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Effect of Sprinkler and Border Irrigation on Topsoil Structure in Winter Wheat Field*1

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ABSTRACT

A two-year experiment was carried out on the effect of sprinkler irrigation on the topsoil structure in a winter wheat field. A border-irrigated field was used as the control group. The total soil porosity, pore size distribution, pore shape distribution, soil cracks and soil compaction were measured. The sprinkler irrigation brought significant changes to the total soil porosity, capillary porosity, air-filled porosity and pore shape of topsoil layers in comparison with the border irrigation. The total porosity and air-filled porosity of the topsoil in the sprinkler irrigation were higher than those in the border irrigation. The changes in the air-filled and elongated pores were the main reasons for the changes in total porosity. The porosities of round and irregular pores in topsoil under sprinkler irrigation were lower than those under border irrigation. Sprinkler irrigation produced smaller soil cracks than border irrigation did, so sprinkler irrigation may restrain the development of macropore flow in comparison with border irrigation. The topsoil was looser under sprinkler irrigation than under border irrigation. According to the conditions of topsoil structure, it is preferable for crops to grow under sprinkler irrigation than under border irrigation.

Key Words: macropore flow, soil compaction, soil crack, soil pore shape, soil porosity

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The North China Plain is one of the largest areas for winter wheat (*Triticum aestivum L.*) production in China (Zhang *et al.*, 1999; Liu *et al.*, 2003). In the growing season of winter wheat, irrigation is a common practice to meet winter wheat's consumption on water. Owing to its potential of improving water use efficiency and grain yields, sprinkler irrigation has been increasingly used in the North China Plain (Liu and Kang, 2007).

Drops of sprinklers break aggregated and compact thin surface layers and lead to formation of seal or crusts and hard setting (Ragab, 1983; Tarchitzky *et al.*, 1984; Adeoye, 1986). Under simulated rainstorm or sprinkler irrigation, pores in topsoil varied with intensity, drop size and amount of water applied. Porosity reduction is mainly due to size decrease of elongated pores and is associated with the increase of runoff rate, especially in bare soil (Panini *et al.*, 1997; Sun *et al.*, 2008). In a crop field, however, the water for sprinkler irrigation is intersected by plant canopy, which gives rise to different distribution (Li and Rao, 2000; Lamm and Manges, 2000; Kang *et al.*, 2005). The effect of sprinkler irrigation on soil structure might be different in winter wheat fields and bare fields.

Soil structure is a key factor affecting water movement and retention in soil, erosion, crusting, nutrient recycling, root penetration and crop yields (Bronick and Lal, 2005). White (2006) defined soil structure in terms of the arrangement of primary particles into peds; the size, shape and arrangement of peds; and the voids or pore spaces that separate particles and peds. There is a close interrelationship

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between soil aggregates and pores. Break-down soil aggregates may cause decreased porosity and changed pore size and shape distribution, especially in topsoil (Li *et al.*, 2004). Cousin *et al.* (2005) identified five stages of a structural crust developing in a loamy clay soil using quantitative image analysis. The results indicated that the percolation threshold decreases from 130 μm at the second stage down to 40 μm at the fifth stage. Leij *et al.* (2002) modeled the dynamics of the soil pore-size distribution, however, the development and application of the model is hampered by a lack of definitive data on soil structural and hydraulic dynamics. Cameira *et al.* (2003) indicated that macropores were the main contributing pores to the total flow under both conventional tillage and minimum tillage, in spite of the very low macroporosities. Mirzaei and Das (2007) carried out a numerical study to investigate how the presence of micro-scale heterogeneities affects the dynamics of dense non-aqueous phase liquid and water flow in porous domain.

This present study was performed to compare the effects of sprinkler irrigation and border irrigation on topsoil structure in a crop field, including total soil porosity, pore-size and shape distribution, soil cracking and soil compaction.

MATERIALS AND METHODS

A field experiment was conducted from 2003 to 2004 in the Tongzhou Experimental Base for Water-Saving Irrigation Research (39° 36′ N, 116° 48′ E; 20 m above sea level), Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, at Tongzhou District of Beijing, China. It has a temperate, semi-humid monsoon climate with a mean annual temperature of 11.2 °C and precipitation of 550 mm. The experimental soil is a fluvo-aquic soil (Och-Aquic Cambosols), containing 20% sand (> 0.05 mm), 54% silt (0.05–0.002 mm), 26% clay (< 0.002 mm), 13.1 mg kg^{-1} organic matter, and 0.190 m d^{-1} saturated hydraulic conductivity, with a pH 7.59.

The experiment was conducted in a 240 m × 208 m sprinkler-irrigated field with a lateral move sprinkler-irrigation system. Impact sprinklers (ZY2, made in Zhengzhou Fountain and Sprinkler Irrigation Engineering Co., Ltd., China) with a wetting radius of 18 m and a flow rate of 3 m^3 h^{-1} at pressure of 300 kPa were mounted on 1.30 m-high risers as the sprinkler irrigation system. A border-irrigated field, with measured dimension of 208 m × 160 m and on the east side of the sprinkler-irrigated field, was used as the control group. The basin size in the border-irrigated field was 50 m × 5 m.

Winter wheat in the sprinkler field was irrigated when the mean soil matric potential of the 0–40 cm soil layer decreased to about −45 kPa. The irrigation duration was determined by the distribution of main wheat-root zones and was usually about 4–5 h, with about 40–50 mm of water each time.

The date and water amount of border irrigation were determined by the water content in the field soil and the growing condition of winter wheat. The border irrigation practice was similar to local irrigation practices. Irrigation dates and water amounts are listed in Table I.

TABLE I

Amounts of water applied in sprinkler and border irrigation in the field experiment from 2003 to 2004

Sprinkler irrigation				Border irrigation			
2003		2004		2003		2004	
Date	Amount	Date	Amount	Date	Amount	Date	Amount
	mm		mm		mm		mm
April 10	38.3	April 9	49.0	April 13	118.1	April 9	89.7
April 21	54.5	April 26	50.0	May 5	93.3	May 25	71.3
May 4	50.1	May 25	51.5	May 22	91.0		
May 21	53.5						
Total	196.4	Total	150.5	Total	302.4	Total	161.0

Winter wheat was sown on October 16, 2002 and October 18, 2003 at a row spacing of 0.15 m and a sowing rate of 375 kg ha^{-1}. The high sowing rate was due to the low seed-germination rate and plant survival rate under low temperature conditions in winter. The crops were harvested on June 15, 2003 and June 15, 2004. Fertilizers were uniformly applied twice in each season: once as basal fertilizer when the soil was plowed and the second as top-dressing with irrigation after the crops revived. The amounts of basal fertilizer applied were 45, 45 and 30 kg ha^{-1} for N, P_2O_5 and K_2O, respectively. The top-dressing fertilizer applied in the two seasons was urea at 138 kg N ha^{-1}. Other cultivation practices, including applications of pesticides and herbicides, were the same with those applied locally for high-yield wheat production.

Soil was sampled in sprinkler-irrigated and border-irrigated fields after harvesting in 2003 and 2004. Three undisturbed samples from 30 mm depth were collected with PVC cylinders (inner-diameter 60 mm, height 50 mm). All the soil samples were brought back to laboratory and air-dried for about one week.

The air-dried soil samples were further oven-dried at 105 °C for 12 hours. Dry soil samples were impregnated with polyester resin under vacuum condition. Afterwards, the soil samples were sawed into thin sections, the surfaces of which were polished with grades of grit silicon carbide. A region of 2 cm × 2 cm in the center of each thin section was chosen and scanned by a self-developed flatbed scanner with resolution of 2 400 dpi. The obtained digital images of the thin sections were saved as TIFF (Tagged Image File Format) files.

Threshold is the key to distinguish pores and solid. Thresholds for total soil porosity and capillary porosity were obtained from Sun *et al.* (2008).

Digital images of all undisturbed samples were converted to binary images using a classification function of ENVI 3.5. Then, statistical parameter tables were generated with a statistical function. Finally, the total porosity of the samples was calculated through summation of the percentage values of the digital number for the total porosity threshold.

In ArcGIS 9.0, the binary image of each soil sample was opened, and an attribute table was created with a region group function. The attribute table was then exported to an Excel spreadsheet and sorted based on the field of connection pixel number. Based on corresponding threshold, capillary porosity can be obtained through calculation of the percentage values of the patches.

The air-filled pore in the experimental soil has an equivalent diameter of more than 0.71 mm (Sun *et al.*, 2008). The air-filled porosity of each sample was calculated with the total porosity minus capillary porosity, as the following equation:

$$P_{\mathrm{a}} = P_{\mathrm{t}} - P_{\mathrm{c}}$$

where P_{a} is the air-filled porosity (%), P_{t} is the total porosity (%), and P_{c} is the capillary porosity (%).

The binary images were converted from raster-format files to vector-format files using ArcGIS 9.0 software. A topological function was used to analyze the vector-format file to produce an attribute table of areas (A) and perimeters (P) of all the patches corresponding to pores. The attribute table was then exported to an Excel file. Based on the A/P^2 ratios for each patch (pore), all pores were classified into three shapes: round ($A/P^2 > 0.040$), elongated ($A/P^2 < 0.015$) and irregular (A/P^2 between 0.015 and 0.040) (Bouma *et al.*, 1977; Pagliai *et al.*, 1983; Fox *et al.*, 2004).

After harvesting in 2004, eleven samples were selected randomly from each experimental field to measure the widths of soil-surface cracks in both irrigation fields with a vernier caliper. Soil compaction was also measured with an SC 900 soil compaction meter by selecting twenty-five points randomly from each field at a depth of 200 mm.

RESULTS AND DISCUSSION

Effects of sprinkler irrigation and border irrigation on topsoil porosities

The total porosities of the 0–20 mm topsoil layer under sprinkler and border irrigation in 2003 and

2004 are shown in Fig. 1. The total porosity in topsoil under sprinkler irrigation was 1.2–1.4 times that under border irrigation. The total porosities of topsoil were 38.3% and 37.8% under sprinkler irrigation and 32.6% and 26.0% under border irrigation in 2003 and 2004, respectively. In comparison, total porosity decreased drastically from the 0 to 5 mm depth and then slightly increased from 5 to 15 mm depth under sprinkler irrigation. Total porosity decreased from the 0 to 15 mm depth in 2003, and gently increased in 2004 under border irrigation. For the entire profile from 0 to 20 mm depth, the mean total porosities under sprinkler irrigation were 27.7% in 2003 and 30.2% in 2004, while those under border irrigation were 27.5% and 27.5%, respectively. These results showed that the total porosity of topsoil under sprinkler irrigation was higher than that under border irrigation.

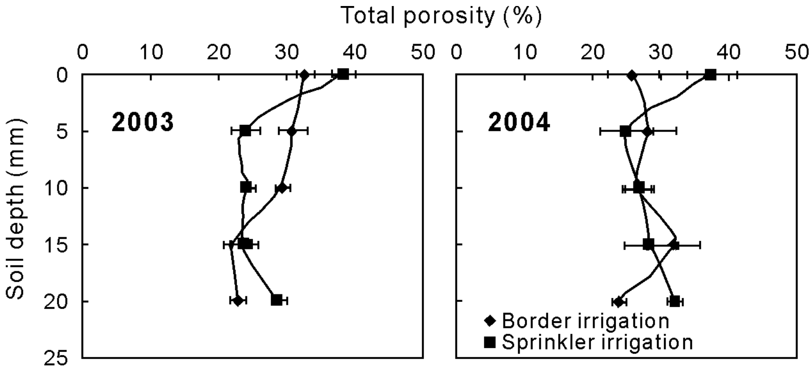

Fig. 1 Total porosities of 0–20 mm topsoil layer under sprinkler irrigation and border irrigation.

The capillary and air-filled porosities are shown in Fig. 2. The variation in the capillary porosity *vs.* depth was similar to the total porosity under sprinkler irrigation but differed from that under border irrigation. Capillary porosity decreased from 0 to 5 mm depth and then increased from 5 to 15 mm depth under sprinkler irrigation, but decreased from 0 to 15 mm depth under border irrigation in 2004. The mean capillary porosity from 0 to 15 mm depth under sprinkler irrigation was 0.81–0.84 times that under border irrigation, suggesting that sprinkler irrigation induced fewer small pores in topsoil than border irrigation. The decreased capillary pores might reduce soil evaporation, which may explain why soil water

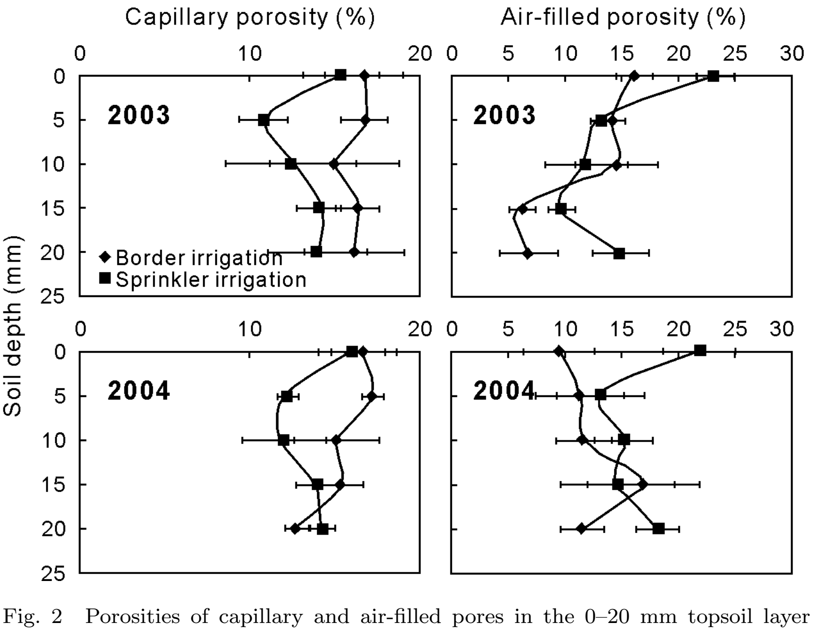

Fig. 2 Porosities of capillary and air-filled pores in the 0–20 mm topsoil layer under sprinkler irrigation and border irrigation.

storage is reduced more slowly under sprinkler irrigation than under border irrigation (Gong *et al.*, 2001; Sun *et al.*, 2006).

The variations in air-filled porosities with depth under both irrigation systems were similar to those of their respective total porosities (Fig. 1). The air-filled porosities of topsoil under sprinkler irrigation were 1.4–2.3 times (23.1% in 2003 and 23.8% in 2004) those under border irrigation (16.1% in 2003 and 9.4% in 2004). The mean air-filled porosities of the 0–20 mm soil layer under sprinkler irrigation were 14.5% in 2003 and 16.6% in 2004, *i.e.*, 1.3–1.4 times the respective values (11.5% and 12.1%) under border irrigation. Despite of the similar trend, there were smaller differences among air-filled porosities in sprinkler-irrigated field than in border-irrigated field. Air-filled porosity is an important parameter for assessing soil aeration, soil's structural quality and design of soil drainage system (White, 2006), and it can also affect topsoil aeration which in turn affects crop growth.

Our observations of total, capillary and air-filled porosities demonstrate that for crop growth, the aeration and water storage of topsoil are better under sprinkler irrigation than under border irrigation, which is likely attributed to the fact that water flows under unsaturated condition in sprinkler irrigation but under saturated condition in border irrigation (Sun *et al.*, 2006). Sprinkler droplets could compact the soil surface and break soil aggregates into smaller pieces. Water flows into capillary pores under sprinkler irrigation and the pieces carried by water can be plugged in the pores. However, soil aggregates broken by saturated water in border irrigation can flow with water into all soil pores, especially air-filled pores, to block them. Variation in porosities of border irrigation was probably a result of higher irrigation amount in 2003 than in 2004 (Table I).

Effects of sprinkler irrigation and border irrigation on topsoil pore shape

The variations in porosities of pores in different shapes in the 0–20 mm topsoil layer under sprinkler irrigation and border irrigation are presented in Fig. 3. The porosity of round pores was lower than 5% under both irrigation systems. The porosity of round-pores under sprinkler irrigation decreased from 0 to 10 mm depth and then increased from 10 to 20 mm depth. Under border irrigation, the porosity of round pores exhibited different trends in 2003 and 2004.

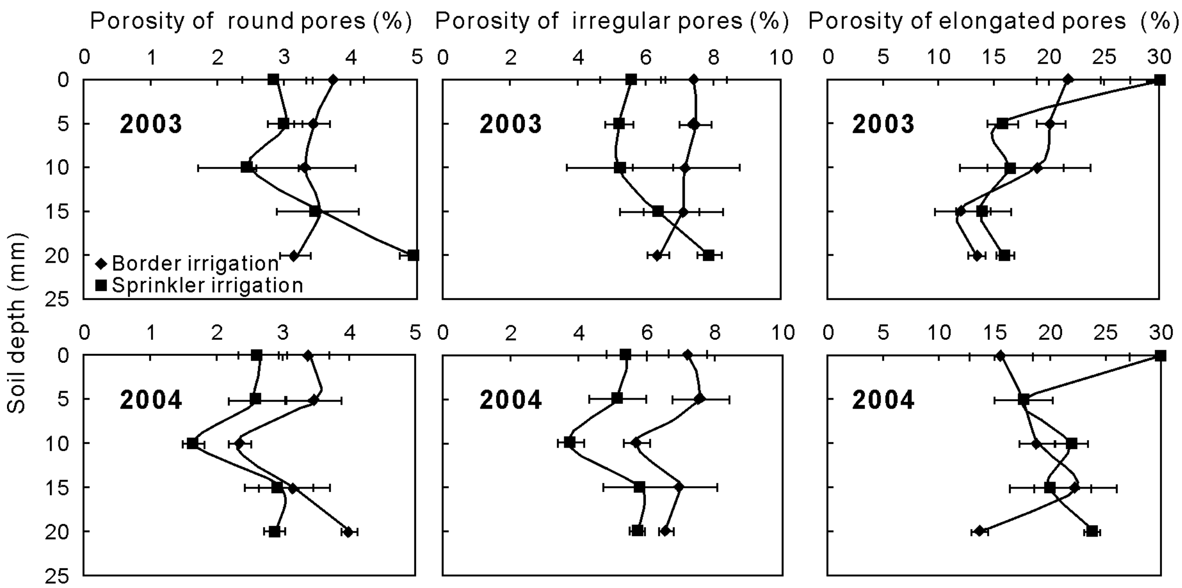

Fig. 3 Porosities of pores in different shapes in 0–20 mm topsoil layer under sprinkler irrigation and border irrigation.

The porosity of irregular pores in the 0–20 mm soil layer changed similar to the round pores under both irrigation systems. The porosity of irregular pores from 0 to 15 mm depth under sprinkler irrigation was lower than that under border irrigation. The mean porosities of irregular pores from 0 to 15 mm depth under sprinkler irrigation were 5.6% in 2003 and 5.0% in 2004, which were 0.73–0.77 times those under border irrigation (*i.e.*, 7.3% and 6.9%). The porosity of irregular pores was lower than 8% in the 0–20 mm soil layer under both irrigation systems, being higher than that of round pores.

The variation in the porosity of elongated pores was similar to that in the total porosity under both sprinkler irrigation and border irrigation. The porosity of elongated pores in topsoil under sprinkler irrigation was higher than that under border irrigation. Porosities of elongated pores in topsoil under sprinkler irrigation were 29.9% in 2003 and 29.8% in 2004, which were 1.4–1.9 times the corresponding values under border irrigation (*i.e.*, 21.4% and 15.5%). The mean porosities of elongated pores in the 0–20 mm topsoil profile under sprinkler irrigation were 18.2% in 2003 and 22.5% in 2004, which were 1.1–1.3 times the corresponding values under border irrigation (*i.e.*, 17.0% and 17.4%).

Round pores are less effective in water transmission in comparison with irregular and elongated pores (Valentin, 1991; Fox *et al.*, 2004), which indicates that water infiltration may be more effective under sprinkler irrigation than under border irrigation.

Effects of sprinkler irrigation and border irrigation on cracks of soil surface

The widths of cracks of soil surface under both irrigation systems after wheat harvesting in 2004 are shown in Table II. The cracks were significantly narrower under sprinkler irrigation than under border irrigation; the maximum width under sprinkler irrigation was 6 mm with a mean value of 3 mm, which was about 50% lower than that under border irrigation. The width coefficient of variation (CV) of soil surface cracks was smaller under sprinkler irrigation than under border irrigation. Soil cracks are important for producing macropore flow. Due to reduced crack size, sprinkler irrigation may restrain the development of macropore flow in comparison with border irrigation. The water distribution under sprinkler irrigation was more uniform than that under border irrigation, which is favorable to the growth of winter wheat.

TABLE II

Crack widths in soil surface under sprinkler and border irrigation in 2004

Treatment	No. of samples	Minimum	Maximum	Mean	SD[a)]	CV[b)]
		mm				
Sprinkler irrigation	11	1.26	6.04	2.95	1.44	0.49
Border irrigation	11	1.70	13.60	6.49	3.90	0.60

[a)]Standard deviation; [b)]Coefficient of variation.

Effects of sprinkler irrigation and border irrigation on topsoil compaction in winter wheat field

The 0–200 mm soil layer compaction under both irrigation systems is shown in Fig. 4. Soil compaction increased slightly from 0 to 75 mm depth and increased greatly from 75 to 200 mm depth under sprinkler irrigation, while it decreased from 0 to 25 mm depth and then increased from 25 to 200 mm depth under border irrigation. The compaction of topsoil under sprinkler irrigation was less than that under border irrigation. In the 25–50 mm soil layers, there was no difference in soil compaction between sprinkler irrigation and border irrigation ($P > 0.05$). In 75–200 mm soil layers (except 100 mm), the soil compaction under sprinkler irrigation was less than that under border irrigation. The differences in 75–200 mm soil layers between sprinkler irrigation and border irrigation might be attributed to root system. Liu *et al.* (2000) noticed that the root lengths and the weight densities of winter wheat under sprinkler irrigation are larger than those under border irrigation of 0–200 mm soil layers. According to our field observations, there was a soil crust with a thickness < 10 mm under sprinkler irrigation and a hard layer about 60 mm thick under border irrigation. Soil compaction is the comprehensive reflection of soil structure. These results indicate that the topsoil is looser under sprinkler irrigation than under border irrigation. High soil compaction may cause reduction in root penetration and water infiltration rate, and consequent reduction in crop yield (Connolly, 1998). It appears that the soil condition in view of topsoil compaction is more favorable to crops under sprinkler irrigation than under border irrigation.

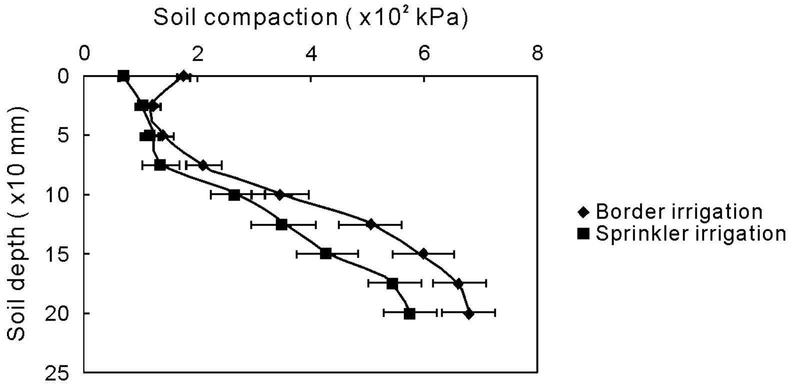

Fig. 4 Compaction in the 0–200 mm soil layer under sprinkler irrigation and border irrigation in 2004.

CONCLUSIONS

Sprinkler irrigation brought about more significant changes in soil porosity and pore shape of topsoil layers in comparison with border irrigation. The total porosity and air-filled porosity in topsoil were higher under sprinkler irrigation than under border irrigation. The reduction of capillary pores gave rise to reduction of soil evaporation under sprinkler irrigation. The porosities of round and irregular pores in topsoil were lower under sprinkler irrigation than under border irrigation. The porosities of elongated pores in the topsoil layer were higher under sprinkler irrigation than under border irrigation. Sprinkler irrigation resulted in smaller soil cracks in comparison with border irrigation. Sprinkler irrigation could reduce the development of macropore flow in comparison with border irrigation. The topsoil was looser under sprinkler irrigation than under border irrigation. The conditions of topsoil structure indicated that the soil conditions under sprinkler irrigation were better for crop growth compared with those under border irrigation.

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