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Scientia Horticulturae 106 (2005) 275–292
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Effect of soil water potential on radish (*Raphanus sativus* L.) growth and water use under drip irrigation

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Received 21 September 2004; received in revised form 15 March 2005; accepted 23 March 2005

Abstract

Radish (*Raphanus sativus* L.) is a moisture loving vegetable and is widely planted in China. Soil water is one of most important factors affecting the yield and quality of radishes. Field experiments for the effect of soil water potential on radish growth and water use were carried out in 2001 and 2002. The experiment included five treatments, which controlled soil water potential (SWP) at 20 cm depth immediately under emitter higher than −15, −25, −35, −45 and −55 kPa. The results show that different SWP treatments affected temporal and spatial distribution of soil water. As the target SWP value decreased, the average SWPs between 0 and 90 cm depth decreased, and the dry domain in the root zone became larger. The variability of SWPs values at 0–90 cm depths before and after irrigation increased as the target values decreased. Irrigations scheduled between −15 and −55 kPa had no significant effects on radish growth and yield, but affected radish root distribution and market quality. The lower the target SWP value was, the more radish roots developed. The lowest radish cracking rate and the most radishes of Grade 1 occurred at a SWP of −35 kPa in 2002. Different SWP treatments affected radish evapotranspiration (ET) and WUE. The total radish ET decreased as SWPs decreased in both years. The highest radish WUE values were achieved with SWPs of −55 and −35 kPa in 2001 and 2002, respectively, and the lowest WUE values were recorded at a SWP of −15 kPa in both years. The SWP of −35 kPa at

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0304-4238/$ – see front matter
doi:10.1016/j.scienta.2005.03.012

20 cm depth immediately under drip emitter can be used as an indicator for radish drip irrigation scheduling in the North China Plain.

Keywords: Radish; Drip irrigation; Soil water potential

1. Introduction

Soil water potential (SWP), a measure of the holding strength of the soil matrix for water, is a critical variable in crop yield, runoff, erosion, evapotranspiration and irrigation scheduling (Phene et al., 1989). In general, optimum SWP can meet the physiological needs of plant growth and be favorable for water and nutrition uptake. Low SWP will result in adverse impacts on crop growth, for example, increased soil strength impedes root penetration; stoma resistance increases, decreasing photosynthesis. Too high SWP causes drainage and loss of nutrients, and also has negative effects on crop growth. At high SWP root growth and functions will be affected by inadequate oxygen diffusion into the soil (Hodnett et al., 1990).

Rhoads and Stanley (1973, 1974) reported that the highest yields of corn (*Zea mays* L.) could be obtained when SWP in the upper 30 cm maintained above −10 kPa (for sands) to −40 kPa (for clays). Long-day onion (*Allium cepa* L.) was subjected to five SWP treatments (−10, −20, −30, −50, and −70 kPa) to evaluate the effects of several SWP on onion yield and quality by Shock et al. (2000) and the results showed that depending on the year, the optimum SWP for maximum profits of drip-irrigated onion was in the range of −10 to −17 kPa, and a SWP closer to −17 kPa was the best. Hegde and Srinivas (1989) investigated different SWP (−25, −45, −65 and −85 kPa at 15 cm depth) on growth, yield and water use of banana (*Musa sapientum* L.). A SWP from −25 to −45 kPa resulted in better growth, dry matter and yield, and the SWP from −65 to −85 kPa adversely affected growth and productivity of banana. Hegde (1987) indicated the treatment with the soil matric potential at 18 cm depth about −20 kPa obtained the maximum radish (cv. Japanese White) root yield, highest ET and moderately high WUE, but the different in root yield between irrigations scheduled at −20 and −40 kPa was not significant.

In northern China, radish is widely cultivated and generally planted in raised beds in spring and autumn. Radish yields and quality dramatically fluctuate due to frequent droughts and poor irrigation management.

Drip irrigation lends itself readily to establish a nearly constant water regime in the root zone and the fluctuation of the SWP can be held to a minimum without difficulties (Horton et al., 1982), which ensure plants growing under proper soil water for the optimum yield and size.

The objectives of this study are: (1) to measure the effects of different SWPs on radish growth, yield, water use and water use efficiency; and (2) to define the basis for irrigation scheduling of drip-irrigated radish and water resource planning in the North China Plain.

2. Materials and methods

2.1. Experimental site

Field experiments were conducted at Luancheng Agro-ecosystem Station (LAES), Chinese Academy of Sciences during 2001 and 2002. LAES is located in Luancheng County, Hebei Province (latitude: 37°53′N, longitude: 114°41′E, 50 m above sea level). The annual rainfall is about 480 mm, concentrated from July to September. The spring and early summer are normally quite dry. The dominant soil is silt loam with an average bulk density of 1.53 g/cm^3. The soluble mineral content of the area's groundwater is less than 0.5 g/l. The water table is about 28 m and groundwater contribution to the root zone is therefore negligible.

2.2. Experimental design

Five treatments for SWP were designed for this study, with SWP at 20 cm immediately under emitter higher than −15 kPa (N1), −25 kPa (N2), −35 kPa (N3), −45 kPa (N4) and −55 kPa (N5), respectively. All treatments were repeated three times with the experimental plots following a complete randomized block design.

Each plot had a valve, a flow meter and a pressure gauge to control the operating pressure and measure the irrigation water volume. Thin-wall drip tapes with 0.3 m emitter spacing and a flow rate of 3.72 l/m h at the operating pressure of 0.042 MPa were placed on the center of raised beds.

2.3. Agronomic practices

Seeds of radish cv. 'Dahongpao' and 'Mantanghong' were planted on 31 July and 17 August during 2001 and 2002, respectively. After emergence, seedlings were thinned to leave only one seedling at each location maintaining a plant density of approximately 100,000 ha^{-1}. Radishes were harvested on 19 October and 9 November in 2001 and 2002, respectively.

Each plot was 5.6 m × 6.0 m, and contained seven raised beds. The spacing and length of raised beds was 0.8 and 6.0 m, respectively. Radishes were double-row planted on each bed with row spacing of 0.3 m and interplant spacing of 0.25 m (Fig. 1).

When the soil was plowed, fertilizer was applied and the applications of N, P and K (179, 70 and 52 kg/ha, respectively) were the same for all plots.

2.4. Observation and equipments

2.4.1. SWP

One set of mercurial tensiometers with 30 sensors was installed for each treatment to observe SWP. Sensors placement for all treatments were alike (Fig. 1). Observations were made daily at 8:00 a.m. for each of the mercurial tensiometers. Once the plant density was established, the tensiometers at 0.2 m immediately under drip emitter were observed every 2 h during the daytime to check SWP in order to determine the irrigation time.

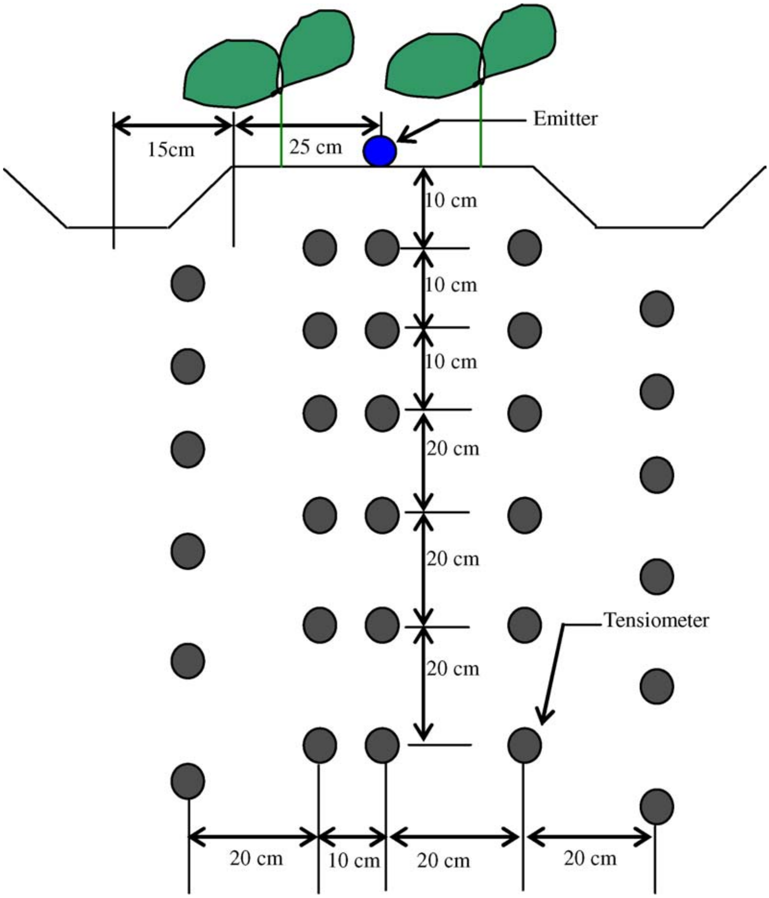

Fig. 1. Placement of tensiometers for each experimental treatment.

2.4.2. Radish water use

In 2002, one weighing lysimeter was installed in the center of one of the radish plots to measure water use. Each lysimeter consisted of an inner tank for crop cultivation and an outer tank for protection. The volume of the inner tank was $0.36\ m^3$ ($0.8\ m \times 0.5\ m \times 0.9\ m$), with a drainage pipe at the bottom of the inner tank. The soil depth and sandy filtering layer was 0.7 and 0.15 m, respectively. Soils at the different depths were collected separately, and then returned to the same depth during installation of the outer and inner tanks. The topsoil in the lysimeters was shaped to the same form as the field beds. Four radishes plants were in each tank. The drip tapes for the beds were installed across the lysimeters for irrigation. There was a moveable electric weighing system to weigh the lysimeters one at a time. The lysimeter in N2 was weighed every day, and others were weighed once every 2 days.

Because observation of the lysimeters started on 16 September (30 days after seeding) in 2002, the total water use for the entire period for each treatment in 2001 and 2002 was estimated using the water balance method as:

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

where I is the irrigation amount, P is the precipitation, ΔS is the change of soil water storage, R is the surface runoff and D is the 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. Because rainfall during the growing season was small, surface runoff was ignored. Deep percolation was estimated according to Darcy's equation:

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

where D is the deep percolation (mm/day), ψ_{m2} and ψ_{m1} are the matric potentials at 90 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). $K(\psi)$ is unsaturated hydraulic conductivity (mm/day), estimated by:

$$K(\psi) = K_s\left(\frac{\psi}{\psi_b}\right)^{-2-3\lambda} \tag{3}$$

where K_s is the saturated hydraulic conductivity, ψ_b is the air-entry value, which was 3 mm/day and 1.28 at 60–85 cm depth for this soil, respectively. λ is an empirical coefficient, which was 1.40 at 60–85 cm depth.

2.4.3. Twenty centimeter diameter pan evaporation over canopy (EW_{20}) and weather data

A 20 cm diameter evaporation pan was installed over the canopy of radish in plot N2. The height of the evaporation pan was adjusted according to the growth of radish. Pan evaporation was observed at 8:00 a.m. daily. The meteorological data were obtained from the LAES weather station.

2.4.4. Radish root growth and yields

Three plants were randomly selected and fixed in one plot of each treatment for leaf area measurement at 10-day intervals during the radish-growing season in 2001 and 2002. Three other plants were randomly selected and sampled in another plot of each treatment for dry mass (leaf and succulent root) investigation at 10-day intervals in 2001 and 2002.

In 2001, root weight density of each treatment was obtained from soil cores extracted between rows with an auger (55 mm in diameter, 10 cm high with a volume of 237.46 cm^3) at 22 September. In each plot, the distances to the center of raised beds for sampling were 0, 7.5, 15.0, and 22.5 cm, and sample depths were 0–10, 10–20, 20–30, 30–40 cm depth.

In 2002, radishes in the middle three rows of one plot of each treatment were harvested for analysis. Fresh fruit weight (g/fruit) for size categories were as follows: >500 g (Grade 2), 250–500 g (Grade 1) and <250 g (Grade 3).

Table 1
Weather data during radish different development periods of 2001 and 2002

Week	Temperature (°C)						Relative humidity (%)		Pan evaporation (mm/day)	
	Maximum		Mean		Minimum		2001	2002	2001	2002
	2001	2002	2001	2002	2001	2002				
1	31.7	30.1	26.5	24.7	22.1	19.4	85	82	4.7	3.8
2	31.3	31.9	24.5	26.0	17.8	21.1	78	82	5.6	4.7
3	29.7	27.8	24.2	21.3	19.7	16.2	87	76	3.5	4.1
4	30.2	26.9	24.6	19.5	19.4	14.2	80	77	5.0	3.6
5	29.5	25.2	22.5	17.4	15.4	10.7	79	80	4.6	4.0
6	28.0	27.3	20.8	18.8	14.6	9.7	80	67	4.0	4.5
7	28.2	26.7	21.6	16.9	15.7	7.9	74	56	3.4	6.5
8	24.1	22.7	17.8	14.2	12.9	7.3	80	61	3.6	4.6
9	25.1	20.7	17.3	13.6	10.3	8.1	71	72	4.3	2.9
10	20.6	13.6	14.1	8.0	7.8	3.6	75	65	3.5	2.8
11	21.1	11.1	15.6	5.6	10.4	1.0	74	59	2.7	2.6
12	20.0	13.1	13.6	5.8	7.3	−0.4	72	56	3.3	2.5

2.4.5. *Statistical analysis*

The treatments were run as a single-factor analysis of variance (ANOVA). The ANOVA was performed at $\alpha = 0.05$ level of significance to determine if significant differences existed among treatment means. The multiple comparisons were done for significant effects with the LSD test at $\alpha = 0.05$.

3. Results and discussion

3.1. *Irrigation management and weather*

The average weekly temperatures and relative humidity of 2001 were higher than those on corresponding period of 2002, and the average weekly evaporation was similar during the 2 years (Table 1). Total rainfall was 75.0 and 68.9 mm in 2001 and 2002, respectively. The 68% and 69% rainfall was in the first 4 weeks (radish seedling stage), 22% and 7% was in the middle 4 weeks (radish leaf development stage), and 10% and 24% was in the last 4 weeks (radish succulent root formation stage) in 2001 and 2002, respectively (Fig. 2).

Irrigation treatments were initiated on 24 August (24 days after seeding) and on 18 September (32 days after seeding) in 2001 and 2002, respectively. Prior to that date, all the treatments were given uniform irrigations to ensure germination. Irrigation was applied only when the SWP at 20 cm depth immediately under drip emitter reached the target values for N1, N2, N3, N4 and N5. The irrigation amount each time was nearly equivalent for different treatments. The total irrigation quantities for N1, N2, N3, N4 and N5 were 103.1, 86.8, 68.1, 55.3, and 44.9 mm in 2001 and 78.9, 56.5, 41.6, 32.1 and 21.3 mm in 2002, respectively (Fig. 3).

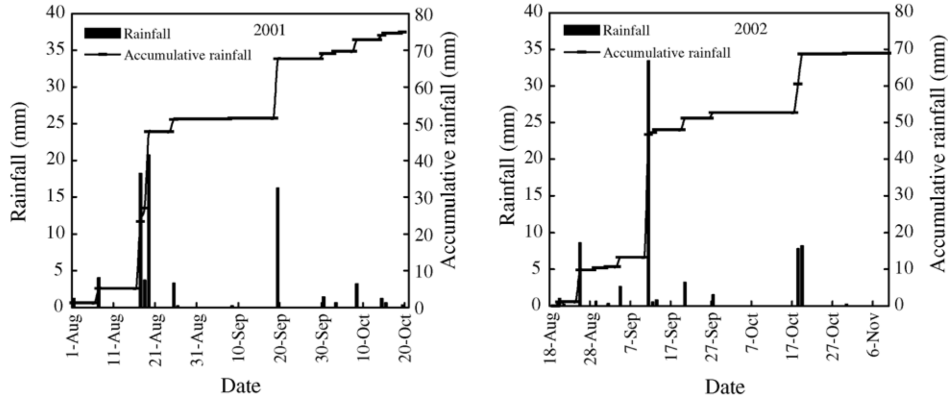

Fig. 2. Rainfall and accumulative rainfall during radishes growing periods in 2001 and 2002.

3.2. SWP distribution under different treatments

Fig. 4 illustrates the SWP at 20 cm depth immediately under drip emitter for five treatments in 2001 and 2002. In the 2 years, because enough water application during germination period and much rainfall at the seedling stage, SWPs for all of the five treatments were very close and higher than −25 kPa. During the root enlargement period, SWPs were well controlled at the target values, except for short periods when rainfall exceeded 5 mm.

Figs. 5 and 6 show the spatial distributions of SWPs in the vertical transect perpendicular to the drip tape for each treatment before and after irrigation at leaf development and succulent root formation stages in 2001 and 2002, respectively. It is clear that the soil moisture of all treatments in 2001 was less than that in 2002.

During the leaf development stage, the SWPs of each treatment below the depth of 70 cm in 2001 and 50 cm in 2002 were similar, whereas the SWPs above 30 cm in 2001 and 50 cm in 2002 were different, which decreased gradually from N1 to N5 treatments. No

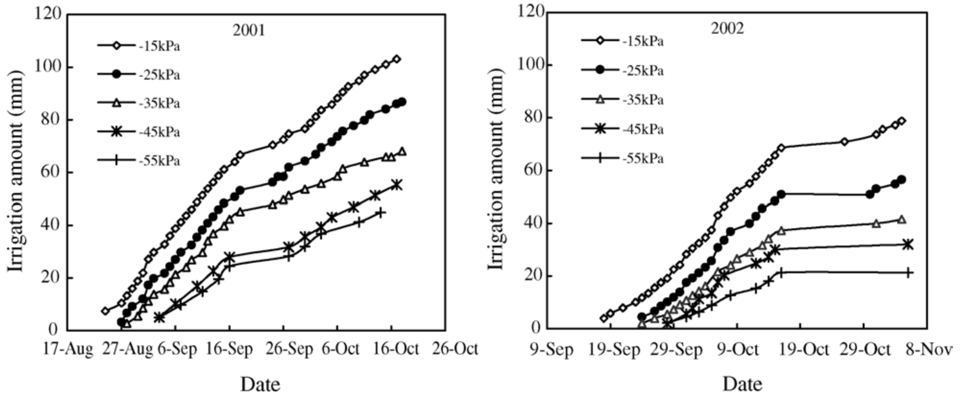

Fig. 3. Water applied for radishes under different treatments during the treatment periods in 2001 and 2002.

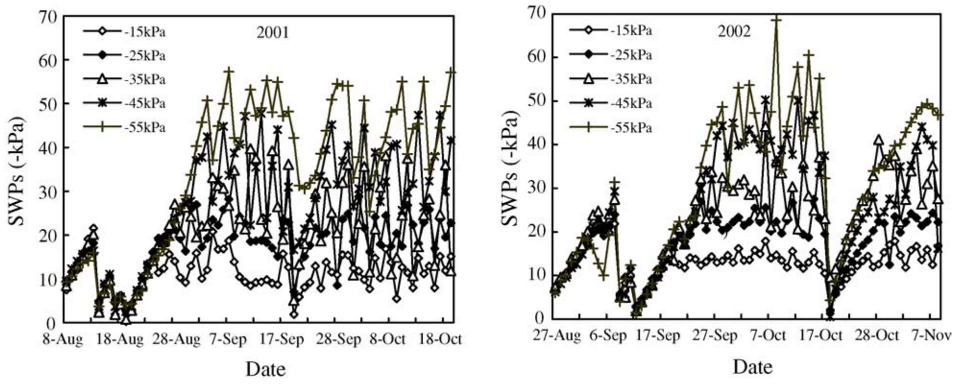

Fig. 4. The changes of soil water potential in 20 cm depth immediately under emitters for different treatments in 2001 and 2002.

matter before or after irrigation, there were no obvious changes in the spatial distributions of SWPs in all treatments in both years. During the succulent root formulation stage, the soils for all treatments were drier than those of early period. As the target values decreased, the average SWPs values through the whole root zone decreased, and the dry domain expanded. Unlike the profiles of SWPs before and after irrigation in the early stage, the SWPs of N1, N2 and N3 fluctuated a little after irrigation, but those of N4 and N5 changed dramatically. The results are accordant to the findings of Hodnett et al. (1990). He indicated that the SWPs values at low SWP treatment oscillated evidently comparing to those at high SWP after irrigation and rainfall.

3.3. Radish growth

3.3.1. Leaf area development

Fig. 7 illustrates the changes of leaf area index (LAI) for the five treatments from seedling stage to harvest in 2001 and 2002. The figures show sigmoid shapes for the LAI versus time relationship in both years. During seedling period, the LAI values for all treatments were small, and began to increase at leaf development stage. When near the succulent root formation stage, the LAI values of different treatments reached their maximum successively, and then decreased a little at the end of experiments.

3.3.2. Succulent root development

Fig. 8 shows the changes of succulent root circumference for the five treatments in 2001 and 2002. The five circumferences accretion versus time relationships in 2001 and 2002 were sigmoid shapes. During the early growing period, radish succulent roots were small and began to expand rapidly about 25 days after planting. About 65 days after planting, radish growth rates began to slow.

3.3.3. Dry mass production

Fig. 9 shows the changes of dry masses of radish roots for the five treatments in 2001 and 2002. The curves for the five treatments in the 2 years appear to be double-sigmoid. Before

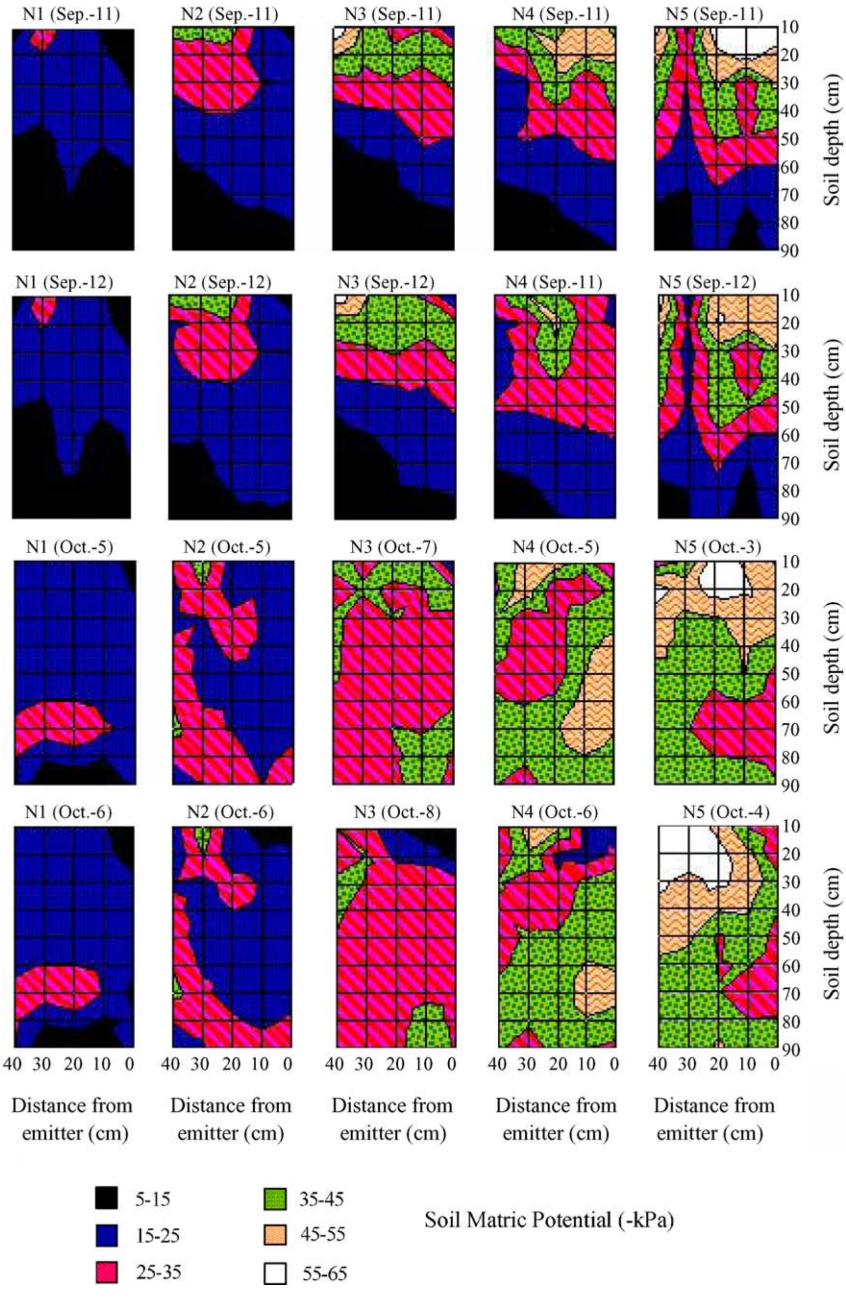

Fig. 5. Transect of spatial distribution of SWPs perpendicular to drip tape for different treatments before and after irrigation at leaf development and succulent root formation stages in 2001.

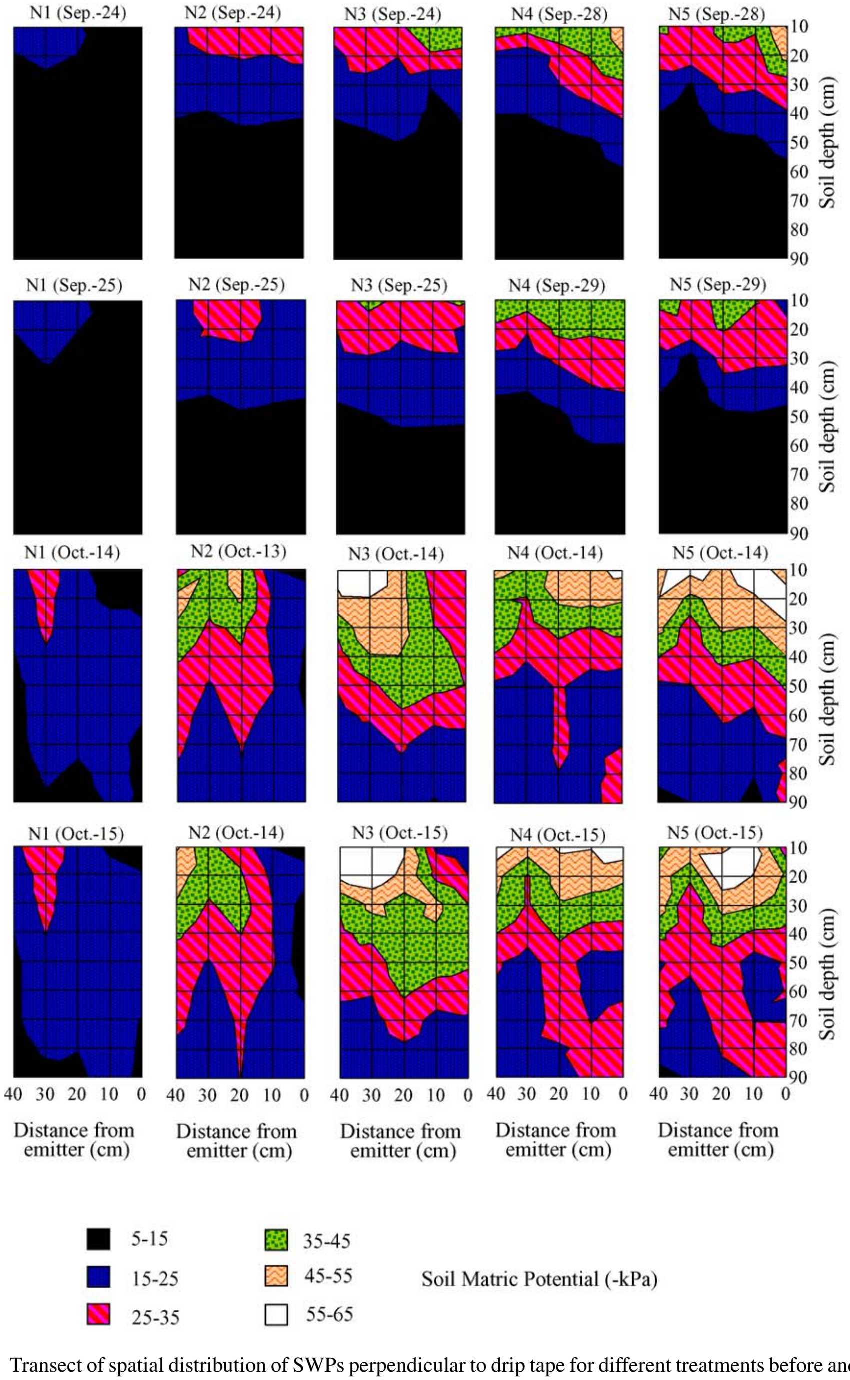

Fig. 6. Transect of spatial distribution of SWPs perpendicular to drip tape for different treatments before and after irrigation at leaf development and succulent root formation stages in 2002.

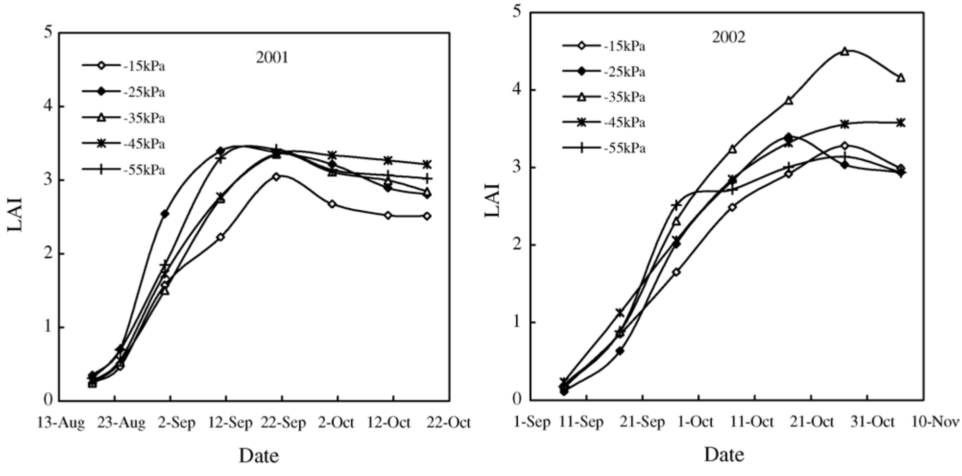

Fig. 7. The changes of LAI during radish growing periods for different treatments in 2001 and 2002.

radish LAI values were close to the maximum values, which appeared on 12 September in 2001 and 2 October in 2002, the dry masses of radish roots for all treatments accumulated slowly, and then began to increase rapidly. About half a month later, the dry masses accumulated slowly again. The slowly growing stage lasted about 10 days, and then the dry masses increased dramatically again before harvest.

3.3.4. Root distribution

Fig. 10 illustrations the roots weight density for the five treatments on 22 September 2001.The most radish roots of each treatment developed in the soil 15 cm horizontally to the center of raised beds at the depth of 10–20 cm. It is clear that high SWP treatments (N1 and N2) resulted in lower roots weight density (about 150×10^{-6} g/cm^{-3}); whereas the

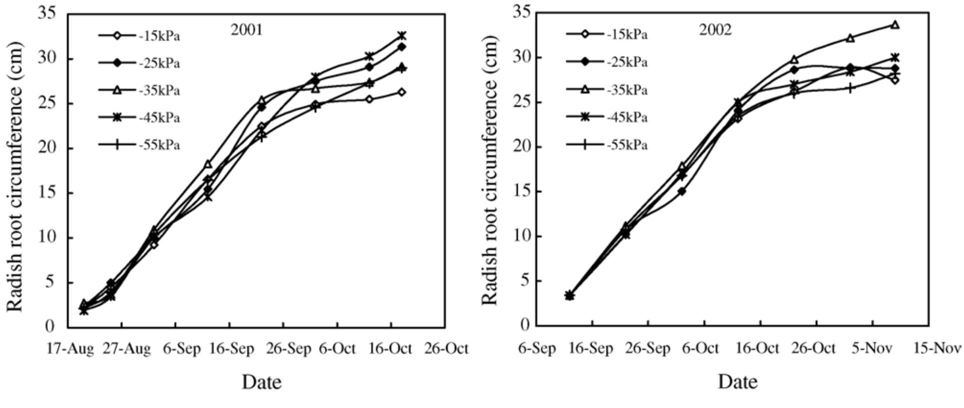

Fig. 8. The succulent root body expanding during radish growing periods for different treatments in 2001 and 2002.

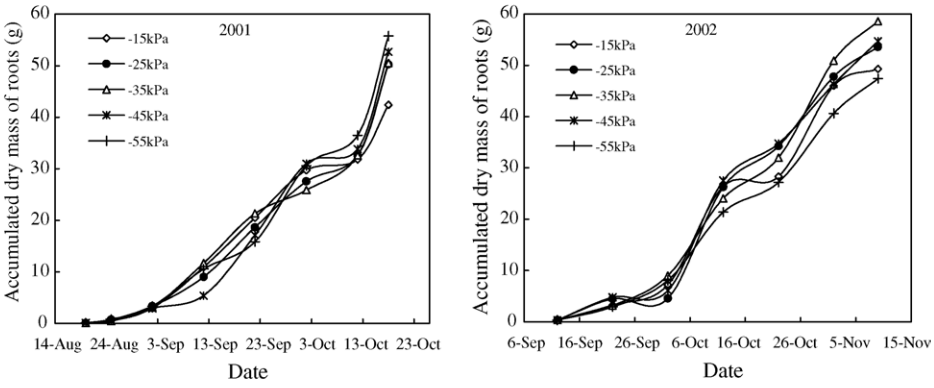

Fig. 9. Development of succulent root dry masses during radish growing periods for different treatments in 2001 and 2002.

low SWPs treatments (N4 and N5) led to higher roots weight density (about 1100×10^{-6} g/cm^{-3}).

3.4. The fresh root yields and market quality

The highest yield was recorded at −55 kPa in 2001 and −35 kPa in 2002, and followed a N5 > N4 > N3 > N2 > N1 order in 2001 and N3 > N4 > N5 > N2 > N1 order in 2002 (Table 2). But, significant differences among yields were not found according to statistic analysis in both 2001 and 2002. However, there were significant differences in radish market quality. Among all the five treatments in 2002, N3 had the lowest cracking rate (1.4%) and the most radishes (59.7%) of Grade 1 ($250 < W < 500$ g), N1 had the highest cracking rate (18.9%), and N5 had the less radishes (41.7%) of Grade 1. These results indicate that SWP −35 kPa was favorable for radish growth while too high or too low SWP were less beneficial.

3.5. Radish water use under different SWPs

Fig. 11 illustrates 2-day ET for all of the five treatments from 13 September to 5 November 2002. The results indicate that the process of radish water use can be divided into two stages. The first stage was from the 1st 2 days to the 18th 2 days (13 September–17 October 17) and the second stage was from the 19th 2 days to the end. In the first stage, radish ET values were relatively more for all of the treatments. EW_{20} was also much during this period. The maximum 2-day ET values for N1, N2, N3, N4 and N5 were 12.7, 12.5, 16.0, 12.8 and 11.5 mm, respectively. The 2-day ET value was no more than 16 mm for the most treatment, while the 2-day EW_{20} was no more than 15 mm. In the second stage (from 17 October to the end), radish ET values were relatively smaller for all of the five treatments. The maximum 2-day ET values for N1, N2, N3, N4 and N5 were 5.1, 5.5, 6.1, 5.7 and 4.8 mm, respectively. The 2-day ET values did not exceed 7 mm for all the treatments, and 2-day EW_{20} value was no more than 8 mm. The general tendency for all the

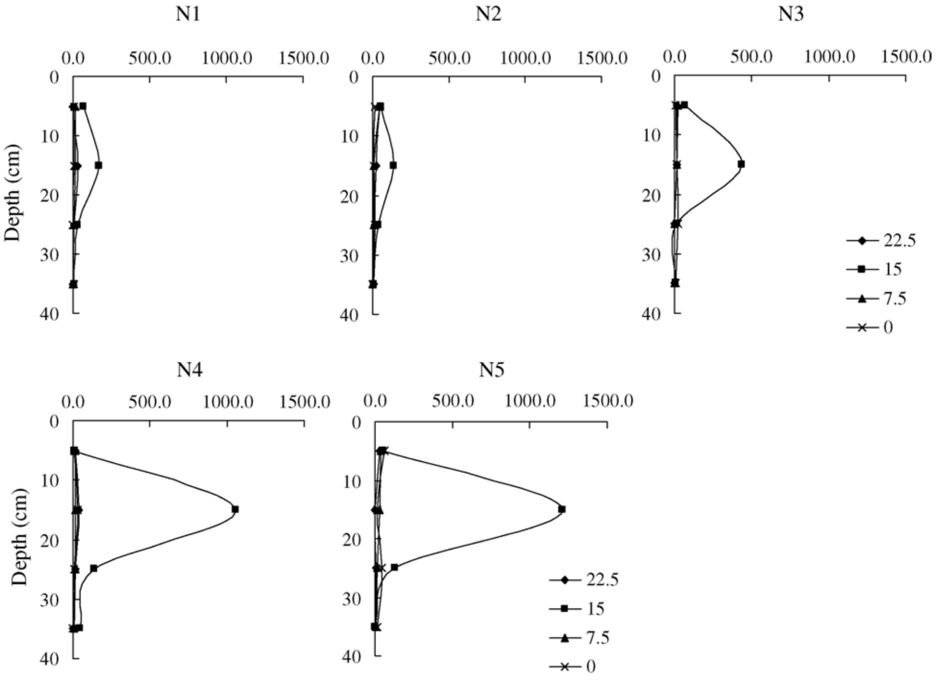

Fig. 10. The root weight density for different treatments on 22 September 2001.

Table 2
Yield and market quality of radish as affected by SWPs in 2001 and 2002

	Average root weight (g)	Yield (Mg/ha)	Number measured	Rate of cracking (%)	Root weight distribution		
					$W > 500$ g (Grade 2)	250 g $< W < 500$ g (Grade 1)	$W < 250$ g (Grade 3)
2001							
N1	473.9 a	47.4 a					
N2	485.3 a	48.5 a					
N3	491.6 a	49.2 a					
N4	497.9 a	49.8 a					
N5	505.9 a	50.6 a					
2002							
N1	451.2 a	45.1 a	74	18.9 a	48.7 a	43.2 bc	8.1 a
N2	454.5 a	45.4 a	73	5.5 bc	28.8 b	58.9 ab	12.3 a
N3	478.6 a	47.9 a	72	1.4 c	34.7 ab	59.7 a	5.6 a
N4	466.8 a	46.7 a	70	10 b	40.0 ab	50.0 abc	10.0 a
N5	462.6 a	46.3 a	72	11.1 b	50 a	41.7 c	8.3 a

The same letters are not significantly different at 0.05 level, and different letters mean significant difference at 0.05 level.

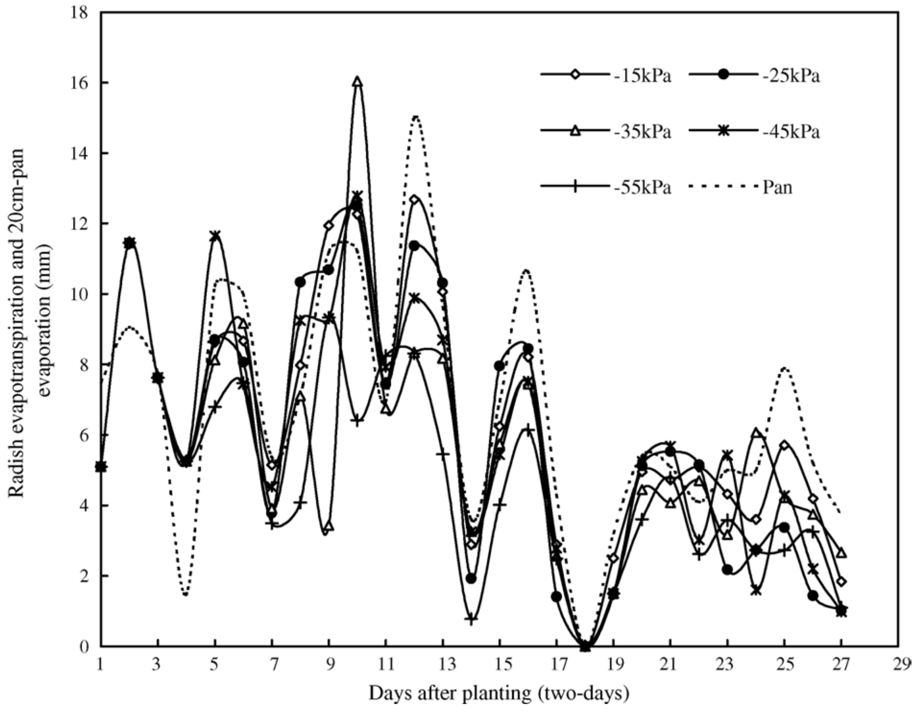

Fig. 11. Two days ET curves for different treatments during radish growth period from 13 September to 5 November 2002.

treatments was similar to that for EW_{20}. This is in agreement with results obtained by Yuan et al. (2001). He used 20 cm pan measurements to determine the water requirement of tomato planted in unheated greenhouse, and found that accumulative value of ET usually approximated the accumulative value of water surface evaporation of a 20 cm pan installed at the top of tomato canopy.

Fig. 12 illustrates the cumulative ET values for the five treatments from 13 September to 5 November 2002. The general tendency for all of the five treatments was similar to that for EW_{20}. The cumulative ET and cumulative EW_{20} followed an EW_{20} (182 mm) > N1 (171 mm) > N2 (160 mm) ≈ N4 (160 mm) > N3 (154 mm) > N5 (128 mm) order.

Table 3 presents the changes of soil water storage (ΔS), drainage below crop root zone (D), and the total ET for different treatments in 2001 and 2002. Total ET values in 2001 followed a N1 (265 mm) > N2 (218 mm) > N3 (190 mm) ≈ N4 (189 mm) > N5 (179 mm) order. The highest ET value was 86 mm (48%) more than the lowest value. Total ET values in 2002 were ordered from N1 (244 mm) > N2 (232 mm) > N3 (206 mm) ≈ N4 (208 mm) ≈ N5 (207 mm). The highest ET value was 38 mm more than the lowest value, a decrease of 19%. The total ET order among the five treatments was a little different with the ET determined using the weighing lysimeter. These differences may be the result of sampling error in the observation of soil moisture content and/or calculation of drainage losses when using the water balance method.

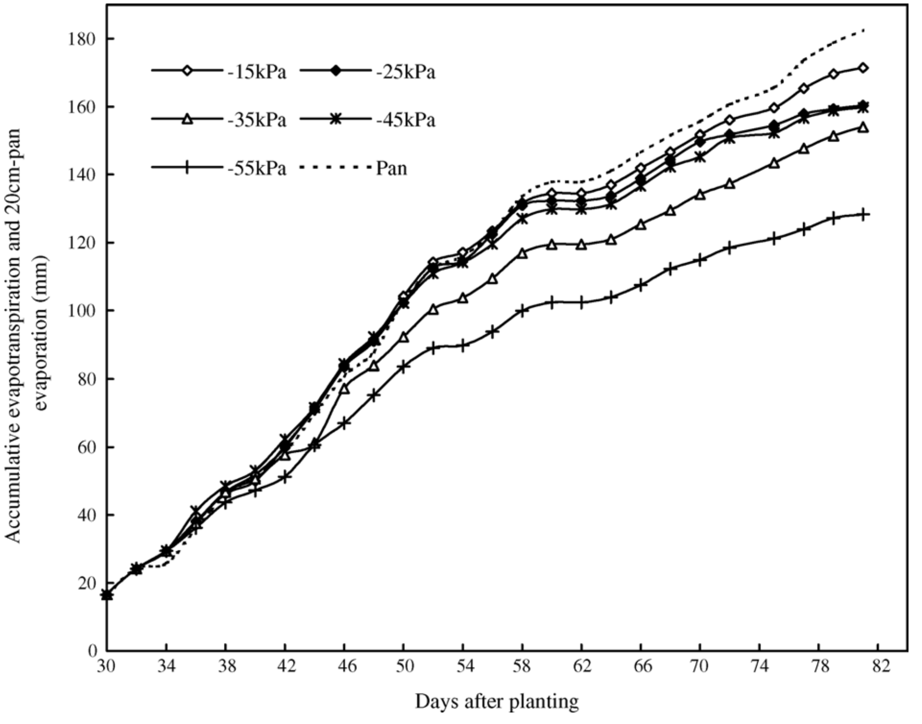

Fig. 12. Accumulative evaporation of 20 cm pan and ET of radish for different treatments during radish growing period from 13 September to 5 November 2002.

Table 3
Radish evapotranspiration calculated using water balance equation and lysimeter, and WUE for different treatments in 2001 and 2002

	I (mm)	*P* (mm)	*D* (mm)	Δ*S* (mm)	WB total water use (mm)	Lysimeter water use (mm)	WUE (kg/ha mm)
2001							
N1	175	75	4	−18	265		179
N2	145	75	5	−3	218		223
N3	120	75	4	1	190		259
N4	115	75	5	−4	189		263
N5	102	75	0	−2	179		283
2002							
N1	146	69	11	−40	244	171	185
N2	136	69	0	−27	232	160	196
N3	115	69	0	−22	206	154	232
N4	111	69	3	−32	208	160	224
N5	105	69	2	−36	207	128	223

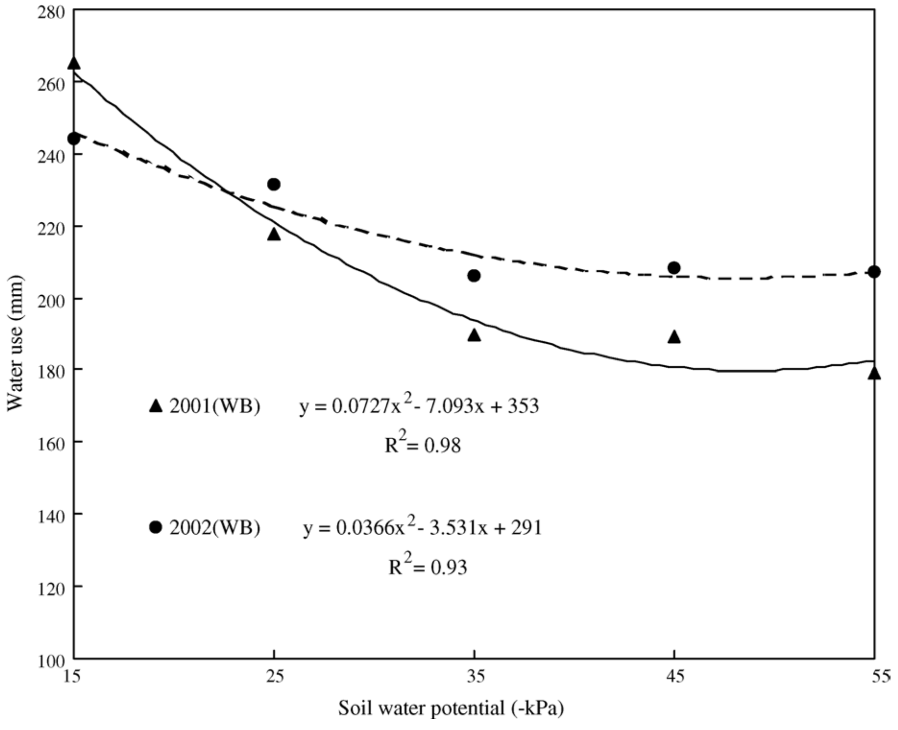

Fig. 13. Relationship between ET (calculated by water balance method and lysimeter) and soil water potential in 2001 and 2002.

The general tendency of the total ET versus the SWPs during the 2 years was similar: the ET decreased as SWPs decreased (Fig. 13). The relationships between the total ET and SWPs (ψ: −kPa) in 2001 and 2002, respectively, can be expressed as follows:

$$\mathrm{ET} = 0.0366\psi^2 - 3.531\psi + 291 \quad (R^2 = 0.93) \tag{4}$$

$$\mathrm{ET} = 0.0727\psi^2 - 7.09\psi + 353 \quad (R^2 = 0.98) \tag{5}$$

3.6. Water use efficiency (WUE) under different SWPs

Water use efficiency (WUE) is the relation between yield and the ET, and computed based on radish yield dividing by the water used (calculated based on the water balance equation). The results presented in Table 3 indicate that radish WUE for the five treatments were ordered from N5 > N4 > N3 > N2 > N1 in 2001 and N3 > N4 ≈ N5 > N2 > N1 in 2002. The radish WUE values for N5 and N3 treatments were the highest in 2001 and 2002, respectively, and those for N1 were the lowest in both years. These results suggest that the application of too much water reduced radish WUE.

N3 treatment had the lowest cracking rate, the most radishes of Grade 1, and the highest WUE in 2002, so the SWP threshold of −35 kPa at 0.2 m depth immediately under the drip emitter can be suggested for radish (cv. Mantanghong) drip-irrigated scheduling, and it is also reasonable to recommend SWP threshold of −35 kPa as an indicator for other radish variety, such as ‘‘Dahongpao’’.

4. Summary and conclusions

Different SWP treatments did affect temporal and spatial distribution of soil water. As the target values of the SWP decreased, the average SWPs at 0–90 cm depth decreased, ant the dry domain in the root zone became larger. Moreover, the variability of SWPs values at 0–90 cm depths before and after irrigation increased as the target values decreased.

Different SWP treatment had no significant impacts on radish growth and development, but they did affect radish roots distribution and market quality very much. The high SWPs treatments (N1 and N2) resulted in lower roots weight density; whereas the low SWPs treatments (N4 and N5) led to higher roots weight density. The lowest cracking rate and the most radishes of Grade 1 occurred at a SWP of −35 kPa.

Radish ET decreased as SWPs decreased. The highest ET values were 86 mm (48%) and 38 mm (19%) more than the lowest values in 2001 and 2002, respectively. The radish WUE values for N5 and N3 treatments were the highest in 2001 and 2002, respectively, and those for N1 were the lowest in both years.

Considering the radish quality and WUE, the SWP of −35 kPa at 20 cm depth immediately under drip emitter can be used as an indicator for radish drip irrigation scheduling in the North China Plain.

Acknowledgements

This study forms part of the works of Project 40125002 supported by the National Science Fund for Distinguished Young Scholars and Project 40071020 supported by the National Science Foundation of China.

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