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Postprint: Simulation of Soil Water Dynamics under Different Irrigation Regimes in Sandy Loam Cropland in the Middle Reaches of the Heihe River

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Abstract

Farmland in arid regions with sandy loam soil is characterized by low fertility, poor water retention, high infiltration losses, and low crop yields. Elucidating the patterns of soil water movement in sandy loam farmland is of great significance for conserving water resources and increasing crop yields. This study took newly reclaimed sandy loam maize farmland in the middle reaches of the Heihe River as the research object, establishing experimental plots for three irrigation modes: flat plastic mulch irrigation, ridged plastic mulch irrigation, and drip irrigation under mulch. The HYDRUS-2D model was employed to simulate soil water movement processes in maize farmland under different irrigation modes. The results show that: (1) The simulated values from the HYDRUS-2D model in this study demonstrated high agreement with measured data, with R2 reaching above 0.864 and RMSE remaining below 0.006 cm3 · cm-3, validating the feasibility and reliability of the model for simulating soil water dynamics in sandy loam farmland. (2) Compared with flat plastic mulch irrigation, ridged plastic mulch irrigation increased soil volumetric water content in the crop root zone by approximately 20% while reducing infiltration losses by 13.3% under the condition of reduced irrigation water amount of 2099 m3 · hm-2; whereas drip irrigation under mulch reduced irrigation water consumption by 50% and infiltration loss by 50.7% compared with flat plastic mulch irrigation. (3) The drip irrigation under mulch mode, characterized by 'frequent irrigation with small amounts', enabled water to replenish the crop root zone more directly and efficiently, increased soil volumetric water content in the maize root zone to a greater extent, and further reduced infiltration. Therefore, drip irrigation under mulch is recommended for sandy loam farmland in the middle reaches of the Heihe River to achieve the goal of water conservation and yield improve-

ment. (4) The HYDRUS-2D model parameter system constructed in this study can also provide a reference for simulating irrigation water dynamics in similar sandy loam farmland in northern China.

Full Text

Soil Moisture Dynamic Simulation Under Different Irrigation Patterns in Sandy Loam Farmland of the Middle Heihe River Basin

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Abstract

Farmlands in arid regions are characterized by low soil fertility, poor water-holding capacity, substantial leakage, and low crop yields. Understanding soil moisture movement patterns in sandy loam farmland is crucial for water conservation and crop yield improvement. This study focused on newly reclaimed sandy loam maize farmland in the middle reaches of the Heihe River, establishing three experimental plots with different irrigation patterns: flat mulching irrigation, ridge mulching irrigation, and subsurface drip irrigation under plastic film. The HYDRUS-2D model was employed to simulate soil moisture migration processes under these different irrigation regimes. The results demonstrated that: (1) The simulated values from the HYDRUS-2D model showed strong agreement with measured data, with R^2 exceeding 0.864 and RMSE below 0.006 cm^3 cm^{-3}, validating the model's feasibility and reliability for simulating soil moisture dynamics in sandy loam farmland. (2) Compared with flat mulching irrigation, ridge mulching irrigation increased root zone soil volumetric water content by approximately 20% while reducing seepage losses by 13.3%, despite a 2099 m^3 ha^{-1} reduction in irrigation volume. (3) Subsurface drip irrigation under film reduced irrigation water consumption by 50% and leakage by 50.7% compared with flat mulching irrigation. (4) The "frequent irrigation with small amounts" characteristic of subsurface drip irrigation enabled more direct and efficient water replenishment to the crop root zone, substantially increasing root zone soil volumetric water content while further reducing leakage. Therefore, subsurface drip irrigation under film is recommended for sandy loam farmland

in the middle Heihe River basin to achieve water savings and yield increases. The HYDRUS-2D model parameter system developed in this study can also serve as a reference for simulating irrigation water dynamics in similar sandy loam farmlands across northern China.

Keywords: sandy loam; soil volumetric water content; HYDRUS-2D model; irrigation optimization; maize farmland; middle reaches of the Heihe River

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1.1 Study Area Overview

The study area is located in Pingchuan Town, Linze County, Zhangye City, Gansu Province, in the middle reaches of the Heihe River. The terrain is flat with an average elevation of 1374 m. The region exhibits typical temperate continental arid climate characteristics, with an average annual precipitation of 117 mm (concentrated in May-September, accounting for approximately 85% of annual rainfall) and annual evaporation reaching 2390 mm—about 20 times the precipitation. The average annual temperature is 7.6°C, with maximum and minimum temperatures of 39.1°C and -27.3°C, respectively. The annual sunshine duration is 3045 hours, and accumulated temperature $ 10°Cis3085°Cd.Theannualradiationtotalis6.1×10^{9}$ J m^{-2}. Local farmland types consist of two categories: long-cultivated old farmland along the Heihe River banks and newly reclaimed farmland developed from desert areas since the 1990s. This study focused on newly reclaimed sandy loam farmland located in the oasis-desert transition zone in northern Linze County (100°07 E, 39°21 N), near the Gansu Linze Farmland Ecosystem National Field Scientific Observation and Research Station. Daily precipitation and evaporation data from May-September 2023 are shown in [Figure 1: see original paper].

1.2 Experimental Design

In May 2023, irrigation experimental plots were established in newly reclaimed sandy loam farmland (reclaimed in 2020). Three adjacent 25 m × 25 m plots were designated for flat mulching irrigation, ridge mulching irrigation, and subsurface drip irrigation under film (referred to as flat mulching, ridge mulching, and subsurface drip irrigation, respectively). All plots were planted with seed maize. The flat mulching plot employed flood irrigation, with each irrigation event designed at 8995.5 m^3 ha^{-1} (based on local long-term averages for seed maize), approximately 15-day intervals, totaling 6 irrigation events and 375.36 mm of water. The ridge mulching plot followed the same irrigation timing but with total irrigation reduced to 6896.5 m^3 ha^{-1} according to the Gansu Provincial Industry Water Quota (2023 edition). For subsurface drip irrigation, drip lines were placed 10 cm below the surface (based on soil conditions and maize root development), with 5 drip emitters per plot at flow rates of 5, 10, and 15 $cm \cdot d^{-1}$, totaling 4497.8 m^3 ha^{-1} across 15 irrigation events.

Following the first irrigation in late May, three sampling points were selected along diagonal transects in each plot. Soil samples were collected before each irrigation/fertilization event from 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm depths using core samplers and augers to determine soil volumetric water content, residual water content, saturated water content, saturated hydraulic conductivity, particle composition, and bulk density. Flat mulching samples were collected from both bare and mulched areas, while ridge mulching and subsurface drip irrigation samples were taken from mulched zones. All samples were analyzed following standard agrochemical methods. Post-harvest yields were 513 kg ha^{-1} for flat mulching, 570 kg ha^{-1} for ridge mulching, and 535 kg ha^{-1} for subsurface drip irrigation.

1.3.1 Soil Water Characteristic Parameters

Soil water characteristic parameters were predicted using the Rosetta software based on bulk density and clay, silt, and sand contents. To improve simulation accuracy for the study area, measured soil water content data were compared with Rosetta predictions to obtain discrepancy data. Using HYDRUS-2D's parameter inversion function, key parameters including residual water content ( ), saturated water content ( ), and saturated hydraulic conductivity (K) were iteratively optimized until simulated soil moisture distributions closely matched observed values. Soil particle size followed USDA standards: clay (<2 m), silt (2-50 m), and sand (>50 m). Adjusted parameters are shown in .

Soil water movement was described using the Richards equation, with soil hydraulic properties characterized by the van Genuchten-Mualem model. Root water uptake was simulated using the Feddes model with parameters referenced from previous studies in the region [Figure 3: see original paper].

1.3.2 Free Drainage Boundary Leakage Model

The HYDRUS series models reliably assess deep leakage losses. In this study, leakage was calculated using HYDRUS-2D's boundary water flux module. With left and right boundaries set as zero-flux boundaries, leakage occurred only at the lower boundary. The free drainage boundary flux (velocity) data were exported from HYDRUS-2D and time-integrated to obtain total leakage, expressed in mm d^{-1}.

1.4 Model Construction

The model domain was defined as follows: For flat mulching, a rectangular region of 100 cm (radial) × 100 cm (vertical) with a 60 cm mulched zone centered on the upper boundary. Ridge mulching used a 100 cm × 110 cm domain with 10 cm ridge height and 50 cm mulched ridge top. Subsurface drip irrigation used the same dimensions as flat mulching but with circular water application sections representing emitters at 10 cm depth.

Upper boundary conditions: Bare areas were set as atmospheric boundaries (green lines in figures); mulched areas were zero-flux boundaries due to film impermeability. Vertical boundaries were zero-flux (white lines) assuming negligible horizontal water movement, given the high sand content and dominant vertical infiltration. The lower boundary was set as free drainage (olive green lines) since groundwater depth exceeds 10 m and soils are highly permeable. Observation nodes were placed at 10, 30, 50, 70, and 90 cm depths (red points) to monitor and simulate soil volumetric water content dynamics during the growing season. Simulation time was discretized in days from day 0 to 122, with initial time step of 0.001 d, minimum step of 0.00001 d, and maximum step of 1 d.

1.5 Model Validation

Flat mulching data were used for parameter calibration and model accuracy verification. The calibrated HYDRUS-2D model was then applied to simulate soil moisture dynamics under ridge mulching and subsurface drip irrigation, with results compared against measured data from root zones (0-40 cm). Model performance was evaluated using root mean square error (RMSE), mean relative error (MRE), and coefficient of determination (R^2). According to literature [15,28-29], $R^2 > 0.8$, RMSE < 0.01 cm^3 cm^{-3}, and MRE $< 10\%$ indicate satisfactory simulation results.

2.1.1 Analysis of Measured Soil Volumetric Water Content

Under flat mulching, average soil volumetric water content across all layers ranged 0.096-0.181 cm^3 cm^{-3}, with minimum values in 80-100 cm depth (0.096 cm^3 cm^{-3}) and maximum in bare zone surface layers (0.181 cm^3 cm^{-3}). This reflects the sandy loam texture with low clay content in deeper layers, resulting in poor water-holding capacity that decreases with depth. The largest variance occurred in mulched 80-100 cm layer (0.003), indicating high variability due to rapid infiltration. All mulched zone measurements showed weak variation (CV $< 10\%$), while bare zone 20-40 cm layer showed moderate variation (CV $=$ 11.3%).

2.1.2 Model Accuracy Verification

Comparison of simulated and measured soil volumetric water content under flat mulching across 0-100 cm depth showed good agreement, with points evenly distributed around the 1:1 line [Figure 5: see original paper]. R^2 values were 0.864 for mulched zones and 0.921 for bare zones, with RMSE of 0.005 cm^3 cm^{-3} and 0.006 cm^3 cm^{-3}, and MRE of 4.06% and 5.32%, respectively. These results confirm that the optimized HYDRUS-2D model provides reliable simulations for soil moisture dynamics in newly reclaimed sandy loam farmland in the middle Heihe River basin.

2.2 Ridge Mulching Mode

The calibrated HYDRUS-2D model achieved $R^2 = 0.864$ for ridge mulching, confirming its applicability. Ridge mulching significantly increased 0-40 cm soil volumetric water content in mulched areas compared with flat mulching [FIGURE:8-9]. The average water content followed the order: 0-20 cm > 80 cm > 40-60 cm > 20-40 cm > 80-100 cm. The 0-20 cm layer near the ridge center (root-dense zone) showed highest water content, demonstrating that ridge mulching effectively improved shallow root zone moisture. Although irrigation methods and timing remained unchanged from flat mulching, ridge mulching enhanced water productivity and achieved water savings. However, similar to flat mulching, the plastic film prevented direct water replenishment beneath the mulched area, limiting moisture in the central root zone.

2.3 Subsurface Drip Irrigation Mode

For subsurface drip irrigation, the model achieved $R^2 = 0.864$, demonstrating good applicability. This irrigation method directly supplements moisture to the root-dense zone. At 5 $cm \cdot d^{-1}$ emitter flow, water primarily affected the 0-40 cm layer; at 10 $cm \cdot d^{-1}$, water reached 40-60 cm; and at 15 $cm \cdot d^{-1}$, water penetrated to 60-80 cm [FIGURE:10-13]. The 0-20 cm and 20-40 cm layers showed the most significant moisture changes, with higher water content maintained longer after irrigation compared with ridge mulching. Although single irrigation amounts were much smaller than ridge mulching, the direct root zone application resulted in higher 0-40 cm water content and lower 40-60 cm content, effectively controlling water within the root zone and reducing deep percolation.

2.4 Comparison of Simulated Leakage Under Different Irrigation Modes

To ensure water supply and yield stability, local farmers traditionally use flood irrigation, causing deep percolation when soil moisture exceeds saturation. Simulated leakage comparison revealed the following order during the growing season: flat mulching > ridge mulching > subsurface drip irrigation [Figure 14: see original paper]. Ridge mulching reduced maximum leakage by 16.5% and total leakage by 13.3% (from 375.36 mm to 325.47 mm) compared with flat mulching. Subsurface drip irrigation reduced maximum leakage by 55.5% and total leakage by 50.7% (to 184.87 mm) compared with flat mulching, and by 43.3% compared with ridge mulching. The "small amount, frequent irrigation" approach of subsurface drip irrigation substantially reduced water loss.

3.1 Comparison of Different Irrigation Modes

Both ridge mulching and subsurface drip irrigation achieved water-saving and yield-increasing effects compared with flat mulching. Ridge mulching reduced water use by 23.3% while increasing yield by 11.1%; subsurface drip irrigation reduced water use by 50% while increasing yield by 4.3%. The model quantified spatiotemporal water distribution patterns: ridge mulching increased root zone moisture through lateral infiltration but still exhibited significant deep leakage, consistent with high hydraulic conductivity of sandy soils . Subsurface drip irrigation, through its "small water, frequent irrigation" strategy, precisely controlled water within the root zone (0-40 cm), reducing deep leakage to only 49.3% of flat mulching and 56.7% of ridge mulching. This makes subsurface drip irrigation ideal for sandy loam farmland in the middle Heihe River basin.

Ridge mulching improves soil aeration and root development, enhancing water and nutrient uptake efficiency. The ridge furrow collects water, increasing hydraulic head during irrigation and promoting lateral water movement to the root zone. However, strong infiltration in sandy soils means large single irrigation amounts still cause substantial deep percolation before uniform lateral distribution can occur. Subsurface drip irrigation addresses this by delivering water directly to the root zone at high frequency, mitigating drought stress caused by severe water percolation in sandy soils and maintaining optimal moisture levels for crop growth.

3.2 Model Guidance for Similar Soil Farmland

The HYDRUS-2D model demonstrates strong regional adaptability for simulating water, heat, and solute transport in unsaturated porous media. This study validated the model using measured soil moisture data from sandy loam farmland, achieving $R^2 = 0.864$-0.921 and RMSE < 0.006 cm^3 cm^{-3} across different irrigation modes. The model accurately captured rapid water percolation characteristics of sandy soils and is particularly suitable for analyzing deep leakage under various irrigation patterns. Similar studies have successfully applied HYDRUS-2D in the Hetao Irrigation District and other arid regions of northern China. The parameter system developed here can be extended to similar sandy loam farmlands, providing scientific guidance for irrigation management departments to optimize irrigation amounts and frequencies, achieve precise root zone moisture control, and promote transformation toward "high-efficiency water saving and stable high yield."

3.3 Outlook

Crop evapotranspiration varies with growth stage, meteorological conditions, soil texture, and irrigation regime, affecting model parameters. While this study simulated soil moisture dynamics under different irrigation modes, it did not deeply explore precipitation effects on evapotranspiration or differences in root growth and water uptake characteristics among irrigation modes. Future research should incorporate these factors to adjust model parameters and achieve true optimization of water use efficiency and crop yield. Additionally, integrating HYDRUS-2D with remote sensing data could enhance regional-scale simulation capabilities for water productivity distribution patterns in arid oasis farmlands.

4 Conclusions

Based on field experiments and model calibration, this study analyzed spatiotemporal variation characteristics of soil volumetric water content under different irrigation modes in sandy loam farmland of the middle Heihe River basin. The main conclusions are:

1) The calibrated HYDRUS-2D model showed good agreement with field measurements (R^2 = 0.864-0.921, RMSE < 0.006 cm^3 cm^{-3}), demonstrating reliable performance for simulating soil moisture dynamics in this region.
2) Ridge mulching increased root zone soil volumetric water content by ~20% and reduced leakage by 13.3% compared with flat mulching, despite 2099 m^3 ha^{-1} less irrigation water. Subsurface drip irrigation reduced irrigation water by 50% and leakage by 50.7%.
3) The "frequent irrigation with small amounts" approach of subsurface drip irrigation directly replenished the root zone, increasing root zone water content by 16.5% while reducing leakage by over 43% compared with ridge mulching. This makes it the recommended irrigation mode for local sandy loam farmland.
4) The HYDRUS-2D parameter system developed in this study has broad applicability for similar sandy loam farmlands in arid regions, providing a scientific basis for optimizing irrigation management and promoting water-saving, high-yield agriculture.

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