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Water and salt regulation and its effects on *Leymus chinensis* growth under drip irrigation in saline-sodic soils of the Songnen Plain

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ABSTRACT

Field experiments were carried out to investigate water and salt management and its effects on *Leymus chinensis* growth under drip irrigation on saline-sodic soils of the Songnen Plain, China. The ECe of the experiment soil here is 15.2 dS/m and SAR_e is 14.6 $(mmol_c\, L^{-1})^{1/2}$. The threshold of soil matric potential (SMP) was preset in different treatments (−5, −10, −15, −20 and −25 kPa) to control the timing of the irrigation cycle using vacuum tensiometers buried at 0.2 m depth immediately under drip emitters. Drip irrigation frequency and soil matric potential significantly influenced water and salt distributions and *L. chinensis* growth. In the root zone, the soil water content increased with the SMP, but at deeper layers there were no significant differences in soil water content due to the effect of groundwater. Electrical conductivity showed that there was a low-salt zone near the emitters and that drip irrigation inhibited the buildup of salts in the root zone. There was more leaching of salts for −5 and −10 kPa treatments than for the −15, −20 and −25 kPa treatments. After two years of drip irrigation, the surface salts were well leached, and had moved down with the water to depths below 40 cm. The pH of each treatment was a little decreased and the soil nutrient of S1–S5 were all increased after reclamation, but there were no obvious differences of the five treatments. The best growth was achieved with soil matric potentials of −5 and −10 kPa: the plant height, number and length of spikes, number of tillers, coverage and aboveground biomass all attained their maximum values during the growth periods of *L. chinensis*, with no significant differences between those two treatments. Thus, in the Songnen Plain, drip irrigation can be used on transplanted *L. chinensis* for restoration of saline-sodic soils. The results provide theoretical and technological guidance for sustainable reclamation salt-affected soil and the quick restoration and reconstruction of saline-sodic grassland.

1. Introduction

The Songnen Plain covers an area of about 17.0×10^6 ha in the central part of northeastern China; it is one of the three saline-sodic soil distributing regions in the world (Deng et al., 2006; Wang et al., 2009). In the past it was good pasture and had many fine grasses, the main species in the Songnen Plain being *Leymus chinensis* (Liu and Han, 2008). In recent years, because of overgrazing and irrational utilization, soil salinization of the grassland of Songnen Plain has become very serious, and *L. chinensis* meadows have degenerated quickly. About 70% of the grassland in Songnen Plain is salinized, with current increases of 1.5–2% annually (Zheng and Li, 1993; Shang et al., 2003). Every year an additional 20.0×10^3 ha is affected. Currently, >30% of the saline grassland has large sodic areas with only sporadic *Suaeda salsa* coverage, so it has been abandoned and cannot be used (Li, 2000; Yin et al., 2003; Li et al., 2003).

The salinization and sodication of the soil in the Songnen Plain is very serious. The major salts are $NaHCO_3$ and $NaCO_3$, and the ESP is 48.3% (Wang et al., 2004; Li et al., 2006). The structure of this soil is very poor, and the permeability is very low: hydraulic conductivity at saturation is only 0.02–0.22 mm d^{-1}, which is in the low water-permeability range (Chi and Wang, 2010). The rate of infiltration decreases quickly 10 min after irrigation, and by about 15 min after irrigation the water nearly ceases infiltrating (Wang et al., 2004). Thus there are difficulties in renewing the *L. chinensis* grassland under these conditions.

With more attention paid to the environment, people have realized the importance of recovery of the grassland, and have taken many measures in its reclamation. The traditional methods mainly included enclosure to exclude grazing (Yang and Baoyin, 2008; Zuo et al., 2009), tillage (Gilbert et al., 2003), and application of manure, gypsum and sand (Li et al., 2003; Guo et al.,

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1998). These methods have played some part in the restoration of saline grassland, but they have some limitations: e.g. enclosure requires a long time to enable grassland to reach a good condition, and the other methods involve physical limitations in their application and high costs. Therefore, considering the characteristics of the soils in the Songnen Plain, it is important to find a good way to quickly restore and reconstruct the saline-sodic grassland.

Drip irrigation can distribute water uniformly, precisely control the amount of water, increase plant yields, reduce evapotranspiration (ET) and deep percolation, and decrease dangers of soil degradation and salinity (Batchelor et al., 1996; Ayars et al., 1999; Karlberg and Frits, 2004). In addition, drip irrigation can supply water at low discharge rates and high frequencies over an extended period, and minimize salinity levels in the soil water by the leaching of salts (Keller and Bliesner, 1990). Because of the point-source characteristic of drip irrigation, the salts will be pushed toward the fringes of the wetting area along with water, and form a desalinization zone in its center, in close proximity to the emitter (Goldberg et al., 1976; Kang, 1998). Many studies have shown that drip irrigation on saline soil is an important method for improving saline land (Wan et al., 2007; Chen et al., 2009, Kang et al., 2010). Soil matric potential (SMP), 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). Installing a tensiometer at a depth of 0.2 m is an efficient method for scheduling of drip irrigation (Kang, 2004). Jiao et al. (2007) experimented on saline soils in Ningxia Province by presetting the threshold SMP of −5, −10, −15, −20 and −25 kPa to control the timing of the irrigation cycle using vacuum tensiometers buried 0.2 m deep immediately under drip emitters. They found that the highest plant production was for SMP of −5 kPa. Based on this research, the authors' research group used this method for grassland restoration, with irrigation applied when the SMP reached the target values.

The objectives of this study were (1) to show the soil water and salt distributions for different SMP threshold regimes under drip irrigation, (2) to examine the effects of different SMP thresholds on *L. chinensis* growth, and (3) to provide a basis for irrigation scheduling and for use in rapid grassland restoration and reconstruction on saline-sodic grassland in northeast China.

2. Materials and methods

2.1. Experimental site

The field experiments were carried out during 2008 and 2009 in Da'an sodic land experiment station of China. The station (45°35′58″–45°36′28″N, 123°50′27″–123°51′31E) is in the western part of the Songnen Plain, northeast China. The climate of the area is a combination of temperate, semi-humid and semi-arid monsoon. Annual average temperature is 3–5 °C. Annual average precipitation is 413.7 mm, of which 70–80% is during July–September. The average evaporation in this region is 1791.6 mm, up to 4–5 times the annual precipitation. Seasonal drought is frequent in spring and autumn, and 90% of springs experience drought, the Salts accumulate in the soil profile. The groundwater level changes from 1 to 3 m. The soil in this area is a severely saline-sodic soil, which is nature of the soil and average bulk density of 1.5. Irrigation mainly depends on groundwater pumped from depths of 110 m; the electrical conductivity of the irrigation water is 0.92 dS/m and the pH value is 8.22. A drainage ditch about 1.5 m far from the experimental area was arrangement in the field at a length of 50 m, width of 0.5 m and depth of 0.35 m. The soil physical and chemical properties are shown in Table 1.

2.2. Experimental design

There were five SMP treatments, with SMP at 0.2 m immediately under emitters of −5, −10, −15, −20 and −25 kPa for the S1–S5 treatments, respectively. Irrigation was applied only when the SMP reached the targeted values for the S1–S5 treatments. All treatments were replicated three times, with experimental plots in a complete randomized block design.

Each treatment plot was equipped with an independent gravity-type irrigation system. The irrigation system consisted of a plastic barrel (400 L) used as a water source, 18 drip tubes (six tubes per plot), a ball valve installed under the bottom of the barrel to control irrigation and an outlet 1.2 m above the ground surface. Drip tubes with emitters spaced 0.2 m apart were placed at the center of each raised bed (Fig. 1).

2.3. Agronomic practices

The field experiments were conducted during the *L. chinensis* growing season (from early May to late September) in 2008. The *L. chinensis* were transplanted from a wild *L. chinensis* community local to the experimental land. Each plot was 4.8 m × 4 m, and contained six raised (15 cm in height) beds. The width and length of the beds were 0.8 m and 4.0 m, respectively (Fig. 1). *L. chinensis* were single-row planted on each bed with row spacing of 0.8 m and interplant spacing of 0.4 m. Before each irrigation, 40 g of urea, 10 g of phosphate, and 16 g of potassium dihydrogen phosphate were added into the barrel, so that fertilizer was applied with the irrigation water.

2.4. Observations and equipment

2.4.1. SMP

Five tensiometers were installed at a depth of 0.2 m under drip emitters for each treatment to determine SMP. The tensiometers were read daily at 7:00 a.m., 14:00 p.m. and 18:00 p.m. Irrigation was started when the SMP fell below the target value. Each application of irrigation water was 3.5 or 7 mm according to the water requirements of plants at the different growth periods.

2.4.2. L. chinensis growth

The height, number and length of spikes, number of tillers, extended distance, coverage and aboveground biomass were measured. Quadrats of 1 m^2 were randomly selected and fixed in each plot of all treatments for observations of height, number and length of spikes, number of tillers, extended distance at 30-d intervals during *L. chinensis* growth. Another 1 m^2 area was randomly selected and sampled in each plot for aboveground biomass at the end of the growth period. The coverage of *L. chinensis* was measured using a plant canopy analyzer (LAI-2000, LI-COR, America) on 14 August 2009, which was during the vigorous growth stage.

2.4.3. Soil physical–chemical properties

Soil samples were obtained from each plot with an auger (2.0 cm in diameter and 15 cm in height) on 20 September 2009. The horizontal distances to drip emitters for sampling were 0, 8, 16, 24, 32 and 40 cm, and sample depths were 0–120 cm. The soil water content was determined gravimetrically. The three replications of soil samples were mixed into one sample per treatment for analyzing electrical conductivity. All soil samples were air-dried and sieved, and the electrical conductivity of saturated-soil extract (ECe) and pH were determined using conductivity meter (DDS-11A, REX, Shanghai) and pH meter (PHS-3C, REX, Shanghai). Distilled water was added to a 50-g soil sample while stirring with a spatula until it reached the criteria for saturation according to guidelines in USDA Handbook 60 (USDA, 1954). Saturated

Table 1
Physical and chemical properties of tested soil.

Soil layers (cm)	pH	EC_e (dS/m)	Total salt (g/kg)	Total nitrogen (g/kg)	Total phosphorus (g/kg)	Total potassium (g/kg)	Organic carbon (g/kg)
0–10	9.79	15.25	4.17	0.50	0.10	34.80	6.10
10–20	9.77	13.56	3.83	0.60	0.11	33.80	7.80
20–30	9.82	13.2	5.83	0.60	0.11	32.30	7.90
30–40	9.88	12.02	7.5	0.40	0.10	30.10	7.40
40–60	9.86	11.39	4.92	0.30	0.09	30.20	4.10
60–80	9.69	8.6	3.99	0.30	0.08	28.50	3.90
80–100	9.62	5.16	3.35	0.20	0.08	29.10	2.90
100–120	9.42	3.69	4.44	0.20	0.08	31.90	1.60

Note. Soil samples were measured by the saturated-soil extract, water samples were obtained using a centrifuge, and the water extract was measured for total dissolved solids, ECe and pH.

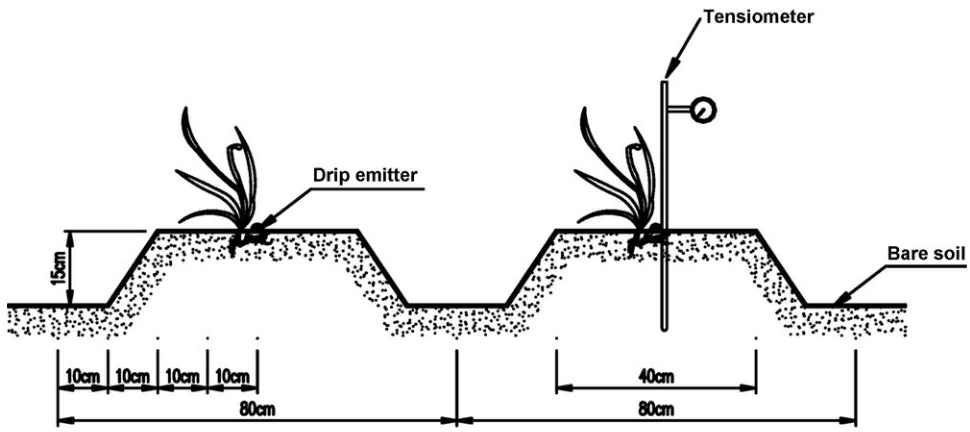

Fig. 1. The schematic diagram of ridging.

pastes were allowed to stand for 16 h, and then a water sample was obtained using a centrifuge. Total nitrogen was determined by Kjeldahl's method. Soil samplers were digested with H_2SO_4–$HClO_4$ to measure total phosphorus with molybdenum-antimony anti-spectrophotometric method. Total potassium was measured with the method of alkali fusion and flame photometer. Soil organic carbon was measured by dichromate oxidation with heating (Bao, 2000).

2.4.4. Evaporation and rainfall

A 20 cm diameter evaporation pan and a rain gauge were installed in plot S2. The height of the evaporation pan was adjusted according to the growth of *L. chinensis*. Pan evaporation and rainfall were observed at 8:00 a.m. daily.

2.4.5. Statistical analysis

The treatments were run as a single-factor analysis of variance (ANOVA) by SPSS Version 16.0. The ANOVA was performed at $\alpha = 0.05$ level of significance to determine if significant differences existed among treatment means.

3. Results and discussion

3.1. The amount of precipitation, evaporation and irrigation of different treatments during the growth period

The total rainfall was 244.2 and 271.65 mm in 2008 and 2009, respectively, during the growing season. The rainfall amount during 2008 and 2009 is shown in Fig. 2. In 2008, rainfall was uniform distributed from May to September. About 80% of the total rainfall in 2009 was in June–July, and very little after August – the weather was extremely dry, and the evaporation very high during this time. The total evaporation in 2009 during *L. chinensis* growing season was 537.8 mm, which was 2.3 times the precipitation during that time.

The date of transplanting of *L. chinensis* was 14 June 2008, and on 7 July 2008 the different SMP treatments began. Before the treatment, all plots were irrigated with the same amount of water in order to maintain uniform *L. chinensis* growth. The cumulative

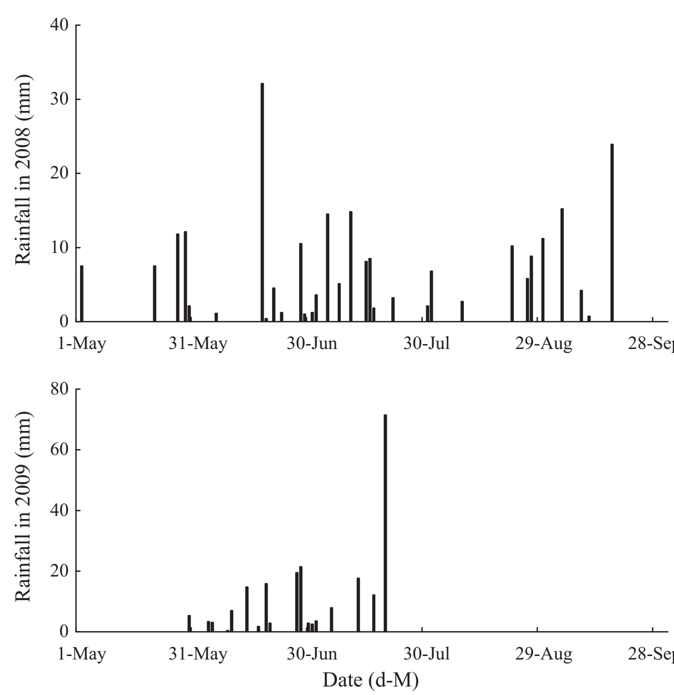

Fig. 2. Rainfall during *L. chinensis* growth season in 2008 and 2009.

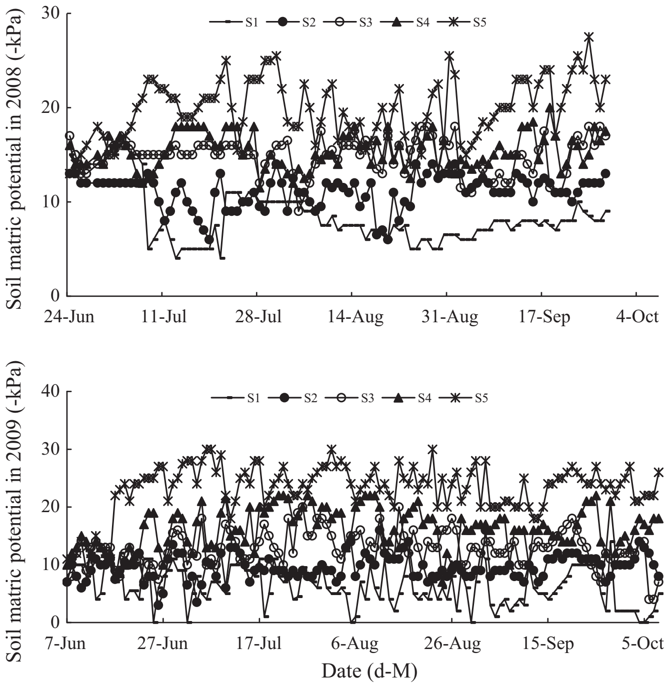

Fig. 3. The change of soil matric potential at 0.2 m depth under emitters for different treatments in 2008 and 2009.

irrigation amounts of the S1–S5 treatments were 135, 131, 124, 111 and 83 mm in 2008, respectively, and 411, 383, 359, 307 and 214 mm in 2009. In the first year, because the plant height of *L. chinensis* was small and it had to establish itself after transplanting, the different SMP made little difference since there were multiple and frequent rainfall events during the growth period. In the second year, there were significant effects of each treatment, particularly the higher irrigation volumes of S1 and S2 treatments compared to S3–S5 treatments.

3.2. SMP distribution under different treatments

During the experiment, the SMP at depths of 0.2 m was generally affected by the target values of SMP (Fig. 3), and the average SMP increased with the increase of the target value. The variation range of SMP in the first year was very small following irrigation. The effect of irrigation on SMP of S1 was very low, with SMP remaining almost unchanged after irrigation for 1 or 2 d, and any effect on S2 was also not obvious. However, the change in S5 was more evident; it increased rapidly after irrigation, because the surface of the saline-sodic soil is compacted, water permeability is poor, and so if irrigated frequently, the water does not infiltrate quickly, and so the SMP cannot respond quickly. Compared to the first year, the response of SMP to irrigation in the second year was faster. When SMP reached the target value, the irrigation was commenced, and SMP increased soon after. SMP regularly fluctuated around the target of each treatment. The SMP of all treatments was very sensitive to irrigation, and when the irrigation began the SMP quickly responded. After one year of drip irrigation, the soil structure was ameliorated, the permeability had improved, and the irrigation water infiltrated more easily.

3.3. Distribution of soil water content in profiles of different treatments

Rainfall was frequent during the growth period in the first year, and the amount of irrigation water used was small; the volumes of irrigation water of S1–S5 treatments were not significantly different, and so the soil water contents of treatments were similar. Affected by soil surface evaporation, the soil water content in the surface soil was a little lower than for the 10–20-cm layer. Due to the supply of water from above and the effect of the groundwater, the soil water contents in the 80–120-cm layer were almost the same for the five treatments. The soil water content was higher in the second than in the first year, and soil water was concentrated in the 20–40-cm layer; with increased SMP, the soil water content increased. In the root layers, the soil water content of the S1 treatment was highest and that of S5 the lowest (Fig. 4). However, in deeper layers, the soil water content was not significantly different due to the effect of groundwater.

Table 2
The nutrient content of each treatment after reclamation.

Treatment	Total nitrogen (g/kg)	Total phosphorus (g/kg)	Total potassium (g/kg)	Organic matter (g/kg)
S1	0.66	0.22	38.2	7.89
S2	0.64	0.27	39.4	8.73
S3	0.67	0.25	37.5	8.22
S4	0.61	0.21	36.4	7.81
S5	0.63	0.26	37.2	7.33

3.4. Distribution of EC_e in soil profiles of different treatments

The distribution of salts was effected by drip irrigation. Before planting *L. chinensis*, a mass of salts had accumulated at the soil surface, and the EC_e was 15.25 dS/m (Fig. 5). After cropping under drip irrigation, soil salts in all sampled layers decreased significantly, especially in the 0–10-cm layer. Around the emitter, there was a low salinity zone that expanded outward with increased SMP. In the first year, the depth of low salinity was about 10 cm and in the second year it reached 0.2 m, with the range larger with increased SMP. After one year of drip irrigation, the salt was mainly distributed in the 20–30-cm layer; however, in the second year, with the increased amount of irrigation water, the salts were leached to deeper layers, and were concentrated in the 40–60-cm layer. After two years of drip irrigation, the salts in the root layers had been well leached, and moved down with water and entered deeper levels. For S4 and S5 treatments, the differences between layers were not significant, as the quantities of irrigation water for the two treatments were similar. The drip irrigation inhibited the buildup of salts in the root zone and the effect was stronger with increased SMP; the higher the SMP was, the better the salts were leached. After two years of drip irrigation, the salts of S1 and S2 were more leached than for the S3–S5 treatments.

3.5. The effect on pH and soil nutrient

The pH of each treatment was a little decreased after reclamation; the values were 9.71, 9.70, 9.74, 9.73 and 9.77 of S1–S5. The soil nutrient content of total nitrogen, total phosphorus, total potassium, organic carbon were all increased after reclamation, but there were no obvious differences of the five treatments (Table 2).

3.6. The effect of different SMP on L. chinensis growth

*L. chin*ensis was transplanted on 14 June 2008. The effect of different SMP on *L. chinensis* mainly reflected in height, spike number and length, number of tillers, coverage, and aboveground biomass.

3.6.1. The effect on L. chinensis height

The plant height of different treatments from 13 May to 30 August after two years of drip irrigation are shown in Fig. 6.

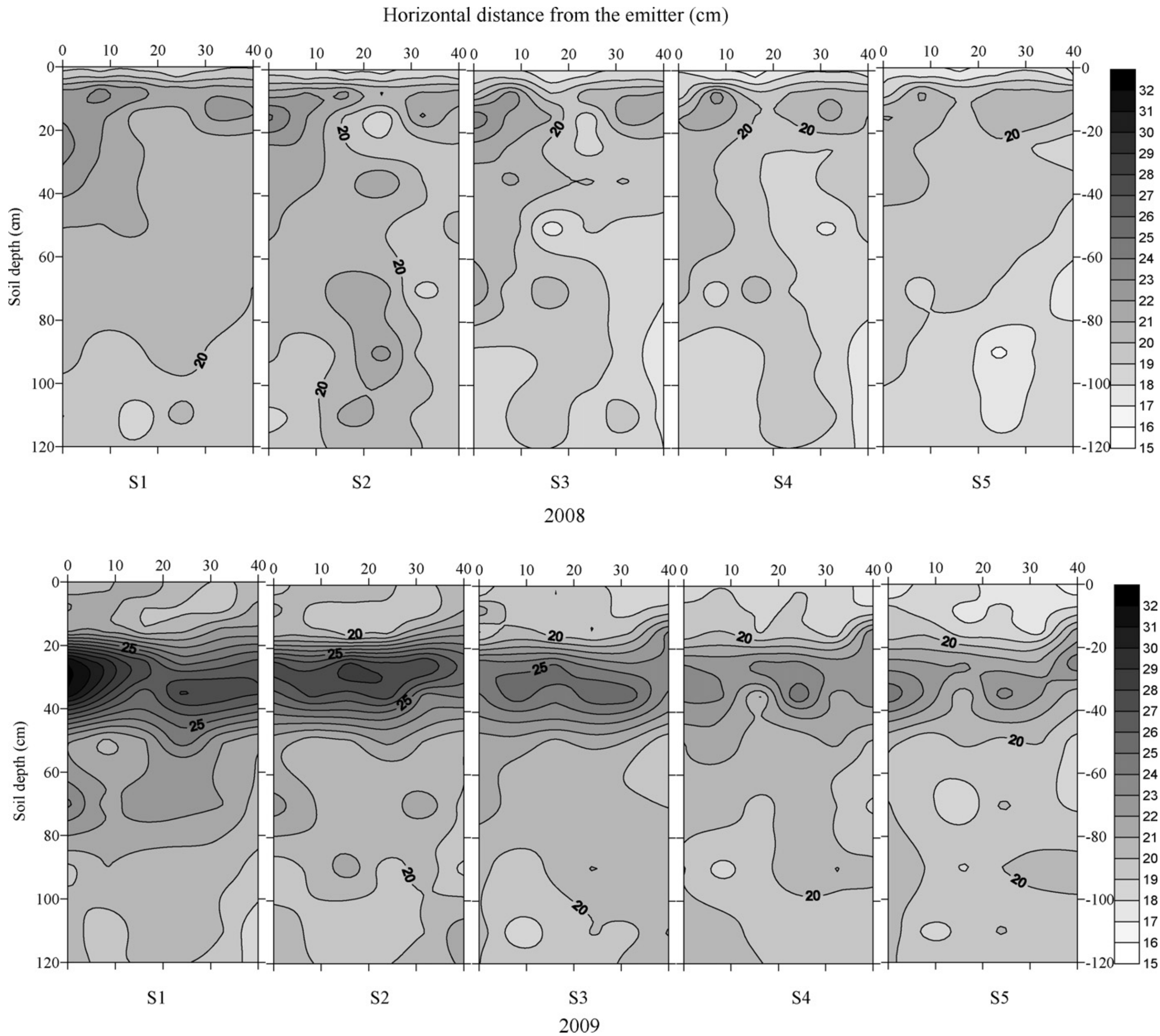

Fig. 4. Distribution of soil water content (%) in profile for different treatments in 2008 and 2009.

During the growth of *L. chinensis*, the height trends of all treatments were similar (Table 3); at the green stage in May 2009, the height of all treatments was very similar, at about 0.2 m. During the jointing stage, *L. chinensis* grew quickly, and height increased quickly following drip irrigation; the growth rate reached >0.6 cm d^{-1} for the S1 and S2 treatments, and 0.46, 0.44 and 0.39 cm d^{-1} for the S3–S5 treatments, respectively. After this stage, the growth slowed and the height of all treatments reached a maximum. During August, the height of *L. chinensis* remained stable. Plant height generally increased with increased SMP, and the heights of S1 and S2 treatments were not significantly different, but were much larger than for S3–S5 treatments.

Table 3
The growth of *Leymus chinensis* after one year drip irrigation.

Treatment	Height (cm)	Number of tillers	Coverage (%)
S1	16.78	10	13.20
S2	15.51	11	12.50
S3	14.17	11	11.70
S4	15.42	10	12.12
S5	14.17	10	10.80

3.6.2. The effect on spike number and length

The spike number and lengths during the *L. chinensis* heading stage for the five treatments are shown in Fig. 7. In 2009, the heading stage was from early June to the end of July. During this stage, the trends of spike number and lengths for all treatments were similar. From early to mid-June, the spike number and lengths increased very quickly, and the growth slowed from the end of June to July. After the heading stage, the spike number and length no longer changed. The spike number and length generally increased with increased SMP, with no significant differences between the spike number and lengths of the S1 and S2 treatments, similar to the effect on plant height.

3.6.3. The effect on tillers

L. chinensis develops rhizomes and has a high tillering ability. The tillering state of *L. chinensis* in terms of density, the verti-

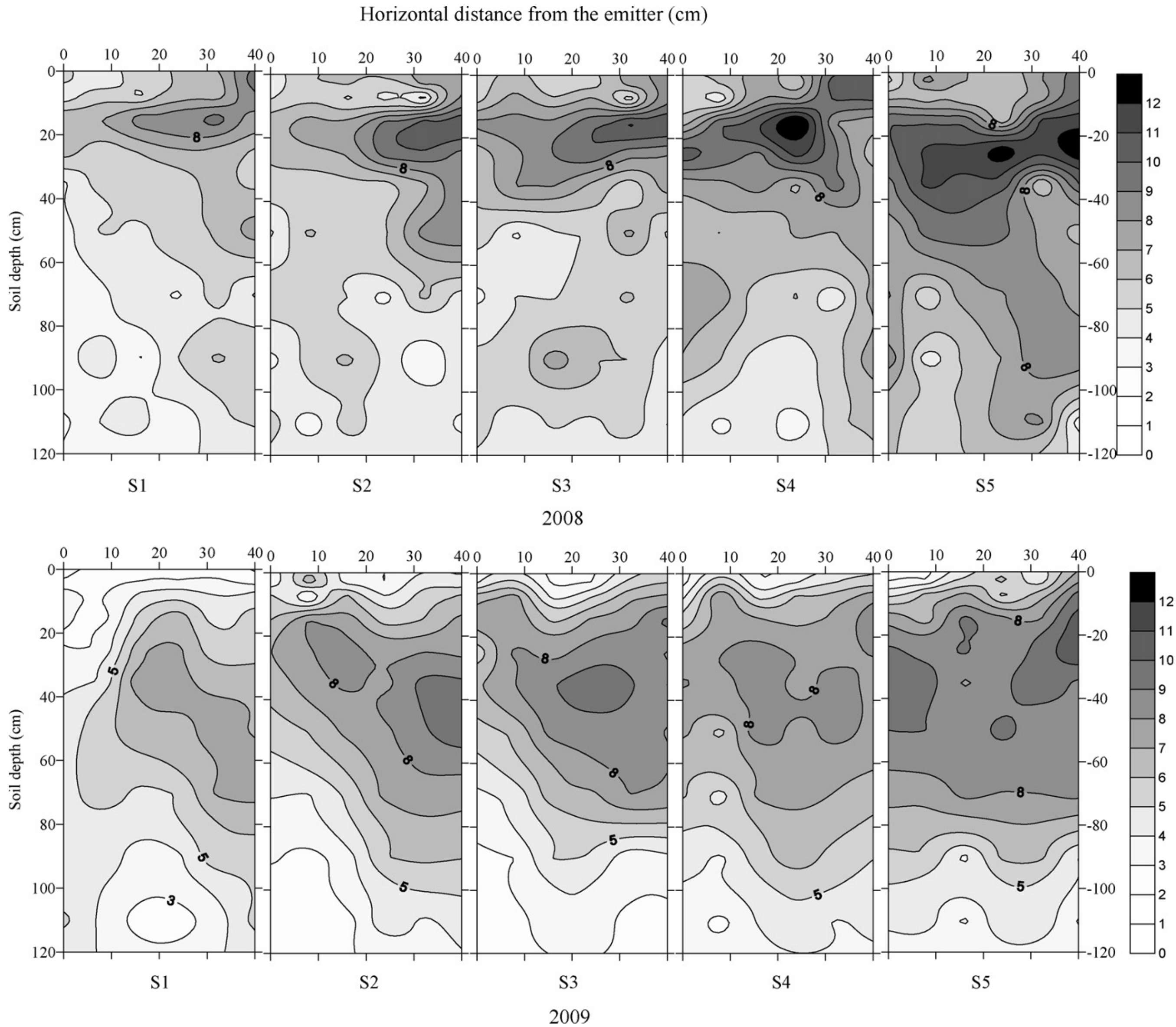

Fig. 5. Distribution of ECe (dS/m) in profile for different treatments in 2008 and 2009.

cal extended distance and parallel extended distance is shown in Table 4. The density and the extended distance at the vertical ridge direction of the five treatments decreased with reduced SMP. Treatments S1 and S2 had more tillers and longer extended distance in the vertical ridge direction than the S3–S5 treatments. The parallel extended distances of S1 and S2 were not significantly different, but were both significantly different to S3–S5 treatments. The higher the SMP, the greater was the tillering ability of *L. chinensis*, with more in the vertical than the parallel direction.

3.6.4. The effect on L. chinensis coverage

The coverage of S1–S5 treatments were 60, 67, 53, 43 and 17%, respectively. S1 and S2 were higher than the other three treatments, and were ≥60%. The coverage of S3–S5 increased with increased SMP. The S5 treatment had the lowest coverage of only 17%. The SMP had close relationship to the coverage of *L. chinensis*.

3.6.5. The effect on aboveground biomass

At the end of the growth period in the second year, the aboveground biomass of *L. chinensis* was surveyed: in 1 m^2 quadrats of

Table 4
Tillers of *Leymus chinensis* for different treatments in 2009.

Different treatments	*Leymus chinensis* density (plant number point^{-1})	Expended distance at the vertical ridge direction (cm)	Expended distance at the vertical ridge direction (cm)
S1	54.00^{a}	22.04^{a}	21.75^{a}
S2	53.00^{a}	22.56^{a}	21.61^{a}
S3	43.38^{b}	17.49^{b}	21.32^{b}
S4	44.25^{b}	17.21^{b}	21.18^{bc}
S5	41.15^{b}	17.20^{b}	21.02^{c}

Values in a row followed by the same letter are not significantly different at P≤0.05.

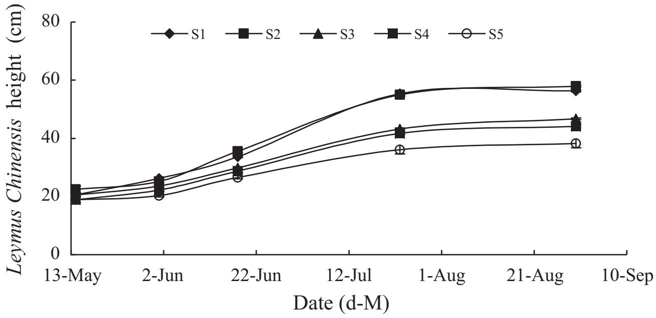

Fig. 6. *L. chinensis* height for different treatments in 2009.

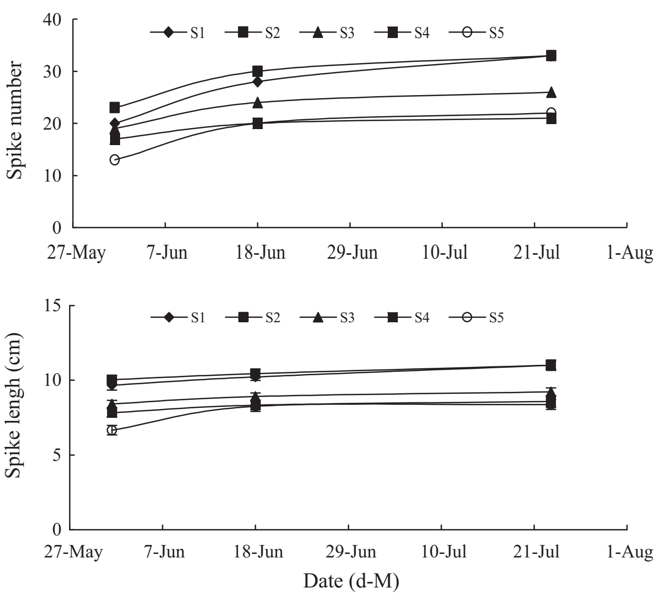

Fig. 7. *L. chinensis* spike number and length for different treatments in 2009.

the S1–S5 treatments it was 285.48, 279.32, 232.24, 220.31 and 215.29 g, respectively. The aboveground biomasses of the S1 and S2 treatments were not significantly different, but were significantly more than those for the S3–S5 treatments.

4. Conclusions

After two years of drip irrigation on saline-sodic soils, there were large effects on water and salt distributions and on *L. chinensis* growth.

In the root zone, the soil water content increased with increased SMP, but in the deeper layers the soil water content was not significantly different due to the effect of groundwater. Drip irrigation inhibited the buildup of salts in the root zone and the effect was stronger with SMP, producing a low-salt zone near the emitters. The higher the SMP, the more the salt was leached. The salts of treatments S1 and S2 were leached more than for those of the S3–S5 treatments. The EC_e of treatments S1–S5 all decreased compared to the unreclaimed land, with the effect stronger with increased SMP. After two years of drip irrigation, the surface salts had been well leached and moved down with the water to deeper levels. The pH of each treatment was a little decreased and the soil nutrient of total nitrogen, total phosphorus, total potassium, organic carbon of S1–S5 were all increased after reclamation, but it had no obvious differences of the five treatments.

During the growth of *L. chinensis*, the height, spike number and length, tillers, coverage, and aboveground biomass were clearly affected by SMP irrigation regimes, which generally increased with increased SMP. Additionally, the S1 and S2 treatments were not significantly different, but had higher values than the S3–S5 treatments.

Based on the results of the different treatments, it is recommended that in the Songnen Plain drip irrigation be used on transplanted *L. chinensis* for the restoration and reconstruction of saline-sodic soils. With SMP between −5 and −10 kPa, the salts were more leached, and the soil water could attain a good quality that was optimal for *L. chinensis* growth. This provides theoretical and technological guidance for sustainable reclamation and use of salt-affected soil, and also for quick restoration and reconstruction of saline-sodic grassland.

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