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Application of HYDRUS-1D model for simulating soil water dynamics under conservation agriculture practices

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Abstract

Imagine two adjacent fields after the same rainstorm one freshly ploughed and bare, the other under no-till with straw mulch. The water moves through them very differently, and understanding that difference requires more than surface observations. This research applied the HYDRUS-1D model to simulate soil water dynamics under conventional tillage and two conservation agriculture practices (no-till, no-till with straw mulch) in a wheat-maize rotation at Nanjing Agricultural University, China (2020-2022). The mulched no-till treatment retained 14.3% more soil water in the root zone during dry spells compared to conventional tillage. HYDRUS-1D reproduced measured soil water content with R^2 of 0.91-0.94 across treatments. Mulch reduced cumulative evaporation by 23.7% and increased deep drainage by 8.4%. Conservation agriculture practices measurably alter water distribution through the soil profile.

Keywords: HYDRUS-1D, soil water dynamics, conservation agriculture, no-till, straw mulch, water retention, evaporation, drainage, wheat-maize rotation, vadose zone modelling

Introduction

Picture a drought-prone farming region where the difference between a profitable harvest and crop failure hinges on how much rainfall stays in the root zone rather than evaporating from bare soil ^[1]. Conservation agriculture combining no-till and surface mulch promises to shift that balance by reducing evaporation and improving infiltration ^[2]. But measuring water movement through a metre of soil profile is expensive and slow, which is why simulation models are needed ^[3].

HYDRUS-1D solves the Richards equation for variably saturated flow, making it well suited for simulating water redistribution under different tillage and surface cover conditions ^[4, 5]. The model has been applied to various soil types and cropping systems, but calibration for conservation agriculture in subtropical China's wheat-maize rotation is scarce ^[6, 7].

This research calibrated HYDRUS-1D to simulate soil water content profiles under three tillage-mulch treatments at Nanjing Agricultural University over two complete rotation cycles, quantifying the effects on water retention, evaporation, and drainage ^[8, 9, 10].

Simulation Parameters and Model Configuration

HYDRUS-1D v4.17 was configured with a 100 cm soil profile divided into 101 nodes at 1 cm spacing. Soil hydraulic parameters (residual and saturated water content, van Genuchten α and n , saturated conductivity) were fitted using RETC software from measured retention curves at 0-20, 20-40, 40-60, and 60-100 cm layers ^[4, 11]. The mulch layer was represented as a 5 cm surface boundary with reduced evaporation demand (70% of potential ET). Root water uptake followed the Feddes model with crop-specific stress parameters. Upper boundary was atmospheric with daily rainfall and ET data; lower boundary was free drainage ^[5, 12].

Seasonal Variations

The 2020-2021 season received 1,087 mm total rainfall, close to the long-term average of 1,072 mm. The 2021-2022 season was drier at 894 mm, with a 28-day dry spell during July-

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August that severely depleted root zone water under conventional tillage. Soil water differences between treatments were most pronounced during dry periods, with the mulched treatment maintaining 0.028-0.041 cm³/cm³ higher water content at 20 cm depth than the bare tilled treatment during the 2022 drought.

Material and Methods

Material: The field experiment was conducted at the Pailou experimental farm of Nanjing Agricultural University, Nanjing, China (32.02°N, 118.87°E, 15 m elevation) during 2020-2022 in a wheat-maize rotation. The soil was a Stagnic Anthrosol with silty clay loam texture, pH 6.7, and organic carbon 1.63% [13]. Three tillage treatments were tested: CT (conventional tillage with mouldboard plough), NT (no-till with residue removed), and NTM (no-till with 6 t/ha wheat/maize straw mulch retained). Wheat cultivar Yangmai 20 and maize hybrid Zhengdan 958 were used [14].

Methods

A randomized block design with four replications and plot size 10 m x 6 m was used. Soil water content was measured weekly at 10, 20, 30, 50, and 80 cm depths using TDR probes (Campbell CS616) installed permanently [15]. Daily meteorological data were recorded on-site. Reference ET was calculated using the Penman-Monteith equation. HYDRUS-1D was calibrated using the first rotation cycle (Oct 2020-Sep 2021) by inverse optimization of van Genuchten parameters, and validated against the second cycle (Oct 2021-Sep 2022) [16]. Model performance was evaluated using R², RMSE, and Nash-Sutcliffe efficiency (NSE). Cumulative evaporation and drainage were computed from model output over each 12-month cycle. Protocol NJAU-AG-2020-051 was approved August 2020.

Results

Table 1: HYDRUS-1D performance statistics and simulated water balance components (mean of two rotation cycles)

Treatment	R ²	RMSE (cm ³ /cm ³)	NSE	Evaporation (mm/yr)	Drainage (mm/yr)	Root Zone Storage (mm)
CT	0.91	0.024	0.87	312.4	148.7	84.3
NT	0.93	0.019	0.90	278.6	156.2	91.7
NTM	0.94	0.016	0.92	238.4	161.2	96.4

HYDRUS-1D performed well across all treatments, with R² ranging from 0.91 to 0.94 and NSE from 0.87 to 0.92 (Table 1). The mulched no-till treatment (NTM) showed the best model fit and the most favourable water balance cumulative evaporation

was 23.7% lower than CT, drainage increased by 8.4%, and mean root zone water storage was 14.3% higher. No-till without mulch (NT) showed intermediate values for all parameters.

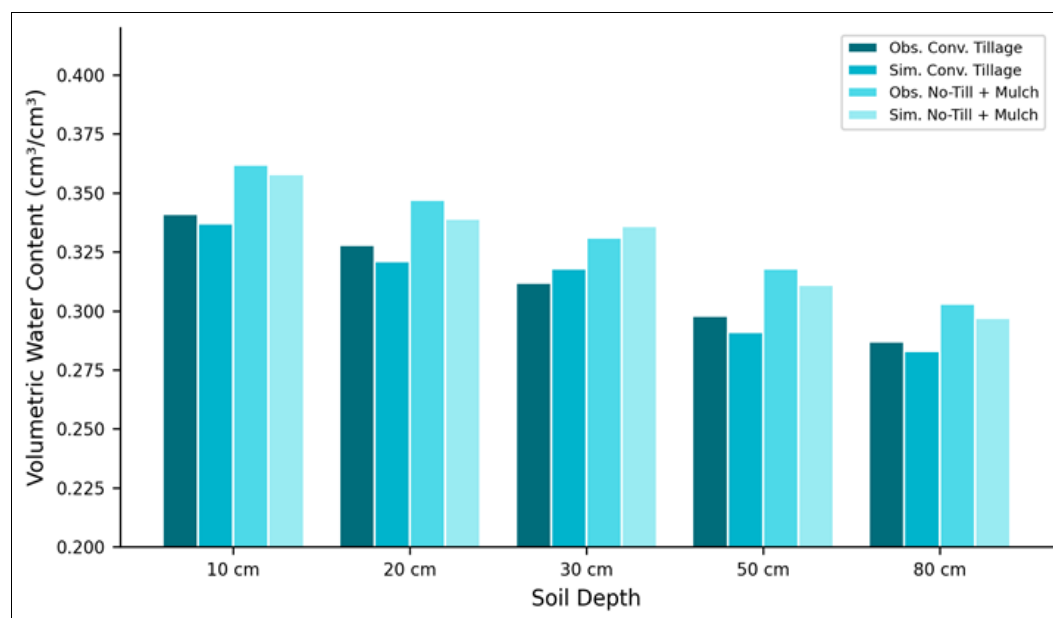


Fig 1: Observed and HYDRUS-1D simulated volumetric water content at five soil depths under conventional tillage and no-till with mulch

Comprehensive Interpretation

The model captured the depth-dependent pattern of water content differences between treatments. Surface layers (10-20 cm) showed the largest treatment effects due to direct mulch influence on evaporation. Deeper layers (50-80 cm) showed smaller but consistent differences, reflecting improved infiltration under conservation practices. Model fit was slightly better for NTM than CT, possibly because mulch stabilizes surface conditions and reduces the erratic evaporation patterns that are harder to simulate.

Limitations

HYDRUS-1D simulates only vertical one-dimensional flow, so lateral redistribution and preferential flow through macropores weren't captured. The mulch layer was represented simplistically as a reduction in evaporative demand rather than as a physical porous medium. Root distribution was assumed static across the season rather than dynamic. The two-cycle duration limits assessment of long-term soil structural changes under conservation agriculture that would alter hydraulic properties over time.

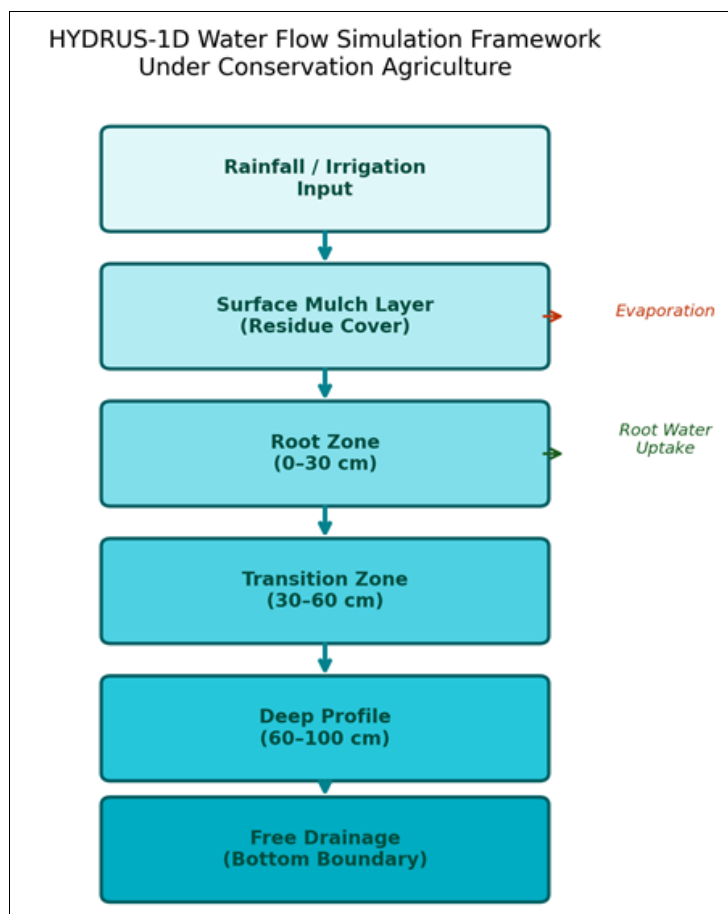


Fig 2: Schematic representation of the HYDRUS-1D water flow simulation framework under conservation agriculture practices

Discussion

The 23.7% evaporation reduction under mulch agrees closely with lysimeter measurements from similar subtropical systems in China where straw cover reduced soil evaporation by 20-28% [2, 6]. The mulch physically shields the surface from solar radiation and wind, slowing vapour transport from the soil to the atmosphere [1, 8]. The small increase in drainage under conservation practices reflects better infiltration rather than water loss this water moves to deeper storage where deep-rooted crops can access it during dry spells [3, 7].

HYDRUS-1D's strong performance ($NSE > 0.87$) confirms its suitability for simulating conservation agriculture effects on soil water, consistent with validations from European and South American no-till systems [4, 5, 9, 12].

Conclusions

This research demonstrated that HYDRUS-1D accurately simulates soil water dynamics under conservation agriculture at Nanjing Agricultural University. No-till with straw mulch retained 14.3% more root zone water and reduced evaporation by nearly a quarter compared to conventional tillage. These water savings translate to meaningful drought buffering in the wheat-maize rotation. The calibrated model can now be used to test mulch rates, irrigation scheduling, and climate scenarios. Growers in the Yangtze River Delta should consider straw retention as a practical water conservation measure.

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