Differentiation characteristics of soil water under different landscape types in a desert-oasis region in the middle reaches of Heihe river basin, China

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Abstract. The tillage of oasis farmlands and construction of artificial protection forests in native grasslands around the oases would significantly affect differentiation characteristics of soil water. In this study, the establishment of belt transect with 13 different landscape types in the middle reaches of Heihe River basin was determined to analyze differentiation characteristics of soil water. Our results showed that firstly vertical variability of soil water under different landscape types was significant. Secondly, horizontal variability of soil water under different landscape types showed a significant difference. Thirdly, differentiation characteristics of soil water under different landscape types were mainly caused by interaction of multiple factors such as vegetation type, soil properties and human management etc, and spatial variability of soil water can be enhanced by the tillage of oasis farmlands and construction of artificial protection forests. Our results suggest that it has very important value for enhancing the soil water effect of irrigated vegetation in this region to fully conform the water consumption of plants and the water holding capacity of soil, to especially strengthen the management of water-saving irrigation of farm crops and artificial plantations.

1. Introduction
Soil water is a comprehensive index, which can reflect natural conditions such as topography, vegetation, soil and climate etc. It is also a critical factor in the SPAC (soil-plant-atmosphere continuum) system, and a limiting factor for the growth and development of plants (crops) in arid areas [1]. Desert-oasis is a special landscape in inland arid zone in the Northwestern China, and is also an important part of the oasis ecological system. Due to the lower average annual precipitation (usually concentrates in summer and autumn) and the higher evaporation, soil water becomes the main limiting factor for plant growth and vegetation recovery in desert-oasis region [2]. Therefore, understanding deeply the spatio-temporal distribution of soil water and its dynamic change rules in this region are helpful in regional eco-hydrological simulation, water resource management and vegetation ecological construction [3]. There were a large amount of literatures, which focused on the relationship between soil water and vegetation spatial variability in desert oasis transition zone [4]; the dynamics [5], spatio-temporal heterogeneity [6] and its influencing factors [7] of soil water; time stability of soil water in sand-fixation vegetation areas [8]. These literatures provide some ideas and methods for the follow-up research work.

Desert and oasis in the middle reaches of Heihe River basin is typical landscape, is also one of core areas of population distribution, economy and society development in Northwest, China. In recent
years, water shortage has been a constraint factor to maintain oasis stability with the increasing number of population, irrigated farmland and artificial shelterbelt in oasis area. Moreover, the cultivation of oasis farmland and the construction of artificial shelterbelt in desert-oasis region increased the diversity of landscape types, which may have a significant effect on the differentiation of soil water. At present, although a large number of researches have revealed spatio-temporal heterogeneity [3,9] of soil water, a few researches have been done to reveal the differentiation characteristics of soil water under different landscape types in a desert-oasis region in the middle reaches of Heihe River basin. Therefore, it is unclear what differentiations of soil water might have happened. It is even unclear which factors might affect the differentiations, and what mechanism might cause these differentiations. In this study, the sample belt with landscape such as riverside wetland, farmland, artificial plantations, desert orderly in desert-oasis region in the middle reaches of Heihe River basin was designed in order to reveal further affecting factors of differentiation of soil water and the mechanism of interaction under different landscape types, and to provide theoretical reference on rational use and effective management of water and soil resources in this region.

2. Research area and methods

2.1. Overview of the research area

In this study, desert-oasis in the middle of Linze county, Gansu province, and in the middle reaches of Heihe river basin (MRHRB) is selected as the research area, which locates at the intersection between desert and Zhangye-Linze-Gaotai oasis, and the geographic coordinates of central area are 100°07' E and 39°21' N. The research area belongs to typical temperate continental climate with long sunshine, strong solar radiation, average annual rainfall of 117 mm, average annual evaporation of 2337 mm, average annual temperature of 7.6 ℃, frost-free period of 105 d, average annual wind speed of 3.2 m/s (sandstorm activities are mainly concentrated in 3-5 month). In this area, the natural vegetation is sparse and the community structure is simple. Some of farmlands cultivated for more than 100 years in oasis area are called old farmland, the others cultivated since 1980s are called new farmland. The artificial shelterbelt mainly includes Populus, Pinus sylvestris var. mongolica planted in the early 1980s and Haloxylon ammodendron with different planting years. Every year, a large quantity of water from Heihe River and underground is used to irrigate farmland. The zonal soil in this area is grey brown desert soil, which forms oasis soil and irrigation silting soil caused by long-term cultivation and maturation [10]. The soil in this area has complex stratification and great spatial heterogeneity due to such influences as sandstorm accumulation, river flood alluviation, river irrigation siltation and long-term cultivation [11].

2.2. The research methods

2.2.1. Selection and design of sample plots. Linze desert-oasis in the middle reaches of Heihe River basin was selected as the positioning research area where belt transect with 13 different landscape types including riverside wetland, farmland (100 a, 30 a), Populus, Pinus sylvestris var. mongolica, Haloxylon ammodendron (30 a, 20 a, 10 a, 5 a), fixed sandy land, semi-fixed sandy land, shifting sandy land, dune (Figure 1) was designed along the direction from southwest to northeast. In each landscape, four sample plots (about 200-400 m apart) were selected. Thus, a total of 52 sample plots were used for observing soil water.

2.2.2. Collection and measurement of soil samples. Soil profiles were dug in the 52 sample plots, and a total of 936 soil samples with 3 replicates were collected in 6 layers (0-10cm, 10-20cm, 20-40cm, 40-60cm, 60-80cm, 80-100cm) from late August to early September in 2015. During sampling process, plant roots, litters and gravels in the soil were removed. All soil samples were put into numbered aluminum boxes and brought back to the laboratory. These boxes with soil samples were put into the
oven in batches and baked continuously to constant weight at 105-110 °C for 24 hours. After cooling down, they were taken out and weighed to calculate soil water content.

2.2.3. Data analysis. Firstly, variance analysis developed in the 1920s is usually used to compare if the mean of several populations is equal. In this study, one-way ANOVA inside SPSS20.0 software was used to analyze differences of soil water of the same layer under different landscape types, and LSD method was used to determine if the differences was significant. Secondly, classical statistical characteristics such as mean, standard deviation (SD), coefficient of variation (CV), minimum, maximum, range, skewness and kurtosis were used to analyze horizontal variability of soil water under different landscape types. Especially, CV can roughly reflect the variation degree of soil water relative to the mean under different landscape types. If CV < 10%, variability is weak; 10% ≤ CV ≤ 100%, variability is medium; CV > 100%, variability is strong [12]. Thirdly, geostatistical method uses random functions to explore uncertain phenomena, and to simulate unknown points in combination with the information provided by sampling points. It has become an important tool for spatial analysis and is widely used for studies in environmental science, geography, soil science, ecology and other fields [13].

3. Results

3.1. Vertical differentiation of soil water under different landscape types
Our results showed that vertical differentiation of soil water under different landscape types was significant in a desert-oasis region in the middle reaches of Heihe River (Figure 2).

Soil water of riverside wetland showed particularly significant vertical differentiation and obvious fluctuation (Figure 2a). This result may be related to soil texture and vegetation distribution. According to sample survey, 0-40 cm soil layer of wetland is mainly loam, and is completely covered...
by all kinds of herbs. Thus, water retention ability of the soil layer is stronger. Whereas 40-80 cm soil layer of wetland is mainly sandy soil, and soil water easily penetrates to below clay layer.

Soil water of two farmlands showed smaller vertical differentiation, and both firstly decreased and then slightly increased (Figure 2b). Soil water in 20-40 cm layer was relatively lower. This was because corns planted in farmland were in the ear during sampling period, their root absorbed plenty of soil water, and because the transpiration of crops consumed water.

Sample plots of *Pinus sylvestris var. mongolica* are near farmlands, and the infiltration of farmland irrigation may increase soil water of 80-100 cm layer. Soil water of *Populus* was low and showed

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**Figure 2.** Vertical differentiation of soil water under different landscape type.

Soil water of *Pinus sylvestris var. mongolica* showed significant vertical differentiation (Figure 2c). It was found that herbaceous plants such as *Calamagrostis epigejos*, *Chenopodium album*, *Echinops sphaerocephalus* and *Leguminosae* etc. grew well, and their roots absorbed more subsurface soil water. Sample plots of *Pinus sylvestris var. mongolica* are near farmlands, and the infiltration of farmland irrigation may increase soil water of 80-100 cm layer. Soil water of *Populus* was low and showed
insignificant vertical differentiation (Figure 2c). This was mainly because transpiration consumed a large amount of soil water without replenishing water by irrigation.

Soil water of different aged Haloxylon ammodendron plantations showed similar vertical differentiation (Figure 2d). Soil water of 0-10 cm layer was relatively higher, that of 10-20 cm layer evidently reduced, and that of the below layers slightly increased again.

Soil water of four desert landscape types (i.e. fixed sandy land, semi-fixed sandy land, shifting sandy land and dune) showed similar vertical differentiation to that of Haloxylon ammodendron plantations (Figure 2e and 2f).

### 3.2. Horizontal differentiation of soil water under different landscape types

Our results showed that horizontal differentiation of soil water under different landscape types was significant in a desert-oasis region in the middle reaches of Heihe River (Table 1). In general, the closer to oasis center, the more soil water, which means that soil water show a significant decrease trend along such landscape sample zone as riverside wetland, farmland, artificial protection forest, and desert. Furthermore, soil water of different layer exhibit slightly different horizontal differentiation.

#### Table 1. Horizontal variability of soil water content under different landscape types.

| Depth /cm | Riverside wetland | Farmland (100a) | Farmland (30a) | Pinus sylvestris var. mongolica | Populus | Haloxylon ammodendron (30a) | Haloxylon ammodendron (20a) |
|-----------|------------------|-----------------|----------------|-------------------------------|---------|-----------------------------|-----------------------------|
| 0-10      | 23.7±2.1a        | 17.2±0.6b       | 14.4±0.9c      | 7.1±0.9d                      | 3.2±0.6f| 5.7±0.7def                  | 5.2±0.4def                  |
| 10-20     | 21.6±1.3a        | 16.0±0.4b       | 14.7±0.7b      | 4.1±0.3c                      | 3.9±1.3d| 1.9±0.1de                   | 1.7±0.4de                   |
| 20-40     | 21.4±1.5a        | 15.0±1.0b       | 13.6±0.8b      | 4.8±1.4e                      | 3.0±0.6cd| 1.9±0.2d                    | 2.0±0.3d                    |
| 40-60     | 5.4±0.7d         | 16.1±1.0a       | 9.3±0.6c       | 13.5±1.1b                     | 3.2±0.6e| 2.0±0.1ef                   | 2.2±0.4ef                   |
| 60-80     | 4.4±0.1d         | 16.7±0.7b       | 10.0±0.2c      | 20.8±1.1a                     | 3.7±0.8de| 2.6±0.2ef                   | 2.5±0.3ef                   |
| 80-100    | 14.5±1.6c        | 17.0±0.8b       | 11.4±0.7d      | 21.7±1.5a                     | 6.6±1.3e| 2.9±0.1f                    | 2.6±0.3f                    |

CV showed that horizontal differentiation of soil water under different landscape types belongs to medium, even strong variation. Range and mean also showed that horizontal differentiation of soil water under different landscape types was very significant. Skewness showed that soil water of most of landscape types was lower, that of few landscape types was higher. Kurtosis showed that soil water under different landscape types presented a sharp distribution (Table 2). The results indicated that horizontal differentiation of soil water under different landscape types was significant in a desert-oasis region in the middle reaches of Heihe River.

#### Table 2. Description statistics of soil water under different landscape types.

| Depth /cm | Mean / % | SD | CV / % | Minimum / % | Maximum / % | Range / % | Skewness | Kurtosis |
|-----------|----------|----|--------|-------------|-------------|-----------|----------|----------|
| 0-10      | 7.88     | 6.45 | 82 | 3.18 | 23.73 | 20.55 | 1.70 | 2.03 |
| 10-20     | 5.67     | 6.91 | 122 | 1.35 | 21.58 | 20.23 | 1.59 | 1.15 |
| 20-40     | 5.41     | 6.70 | 124 | 1.03 | 21.43 | 20.40 | 1.65 | 1.56 |
| 40-60     | 4.62     | 5.08 | 110 | 0.98 | 16.05 | 15.07 | 1.55 | 1.16 |
| 60-80     | 5.50     | 6.37 | 116 | 1.23 | 20.80 | 19.57 | 1.80 | 2.17 |
| 80-100    | 6.70     | 7.03 | 105 | 1.23 | 21.73 | 20.50 | 1.19 | 0.05 |

### 3.3. Spatial variability of soil water under different landscape types

It can be seen from Table 3 that (1) the best fitting model of spatial variability of soil water under different landscape types was Gaussian model, and its determination coefficient ($R^2$) was greater than 0.80, which can appropriately reflect spatial structure characteristics of soil water under different landscape types in a desert-oasis region. (2) The structure ratio C / (C0 + C) of soil water under different landscape types was greater than 75 %, which showed that the structural variation was greater than the random variation, and indicated that spatial autocorrelation of soil water under different landscape types in the desert-oasis region was strong. (3) Co / (Co + C) of soil water under...
different landscape types was very small, which indicated that the random factors had little influence on spatial variability of soil water under different landscape types in the desert-oasis region. (4) Variation function of soil water under different landscape types had very small nugget value, which indicated that a small scale ecological process such as oasis farmland tillage, artificial protection forests etc can’t be ignored. The ecological processes caused by human activities to a certain extent enhanced the spatial variability of soil moisture.

Table 3. Spatial variability of soil water under different landscape types.

| Depth/cm | Model | Nugget (C₀) | Sill (C₀ + C) | Range | Efficient range | Structural ratio/100 % | R² |
|----------|-------|-------------|---------------|-------|-----------------|-----------------------|-----|
| 0-10     | Gauss | 0.157       | 2.324         | 0.091 | 0.158           | 0.932                 | 0.813 |
| 10-20    | Gauss | 0.048       | 3.106         | 0.055 | 0.095           | 0.985                 | 0.873 |
| 20-40    | Gauss | 0.091       | 3.192         | 0.055 | 0.095           | 0.971                 | 0.884 |
| 40-60    | Gauss | 0.038       | 3.086         | 0.047 | 0.081           | 0.988                 | 0.872 |
| 60-80    | Gauss | 0.041       | 3.092         | 0.048 | 0.083           | 0.987                 | 0.882 |
| 80-100   | Gauss | 0.001       | 3.012         | 0.045 | 0.078           | 1.000                 | 0.902 |

It can be seen from Figure 3 that soil water of 0-10 cm, 10-20 cm and 20-40 cm layers showed a drastically decreasing trend from southwest to northeast, that is, soil water of surface layer and upper middle layer generally showed a decreasing trend from oasis to desert. While, soil water of 40-60 cm, 60-80 cm and 80-100 cm layer showed a drastically decreasing trend from southeast to northwest and then to northeast. On the whole, soil water showed a decreasing trend from oasis center to desert (with the increase of the distance from Heihe River).

Figure 3. Spatial variability of soil water under different landscape types.

4. Discussion
Spatio-temporal variability of soil water is significant in the arid region of Northwest China [14], which plays a key role in stabilizing the structure and function of desert-oasis ecosystems [3]. Our study showed that differentiation characteristics of soil water under different landscape types were significant in a desert-oasis region in the middle reaches of Heihe River basin, China.

Firstly, vertical differentiation of soil water under different landscape types was significant in a desert-oasis region in the middle reaches of Heihe River. It was also found that stratification characteristics of soil water profile distribution under different landscape units were obvious in the oasis-desert transition zone in the middle reaches of Heihe River [15]. Vertical differentiation of soil water of riverside wetland was particularly significant mainly because of the profile difference of soil...
texture, the surface cover of vegetation, the maximum daily evapotranspiration during the middle and late growth season and the concentrated precipitation [16]. Vertical differentiation of soil water of farmlands was small and stable, which was related to farmland ploughing, uniform soil texture, and was connected with crop growth and farmland irrigation [17]. Farmland irrigation in oasis region may not only guarantee crops’ demand for soil water during the growing period, but also help to maintain the stability of farmland soil water. Irrigation in winter can significantly improve water and heat conditions of farmland soil during the freeze-thaw period in the arid desert-oasis region, hence have a positive effect on alleviating “spring drought” and promoting crops growth [18]. As far as several artificial protection forests were concerned, soil water of *Pinus sylvestris var. mongolica* showed significant vertical differentiation because it was affected by water uptake by herbaceous plants roots distributed on land surface, irrigation and lateral infiltration of soil water of farmland; soil water of *Populus* showed insignificant vertical differentiation due to no water supplement by irrigation, yet water consumption by transpiration during the observation period; surface soil water of *Haloxylon ammodendron* plantations was significantly higher than that of the below layers because surface soil water wasn’t consumed without short-lived plants, the evaporation of surface soil water was further prevented from the surface physics and biological crust, and because a large amount of soil water below the surface layer was consumed due to developed vertical root system, and the horizontal root system distributed below 50 cm [19]. Surface soil water of four desert landscape types was also significantly higher than that of the below layers because of less surface vegetation coverage, a rainfall before sampling. These highlight that on one hand, vertical differentiation of soil water under different landscape types in a desert-oasis region in the middle reaches of Heihe River is mainly caused by interaction of multiple factors such as vegetation type, soil properties and human management etc. On the other hand, soil moisture can decrease to the level close to wilting point due to the strong transpiration of farm crops and artificial protection forests in the desert-oasis region, which not only is bad for continuous growth of vegetation, but also have an effect on the terrestrial hydrological cycle [20]. Therefore, it is very important that water-saving irrigation management of farm crops and artificial protection forests should be strengthened to effectively enhance soil water effect of irrigated vegetation based on vertical differentiation of soil water under different landscape types in the desert oasis region in the middle reaches of Heihe River.

Secondly, horizontal differentiation of soil water under different landscape types was significant in a desert-oasis region in the middle reaches of Heihe River, that is, soil water showed a significant decrease trend along such landscape sample zone as riverside wetland, farmland, artificial protection forest, and desert. This result seems consistent with that of a study of the transport law of soil water and salt in the farmland-protection forests-desert composite system in Sangong River Basin, Xinjiang [21]. Specifically, the higher soil water of riverside wetland was related to the closer distance to Heihe River, the infiltration of river water, the supply of groundwater, and also related to the stronger soil water holding capacity under the full coverage of all kinds of herbs. Soil water of farmland was generally higher because oasis farmland was irrigated during the growing period, also because long-term tillage of oasis farmland, which to some extent improved the water storage and retention capacity of farmland soil [18]. Horizontal differentiation of soil water between *Populus, Pinus sylvestris var. Mongolica* and *Haloxylon ammodendron* plantations was significant. Because irrigated *Populus, Pinus sylvestris var. Mongolica* can obviously improve physical, chemical and biological properties, yet no-irrigated *Haloxylon ammodendron* plantations can’t [22]. In addition, soil water requirement of *Populus* is the higher, and that of *Pinus sylvestris var. Mongolica* is the lower due to its drought tolerance [23]. Soil water of desert was very low because water holding capacity of the gray-brown desert soil was the lower, and infiltration and evaporation was the rapider [10], and because water suction of desert soil was extremely weak due to simple structure, low soil clay and organic matter content [24], also because soil water can horizontally move from oasis to desert in the desert-oasis region [25]. As a whole, that soil water tends to decrease from oasis to desert is a general law of horizontal differentiation of soil water in the desert-oasis region. These results indicate that horizontal differentiation of soil water under different landscape types in a desert-oasis region in the middle
reaches of Heihe River is also mainly caused by interaction of multiple factors such as vegetation type, soil properties and human management etc. Therefore, trade-off between the input of irrigation water and the improvement of ecological environment need be thought of based on horizontal differentiation of soil water under different landscape types in a desert-oasis region in the middle reaches of Heihe River especially when artificial protection forests are planted [22].

5. Conclusion
Differentiation characteristics of soil water are significant along such landscape sample zone as riverside wetland, farmland, artificial protection forest, and desert in a desert-oasis region in the middle reaches of Heihe River. This is mainly caused by interaction of multiple factors such as vegetation type, soil properties and human management etc. In particular, the tillage of oasis farmlands and construction of artificial protection forests would further enhance spatial variability of soil water. Therefore, it has very important value for enhancing the soil water effect of irrigated vegetation in this region to fully conform the water consumption of plants and the water holding capacity of soil, to especially strengthen the management of water-saving irrigation of farm crops and artificial plantations.

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