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Full Length Research Paper

Water and nitrogen distribution in uncropped ridge-tilled soil under different ridge width

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Nitrate leaching to ground and surface water is an increasing concern in agriculture. A ridge-tillage configuration, with placement of nitrate nitrogen (NO_3^--N) or its source in the elevated portion of the ridge, can potentially isolate fertilizer from downward water flow and minimize nitrate leaching. In the experiment, the simultaneous distribution of water, nitrate, and ammonium under three ridge widths was measured using the gravimetric method. Monitoring of the water movement revealed that vertical water movement was much greater than horizontal movement. Compared with 30 and 90 cm ridge width, soil water content at 60 cm ridge width could better meet crop water requirement and relatively decreased irrigation volume. The distribution of NO_3^--N in the soil was similar to distribution patterns of water, while ammonium distribution measurements indicated that there existed an extremely high ammonium concentration in the furrow for ridge-furrow system. These results support the conclusion that water infiltrated in furrows and primarily moved laterally to ridge positions, minimizing downward water movement under the ridge. In this experiment, we recommend that the suitable ridge width for ridge tillage management should be within the range of 60 to 75 cm.

Key words: Ridge tillage, ridge width, wetted front, soil water content, nitrate-nitrogen distribution, ammonium distribution.

INTRODUCTION

In China's arid and semiarid region, nitrate leaching is an increasing concern for ground and surface water quality. Nitrogen fertilizers applied to cropland are of considerable importance because of their yield-increasing benefits. However, nitrogen fertilizers applied in excess of crop uptake may be susceptible to leaching below the root zone (Malhi et al., 2004). Losses of nitrate-nitrogen (NO_3^--N) by leaching represent a cost to farmers and can cause environmental damage, especially in northwest of China (Ma et al., 2005).

To help minimize NO_3^--N loss from agricultural lands and protect environment, improved soil management practices need to be adopted. Ridge tillage (RT) is a cultural practice widely used throughout the world with many different modifications in which plants are grown on soil formed into raised beds or ridges (Hatfield et al., 1998). Ridge tillage has proven to be an effective management system offering potential for modifying the pattern of soil water and solute movement (Laflen et al., 1978). Lal (1990) provided an overview on the use of RT in different agricultural system with a wide variety of climate, crops and labour intensity. Several strategies have been investigated that ridges could affect soil temperature and water content, as well as soil water and solute movement compared with traditional flat farming (Waddell and Weil, 2006). Willis et al. (1963) reported

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that the planting model with 0.076 m high ridges could improve the water conservation of sandy loam soil during crop growth. Bargar et al. (1999) found that water infiltrated in furrows and primarily moved laterally to row positions, minimizing downward water movement under the row. Their results explain greater solute movement under furrows than under rows, as found in several short-term studies (Wang et al., 2011). As far as is known, much of current knowledge of the RT is predominantly derived from studies conducted in water movement and little work exist concerning water and nitrogen distribution associated with ridge width. Wang et al. (2001) suggested that surface cover, ridge (oriented) roughness, ridge width and random roughness factors in a wind erosion equation predict excellent erosion control for this tillage system. A study for rice and wheat revealed that the yield-increasing effect for 60 cm ridge width with two rows crops under ridge tillage was higher than those of 80 cm ridge width with three rows (Sayre, 1997). Therefore, it needs to establish an evaluation of water and ammonium as well as nitrate movement in ridge-tilled soil under different ridge: furrow ratios.

Our objective was to obtain water and nitrogen (both ammonium and nitrate) distribution measurements in uncropped ridge-tilled soil under furrow irrigation using the gravimetric method. A secondary purpose was to improve understanding of the establishment of the optimum ridge width range for ridge-tilled system and to provide recommendations for the system design and operation, especially in Northwest China. We proposed the testable null hypothesis that changing ridge width does not affect soil water content and movement. In the experiment, we conducted the study without growing plants to avoid the added complication on soil water movement and storage caused by vegetation. Under field conditions, soil water recharge for RT is complicated by the variability in amount, intensity, duration, and frequency of natural rainfall events, and by the effect of surface configuration and residue on infiltration and evaporation. The presence of vegetation causes additional complexity by affecting infiltration and evaporation and soil water extraction by roots directly affects soil water content (Kemper et al., 1975).

MATERIALS AND METHODS

Soil properties and experimental equipment description

Three horizons were identified for the clay-loam soil used in this experiment: topsoil (0 to 20 cm), argillic horizon (20 to 60 cm) and parent material horizon (60 to 200 cm). Soils from 0 to 80 cm depth were sampled at an increment of 20 cm in late June following the harvest of winter wheat, representing the soil of each horizon. A large volume of soil was obtained and mixed for every 20 cm soil layer and then used to fill the experimental devices. The field capacity and saturated soil water content for the soil were 0.25 and 0.41 $cm^3 \cdot cm^{-3}$, respectively. Particle size analysis yielded an average value of 8% sand (0.05 to 2 mm), 70% silt (0.002 to 0.05 mm) and 22% clay (< 0.002 mm), which belongs to Eum-Orthic Anthrosol (Cinnamon soil). The saturated hydraulic conductivity determined by the disc infiltration method in the field was 1.65 cm h^{-1}. The physical and chemical properties of the soil are presented in Table 1.

Experimental equipments were self-made plexiglass containers, 200 long, 100 high and 80 cm wide (Figure 1). The supplying water system was Mariotte flask with a flexible hose. It can easily control height above water surface under furrow irrigation. The wetting front was described on the plexiglass surface with a marker pen. Several holes were designed on one side of the container to avoid air resistance during irrigation. Air-dried soil was passed through a 5 mm sieve and packed in the container with 5 cm increments to obtain a constant bulk density of 1.35 $g \cdot cm^{-3}$. The trapezoid ridge and furrow was built using shovel. Ridge direction was north-south. The packed soil was allowed to equilibrate for 24 h to obtain a uniform initial soil water distribution. The trapezoid shape in uniform soil of test device has a negligible impact on flow patterns (Lu, 2000). Fertilizers were mixed into 2 cm below furrow surface in powdered form after ridge was shaped. All containers received 0.2 g N kg^{-1} soil, with the remaining N supplied as urea in the experiments. To reduce evaporation, the soil in the furrow was covered with wheat straw during the whole experiment.

Experimental design

The experiment was laid out in a single factor design with three ridges: furrow ratios, namely 1:2 (30 cm wide ridge and 60 cm wide furrow), 1:1 (60 cm wide ridge and 60 cm wide furrow) and 3:2 (90 cm wide ridge and 60 cm wide furrow). This experimental plan yielded three treatments and each treatment was replicated three times. In the ridge tillage system, ridge height was 15 cm and slope coefficient was 1°. Irrigation amount in the furrow was 80 mm and water surface for each treatment maintained about 10 cm height during irrigation. At the beginning of water infiltration, the positions of the moving wetting front on the soil surface in the vertical plane as well as the horizontal plane were recorded with marker pen on several occasions. At the end of irrigation, soil was sampled with a soil drill (inside diameter 4 cm) immediately in different positions of ridges and furrows. A schematic diagram showing soil sampling positions is presented in Figure 1. The furrow surface was chosen as the reference point for sampling elevation. Depths below the level of the furrow surface are positive, while elevations above the furrow surface in the ridge are negative.

Measurements and data analysis

The radial sampling positions are CF (center of furrow), QF (quarter of furrow), SH (shoulder), QR (quarter of ridge) and CR (center of ridge), respectively. The sampling layout comprised vertical intervals of 10 cm in topsoil (15 cm) and 15 cm below soil (15 cm), respectively, starting 5 cm from the soil surface. For each treatment, soil was sampled at the end of irrigation, 24 and 48 h after water redistribution. Gravimetric soil samples were taken outside the wetted volume to obtain the initial water content and solute concentrations. Soil water content was measured gravimetrically to a depth 60 cm. The initial conditions of soil water and solutions for each of the 9 experiments are shown in Table 2. The soil sampling time for each experiment was about 30 min and the fresh weight of each sample varied from 15 to 110 g, depending on its position. Five grams of each sample was taken for determinations of nitrate (NO_3^--N) and ammonium (NH_4^+-N) and the remaining was used for gravimetric water content determination. The 5 g of the soil sample were extracted with 50 ml of 1 $mol \cdot l^{-1}$ KCl to obtain the NO_3^--N and NH_4^+-N concentrations in the soil. All NO_3^--N and NH_4^+-N concentrations in various solutions were determined using an autoanalyzer (TRAACS-2000, Netherlands).

Table 1. Physical and chemical properties of tested soil.

Depth (cm)	Bulk density ($g \cdot cm^{-3}$)	Organic matter ($g \cdot kg^{-1}$)	Total N ($g \cdot kg^{-1}$)	NH_4^+-N ($mg \cdot kg^{-1}$)	NO_3-N ($mg \cdot kg^{-1}$)	Available P ($mg \cdot kg^{-1}$)
0 to 20	1.30	13.76	0.754	5.44	5.06	11.5
20 to 40	1.45	11.41	0.741	5.22	4.11	9.71
40 to 60	1.37	8.00	0.543	4.88	1.68	5.46
60 to 80	1.35	7.32	0.568	5.12	0.54	6.85
80 to 100	1.38	6.64	0.326	6.03	0.46	9.03

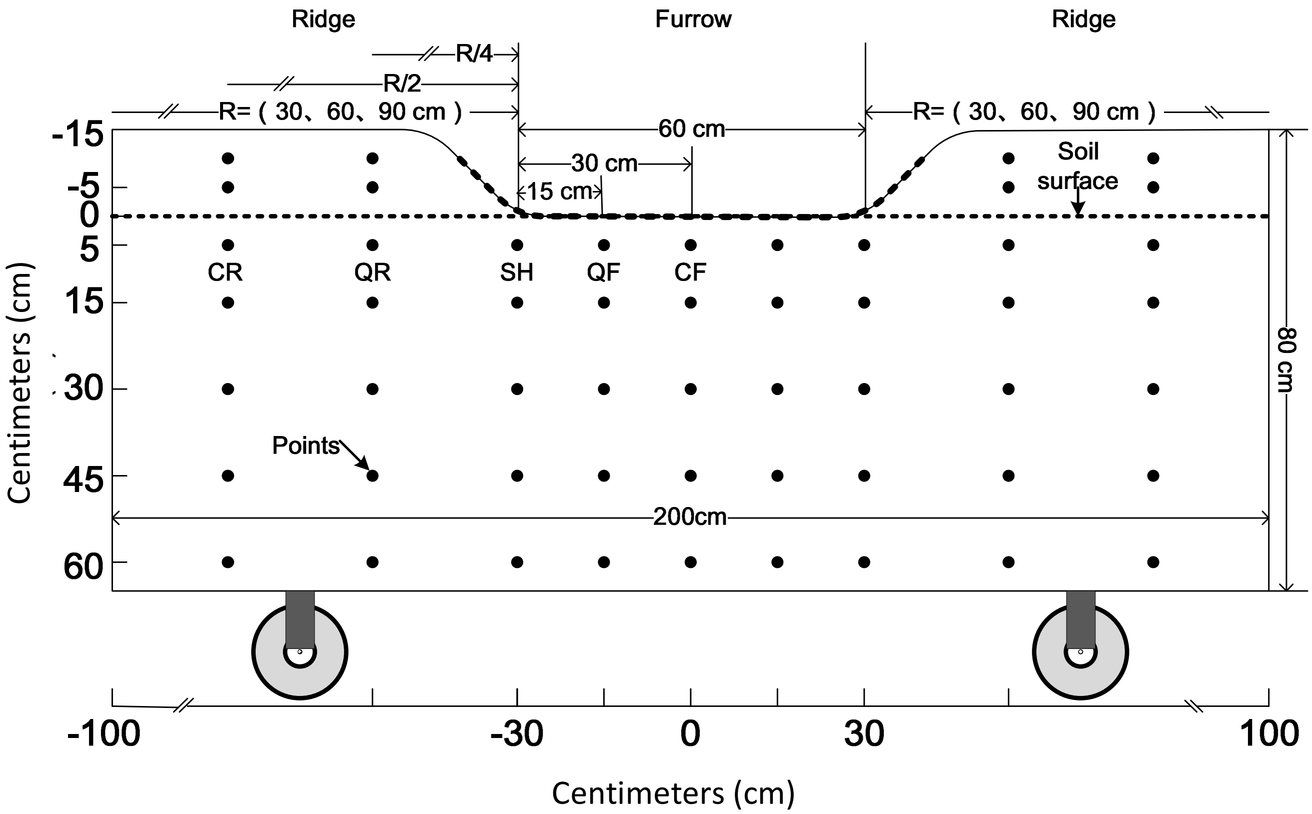

Figure 1. Schematic descriptions of the experimental device and soil sampling positions. Ridge elevations are negative and soil depths are positive relative to furrow surface. F = furrow, R = ridge, CF = center of furrow, QF = quarter of furrow, SH = ridge shoulder, QR = quarter of ridge, CR = center of ridge, 30、60 and 90 cm represent different wide ridge, respectively.

Statistical comparisons were conducted using Excel and the SAS package (SAS Proc GLM, SAS systems for windows, Ver. 9.1, SAS Institute, Cary, NC).

RESULTS AND DISCUSSION

Movement of wetting front

In the ridge-furrow system, most of the root zone was wetted within minutes of irrigation, but the tops of the ridges may take several minutes to several hours (depending on soil structure and height of the ridge) to be wetted by capillarity. Once the surface soil is fully wetted, its low saturated hydraulic conductivity of about 1 mm day^{-1} minimizes further infiltration during furrow irrigation (Li et al., 2003). This ensures that the soil is wetted to a uniform depth along the furrows following irrigation, and the most of the applied water is stored within the root zone. The soil water movement for ridges and furrows at the wetting front belongs to unsaturated soil water movement, which depends on the water potential gradient and unsaturated hydraulic conductivity. Monitoring of vertical and horizontal distance wetting front for all experiments showed that the wetting front moved fast at the beginning and slowed down with increasing time, and that the wetting front moved outward in a like-ellipse shape

Table 2. Summary of the initial conditions of soil moisture, nitrate (NO_3^--N) and ammonium (NH_4^+-N) content at different soil depth for each of the 9 experiments

Depth (cm)	Initial condition	Experiment number									Mean	STD[a]
		1	2	3	4	5	6	7	8	9		
0 to 20	Soil moisture (%)	11.3	11.8	12.1	12.3	12.8	13.0	12.5	11.9	12.2	12.2	0.5
	NO_3^--N mg·kg^{-1}	5.66	5.52	5.63	5.42	5.46	5.31	5.21	5.39	5.47	5.45	0.14
	NH_4^+-N mg·kg^{-1}	5.34	5.52	5.38	5.22	5.26	5.43	5.4	5.32	5.36	5.36	0.08
20 to 40	Soil moisture %	12.0	11.7	12.0	12.0	11.9	12.8	12	11.8	12.1	12.0	0.3
	NO_3^--N mg·kg^{-1}	4.07	4.03	3.98	3.94	4.06	4.14	4.05	4.06	4.16	4.05	0.07
	NH_4^+-N mg·kg^{-1}	5.16	5.24	5.33	5.12	5.23	5.16	5.22	5.28	5.11	5.21	0.07
40 to 60	Soil moisture %	11.8	11.8	12	12	12.2	11.7	12.1	12.8	12.3	12.1	0.30
	NO_3^--N mg·kg^{-1}	1.59	1.63	1.71	1.72	1.85	1.97	1.15	1.61	1.74	1.66	0.21
	NH_4^+-N mg·kg^{-1}	4.56	4.60	4.88	4.73	4.66	4.82	4.46	4.83	4.58	4.68	0.13
60 to 80	Soil moisture %	12.0	11.8	12.1	12.3	11.9	13.0	11.1	12.0	11.8	12.3	0.5
	NO_3^--N mg·kg^{-1}	0.53	0.56	0.52	0.58	0.61	0.66	0.48	0.51	0.52	0.55	0.05
	NH_4^+-N mg·kg^{-1}	5.08	5.09	5.05	5.12	5.09	5.11	5.21	5.12	5.17	5.12	0.04

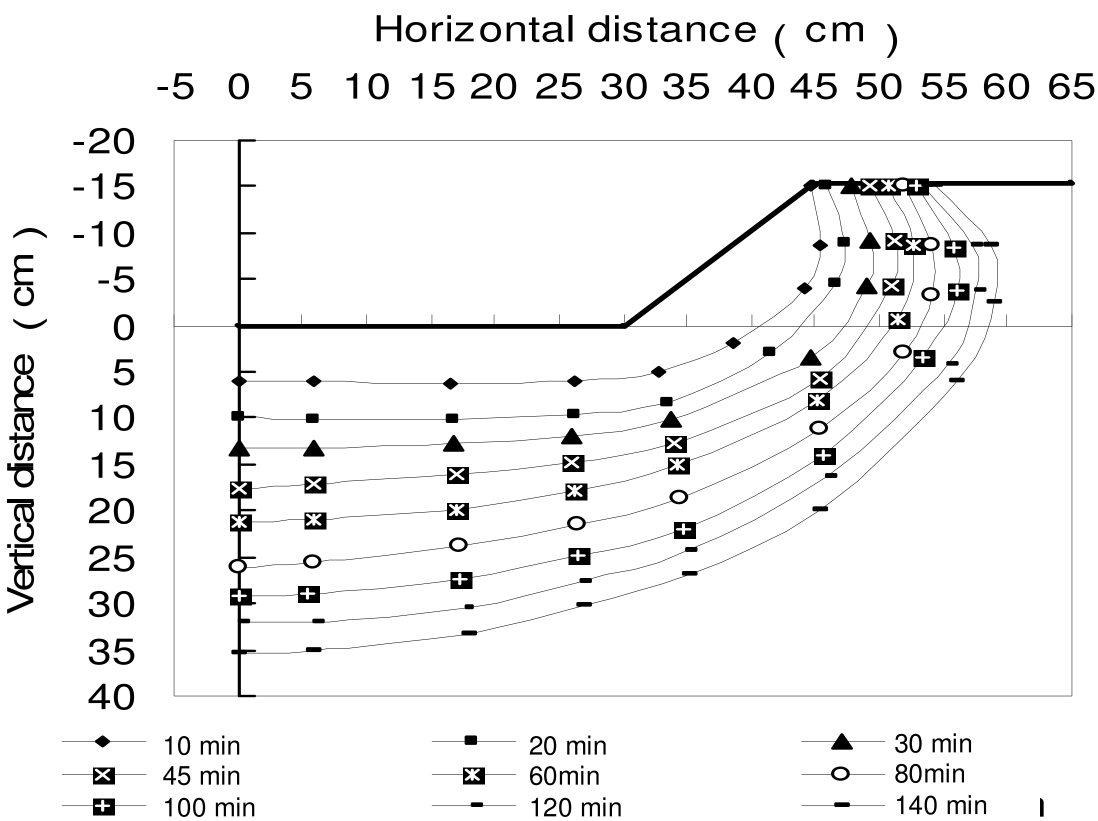

Figure 2. The vertical and horizontal distance of wetting front at different time. Ridge elevations are negative and soil depths are positive relative to furrow surface.

(Figures 2 and 3). It was found from our experiments that the vertical and horizontal maximum distance of wetting front were 42.13 and 62.56 cm, respectively. We also observed that vertical water movement was much greater

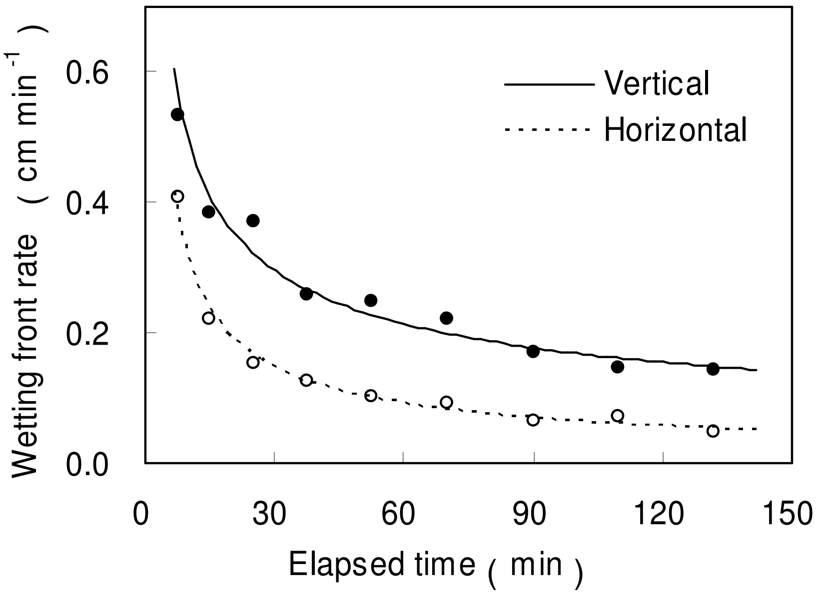

Figure 3. The rate change of vertical and horizontal wetting front at different time.

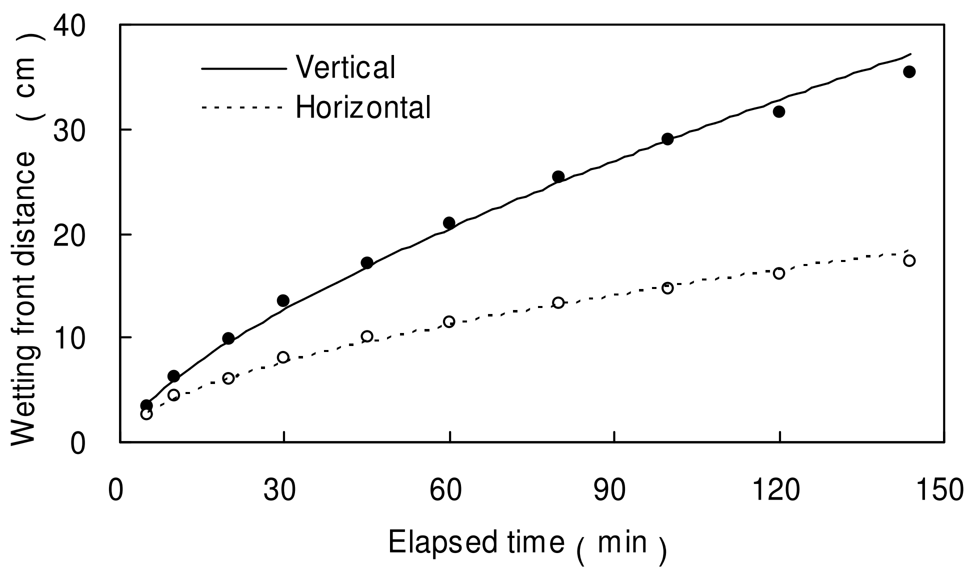

Figure 4. The total distance of vertical and horizontal wetting front at different time.

than horizontal movement due to the multiple roles of gravitational potential gradient, pressure gradient and the potential role of soil suction gradient. Figure 4 illustrates the total distance of vertical and horizontal wetting front with time. This indicated that deeper vertical distance may result in greater leaching of solute in furrows, which is supported by other research (Nie et al., 2009). Therefore, high application rate of water, appropriate ridge wide, short runs, deep clean furrows and increased slopes are recommended (Wang, 2004).

Water distribution in the soil

The width of ridge played an important role in ridge tillage. Inappropriate ridge wide (RW) can cause water loss and affect crop growth. Ridges and furrows had different patterns of soil water content with time during and immediately after irrigation. This indicated that the main infiltration and downward water movement occurred in furrows, with delayed lateral movements to ridge positions.

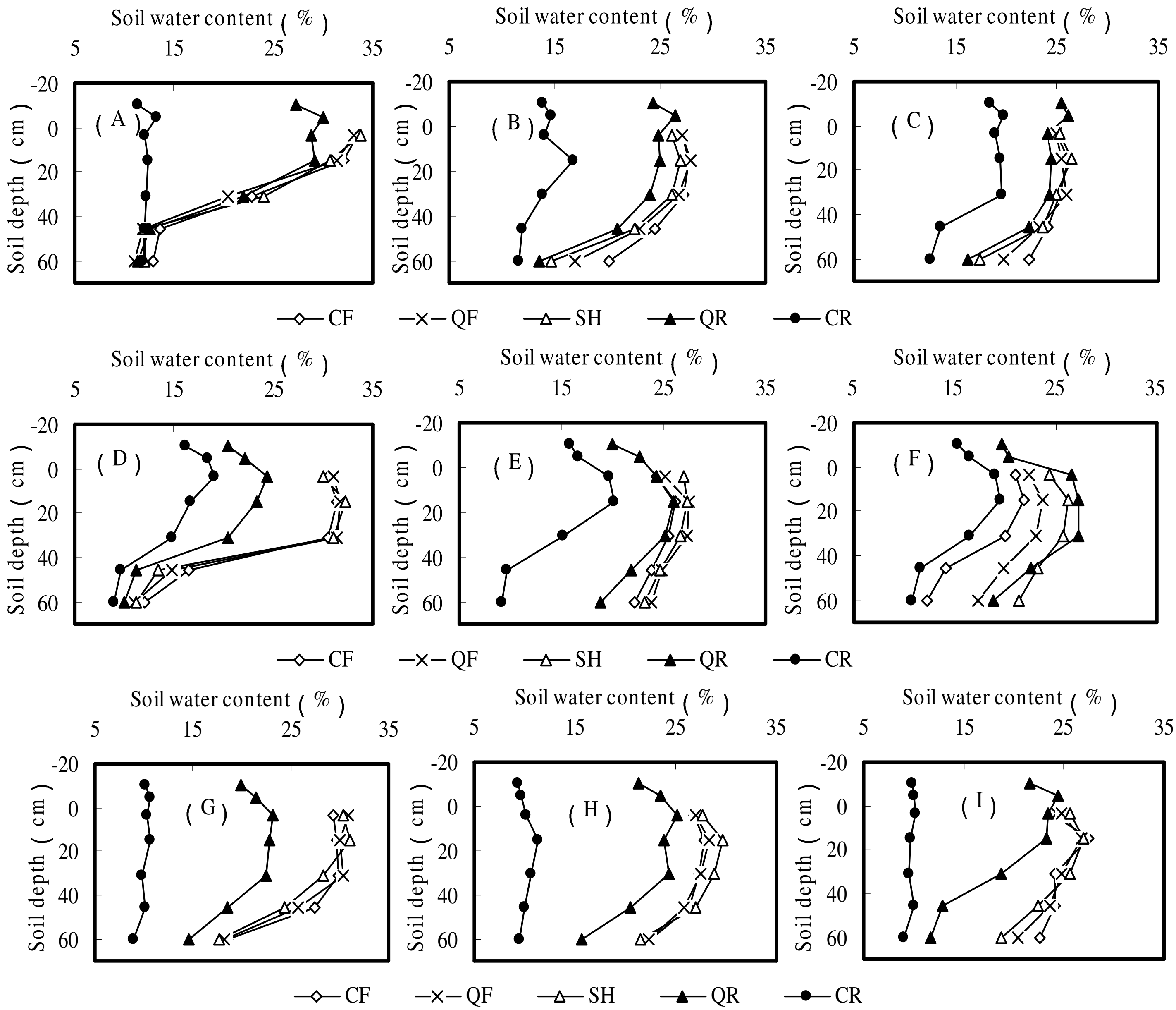

Figure 5. Soil water content distribution of different positions in ridge and furrow at three wide ridges (30、60 and 90 cm). (A) at the end of irrigation (AEI) under 30 cm wide ridge; (B) water redistribution 24 h for AEI under 30 cm wide ridge; (C) water redistribution 48 h for AEI under 30 cm wide ridge; (D) AEI under 60 cm wide ridge; (E) water redistribution 24 h for AEI under 60 cm wide ridge; (F) water redistribution 48 h for AEI under 60 cm wide ridge; (G) AEI under 90 cm wide ridge; (H) water redistribution 24 h for AEI under 90 cm wide ridge; (I) water redistribution 48 h for AEI under 90 cm wide ridge. Ridge elevations are negative and soil depths are positive relative to furrow surface. CF = center of furrow, QF = quarter of furrow, SH = ridge shoulder, QR = quarter of ridge, CR = center of ridge

As shown in Figure 5, the RW had a significant effect on the extent of vertical wetting at different positions. Under three RW, the average of soil water content at 10 cm ridge depth (10 cm below ridge surface) in CR slightly increased with time while the water content at the same elevation in QR decreased. This was caused by soil water redistribution in the ridge and lateral infiltration in the furrow (Wang et al., 2011). Under 30 cm RW, the average water content in CR positions increased with water redistribution, while the water content in QR, SH, QF and CF positions deceased with time (Figure 5A, B and C). These differences were presumably related to greater evaporation. The minimum and maximum water requirements for crop growth were 60% field capacity and 90% field capacity, respectively (Ma et al., 2006). At 60 cm RW, the profile water content were all below field capacity after irrigation and the probability for deep percolation was low (Figure 5D). After 24 h redistribution, soil water content in QR positions reached 82% of field capacity. The plants in CR could absorb water to meet its growth (Figure 5E). After 48 h redistribution, water content in CR increased to 16.38%, which was equal to 70% of field capacity (Figure 5F). Moreover, the soil moisture in center ridge should be more than 16.38% because of the symmetry for furrow irrigation infiltration. During water distribution in the soil, the profile water content from center furrow to center ridge were all above 60% of field capacity, which could satisfy crop growth for water requirements. In the experiment, 70 cm ridge width would be suitable for ridge tillage. Considering water sustainable lateral infiltration after 48 h, more than 60 cm ridge width could also meet crop water requirement and relatively decreased irrigation volume (Wang et al., 2011). For 90 cm RW, the profile average of soil water content in CR was close to initial water content (Figure 5G). During water redistribution, the profile water content in the ridge increased, presumably due to the lateral and vertical infiltration, which made gravitational water near the furrow profile decreased. Soil water redistribution in QR positions greatly increased after 24 h (Figure 5H). After 48 h redistribution, the average soil water content both in the furrow and QR was close to field capacity, while the water content in CR was low and less than 60% of field capacity (Figure 5I). The lower soil water content for CR positions following redistribution after 48 h was in part due to additional distance of travel for water infiltrating in the ridge.

In this experiment, the ridge size had a significant effect on soil water distribution and redistribution. Larger ridge in the 90:60 cm ridge and furrow system could reduce soil water content in center ridge due to less lateral infiltration. The lower soil water for CR positions would affect crop growth (Li and Gong, 2002). As a result, there may exist an optimum threshold ratio between ridge and furrows for different crops. This means that the relationship between ridge: furrow ratios and soil water content may follow a parabolic function distribution. When the ratio is below the threshold value, ridge: furrow ratios may have a positive effect on soil water content, and the result proves contrary when the ratio is above the threshold value. Clearly, in this study, the 60:60 cm ridge and furrow system seems to be more effective for soil water content than the 90:60 cm ridge and furrow system. Corn and wheat are the major food crops in northwest China. It is necessary to determine an appropriate ridge: furrow ratio for crops (Li et al., 2000). Moreover, the pattern of soil water content with time indicates that infiltration and initial water movement occurred largely in furrows, with some infiltration in ridge and shoulder positions, and water subsequently moved laterally and radically to ridge positions by distribution. These results imply greater leaching of solute placed under the furrow compared with uncropped ridge placement at equal elevation, which is consistent with other research (Bargar et al., 1999). We also found that ridge width had significant effects on soil water distribution in ridge and furrow system. Too large or too narrow ridge width was not beneficial to crop growth and water saving. This was in agreement with Li's (1992) and Sayre's (1997) study. They observed that the yield-increasing effect for 60 cm ridge width with two rows rice or wheat under ridge tillage was higher than those of 80 cm ridge width with three rows. Wang et al. (2001) also suggested that surface cover, ridge (oriented) roughness, ridge width and random roughness factors in a wind erosion equation predict excellent erosion control for this tillage system. In this experiment, the optimal ridge width was likely between 60 and 75 cm. At the range from 60 to 75 cm, the soil water content in the ridge and furrow had better distribution which could meet water requirements for crop growth.

Nitrate distribution in the soil

Figure 6 illustrates the distributions of the relative NO_3^--N content in the soil profile for different positions under three ridge widths at the end of irrigation. In this experiment, we found the distribution of NO_3^--N in the soil was similar to distribution patterns of water. One notable result was the accumulation of the nitrate at the boundary of the wetted volume. In CF and QF positions, NO_3^--N content appeared accumulation at 20 cm depths and deep percolation below 40 cm soil depth under 30 cm ridge width (Figure 6A and B). The phenomenon that NO_3^--N accumulated toward the boundary of the wetted volume still existed. The accumulation of nitrate at the boundary of the wetted volume was also observed by Bar-Yosef and Sheikholslami (1976) in their laboratory experiments. At the same ridge width, the distribution of NO_3^--N content at SH, QR and CR positions decreased with the profile depth increasing and the content was lower than that of CF position. This may result from the leaching of nitrate during the process of irrigation. Under 60 cm ridge width, the NO_3^--N content distribution at CR and QR positions decreased with soil depth increasing but there was no obvious accumulation phenomenon. Moreover, the NO_3^--N content between QR and SH positions had no significant difference, which contributed to the nutrient uptake of tillage crop (Figure 6C, D and E). This suggested that the movement of the fertilizer into the ridge and along the furrow in the irrigation water. However, the NO_3^--N content showed significant difference between furrow and ridge under 90 cm ridge width, which made more nutrient retained near the surface of the furrow and away from the roots. Therefore, nitrate leaching was highly dependent on irrigation volume and suitable ridge width. The experiment showed the complexity of soil surface micro-topography and mode of application of N fertilizer (Su et al., 2006). This indicated that the best management practice for application of ridge width was very important in ridge

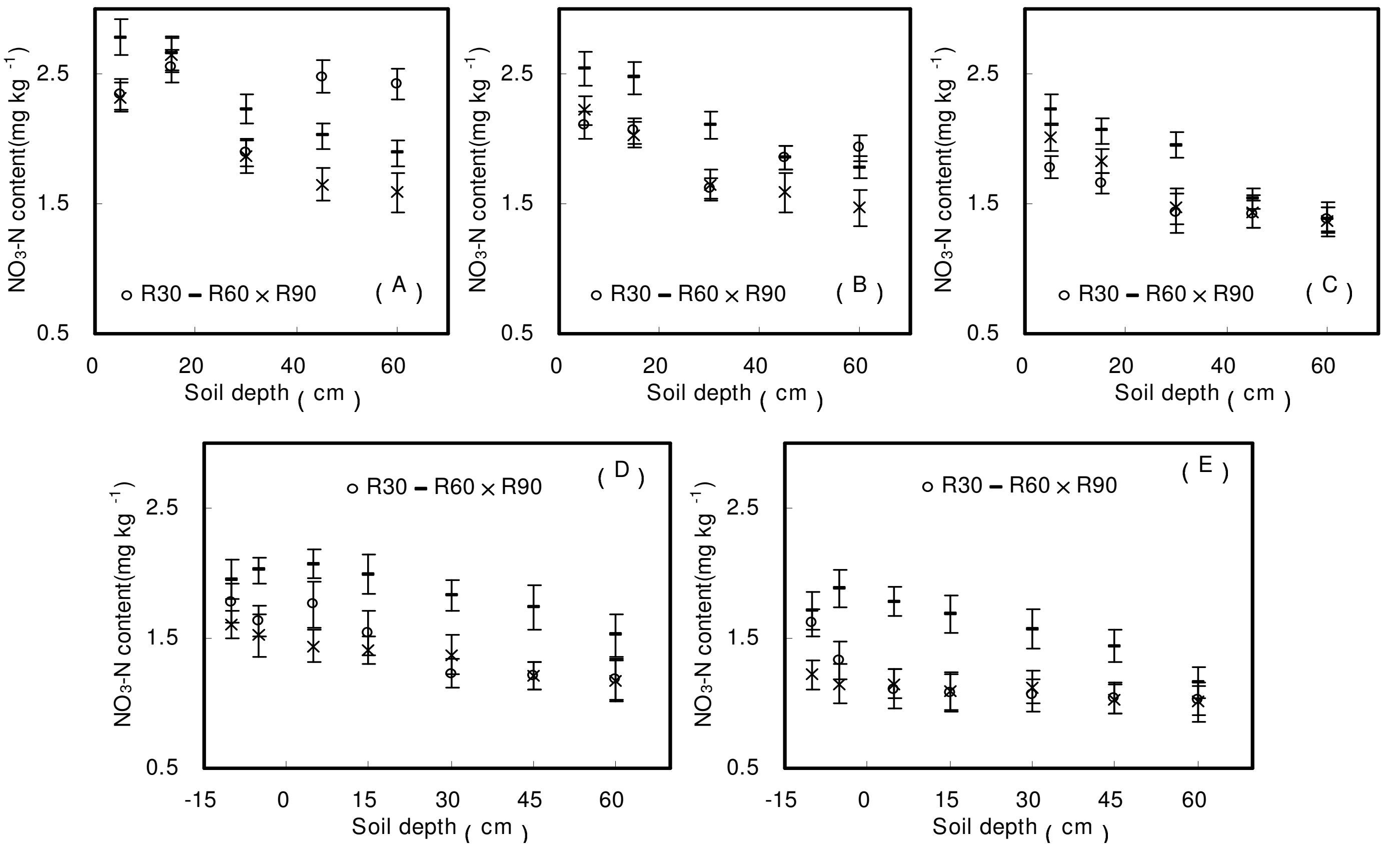

Figure 6. Nitrate nitrogen distribution of different positions in ridge and furrow under three wide ridge (30、60 and 90 cm) at the end of irrigation. (A) center of furrow; (B) quarter of furrow; (C) ridge shoulder; (D) quarter of ridge; (E) center of ridge. Ridge elevations are negative and soil depths are positive relative to furrow surface. Error bars are the L.S.D. at *P*=0.05.

tillage systems.

Ammonium distribution in the soil

Figure 7 illustrates the distribution of the relative ammonium content in the profile soil under different ridge widths. An extremely high NH_4^+-N content was found at the proximity at 20 cm depth of center furrow. Soil adsorption of the applied NH_4^+ at top soil was the primary reason for the extremely high ammonium concentration close to the soil surface. The similar distribution trend for NO_3^--N and NH_4^+-N was observed in this experiment. The effect of ridge width on the peak values was insignificant. The influence of ridge width on NH_4^+-N distribution was restricted to a range between 60 and 75 cm. Beyond this range, NH_4^+-N content remained at the initial value. The total amount of NH_4^+-N within the range of 0 to 20 cm soil depths under 60 cm ridge width followed the trend: CF > QF > SH > QR > CR (Figure 7A, B and C). The NH_4^+-N values had no obvious change within the range of 20 to 30 cm soil depth (Figure 7D and E). This may imply that the influence of ridge width on the ammonium distribution is insignificant. The results from our experiments suggested that the ammonium distribution was mainly controlled by input concentration and ridge width had minor effects. From the point of avoiding the potential possibility of nitrate loss from the root zone, the suitable ridge width within the range from 60 to 75 cm was recommended.

Conclusions

Simultaneous measurements of water and nitrogen distribution under different ridge width were conducted using the gravimetric method. Observations of water movements revealed that infiltration with ridge tillage did not exhibit uniform vertical frontal movement but occurred primarily in furrows, as indicated by more rapid increase in soil water content for furrow than for equivalent ridge positions at soil depths < 30 cm. The null hypothesis that changing ridge width does not affect soil water content and movement was therefore rejected. Following redistribution, ridges and furrows had relatively similar soil water content under 60 cm ridge width. The nitrate concentration at 60 cm ridge width had no obvious accumulation phenomenon. The results of ammonium

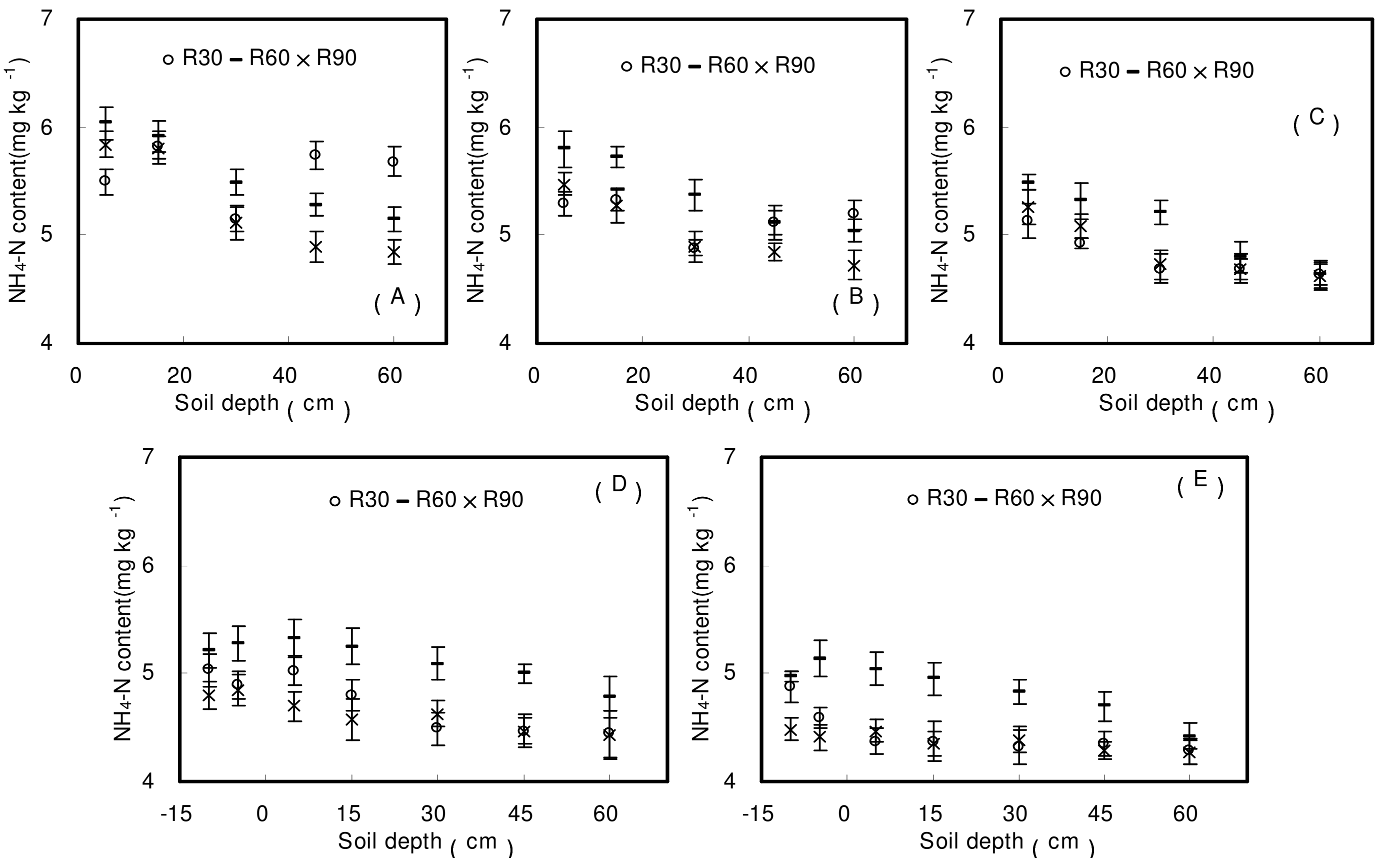

Figure 7. Ammonium nitrogen distribution of different positions in ridge and furrow under three wide ridge (30, 60 and 90 cm) at the end of irrigation. (A) center of furrow; (B) quarter of furrow; (C) ridge shoulder; (D) quarter of ridge; (E) center of ridge. Ridge elevations are negative and soil depths are positive relative to furrow surface. Error bars are the L.S.D. at *P*=0.05.

distribution measurements indicated that there existed an extremely high ammonium concentration in the furrow for ridge-furrow system. From the point of avoiding the potential possibility of nitrate loss from the root zone, the suitable ridge width within the range from 60 to 75 cm was recommended. However, additional research and model simulation is required to investigate the impact of weather, residue management, and surface geometry on water movement under growing vegetation.

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