text{ g})$	
N1	73.3 a SS [§]	64.8 NS	4.3 NS	9.3 NS	25.3 a SS [§]	34.3 NS	39.0 a SS [§]	
N2	51.7 b	75.5	5.3	8.3	19.0 ab	19.0	32.7 ab	
N3	61.0 ab	67.4	4.0	9.3	19.7 ab	28.0	33.0 ab	
N4	54.0 b	70.4	4.7	12.0	12.7 b	24.7	29.3 b	
N6	45.3 b	78.3	5.7	7.7	11.3 b	20.7	24.7 b	
N8	<u>44.3 b</u>	71.7	4.3	5.3	16.7 b	18.0	26.3 b	

Note: Difference between the two underlined items in a column is significant by Duncan's test.

[§] Values in a column with the same letter are statistically homogeneous by Duncan's test.

The results of tuber grade analysis for the two seasons suggest that potato tuber grew best in treatment N1 and worst in treatment N8, with a tendency that potato grows better under a higher irrigation frequency in the range of treatments.

3.6. Potato tuber yield and water use efficiency

Potato tuber yield and water use efficiency are listed in Table 5. In the 2001 season, the yield of potato tubers ranged from 14,139 to 21,234 kg/ha. The highest yield was at N1, 50.2% more than the lowest yield at N8, however, differences among treatments were not significant according to *F*-test (P > 0.05). In the 2002 season, potato tuber yield ranged from 20,000 to 28,241 kg/ha. The total yield for the six treatments were in order of N1 > N3 > N2 > N4 > N6 > N8, and differences among treatments was significant (P < 0.05). N1 was significantly higher than N6 and N8 according to Duncan's test, and N1 was 41.2% higher than N8. The yield difference between any other two treatments was insignificant.

Table 5

Potato evapotranspiration calculated using water balance equation, potato yield and WUE for different treatments

Year	Treatment	ΔS (mm)	D (mm)	I (mm)	P (mm)	ET _c (mm)	Potato yield (kg/ha)	WUE (kg/ha mm)
2001	N1	-6	0.3	192	77	274.7	21234 NS	77.1 NS
	N2	-13	_	192	77	282.0	16750	59.4
	N3	-24	_	192	77	293.0	16889	57.6
	N4	-11	4.4	192	77	275.6	16872	61.2
	N6	-12	_	192	77	281.0	14176	50.4
	N8	-15	4.9	192	77	279.1	14139	50.7
2002	N1	32	-0.3	142	104	214.5	28241 a SS [§]	131.6 a SS [§]
	N2	42	0.2	142	104	203.9	25387 ab	124.5 ac
	N3	34	-0.1	142	104	212.4	25405 ab	119.6 ab
	N4	34	1.0	142	104	210.8	24109 ab	114.4 ab
	N6	39	2.4	142	104	205.1	21157 b	103.2 b
	N8	42	12.0	142	104	192.1	20000 b	104.1 b

[§] Values in a column with the same letter are statistically homogeneous by Duncan's test.

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In both the seasons, there was a tendency that tuber yield decreased as irrigation frequency declined. Interestingly, the yields of N2, N3, and N4 were very close, while there was a sharp yield reduction for N6 and N8.

Water use efficiencies for different treatments are listed in Table 5. WUE followed the same changing pattern as tuber yield.

4. Summary and conclusions

Drip irrigation frequency affected the temporal and spatial distribution of soil water when total irrigation water was the same. Its influencing range varied with potato growing stage, soil depth and the horizontal distance from the emitter. The wetting pattern developed under treatment N1 had a larger range than was initially supposed: soil water at depths of 70 and 90 cm immediately under emitter showed larger changes than those of N4 and N8. The larger dry zone before irrigation and the longer duration of a larger wetted zone associated with a lower irrigation frequency might be able to explain the tuber yield reduction.

Drip irrigation frequency affected root growth to some extent: the higher the frequency, the higher was RLD in 0–60 cm soil layer and the lower was RWD in 0–10 cm soil layer. On the other hand, for the different treatments, there was not much difference in RLD distributed in a horizontal direction, except to the width of 40 cm where N8 had the biggest RLD among the three treatments. Furthermore, potato root growth seemed to not be limited in range, even when the crop was irrigated at the highest frequency.

High frequency irrigation enhanced potato tuber growth and WUE. Reducing irrigation frequency from N1 to N8 resulted in significant yield reductions by 33.4 and 29.1% in 2001 and 2002, respectively. For total ET_{c} , little difference was found among the different irrigation treatments.

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