Effects of irrigation level and method on soil salt balance and crop water use efficiency in arid oasis regions

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Abstract: Fresh water resource scarcity and soil salt accumulation in the root-zone are two key limiting factors for sustainable agricultural development in the oasis region of arid inland basin, northwest China. The aim of this study was to explore an appropriate irrigation scheme to maintain sustainable crop cultivation in this region. The effects of four irrigation levels (full irrigation, mild deficit, moderate deficit, and severe deficit) and three irrigation methods (border, surface drip and subsurface drip) on soil water and salt dynamics, highland barley (*Hordeum vulgare* L.) yield, and crop water use efficiency were studied by field plot experiments. The results showed that soil salt in 0-100 cm profile was accumulated under all experimental treatments after one season of highland barley planting, but the accumulated salt mass decreased with the decrease of the lower limit of irrigation. Salt mass in 0-100 cm soil profile under subsurface drip irrigation was 16.8%-57.8% and 2.9%-58.4% less than that under border and surface drip irrigation, respectively. The grain yield of highland barley decreased first and then increased with the decrease of the lower limit of irrigation under surface drip and subsurface drip irrigation, but it was on the contrary under border irrigation. Mean grain yield for all irrigation levels under subsurface drip irrigation was 5.7% and 18.8% higher than that under border and surface drip irrigation, respectively. Water use efficiency increased with the decrease of the lower limit of irrigation, and the averaged water use efficiency of all irrigation levels under subsurface drip irrigation was 11.9% and 14.2% higher than that under border and surface drip irrigation, respectively. Considering economic benefit and irrigation water requirement, subsurface drip irrigation with the lower limit of irrigation of 50%-55% field capacity is suggested for highland barley planting in the arid oasis region.

Keywords: arid oasis, highland barley, irrigation method, irrigation level, soil salt balance, water use efficiency
DOI: 10.25165/j.ijabe.20231606.7788

Citation: Tang L P, Shi X S, Song Z P, Zhao H, Li F H. Effects of irrigation level and method on soil salt balance and crop water use efficiency in arid oasis regions. Int J Agric & Biol Eng, 2023; 16(6): 158–166.

1 Introduction

Qaidam Basin is located on the northeastern margin of Qinghai-Tibet Plateau, surrounded by mountains over 5000 m above sea level. It is an extremely arid region with typical plateau continental desert climates[1], and more than 60% of its surface area is covered by Gobi desert. All rivers in the basin are inland and their runoff comes from the melting water of ice and snow on the surrounding mountains. The quality of runoff water or groundwater depends on its specific site in the alluvial fan, and its salinity is increasing gradually along the river from its upper to lower reaches[2]. Total oasis area in the basin is about 830×10^3 hm^2, and it is one of the important commercial grain production bases in Qinghai Province, China. The oases are randomly scattered throughout the basin, and the farmland area in each oasis is small, which results in low agricultural water use efficiency, severe waste of water resources and secondary salinization of soils. The contradiction between supply and demand on fresh water resources in this region is very serious[3], and oasis agriculture is facing a great challenge[4,5]. In recent years, crop yield has declined in some farmlands due to the increased salt stress, in which sometimes has to be abandoned to cultivation. Maintaining the sustainable development of agriculture and ecological environment in oasis area has become a key factor affecting local social stability and development[6].

Highland barley, with the characteristics of short growth period and cold and drought resistance, is the main food crop and important feed and industrial raw material in the Qinghai-Tibet Plateau region. It is mainly planted in Tibet Autonomous Region of China and its surrounding regions, as well as other plateau regions in the world[7-9]. Drought is one of the most important abiotic factors affecting the growth of highland barley[10]. Soil water deficit affects many crop properties such as morphology, physiology, and metabolism, and ultimately adversely affects crop growth and its grain yield[11-13]. The theoretical water requirement of highland barley in the whole growth period was 322.7-462.5 mm in Tibet Autonomous Region calculated on meteorological data[14]. The field experimental result of Shi et al. showed that total water use of highland barley in Shigatse District, Tibet was 725.7 mm[10]. Due to the non-uniformity of rainfall, supplementary irrigation is an effective means to achieve stable and high yield of crops in the semi-humid and semi-arid regions with relatively high rainfall[12]. Previous studies have shown that the water use efficiency of highland barley increased with the increase of water deficit stress,

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Received date: 2022-07-13 **Accepted date:** 2023-09-05

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and its irrigation water requirement was decreased accordingly[10,15]. However, due to the extremely arid natural conditions, the water use law of highland barley planting in the oasis region of Qaidam Basin is not well understood at present. Deficit irrigation strategy is the preferred management measure to maintain crop survival and improve its water use efficiency in arid region[16,17], but the potential risk of soil secondary salinization as a result of decreased application of irrigation water is existed[12]. The irrigation regime of highland barley suitable for the natural conditions of extremely arid alpine inland basin has not yet been established.

As a water-saving irrigation technology, drip irrigation (including surface and subsurface drip) can accurately provide water and fertilizer to the root zone of crops[6,18-21]. Its application reduces excessive evaporation loss from soil surface[22,23] and increases crop yield and water and fertilizer utilization efficiencies[24-28]. Therefore, it is feasible to apply water management measures based on deficit irrigation strategy, combining a water-saving irrigation technology, to improve crop water use efficiency to a greater extent in the region where fresh water resource is scarce[13,17,29-31]. This water application strategy is especially suitable to crop irrigation management in arid regions[25,26,32,33].

Due to the restriction of investment on basic farmland construction projects, traditional surface irrigation method is still used in most oasis farmlands in Qaidam Basin at present. Moreover, highland barley, as the main crop planted in the oasis area of the basin, has not yet formed a generally accepted water-saving irrigation regime due to the lack of reliable field experimental data on farmland irrigation. This adversely affects the effective use of local precious freshwater resources and the sound development of oasis agriculture. Therefore, the objectives of this study were: 1) to determine the effects of irrigation level and irrigation method on soil water and salt dynamics as well as the yield and water use efficiency of highland barley; 2) to explore an appropriate irrigation scheme for crop cultivation in the oasis region of arid inland basin to promote the sustainable development of local oasis agriculture.

2 Materials and methods

2.1 General description of experimental site

The experiment was carried out from April to August 2019 in the Nuomuhong Farm of Qinghai Province (96°27'E, 36°22'N, altitude 2790 m above sea level) in the southeast of Qaidam Basin. Nuomuhong oasis, where the Farm is located, is about 20 km long from east to west and 5 km wide from north to south, with an irrigated farmland area of about 6500 hm^2. The mean annual rainfall, water evaporation, and air temperature from 1956 to 2018 are 57.1 mm, 2820 mm, and 4.3°C in this region, respectively, and its frost-free period is 112-143 d. Soil texture in 0-40 cm soil profile is mainly sandy loam in the experimental area, with the clay ($\leq$0.002 mm), silt (0.002-0.020 mm), and sand (0.02-2.00 mm) particle contents of 13.9%, 17.0%, and 69.1%, respectively. The field capacity of the soil is 29.8% (v/v), and its average bulk density and organic matter content are 1.38 g/cm^3 and 10.8 g/kg, respectively. Total nitrogen, phosphorus, and potassium contents in the soil are 0.80, 0.52, and 1.74 g/kg, and available phosphorus and potassium contents are 12.4 and 95.6 mg/kg, respectively. Groundwater level depth in this region is about 13.0 m. Daily meteorological data during the experimental period, including rainfall, air temperature, evaporation, humidity, and wind speed, were obtained from an automatic weather station about 150 m away from the experimental site.

2.2 Experimental design and treatments

The tested crop was Kunlun 14 variety of highland barley (*Hordeum vulgare* L.). According to local production habits, in order to suppress salt accumulation on surface soil, the experimental field was irrigated with water of 90 mm before sowing, and then it was ploughed and sowed after the soil was evaporated to appropriate water content. Diammonium phosphate ($N+P_2O_5\geq$ 64.0%) with a rate of 300 kg/hm^2 was applied as base fertilizer before the plowing. Highland barley was sown manually on April 26, 2019 with a row spacing of 25 cm, and its sowing density was 150 kg seed/hm^2. The growth period of highland barley was divided into five stages including seedling (May 2-May 25), jointing (May 26-June 15), heading (June 16-June 28), filling (June 29-July 21), and maturity stages (July 22-August 17). As topdressing fertilizers, urea was applied once at the seedling stage with a rate of 75 kg/hm^2, and the diluted solution of potassium dihydrogen phosphate was sprayed on leaves twice at the heading stage with a dosage of 2.25 kg/hm^2 each time. The other farmland management measures were the same as local production practices. Highland barley was harvested on August 17, and its whole growth period was 114 d. The variations of daily rainfall and mean air temperature with time after crop sowing are shown in Figure 1 during the experiment. The total rainfall during the growth period of highland barley was 39.2 mm, mainly in June and July, which accounts for 65.1% of the total annual rainfall. The maximum rainfall was 13.7 mm on July 3, and other rainfall events were generally less than 5.0 mm. Averaged daily temperature increased gradually with crop growth time, and it was generally between 10°C and 20°C in the whole growth period of highland barley (Figure 1).

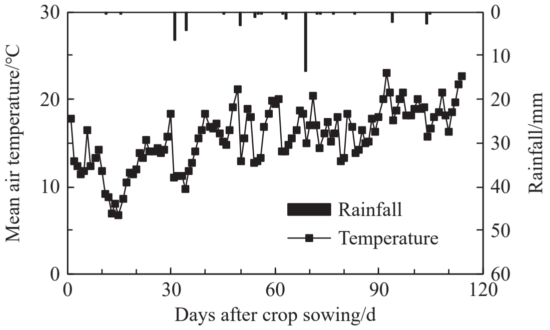
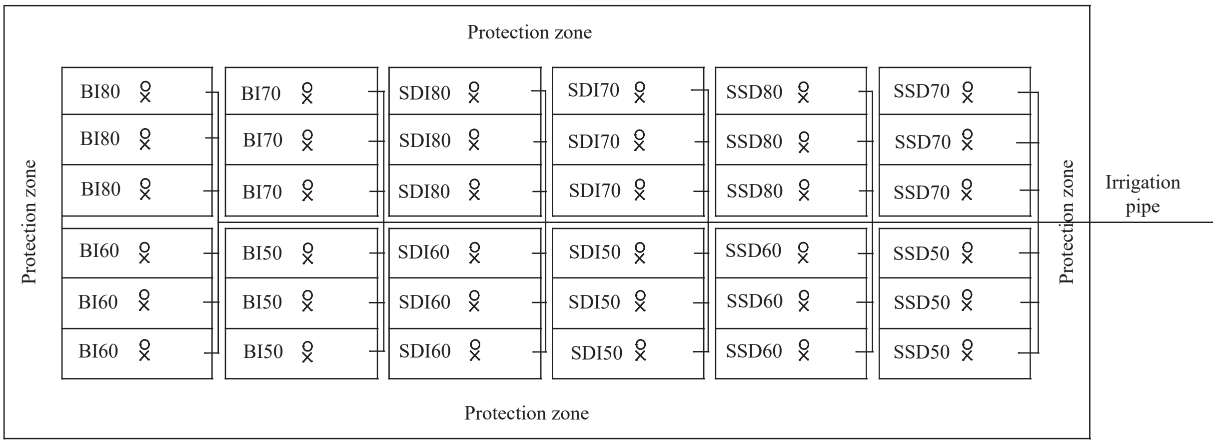


Figure 1 Variations of rainfall and mean air temperature with time after the sowing of highland barley

The entire experimental field was surrounded by a protective zone with a width of 3.0 m, and the same crop was grown in the protective zone. The experimental treatment layout is shown in Figure 2. Experimental plot for each replication was 7.5 m×3.6 m in size, and soil ridges with 40 cm in width and 20 cm in height were set among the plots. In order to prevent the lateral seepage of irrigation water, a plastic film was installed around the each plot from the top of soil ridges to a depth of 60 cm below the ground surface.

Experimental treatments were consisted of four irrigation levels (full irrigation, mild deficit, moderate deficit, and severe deficit) and three irrigation methods (border, surface drip, and subsurface drip), and total experimental treatments were 12. Three replications were set for each treatment. The lower limits of irrigation for full irrigation, mild deficit level, moderate deficit level, and severe deficit level were 80%-85%, 70%-75%, 60%-65%, and 50%-55% of soil field capacity, respectively, throughout the whole crop growth season. The upper limit of irrigation for all experimental treatments was field capacity. When surface drip and subsurface drip irrigation were applied, each drip tape was arranged to control two rows of crops. The lateral spacing between drip tapes was 50 cm, and the distance between adjacent emitters was 25 cm. The working pressure of drip irrigation system was 0.6 MPa, and the flow rate of each emitter was 4.0 L/h. The drip tapes of subsurface drip irrigation were buried at 30 cm below the ground surface. The planned depth of wetting layer at seedling and jointing stages was designated to be 40 cm, and it was 60 cm at heading and filling stages based on the root development depth of highland barley. There was no irrigation in the mature stage of highland barley. Irrigated water was from groundwater, with an electrical conductivity (EC) of 0.78 dS/m, pH value of 7.83, and sodium adsorption ratio of 2.25 $(\mathrm{mmol/L})^{0.5}$. Based on the monitored soil moisture status, crops began to be irrigated when the soil water content averaged in the planned wetting layer approached to the lower limit of irrigation. The irrigation was stopped when the soil water content reached the upper limit of irrigation, that is, the soil field capacity. According to the designed deficit level of soil water, the amount of required irrigation water for each test plot was calculated, and its supply was monitored and controlled by a water meter.



Note: Circle and cross symbols refer to soil moisture monitoring sites and soil sampling points, respectively. BI, SDI, and SSD represent border irrigation, surface drip irrigation, and subsurface drip irrigation, and 80, 70, 60, and 50 represent that the lower limits of irrigation were 80%-85%, 70%-75%, 60%-65%, and 50%-55% of field capacity, respectively.

Figure 2 Schematic diagram of experimental treatment layout

2.3 Soil water content and salinity

During the growth period of highland barley, the volumetric water content of soil was measured every 5-7 d by a portable soil moisture measuring instrument, RIME-PICO TDR (IMKO, Germany), which was located on the side of drip tape in the middle of each test plot (Figure 2). The monitored soil depth was 0-20, 20-40, 40-60, 60-80, and 80-100 cm, respectively. An additional measurement of soil water content was carried out once irrigation or rainfall events occurred.

Soil EC and pH values were measured by DDS-307 conductivity meter (Rainz, Shanghai Daping Instrument Co., Ltd., China) and pH meter (PHS-3C, Shanghai Jingke Instrument Co., Ltd., China), respectively. Soil sampling site was arranged on the side of drip tape in the middle of each test plot (Figure 2), and the soils at the depths of 0-5, 5-20, 20-40, 40-60, 60-80, and 80-100 cm were sampled, respectively. The collected soil samples were naturally air-dried, ground and passed through a sieve with 2 mm aperture, and then soil extracts were prepared at the soil to water ratio of 1:5. After shaking and filtration, the EC and pH values of the soil extracts were determined, respectively. Soil EC and pH values were tested once at each growth stage of highland barley. Total salt content in soil was estimated according to Equation (1)[34]:

$$C_s = 3.6\mathrm{EC}_{1:5} \qquad (1)$$

where, C_S is the total salt content of soil, g/kg; $\mathrm{EC}_{1:5}$ is the electrical conductivity of soil extract with the soil to water ratio of 1:5, dS/m.

Salt balance in soil was calculated was based on Equation (2)[35]:

$$S_t = 100C_s\gamma h \qquad (2)$$

where, S_t is total salt mass in the calculated soil depth, kg/hm^2; C_s is total soil salt content, g/kg; γ is soil bulk density, g/cm^3; h is the calculated soil depth, cm.

2.4 Crop yield

An area of 2 m^2 with uniform growth status was selected in each experimental plot, and the highland barley on this area was harvested and threshed separately. The grains of highland barley in the selected area were dried naturally, measured with an electronic balance, and then converted into crop grain yield per acreage. All measurement procedures in the study were carried out according to relevant specifications or instrument operation instructions.

2.5 Crop water use and water use efficiency

Crop water use was calculated based on water balance method[10]:

$$\mathrm{ET_c} = I + P + R - R_f - D + \Delta W \qquad (3)$$

where, ET_c is the crop water evapotranspiration, mm; I is the amount of irrigated water, mm; P is the effective rainfall, mm; R is the contribution amount from groundwater, mm. Due to the deep groundwater level in the tested region, the contribution amount from groundwater was ignored; R_f is the runoff on soil surface, mm. Soil ridges and plastic films were set around each test plot to isolate runoff, so R_f=0; D is the deep percolation amount below the planned wetting depth, mm. Irrigation water volume applied for each experimental plot was determined based on the difference between soil water content and field capacity, and hence there was no deep ercolation from irrigation; ΔW=W_i – W_f is the change of soil water stored in the planned wetting layer within the calculated period, mm; W_i and W_f are soil water storage at the beginning and the end of calculated period, respectively, mm.

Water use efficiency of crop was calculated according to

Equation (4):

$$\mathrm{WUE} = Y_g / ET_c \tag{4}$$

where, WUE is the water use efficiency of crop, kg/m^3; Y_g is the crop grain yield, kg/hm^2; ET_c is the total crop water use, m^3/hm^2.

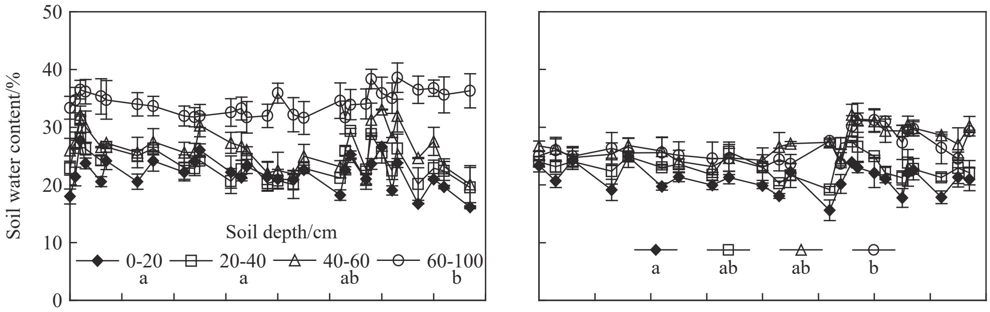
2.6 Data analysis

After examining the normality of experimental data (Shapiro-Wilk test) and the homogeneity of error variances (Levene's test) ($p\geq 0.05$), two-way analysis of variance (ANOVA) was used to test the main and interactive effects of irrigation level and irrigation method on soil salt mass, crop yield, crop water use, and crop water use efficiency. One-way ANOVA was used to further test their statistical significances among different treatment levels. Repeated-measures ANOVA was used to test the statistical significance of soil water content and soil EC over time among different depths after data sphericity test ($p\geq 0.05$). Pairwise comparisons of means were done using Tukey's post hoc tests ($p\leq 0.05$). All data analyses were performed with SPSS20.0 software (SPSS Inc., Chicago, USA).

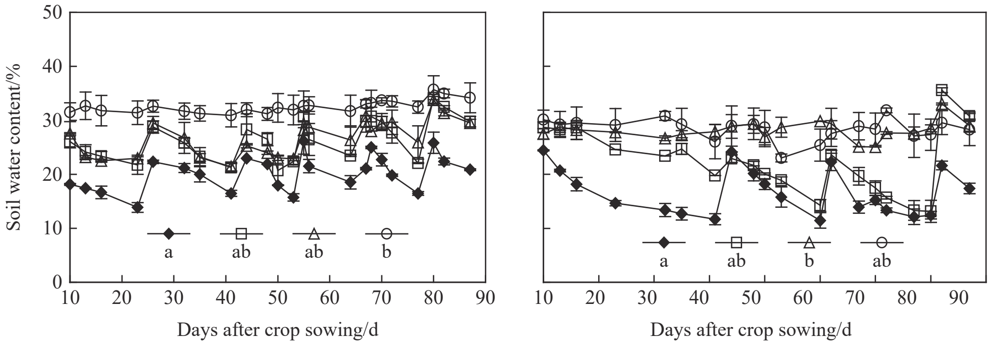
3 Results

3.1 Soil water content

The variation of soil water content with the growth time of highland barley under border irrigation is shown in Figure 3. The change tendencies of soil water content with time under surface drip and subsurface drip irrigation were similar to that under border irrigation, so their figures were not presented. Soil water content at different depths fluctuated regularly with crop growth time because of evapotranspiration and irrigation events, and its fluctuation in the upper soil layer was greater than that in the deep one (Figure 3). Soil water content increased with the increase of soil depth, and the averaged water content in the surface soil of 0-20 cm was significantly smaller than that in the deep soil (≥40 cm). In general, the higher the lower limit of irrigation was, the greater the soil water content was. The results of variance analysis show that the lower limit of irrigation imposed a significant effect on soil water content, while irrigation method did not (Table 1).



a. 80%-85% of field capacity b. 70%-75% of field capacity



c. 60%-65% of field capacity d. 50%-55% of field capacity

Note: Different lower-case letters in the figures represent significant difference ($p\leq 0.05$) between different soil depths. The same as below.

Figure 3 Variation of soil water contents at different depths with the growth time of highland barley under border irrigation at different lower limits of irrigation

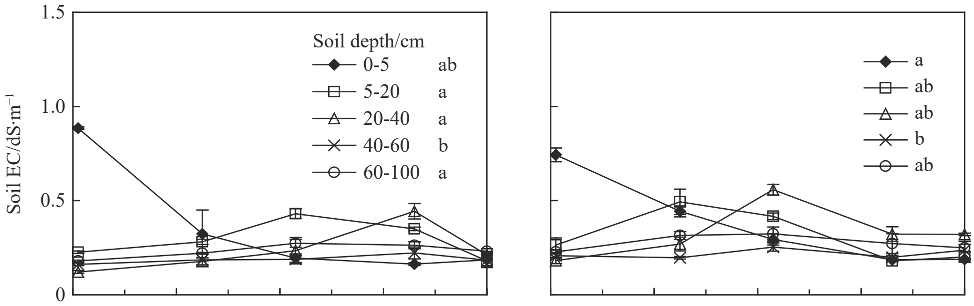
Table 1 ANOVA statistical significance of main and interactive effects of the lower limit of irrigation and the irrigation method on soil water content, soil EC, total salt mass in 0-100 cm soil layer, crop total water use, water use efficiency and grain yield as well as their effect sizes

Items	Soil water content		Soil EC		Total salt mass		Water use efficiency		Total water use		Grain yield	
	p value	Eta^2	*p* value	Eta^2	*p* value	Eta^2	*p* value	Eta^2	*p* value	Eta^2	*p* value	Eta^2
LLI[a)]	0.011$^{*b)}$	0.082	0.000***	0.189	0.000***	0.899	0.000***	0.793	0.000***	0.990	0.262$^{NSc)}$	0.151
IM	0.404^{NS}	0.014	0.000***	0.136	0.000***	0.569	0.031*	0.293	0.000***	0.834	0.119^{NS}	0.163
LLI × IM	0.841^{NS}	0.021	0.000***	0.153	0.003**	0.534	0.266^{NS}	0.294	0.006**	0.564	0.670^{NS}	0.145

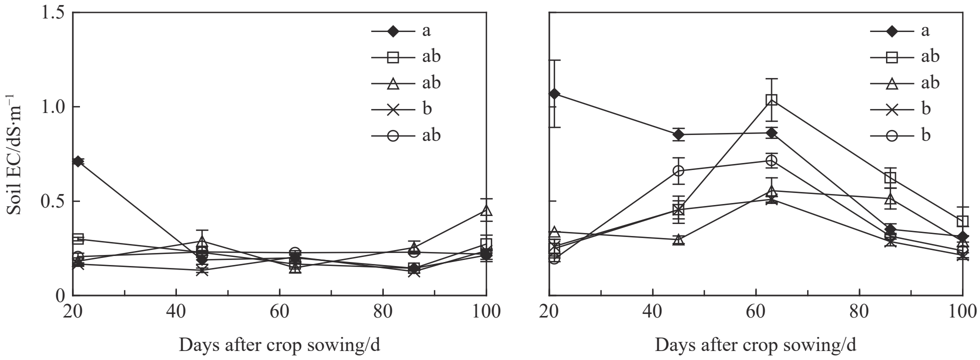
Note: [a)] LLI and IM represent the lower limit of irrigation and the irrigation method, respectively; [b)] *, **, and *** indicate significant at the 0.05, 0.01, and 0.001 probability levels, respectively; [c)] ^{NS} indicates nonsignificant at the 0.05 probability level.

3.2 Soil salinity

Under border irrigation, the EC in 0-5 cm surface soil for different lower limits of irrigation decreased gradually with the extended growth time of crop, but it increased first and then decreased with the time when soil depth was greater than 5 cm (Figure 4). The variation trend of soil EC with crop growth time under surface drip irrigation generally was consistent with that under border irrigation (data not shown). However, the averaged EC value in the monitored soil profile under surface drip irrigation was 2.7%, 33.4%, 17.1%, and 36.9% lower than that under border irrigation, respectively, when the lower limit of irrigation was 80%-85%, 70%-75%, 60%-65%, and 50%-55% field capacity. The variation tendency of soil EC with crop growth time under subsurface drip irrigation was different from that under border and surface drip irrigation, and its variation degree generally was smaller and more uniform compared with these two irrigation methods in the whole growth period of highland barley (Figure 4 and Figure 5). The variation of soil EC with soil depth was complex, which shows different variation tendencies at different times for each experimental treatment (Figure 4 and Figure 5). However, the averaged soil EC in whole crop growth period generally decreased with soil depth. Analysis of variance showed that the lower limit of irrigation and the irrigation method imposed significant main and interactive effects on soil EC (Table 1).

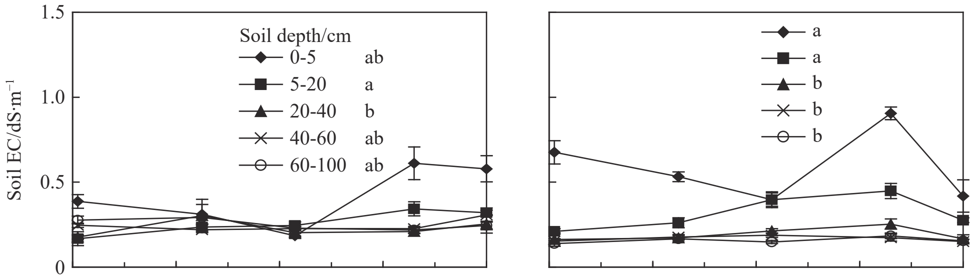


a. 80%-85% of field capacity b. 70%-75% of field capacity

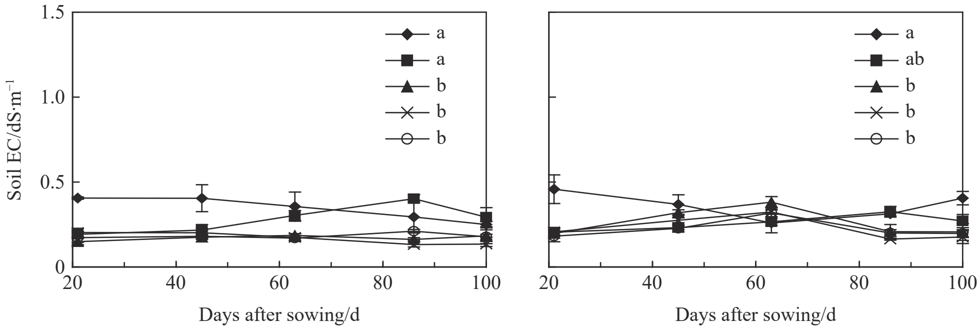


c. 60%-65% of field capacity d. 50%-55% of field capacity

Figure 4 Variation of soil electrical conductivity (EC) at different depths with the growth time of highland barley under border irrigation at different lower limits of irrigation



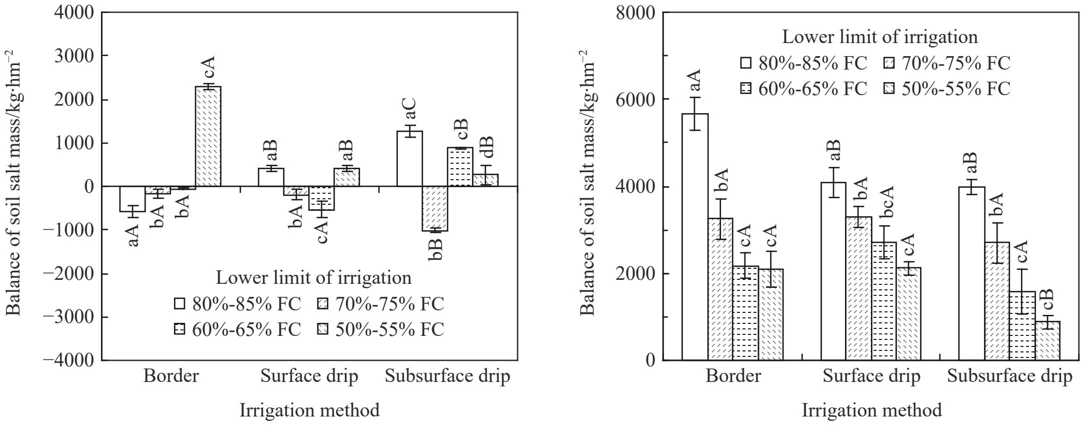
a. 80%-85% of field capacity b. 70%-75% of field capacity



c. 60%-65% of field capacity d. 50%-55% of field capacity

Figure 5 Variation of soil electrical conductivity (EC) at different depths with the growth time of highland barley under subsurface drip irrigation at different lower limits of irrigation

After one season of highland barley planting, total salt mass in 0-20 cm soil under border irrigation was similar to or slightly smaller than that before crop sowing, except for the severe water deficit (50%-55% field capacity) treatment in which the total salt mass was increased (Figure 6a). Total salt mass in 0-20 cm soil under surface drip irrigation was slightly increased when the lower limit of irrigation was 80%-85% and 50%-55% of field capacity and decreased when it was 70%-75% and 60%-65% of field capacity. However, the change degree of total salt mass was relatively small, and it generally was in balance with the initial one. Compared with the initial status before crop sowing, total salt mass in 0-20 cm soil under subsurface drip irrigation was decreased when the lower limit of irrigation was 70%-75% of field capacity, but increased at the other irrigation level treatments.



a. 0-20 cm

b. 0-100 cm

Note: FC refers to field capacity. Different lower-case letters indicate a significant difference among the lower limits of irrigation under the same irrigation method, and different capital letters indicate a significant difference among irrigation methods under the same lower limit of irrigation ($p \leq 0.05$).

Figure 6 Effects of the lower limit of irrigation and the irrigation method on total salt mass in different soil layers

Total salt in 0-100 cm soil profile was in an accumulation state under all tested irrigation methods and irrigation levels (Figure 6b). Statistical analysis results showed that the lower limit of irrigation and the irrigation method imposed significant main and interactive effects on the total salt mass in 0-100 cm soil layer (Table 1). The cumulative salt mass in 0-100 cm soil profile decreased significantly with the decrease of the lower limit of irrigation under three irrigation methods (Figure 6b). Under border irrigation, when the lower limit of irrigation was decreased from 80%-85% of field capacity to its 70%-75%, 60%-65%, and 50%-55%, total soil salt mass in 0-100 cm was decreased by 42.6%, 61.5%, and 63.1%, respectively. The corresponding values were 19.4%, 33.4%, and 48.2% as well as 31.9%, 60.2%, and 77.8% under surface drip and subsurface drip irrigation, respectively. In addition, total soil salt mass in 0-100 cm under border irrigation was significantly greater than that under surface drip and subsurface drip irrigation when the lower limit of irrigation was 80%-85% field capacity (Figure 6b). However, when the lower limit of irrigation was the other irrigation level treatments, the salt mass in 0-100 cm under surface drip irrigation was greater than that under border and subsurface drip irrigation although its difference was not significant. The total salt mass in 0-100 cm soil profile under subsurface drip irrigation was 16.8%-57.8% and 2.9%-58.4% less than that under border and surface drip irrigation for different irrigation level treatments, respectively. These data show that subsurface drip irrigation resulted in the least accumulation of soil salts in the three irrigation methods.

3.3 Crop grain yield

The grain yield of highland barley under surface drip and subsurface drip irrigation decreased first and then increased slightly with the decrease of the lower limit of irrigation, but it was opposite under border irrigation (Table 2). When the lower limit of irrigation was 70%-75%, 60%-65%, and 50%-55% of field capacity, the averaged grain yield of highland barley for the three irrigation methods was decreased by 15.4%, 9.3%, and 10.2%, respectively, compared with that when it was 80%-85% of field capacity. The

Table 2 Grain yield, irrigation water requirement, mean water use rate, total water use, and water use efficiency of highland barley under different lower limits of irrigation and irrigation methods

Treatment		Grain yield/ kg·hm⁻²	Irrigation water requirement/mm	Mean water use rate/mm·d⁻¹	Total water use/mm	Water use efficiency/kg·m⁻³
Irrigation method	Lower limit of irrigation (percentage of field capacity)/%					
Border	80 - 85	8089.7±635.6aA[a),b)]	501	5.4±0.1aA	583.7±2.9aA	1.39±0.09aA
	70 - 75	8185.5±494.2aA	480	5.1±0.1bA	553.6±6.7bA	1.48±0.12abA
	60 - 65	8398.0±163.6aA	361	4.2±0.1cA	452.6±5.7cA	1.67±0.08bAB
	50 -55	7452.4±359.6aA	281	3.8±0.3dA	405.2±2.7dA	2.01±0.17abA
Surface drip	80 - 85	8295.4±674.9aA	474	5.3±0.3aA	573.4±4.9aA	1.45±0.05aA
	70 - 75	6360.1±756.7aA	432	5.0±0.2bA	534.3±11.8bA	1.31±0.11aA
	60 - 65	6693.1±931.2aA	276	3.8±0.3cB	403.7±16.6cB	1.66±0.20abA
	50 -55	7236.0±193.2aA	241	3.4±0.2dB	361.0±4.0dB	2.00±0.05bA
Subsurface drip	80 - 85	9548.5±688.3aA	431	5.1±0.3aB	545.2±19.1aB	1.61±0.05abA
	70 - 75	7385.6±824.8aA	392	4.7±0.4bB	505.9±3.7bB	1.46±0.06aA
	60 - 65	8432.3±843.7aA	276	3.7±0.2cB	395.6±6.8cB	2.13±0.11bB
	50 - 55	8605.9±762.2aA	241	3.6±0.3cC	375.0±6.2cC	2.13±0.06bA

Note: [a)] Mean ± standard deviation; [b)] Different lower-case letters in the same column indicate a significant difference among the lower limits of irrigation under the same irrigation method, and different capital letters indicate a significant difference among irrigation methods under the same lower limit of irrigation ($p \leq 0.05$).

grain yield of highland barley under subsurface drip irrigation was higher than that under border and surface drip irrigation, while the yield under surface drip irrigation was the lowest in the three irrigation methods tested. For all irrigation level treatments, the averaged grain yield of highland barley under subsurface drip irrigation was 5.7% and 18.8% higher than that under border and surface drip irrigation, respectively. However, statistical results showed the lower limit of irrigation and the irrigation method had no significant effect on the grain yield of highland barley (Table 1 and Table 2).

3.4 Irrigation water requirement and water use efficiency

The daily water use rate of highland barley increased first and then decreased with crop growth time, and the rate at heading stage was the largest in the whole crop growth period (data not shown). The variation range of the maximum daily water use rate under different irrigation level treatments was 5.7-6.7, 5.2-6.7, and 5.4-6.6 mm/d for border, surface drip, and subsurface drip irrigation, respectively.

Statistical results indicated that the lower limit of irrigation and the irrigation method imposed significant main and interaction effects on the mean daily water use rate and total water use of highland barley (Table 1). Mean daily water use rate, total water use, and irrigation water requirement of highland barley during the whole growth period decreased significantly with the decrease of the lower limit of irrigation (Table 2). Under the experimental conditions, when the lower limit of irrigation was decreased from 80%-85% to 50%-55% of field capacity, the total water use and irrigation water requirement were decreased by 30.6%-37.0% and 43.9%-49.2% for the tested three irrigation methods, respectively. The averaged total water use of all irrigation level treatments under subsurface drip irrigation was 8.7% and 2.7% lower than that under border and surface drip irrigation, respectively. Irrigation water requirement under subsurface drip irrigation was the least and that under border irrigation was the highest among the tested three irrigation methods. The irrigation water requirement under subsurface drip irrigation was 17.4% and 5.8% lower than that under border and surface drip irrigation, respectively.

The lower limit of irrigation and the irrigation method imposed significant effects on the water use efficiency of highland barley, but their interaction on it was not significant (Table 1 and Table 2). The water use efficiency generally increased with the decrease of the lower limit of irrigation. When the lower limit of irrigation was decreased from 80%-85% to 50%-55% of field capacity, the water use efficiency was increased by 44.6%, 37.9%, and 32.3% respectively for border, surface drip, and subsurface drip irrigations. The averaged water use efficiency for all irrigation level treatments under subsurface drip irrigation was 11.9% and 14.2% higher than that under border and surface drip irrigation, respectively.

4 Discussion

In the oasis of extremely arid inland basin, irrigation is the only way for agriculture to survive. However, the sustainable development of oasis agriculture depends largely on the balance of soil salt in the irrigated farmland and the efficient use of precious freshwater resources.

4.1 Effects of irrigation level on soil water and salt dynamics

When the lower limit of irrigation is used as the criteria to determine whether farmland needs to be irrigated, it determines the amount of water available to crops in soil and the frequency of irrigation. The lower the lower limit of irrigation was, the longer the interval between two successive irrigation events was, and the less water was needed for irrigation (Table 2). Consequently, the greater the fluctuation of soil water content in upper soil layer with crop growth time was (Figure 3), the smaller the averaged soil water content in the planned wetting layer was, and correspondingly the greater the deficit on soil water available to crops was.

Natural water used for irrigation is an important source of soil salt in arid regions, and meanwhile irrigation event itself affects the process of salt migration in soil and the salt balance in crop root zone. The lower the lower limit of irrigation was, the less the irrigation water needed throughout the crop growth period was, and the less the salt carried into soil by irrigation water was. Therefore, the salt accumulation in 0-100 cm soil profile decreased with the decrease of the lower limit of irrigation (Figure 6b). However, the water and salt dynamics in topsoil is closely related to soil surface evaporation and irrigation events. After the irrigated water enters soil, surface evapotranspiration causes the continuous loss of soil water. The lower the lower limit of irrigation was, less water was evaporated and less soil salt was migrated with water movement to soil surface, which resulted in less salt to be accumulated in the topsoil. However, on the other hand, the less irrigation water that moves downward under the gravity potential results in less salts to be leached out of the topsoil[36]. The combined effect of these two factors may be the reason for the different salt accumulation status in 0-20 cm soil layer under different irrigation level treatments (Figure 6a).

4.2 Effects of irrigation method on soil water and salt dynamics

When border and surface drip irrigation are applied, irrigation water is transported to the soil surface of farmland. The irrigated water in farmland moves downward under the gravitational potential and hence soil salts migrate downward correspondingly, but meanwhile the soil water also moves upwards under surface evaporation and results in the gradual accumulation of salts on the surface soil. When subsurface drip irrigation is used, irrigation water is directly delivered to the location where drip irrigation tape is buried. Although water movements on the both directions also exist simultaneously under subsurface drip irrigation, the water migrated upwards is less than that under border and surface drip irrigation due to its relative smaller water content in topsoil after irrigation event. Soil water status and subsequently salt balance under different irrigation methods are the trade-off result of these two opposite movement processes. Irrigation method has different influences on soil water dynamics, but its effect was not significant under experimental conditions (Table 1).

Salts in soil migrate with water movement, and different soil moisture dynamics under different irrigation methods necessarily result in different salt accumulation status in soil. Due to more active soil moisture dynamics, the variation degree of soil EC in the topsoil with time generally was greater than that in the deep soil profile (Figure 4 and Figure 5). Compared with subsurface drip irrigation, border and surface drip irrigation, as surface irrigation methods, need more water to be irrigated to replenish the water deficit in soil due to more water evaporation from soil surface (Table 2), and hence more salts are brought into the soil by irrigation water. This is the reason why the averaged accumulative amount of salts in 0-100 cm soil profile under border irrigation was largest, followed by surface drip irrigation, and subsurface drip irrigation was smallest among the three irrigation methods after one season of highland barley planting (Figure 6b). However, surface drip irrigation is local irrigation, and its spatial distribution of salinity in soil is uneven[6,36,37]. This may be the reason why the salt accumulation in 0-100 cm soil profile under surface drip irrigation was greater than that under border irrigation when the lower limit of irrigation was lower than 70%-75% field capacity (Figure 6b). Statistical analysis results showed irrigation method imposed a significant effect on soil EC and salt accumulation under experimental conditions (Table 1). Moreover, the interaction between irrigation method and the lower limit of irrigation on soil EC and salt accumulation was significant, but the contribution of irrigation method to their variation was smaller than that of the lower limit of irrigation (Table 1).

4.3 Effects of irrigation level and irrigation method on crop yield and water use

Water and salt conditions in soil determine crop growth status. Water deficit in soil inhibits crop growth and yield[38,39], and hence resulted in a general decrease tendency in the grain yield of highland barley with the decrease of the lower limit of irrigation (Table 2). However, in the extremely arid oasis region, soil salt accumulation may adversely affect crop growth and its yield formation[6]. In this study, the slight increasing tendency of the grain yield of highland barley at the designed minimum lower limit of irrigation (50%-55% field capacity) may be related to its relatively low soil salinity in the main root layer of crops under drip irrigation (Table 2, Figure 5 and Figure 6b). Under all irrigation levels and irrigation methods tested in the study, the salt in 0-100 cm soil profile was in an accumulation state after one season of crop planting (Figure 6b). Therefore, in order to maintain a sustainable cultivation on oasis farmland, it is necessary to leach salts from the soil before crop sowing in spring[18,33].

Under experimental conditions, irrigation water requirements averaged for all irrigation level treatments under surface drip irrigation and subsurface drip irrigation were decreased by 12.3% and 17.4%, respectively, compared with that under border irrigation, which is similar to the reported research results[21,23,36]. Surface drip irrigation is more water-saving than border irrigation, and subsurface drip irrigation is better on water-saving than surface drip irrigation. The averaged grain yield and water use efficiency of highland barley under subsurface drip irrigation were 5.7% and 11.9% higher than those under border irrigation, and 18.8% and 14.2% higher than those under surface drip irrigation, respectively, due to less irrigation water requirement and lower salinity in soil profile. This result is similar to that of Al-Ghobari and Dewidar[16] and Piri and Naserin[28]. Therefore, subsurface drip irrigation is more beneficial to promote crop yield and water use efficiency than border and surface drip irrigation. Considering economic benefit and irrigation water requirement, it is recommended that subsurface drip irrigation with the lower limit of irrigation of 50%-55% field capacity can be used as the preferred irrigation scheme for highland barley planting in the oasis region of arid basin. At this time, the grain yield of highland barley was 8605.9 kg/hm^2, and the corresponding water use efficiency was 2.13 kg/m^3.

5 Conclusions

The research results showed that the higher the lower limit of irrigation was, the greater the averaged soil water content was, and the smaller the fluctuation of soil water content in upper soil layer with time was. After one season of highland barley planting, soil salinity in 0-100 cm profile was in a cumulative status under all experimental treatments, and its accumulated amount decreased significantly with the decrease of the lower limit of irrigation. Total salt mass in 0-100 cm soil profile under subsurface drip irrigation was 16.8%-57.8% and 2.9%-58.4% less than that under border and surface drip irrigation, respectively. The grain yield of highland barley under surface drip and subsurface drip irrigation decreased first and then increased slightly with the decrease of the lower limit of irrigation, but it was on the contrary under border irrigation. Averaged grain yield under subsurface drip irrigation with different irrigation levels was 5.7% and 18.8% higher than that under border and surface drip irrigation, respectively. The water use efficiency of crop generally increased with the decrease of the lower limit of irrigation, and the averaged water use efficiency under subsurface drip irrigation was 11.9% and 14.2% higher than that under border and surface drip irrigation, respectively. The effects of the lower limit of irrigation on soil salinity and crop water use efficiency were greater than that of irrigation method. Considering economic benefit and irrigation water requirement, it is suggested that the subsurface drip irrigation with the lower limit of irrigation of 50%-55% field capacity should be adopted for highland barley planting in the oasis region of arid basin.

Acknowledgements

This work was financially supported by the National Key Research and Development Program of China (Grant No. 2018YFC0406604).

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