Soil Moisture Dynamics and Influencing Factors of Three Landscape Types at the Oasis Fringe in the Middle Reaches of the Heihe River: Postprint

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Abstract

Soil moisture is essential for the growth and development of xerophytic plants in arid regions and determines the successional dynamics and direction of xerophytic plant communities. Investigating the dynamic characteristics of soil moisture in different landscape types at the edge of oases in the middle reaches of the Heihe River and formulating practical, effective, scientifically sound, and rational measures for windbreak and sand fixation are particularly important for preventing the desertification process. This study takes three landscape types at the edge of oases in the middle reaches of the Heihe River—shelterbelts, desert-oasis ecotones, and deserts—as research objects, and employs methods such as HYDRUS-2D model simulation, LSD analysis, and Pearson correlation analysis to investigate the dynamic characteristics of soil moisture and influencing factors in the three different landscape types. The results show that: (1) The RMSE of soil volumetric water content is 0.002–0.006 $cm^3 \cdot cm^{-3}$, MRE is 4.22%–5.20%, and R^2 is 0.725–0.967. The simulation results exhibit high agreement with measured data, indicating that the HYDRUS-2D model can be applied to simulate soil moisture dynamics in the study area. (2) The soil volumetric water content in shelterbelt and desert-oasis ecotone landscapes shows a trend of first increasing and then decreasing with increasing soil depth, whereas the desert landscape shows a trend of first decreasing and then increasing. (3) Effective precipitation plays a decisive role in the dynamic changes of soil volumetric water content. Precipitation exceeding 9.5 mm can significantly increase soil water content and infiltration depth in the short term. The soil water infiltration depth at various time periods after precipitation in the desert landscape is higher than that in the shelterbelt landscape and the desert-oasis ecotone landscape. (4) The soil volumetric water content of the three landscape types is correlated with factors such as precipitation, evapotranspiration, bulk density, soil particle composition, and soil water-holding capacity, and shows significant correlations at different levels ($P<0.01$). Among them, precipitation and silt-clay content are significantly positively correlated with soil volumetric water content, while bulk density and sand content are significantly negatively correlated with soil volumetric water content. Therefore, planting windbreak and sand-fixing shrubs in the study area can increase soil silt-clay content, enhance the soil's capacity to collect and utilize rainwater, slow down the infiltration process, and thus exert a positive influence on soil water-holding capacity.

Full Text

Introduction

Soil moisture is essential for the growth and development of xerophytic plants in arid regions and determines the dynamics and direction of community succession. Investigating the dynamic characteristics of soil moisture in different landscape types at the oasis edge in the middle reaches of the Heihe River, and developing effective, scientific, and rational measures for wind prevention and sand fixation are particularly important for halting desertification processes. This study examined three landscape types at the oasis edge in the middle reaches of the Heihe River: protected forest landscapes, desert-oasis transition zone landscapes, and desert landscapes. Using HYDRUS-2D model simulation, LSD analysis, and Pearson correlation analysis, we investigated the dynamic characteristics of soil moisture and influencing factors across these three landscape types. The results showed: (1) the RMSE of soil volumetric water content ranged from 0.002~0.006 cm^3/cm^3, MRE ranged from 4.22%~5.20%, and R^2 ranged from 0.725~0.967. The simulation results demonstrated high agreement with measured data, indicating that the HYDRUS-2D model can be applied to simulate soil moisture dynamics in this study area. (2) The soil volumetric water content in protected forest and desert-oasis transition zone landscapes showed a trend of first increasing then decreasing with soil depth, while desert landscapes showed the opposite pattern of first decreasing then increasing. (3) Effective precipitation played a decisive role in the dynamic changes of soil volumetric water content, with precipitation above 9.5 mm significantly increasing soil moisture content and infiltration depth in the short term. The depth of soil moisture infiltration after precipitation in desert landscapes was greater than that in protected forest and desert-oasis transition zone landscapes. (4) The soil volumetric water content in the three landscape types was related to precipitation, evapotranspiration, bulk density, soil particle composition, and soil water-holding properties, showing significant correlations at different levels. Specifically, precipitation and clay-silt content were significantly positively correlated with soil volumetric water content, while bulk density and sand content were significantly negatively correlated. Therefore, planting windbreak shrubs in the study area can increase soil clay-silt content, improve the soil's ability to collect and utilize rainwater, slow the infiltration process, and thus positively affect soil water-holding properties.

Keywords: soil moisture; dynamic change; infiltration characteristics; influencing factors; middle reaches of the Heihe River

The Heihe River is the second largest inland river in northwest China, spanning Qinghai, Gansu, and Inner Mongolia provinces. The middle reaches of the basin border the Badain Jaran Desert to the northwest. The region experiences intense solar radiation, scarce precipitation, high evaporation, and relatively limited water resources. To protect oasis farmland from wind and sand damage, local communities have established vegetation shelterbelts between the oasis and desert, creating a spatial pattern of alternating farmland, protected forests, desert-oasis transition zones, and desert landscapes in the middle reaches of the Heihe River. In recent years, global warming and some unreasonable socioeconomic activities have intensified water scarcity, and the ecological environment has shown signs of deterioration at various levels, with land desertification showing a trend of further expansion.

Protected forest landscapes at the oasis edge can effectively reduce wind erosion of farmland soil. Research on soil moisture in protected forests contributes to the scientific management of oasis water and soil resources. The desert-oasis transition zone provides ecological functions of wind prevention and sand fixation, and the growth and development of sand-fixing plants are also closely related to soil moisture, which is a key factor in maintaining the stability of the desert-oasis transition zone ecosystem. Desert areas are extremely water-scarce, and understanding the endowment and distribution processes of soil moisture in these areas provides a reference for understanding how desert plants rationally utilize water resources. Therefore, investigating soil moisture conditions in different landscapes at the oasis edge in the middle reaches of the Heihe River and developing effective, scientific, and rational measures for wind prevention and sand fixation are particularly important for halting desertification processes.

Over the years, many domestic experts and scholars have conducted extensive research on soil moisture conditions in different landscape types at the oasis edge in the middle reaches of the Heihe River. Researchers have used numerical models such as HYDRUS-1D to explore vegetation ecological water requirements and soil moisture movement processes in different landscapes at the oasis edge in the middle reaches of the Heihe River. These technical methods have become the main tools for investigating soil moisture dynamics in this region.

1. Materials and Methods

1.1 Study Area Overview

The study area is located near the Heihe River Basin Comprehensive Research Station of the Chinese Academy of Sciences (39°20 52 ~39°22 01 N, 100°09 12 ~100°09 22 E) in Linze County, Zhangye City, Gansu Province. It borders the Badain Jaran Desert to the north and the Linze Oasis in the middle reaches of the Heihe River to the south. The region has a temperate continental desert climate with dry conditions year-round. Annual temperature variation is significant, with an average annual temperature of 7.6°C, maximum temperature of 39.1°C, and minimum temperature of -27.3°C. Average annual precipitation is approximately 117 mm, unevenly distributed throughout the year, mainly concentrated from May to September, accounting for about 70%~80% of annual precipitation. Average annual evaporation is 2390 mm. The annual frost-free period is 152 days, with annual sunshine hours of 3045 h. Northwest winds prevail, with strong sandstorm activity, an average annual wind speed of 3.2 $m \cdot s^{-1}$, and maximum wind speed of 21 $m \cdot s^{-1}$.

From south to north, the main landscape types include protected forest belts, desert-oasis transition zones, and desert. The soil type in protected forest landscapes is mainly sandy loam, with main plant species being *Populus gansuensis* and *Populus bolleana* Lauche. The soil types in desert-oasis transition zone landscapes are mainly aeolian sandy soil and gray-brown desert soil, with main plants including *Haloxylon ammodendron*, *Calligonum mongolicum*, and *Nitraria sphaerocarpa*. The soil type in desert landscapes is mainly aeolian sandy soil, with main plants being *Agriophyllum squarrosum* and *Gra* [Figure 1: see original paper] mineae.

1.2 Sample Selection and Sampling Methods

Starting in May 2021, three 400 m × 400 m observation plots were established in protected forest landscapes (two-white poplar forest), desert-oasis transition zone landscapes (*Haloxylon ammodendron* forest), and desert landscapes (bare land). Based on survey and measurement conditions, three sampling locations were selected at approximately 100 m intervals along the length direction in each plot, near which plant distribution was uniform and growth was similar. Then, at each sampling location, three sampling points were selected in directions approximately 80 cm from the center of the sampling location. During sampling, surface litter near each sampling point was first cleared, and then soil auger samples (D = 5 cm) were collected at 0~20 cm, 20~40 cm, 40~60 cm, 60~80 cm, and 80~100 cm layers, i.e., soil samples were collected in layers from 0~100 cm. Ring knife samples were collected separately and stored. Soil samples from the same layer at the three sampling points at each location were mixed evenly, placed in sample bags and labeled, while ring knife samples were stored separately and labeled. All samples were brought back to the laboratory for determination of soil physicochemical properties and related parameters.

To exclude interference from factors other than meteorological factors (such as human disturbance and animal trampling), soil samples were collected at a frequency of once every 7 days. Additional sampling was conducted at a frequency of once every 2 days for 1 week before normal sampling began. Normal sampling at different plots was conducted according to the designed sampling frequency only after the measured data from three consecutive samples showed stability with no significant differences.

1.3 Measurement Methods

The soil samples brought back to the laboratory were used to determine soil physicochemical property indicators. Soil mass water content ( ) was measured using the 105°C drying method. Residual water content (, also called air-dried soil water content) was measured after air-drying the original soil samples to constant weight, then using the aluminum box drying method. Saturated water content ( ) and saturated hydraulic conductivity (K) were measured using the constant head method. Soil bulk density was measured using the ring knife method. Soil mechanical composition was measured using a laser particle size analyzer (Mastersizer 3000), with classification standards adopting the USDA standard, dividing soil mechanical composition into clay (<0.002 mm), silt (0.002~0.05 mm), and sand (0.05~2 mm) based on particle size. Soil volumetric water content ( ) was calculated from soil mass water content ( ) and soil bulk density. Soil temperature was measured in the field using a handheld digital soil thermometer during sampling. Duplicate experiments were conducted on soil samples from the same layer at each sampling location, and then the experimental data from the three sampling locations in the same landscape were averaged as the relevant indicator values for that landscape type for statistical analysis.

Daily rainfall and evaporation data from May to September 2021 were obtained from daily observation records at the Linze Field Meteorological Observation Station (http://lzd.cern.ac.cn) of the Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences. The Linze Station has automatic meteorological observation instruments in both the desert-oasis transition zone landscape area and the desert landscape area. Since the protected forest landscape is within the fenced area of the Linze Station and all landscapes are in the same climate zone with straight-line distances between sampling points of less than 400 m, meteorological observation data from the desert-oasis transition zone landscape were used to reflect meteorological changes during the study period [Figure 1: see original paper].

1.4 Soil Water Movement Model

1.4.1 Soil Water Movement Process The HYDRUS-2D model, developed by the U.S. Salinity Laboratory, was used to simulate soil water movement processes. In recent years, HYDRUS has become a primary tool for studying water balance and soil moisture dynamics at different scales. Numerous studies have shown that the HYDRUS-1D model can effectively describe soil moisture dynamics in different landscape types in the Mu Us Sandy Land and Horqin Sandy Land, and performs well in investigating soil moisture movement and water exchange in farmland and protected forest landscapes in the middle reaches of the Heihe River. However, compared with the limitation of HYDRUS-1D in capturing multi-dimensional hydrological phenomena, HYDRUS-2D offers rich initial and boundary conditions, can simultaneously handle vertical and horizontal water movement in soil, more accurately simulate water infiltration processes, and has optimized programming language and built-in algorithms. The model can divide the simulation profile into a certain number of finite element grids, i.e., divide a complex continuous structure into several small, simple geometric shapes, and establish a more optimized discrete model through appropriate grid size and shape to improve calculation accuracy and efficiency, thereby increasing the reliability of simulation results. Previous studies have mostly focused on farmland and protected forest landscapes, mainly under irrigation conditions, and have used the HYDRUS-1D model. However, research based on HYDRUS-2D model simulation of soil moisture dynamics in different landscapes at the oasis edge in the middle reaches of the Heihe River, and comparative analysis of spatial and temporal variations in rainfall infiltration among different landscapes, has rarely been reported. Therefore, this study explores the application of the HYDRUS-2D model in different landscapes at the oasis edge in the middle reaches of the Heihe River, uses the model to simulate soil moisture dynamics in protected forest, desert-oasis transition zone, and desert landscapes, and analyzes soil water infiltration characteristics and influencing factors to provide a scientific basis for ecological vegetation construction in wind prevention and sand fixation engineering practices in this region.

The study area has a temperate continental desert climate with dry conditions. Annual temperature variation is significant, with an average annual temperature of 7.6°C, maximum temperature of 39.1°C, and minimum temperature of -27.3°C. Average annual precipitation is approximately 117 mm, unevenly distributed throughout the year, mainly concentrated from May to September, accounting for about 70%~80% of annual precipitation. Average annual evaporation is 2390 mm. The annual frost-free period is 152 days, with annual sunshine hours of 3045 h. Northwest winds prevail, with strong sandstorm activity, an average annual wind speed of 3.2 $\mathrm{m \cdot s^{-1}}$, and maximum wind speed of 21 $\mathrm{m \cdot s^{-1}}$.

1.4.2 Soil Water Characteristic Parameters Soil water characteristic parameters in the study area were obtained using soil transfer functions. The Rosetta model was selected to predict soil hydraulic characteristic parameters in the van Genuchten equation (such as residual water content , shape coefficient n, and air-entry suction α) through neural networks. These parameters were predicted based on soil bulk density and the content of clay, silt, and sand . To more accurately describe soil moisture dynamics in the study area, appropriate adjustments and optimizations were needed for the residual water content , saturated water content , and saturated hydraulic conductivity K predicted by the Rosetta model. Considering regional climate characteristics and measured soil properties at the sample plots, parameter values were mainly adjusted by comparing differences between measured soil water content at sampling points and Rosetta predicted values. The difference between measured and simulated values was judged using root mean square error (RMSE) and mean relative error (MRE). Parameters were repeatedly adjusted through trial calculations until the simulated soil moisture distribution matched the actual conditions at sampling points . The adjusted soil water characteristic parameters are shown in .

1.4.3 Spatial and Temporal Discretization and Boundary Conditions

The simulation time unit was set to days (d) and simulated through time discretization, with time discretization intervals adjusted according to the number of iterations for convergence. This simulation set 11 observation points along the vertical direction in the soil profile [Figure 2: see original paper]. The initial time step was set to 0.0001 d, the minimum time step was 0.0001 d, and the maximum time step was 1 d. The start time was 151 d and the end time was 304 d. The initial condition of the model was set as constant water content, with radial length x = 80 cm and longitudinal length z = 100 cm in the rectangular simulation area. Since no runoff was generated in the sample plots and precipitation and evapotranspiration factors needed to be considered, the upper boundary was set as an atmospheric boundary without runoff. Preliminary survey results showed that the groundwater depth in all sample plots was relatively deep (H > 100 cm), so the lower boundary was set as a free drainage boundary. The soils in the three landscape types at the oasis edge are all aeolian sandy soils, with similar soil texture within the same landscape. The soil body can be regarded as a homogeneous continuous medium. Due to the relatively large porosity of soil particles, soil water mainly infiltrates vertically downward as gravitational water during precipitation events, while lateral infiltration is relatively small. Over a period of time, the lateral infiltration in and out of the control area is equal to zero. Additionally, there is no horizontal water movement at the vertical boundaries of the sample plots, and the water flux (h/ x) is zero. Therefore, the left and right boundaries of the model were set as zero-flux boundaries.

1.5 Model Validation and Data Processing

To determine the accuracy of water dynamic process simulation, the coefficient of determination R^2 ($P < 0.05$), root mean square error (RMSE), and mean relative error (MRE) were used to evaluate differences between measured and simulated values. The calculation formulas are as follows:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(S_i - O_i)^2}$$

$$MRE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{S_i - O_i}{O_i}\right| \times 100\%$$

where S is the simulated value, O is the measured value, i is the sample number, and N is the number of observation samples.

SPSS v26.0 software was used to complete multiple comparison analysis (LSD and Waller-Duncan analysis) and Pearson correlation analysis of simulated soil volumetric water content values and their influencing factors. Origin 2019b software was used for data processing.

2. Results

2.1 Soil Moisture Dynamic Simulation

Using the optimized soil parameters, the HYDRUS-2D model was used to simulate the soil moisture dynamics in May-September 2021 for protected forest landscapes, desert-oasis transition zone landscapes, and desert landscapes at the oasis edge in the middle reaches of the Heihe River [Figure 3: see original paper]. The results showed that the simulated and measured values of soil volumetric water content in protected forest, desert-oasis transition zone, and desert landscapes generally tended to be consistent at different soil layers. However, after effective rainfall occurred at the surface [Figure 1: see original paper], soil moisture content in the 0~20 cm soil layer of different landscapes increased sharply, particularly in desert-oasis transition zone and desert landscapes, while deeper soil layers were relatively less affected.

Comparative analysis of model simulated values and measured data in the 0~100 cm soil layer of different landscapes [Figure 4: see original paper] showed that simulated and measured values were relatively evenly distributed on both sides of the 1:1 line, indicating high fitting degree between simulated and measured values. To further evaluate model accuracy, three evaluation indicators (RMSE, MRE, and R^2) were used to verify the soil volumetric water content simulation effects of different landscape types at different soil layers .

The results showed that RMSE ranged from 0.002~0.006 cm^3/cm^3. Xiao et al. [5] simulated the infiltration process of protected forests in the middle reaches of the Heihe River using the HYDRUS model and found that the RMSE between simulated and measured values was below 0.02 cm^3/cm^3. Hong et al. [19] found that when studying soil moisture dynamic changes in the Mu Us Sandy Land, the RMSE of model simulation results ranged from 0.001~0.012 cm^3/cm^3. The RMSE values in this study fall within the range obtained by the above scholars, indicating that the HYDRUS-2D model with optimized soil parameters has high simulation accuracy in this study area.

The MRE between simulated soil volumetric water content values and measured values was 4.22%~5.20%, indicating that the simulation accuracy meets requirements using the HYDRUS-2D model. R^2 ranged from 0.725~0.967, with data points evenly distributed on both sides of the 1:1 line [Figure 4: see original paper], indicating high agreement between simulation results and measured values, which is basically consistent with the research results of Yi [15]. In summary, using the HYDRUS-2D model with optimized soil parameters to simulate soil volumetric water content in different landscape types at the oasis edge in the middle reaches of the Heihe River can meet accuracy requirements, and the model simulation results are reliable.

2.2 Soil Moisture Distribution Characteristics

The optimized HYDRUS-2D model was used to simulate the daily variation of soil volumetric water content at different soil depths in different landscape types [Figure 5: see original paper]. Differences in soil volumetric water content among landscape types were analyzed based on monthly simulations for each soil layer. The results showed that the simulated soil volumetric water content values in protected forest landscapes ranged from 0.100~0.101 cm^3/cm^3 in each soil layer; in desert-oasis transition zone landscapes, values decreased from 0.106 cm^3/cm^3 (0~20 cm layer) to 0.035 cm^3/cm^3 (80~100 cm layer); in desert landscapes, values decreased from 0.041 cm^3/cm^3 (0~20 cm layer) to 0.029 cm^3/cm^3 (20~40 cm layer), then increased to 0.037 cm^3/cm^3 (80~100 cm layer). Except for the 0~20 cm and 80~100 cm layers, soil volumetric water content simulated values in other layers showed the same significant differences among landscape types ($P < 0.05$). Protected forest landscapes showed particularly significant differences from desert-oasis transition zone and desert landscapes at each soil layer ($P < 0.05$), while no significant differences were observed between desert-oasis transition zone and desert landscapes.

Analysis of vertical changes showed that the monthly average simulated soil volumetric water content in protected forest landscapes decreased from 0.109 cm^3/cm^3 (0~20 cm layer) to 0.085 cm^3/cm^3 (60~80 cm layer), then increased to 0.105 cm^3/cm^3 (80~100 cm layer), showing a trend of first increasing then decreasing with soil depth. Desert-oasis transition zone landscapes showed the same trend, with monthly average values decreasing from 0.038 cm^3/cm^3 (0~20 cm layer) to 0.024 cm^3/cm^3 (20~40 cm layer), then increasing to 0.042 cm^3/cm^3 (80~100 cm layer). Desert landscapes showed a decreasing-increasing trend, with monthly average values decreasing from 0.024 cm^3/cm^3 (0~20 cm layer) to 0.024 cm^3/cm^3 (20~40 cm layer), then increasing to 0.026 cm^3/cm^3 (60~80 cm layer), and finally decreasing to 0.024 cm^3/cm^3 (80~100 cm layer) [Figure 6: see original paper].

2.3 Soil Moisture Infiltration Characteristics

The optimized HYDRUS-2D model was used to simulate the soil moisture infiltration process under different precipitation conditions in different landscape types. Taking precipitation events on day 46 (9.5 mm), day 122 (11.2 mm), and day 136 (32.7 mm) as examples, vertical profile distributions of simulated soil volumetric water content in the 0~100 cm layer were generated for three landscape types after precipitation [Figure 7: see original paper]. The results showed that after precipitation events less than 9.5 mm, soil moisture was mainly concentrated in the 0~10 cm layer in protected forest landscapes and in the 0~20 cm layer in desert-oasis transition zone and desert landscapes. After the 11.2 mm precipitation event, soil moisture content increased significantly in the 40~80 cm layer of protected forest landscapes and in the 0~40 cm layer of desert-oasis transition zone and desert landscapes. After the 32.7 mm precipitation event, infiltration depths in different landscape types changed substantially, indicating that increased precipitation affects soil moisture content and infiltration depth in different landscape types.

When precipitation increased from 9.5 mm to 32.7 mm, soil volumetric water content in protected forest landscapes ranged from 0.101~0.255 cm^3/cm^3, in desert-oasis transition zone landscapes from 0.077~0.118 cm^3/cm^3, and in desert landscapes from 0.030~0.048 cm^3/cm^3. Analysis of changes in soil moisture infiltration depth after three different precipitation events showed that in protected forest landscapes, infiltration depth decreased by 3.7~9.5 cm (average increase of 5.8 cm); in desert-oasis transition zone landscapes, it decreased by 16.5~29.4 cm (average increase of 18.8 cm); and in desert landscapes, it decreased by 29.5~73.1 cm (average increase of 32.4 cm). In summary, compared with desert landscapes, protected forest and desert-oasis transition zone landscapes had higher soil moisture content at each infiltration stage but smaller infiltration depth. Planting windbreak and sand-fixing plants can improve the soil's ability to collect and utilize rainwater, increase soil moisture content, slow the infiltration process, and thus positively affect soil water-holding properties.

2.4 Influencing Factors of Soil Moisture Characteristics

To investigate the influencing factors of soil moisture infiltration characteristics in different landscape types at the oasis edge in the middle reaches of the Heihe River, Pearson correlation analysis was used to analyze the relationships between simulated soil volumetric water content values and their influencing factors in three landscape types , , . The results showed that in terms of meteorological factors, atmospheric precipitation was significantly positively correlated with simulated soil volumetric water content values in all three landscape types, with the highest fitting degree in desert landscapes (Pearson correlation coefficient of 0.812). Soil evaporation was significantly negatively correlated with simulated soil volumetric water content values in all three landscape types, with the highest fitting degree in protected forest landscapes (Pearson correlation coefficient of -0.731). It should be noted that these results were obtained under essentially the same local atmospheric conditions. If differences in measured meteorological data among the three landscapes were distinguished, the correlation degree between influencing factors, particularly soil evaporation, and simulated soil volumetric water content values might differ, requiring further supplementation in subsequent research.

In terms of soil mechanical composition, simulated soil volumetric water content values in protected forest landscapes showed the highest fitting degree with clay content (<0.002 mm soil particles), with a significant positive correlation (Pearson correlation coefficient of 0.967). Desert-oasis transition zone and desert landscapes showed the highest fitting degree with sand content (0.05~2 mm soil particles), both with significant negative correlations (Pearson correlation coefficients of -0.725 and -0.789, respectively). Regarding soil hydraulic properties, simulated soil volumetric water content values in protected forest landscapes showed a significant negative correlation with soil saturated hydraulic conductivity, with the highest fitting degree (Pearson correlation coefficient of -0.953), indicating that soil volumetric water content in protected forest landscapes is mainly regulated by soil saturated hydraulic conductivity. Simulated soil volumetric water content values in desert-oasis transition zone landscapes showed the highest fitting degree with soil residual water content (Pearson correlation coefficient of 0.891). Simulated soil volumetric water content values in desert landscapes showed the highest fitting degree with soil saturated water content, with a positive correlation (Pearson correlation coefficient of 0.721), and the lowest fitting degree with soil saturated hydraulic conductivity, with a negative correlation (Pearson correlation coefficient of -0.655), indicating that soil volumetric water content in desert landscapes is mainly affected by soil saturated water content.

3. Discussion

With continuous deepening of research on soil moisture movement processes in the vadose zone worldwide, the HYDRUS model developed by the U.S. Salinity Laboratory has been widely applied and has gradually evolved into an important tool for theoretical generalization and numerical simulation of soil moisture movement characteristics. This study found that after optimizing soil parameters, the HYDRUS-2D model showed high fitting degree between simulated and measured values in the study area, with RMSE of 0.002~0.006 cm^3/cm^3, MRE of 4.22%~5.20%, and R^2 of 0.725~0.967. The simulation results showed high agreement with measured values, indicating that the model can be applied to simulate soil moisture dynamic changes in different landscape types at the oasis edge in the middle reaches of the Heihe River, particularly showing better simulation effects for soil moisture change characteristics in desert-oasis transition zone and desert landscapes.

3.1 Water Dynamic Characteristics

Soil moisture distribution characteristics refer to the temporal and spatial variation patterns of soil moisture content. Understanding these characteristics is crucial for water resource management and ecosystem health maintenance. This study found significant differences in soil moisture distribution characteristics among the three landscape types at the oasis edge in the middle reaches of the Heihe River ($P < 0.05$), which may be related to the effects of soil texture, structure, and bulk density on soil moisture distribution characteristics.

By analyzing the vertical distribution of soil volumetric water content in different landscape types, different change trends were observed with increasing soil depth. (1) The vertical distribution trend of soil volumetric water content in protected forest landscapes showed an initial increase followed by a decrease. This may be related to the distribution of branches and root structure of protected forests. First, the surface soil in protected forest landscapes is more susceptible to evapotranspiration, resulting in lower surface soil volumetric water content. Second, plant roots in protected forest landscapes gradually disperse with increasing soil depth. Compared with densely concentrated plant roots in upper layers, dispersed plant roots have less water absorption effect on soil, making soil moisture content in the 60~80 cm layer greater than that in the 0~60 cm layer. Third, the 60~80 cm layer has smaller porosity and is subject to water retention from overlying soil, resulting in lower water content. Meanwhile, the soil texture in the 60~80 cm layer is relatively fine and may contain more organic matter and cementing substances, which can improve soil water retention and promote water accumulation in the 60~80 cm layer. Therefore, the maximum soil volumetric water content is located in the 60~80 cm layer. (2) The vertical distribution trend of soil volumetric water content in desert-oasis transition zone landscapes is the same as that in protected forest landscapes, which may be related to root distribution characteristics of transition zone plants. The plant community composition in the transition zone is simple, with plant roots concentrated in the 60~80 cm layer. Plant roots have the effect of consolidating soil, and combined with preferential flow in the root zone, the water-holding capacity of the root zone soil remains relatively stable and consistent. (3) The vertical distribution trend of soil volumetric water content in desert landscapes shows a decreasing-increasing pattern, with the maximum value located in the 80~100 cm layer. This is because the soil in desert landscapes is mainly aeolian sandy soil with weak water-holding capacity. Deep soil moisture content is more strongly associated with groundwater replenishment and is more easily affected by groundwater recharge. Therefore, deep soil has higher volumetric water content, which is consistent with the research results of Fu et al. [41].

3.2 Influencing Factors

The study area is located in an arid desert climate zone, where soil moisture distribution and infiltration characteristics in different landscape types are comprehensively affected by meteorological factors, soil mechanical composition, and other factors. This study found that soil volumetric water content is positively correlated with precipitation, consistent with the research of Hu et al. [5]. It is negatively correlated with soil evapotranspiration, consistent with the research results of Che et al. [39]. Soil evapotranspiration has a certain regulatory effect on hydrological cycles and plant distribution characteristics in arid and semi-arid areas. Soil volumetric water content decreases with enhanced evapotranspiration, and the decrease in soil volumetric water content in turn restricts plant growth and development, reduces coverage, and leads to weakened plant shading effects, further intensifying soil water evapotranspiration. Therefore, soil moisture shows a significant negative correlation trend with evapotranspiration.

Soil particle content shows positive correlation with soil volumetric water content when less than 0.002 mm and negative correlation when greater than 0.05

mm, which is similar to previous research results [31, 40]. Different soil particle compositions lead to different pore conditions. When the proportion of coarse soil particles increases, soil porosity also increases, resulting in weakened soil water retention and enhanced water movement under gravity, increasing infiltration capacity. The soil bulk density in protected forest landscapes (1.42~1.52 $\mathrm{g \cdot cm^{-3}}$) is smaller than that in desert-oasis transition zone landscapes (1.55~1.65 $\mathrm{g \cdot cm^{-3}}$) and desert landscapes (1.46~1.55 $\mathrm{g \cdot cm^{-3}}$), resulting in higher in protected forest landscapes compared with desert-oasis transition zone and desert landscapes. Sun [31] indicated that soil porosity, pore connectivity, and soil particle arrangement are important influencing factors of soil hydraulic properties. Pore connectivity significantly affects saturated hydraulic conductivity, and macropores can reduce soil saturated hydraulic conductivity. When soil aggregate structure is relatively good, the soil water characteristic curve shows an upward trend. In summary, the differences in soil moisture characteristics among different landscape types at the oasis edge in the middle reaches of the Heihe River may be related to differences in soil texture and pore characteristics, which require further research. Additionally, simulation results showed that except for the 0~20 cm and 80~100 cm layers [Figure 5: see original paper], soil volumetric water content simulated values in other layers showed the same significant differences among landscape types ($P < 0.05$), indicating that different landscape types in the study area have basically the same water dynamic change characteristics at 20~80 cm soil depth.

It should be noted that the research group is conducting multiple observation studies on eco-hydrology in the study area. This paper only presents a preliminary exploration of the application of the HYDRUS-2D model in soil moisture dynamic simulation, representing partial stage results. As for the effects of microclimate characteristics, soil pore features, and plant distribution patterns in different landscape types on the spatial and temporal distribution and infiltration of soil moisture, this paper has not conducted in-depth research, and the results may have certain errors. Subsequent research needs to comprehensively consider the effects of various factors on soil moisture dynamic changes based on continuous observations, deepen the research on influencing mechanisms, and further improve HYDRUS-2D model parameters to enhance model simulation accuracy.

4. Conclusions

Based on existing observation data, this study attempted to use the HYDRUS-2D model to simulate soil moisture dynamic changes in different landscape types in arid areas, representing an exploratory practice of soil moisture research methods. Preliminary conclusions are as follows:

(1) Using the HYDRUS-2D model with optimized soil parameters to simulate soil volumetric water content, RMSE was 0.002~0.006 cm^3/cm^3, R^2 was 0.725~0.967, and MRE was 4.22%~5.20%. The simulated values showed high fitting degree with measured values, indicating high model applica-

bility. Therefore, the model can be used for quantitative analysis of soil moisture dynamics in the study area.

(2) Simulation results showed that in the study area, soil volumetric water content in protected forest and desert-oasis transition zone landscapes showed a trend of first increasing then decreasing with soil depth, while desert landscapes showed the opposite trend of first decreasing then increasing. Except for the 0~20 cm and 80~100 cm layers, soil volumetric water content in other layers showed roughly the same significant differences among landscape types ($P < 0.05$). However, monthly soil volumetric water content in protected forest landscapes showed significant differences from the other two landscapes at all soil layers ($P < 0.05$).

(3) The three landscape types responded differently to precipitation infiltration. Compared with protected forest and desert-oasis transition zone landscapes, desert landscapes responded more actively, with greater soil moisture infiltration depth at each infiltration stage. Precipitation above 9.5 mm can significantly increase soil moisture content and infiltration depth in the short term. Planting windbreak and sand-fixing shrubs can better improve the soil's ability to collect and utilize rainwater, slow the infiltration process, and thus positively affect soil water-holding properties.

(4) Simulated soil volumetric water content values in the three landscape types showed significant correlations at different levels with precipitation, evapotranspiration, bulk density, soil particle content, and soil water-holding properties ($P < 0.01$). All were significantly positively correlated with precipitation and clay-silt content, and significantly negatively correlated with evapotranspiration, bulk density, and sand content.

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Note: Figure translations are in progress. See original paper for figures.