Estimation of evapotranspiration from artificial forest in mountainous areas of western Loess Plateau based on HYDRUS-1D model postprint

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Abstract

Evapotranspiration is the most important expenditure item in the water balance of terrestrial ecosystems, and accurate evapotranspiration modeling is of great significance for hydrological, ecological, agricultural, and water resource management. Artificial forests are an important means of vegetation restoration in the western Loess Plateau, and accurate estimates of their evapotranspiration are essential to the management and development of water use strategies for artificial forests. This study estimated the soil moisture and evapotranspiration based on the HYDRUS-1D model for the artificial Platycladus orientalis (L.) Franco forest in western mountains of Loess Plateau, China from 20 April to 31 October, 2023. Moreover, the influence factors were identified by combining the correlation coefficient method and the principal component analysis (PCA) method. The results showed that HYDRUS-1D model had strong applicability in portraying hydrological processes in this area and revealed soil water surplus from 20 April to 31 October, 2023. The soil water accumulation was 49.64 mm; the potential evapotranspiration (ETp) was 809.67 mm, which was divided into potential evaporation (Ep; 95.07 mm) and potential transpiration (Tp; 714.60 mm); and the actual evapotranspiration (ETa) was 580.27 mm, which was divided into actual evaporation (Ea; 68.27 mm) and actual transpiration (Ta; 512.00 mm). From April to October 2023, the ETp, Ep, Tp, ETa, Ea, and Ta first increased and then decreased on both monthly and daily scales, exhibiting a single-peak type trend. The average ratio of Ta/ETa was 0.88, signifying that evapotranspiration mainly stemmed from transpiration in this area. The ratio of ETa/ETp was 0.72, indicating that this artificial forest suffered from obvious drought stress. The ETp was significantly positively correlated with ETa, and the R2 values on the monthly and daily scales were 0.9696 and 0.9635 ($P<0.05$), respectively. Furthermore, ETa was significantly positively correlated with temperature, solar radiation, and wind speed, and negatively correlated with relative humidity and precipitation ($P<0.05$); and temperature exhibited the highest correlation with ETa. Thus, ETp and temperature were the decisive contributors to ETa in this area. The findings provide an effective method for simulating regional evapotranspiration and theoretical reference for water management of artificial forests, and deepen understanding of effects of each influence factors on ETa in arid areas.

Full Text

Preamble

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Estimation of evapotranspiration from artificial forest in mountainous areas of western Loess Plateau based on HYDRUS-1D model

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Abstract: Evapotranspiration represents the most significant water balance component in terrestrial ecosystems, and accurate modeling is crucial for hydrological, ecological, agricultural, and water resource management applications. Artificial forests serve as a vital vegetation restoration strategy in the western Loess Plateau, making precise evapotranspiration estimates essential for water management and sustainable forest development. This study employed the HYDRUS-1D model to estimate soil moisture dynamics and evapotranspiration for an artificial *Platycladus orientalis* (L.) Franco forest in the mountainous western Loess Plateau from April 20 to October 31, 2023. Influencing factors were identified through combined correlation coefficient and principal component analysis (PCA) methods. Results demonstrated strong applicability of the HYDRUS-1D model for characterizing hydrological processes in this region, revealing a soil water surplus of 49.64 mm during the study period. Potential evapotranspiration (ETp) totaled 809.67 mm, comprising potential evaporation (Ep; 95.07 mm) and potential transpiration (Tp; 714.60 mm). Actual evapotranspiration (ETa) reached 580.27 mm, consisting of actual evaporation (Ea; 68.27 mm) and actual transpiration (Ta; 512.00 mm). Both monthly and daily scales showed unimodal trends, with all components increasing initially then decreasing.

The average Ta/ETa ratio of 0.88 indicated that transpiration dominated evapotranspiration in this region. The ETa/ETp ratio of 0.72 revealed significant drought stress in the artificial forest. ETp showed strong positive correlation with ETa, with R^2 values of 0.9696 and 0.9635 ($P<0.05$) on monthly and daily scales, respectively. ETa exhibited significant positive correlations with temperature, solar radiation, and wind speed, and negative correlations with relative humidity and precipitation ($P<0.05$), with temperature showing the strongest relationship. Thus, ETp and temperature emerged as the primary determinants of ETa. These findings provide an effective method for regional evapotranspiration simulation and theoretical guidance for artificial forest water management, while advancing understanding of factor effects on ETa in arid regions.

Keywords: potential evapotranspiration; actual evapotranspiration; evaporation; transpiration; HYDRUS-1D model; Loess Plateau; soil water content

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1 Introduction

Evapotranspiration constitutes the dominant water balance component in terrestrial ecosystems, with approximately 70% of global surface precipitation returning to the atmosphere through this process, exceeding 90% in arid regions (Wegehenkel et al., 2017). Evapotranspiration comprises plant transpiration and soil evaporation, representing the primary pathway for water balance and energy exchange at the soil-plant-atmosphere interface and linking key ecological processes including plant stomatal behavior, water use, and carbon exchange (Chen et al., 2023). Both evaporation and transpiration are critical elements governing water balance and energy exchange among soil, vegetation, and atmosphere, closely related to climatic conditions (e.g., solar radiation, temperature, precipitation), vegetation type (e.g., trees, grasses, shrubs), and vegetation growth status (Lü et al., 2024). In healthy ecosystems, evaporation and transpiration maintain appropriate ratios; for instance, transpiration may be two to three times higher than evaporation in forest ecosystems. Accurate understanding of evaporation and transpiration variations is therefore essential for assessing and managing soil water resources in terrestrial ecosystems (Wolf et al., 2024).

Evapotranspiration is subdivided into potential evapotranspiration (ETp) and actual evapotranspiration (ETa). ETp represents the theoretical upper limit of evapotranspiration when surface water is non-limiting, describing atmospheric capacity to absorb water through evaporation and transpiration (Okkan et al., 2024). ETa represents actual surface evapotranspiration under external constraints. While Peng et al. (2017) projected increasing ETp trends, Lü et al. (2019) suggested ETa decreases with rising ETp. Conversely, Su et al. (2021) observed positive ETp-ETa correlations, closely related to environmental differences and anthropogenic disturbances (Yang et al., 2022). The ETa/ETp ratio serves as a primary climate control factor for vegetation distribution and plays a crucial role in quantifying vegetation responses to climate, enabling assessment of drought stress impacts on plant growth (Ramos et al., 2023). Variations in ETa/ETp driven by increasing aridity and global warming could alter soil moisture and vegetation cover, thereby affecting water and carbon cycles (Feng et al., 2018). Accurate investigation of ETa-ETp relationships is therefore necessary to quantify water deficits and predict ecohydrological responses to climate change in drylands.

Numerical modeling provides an important tool for deconstructing water balance and reproducing water cycle processes (Xiang et al., 2020). Models can effectively simulate hydrological processes and evaluate water resources with minimal observational data, offering advantages of lower cost, time, and effort compared to other methods (Chen et al., 2021). Conventional soil water research involves substantial workload, high costs, and varying degrees of external interference. Integrating traditional field observations with numerical simulation improves model accuracy while enhancing operational efficiency, enabling investigation of soil moisture dynamics and hydrological processes across diverse spatiotemporal scales (Diongue et al., 2023). Based on Richards' principle, the HYDRUS-1D model incorporates soil hydrothermal processes and root water absorption (Thayalakumaran et al., 2018), demonstrating strong applicability and operability for simulating soil water transport and plant evapotranspiration dynamics (Wu et al., 2023). With flexible input/output functions and parameter optimization modules, HYDRUS-1D has been widely applied (Kumar et al., 2023).

Numerous studies have demonstrated HYDRUS-1D' s applicability for quantifying evapotranspiration (Li et al., 2019; Er-Raki et al., 2021; Lu et al., 2024). Beyene et al. (2018) used HYDRUS-1D to simulate deep percolation and ETa from flood irrigation in Ethiopia's Lake Tana floodplains, confirming its effectiveness for predicting deep infiltration and ETa. Lian et al. (2018) simulated daily ETa at 59 locations in a Chinese oasis-desert area, concluding that HYDRUS-1D enables assessment of daily ETa under varying soil moisture and vegetation cover conditions. Yi et al. (2022) estimated groundwater recharge and evapotranspiration under drip irrigation in Northwest China' s arid inland basins, highlighting the model' s role in optimizing irrigation schemes.

Located in East Asia' s hinterland, China' s Loess Plateau features concentrated loess distribution with deep accumulation and extensive coverage (Ge et al., 2022). The region faces severe ecological challenges including intense soil erosion, extensive land resource degradation, and ecological fragility (Yi et al., 2016). Studies show that Loess Plateau evapotranspiration is significantly influenced by environmental factors, land cover, and human activities, with environmental factor effects varying even under single land cover types (Gao et al., 2017; Jiang et al., 2021; Li et al., 2022). Li et al. (2016) observed significant differences in wind speed, temperature, solar radiation, and barometric pressure effects on ETa under different climate scenarios. Cao et al. (2023) identified sunshine duration, temperature, and precipitation as the three primary factors highly correlated with ETa. However, large uncertainties in environmental factors at small watershed scales and varying impact degrees among factors have prevented consensus, necessitating further investigation into ETa patterns, ETa-ETp relationships, and differential environmental factor impacts in Loess Plateau small watersheds.

Compared to other Loess Plateau regions, the western area experiences more severe soil erosion, with low and unevenly distributed precipitation where evapotranspiration considerably exceeds precipitation (Jin et al., 2018). Single precipitation events fail to meet vegetation growth demands, resulting in low vegetation cover and poor ecological conditions. Various artificial forests have been established to address these issues (Li et al., 2021). As evapotranspiration constitutes the primary water consumption pathway in artificial forests, accurate calculation and factor analysis are crucial for improving water use efficiency and ecological conditions (He et al., 2020). Due to high costs and time requirements for field evapotranspiration observations, most existing research uses remote sensing data to study large-scale dynamics, lacking detailed characterization of evapotranspiration and hydrological processes in arid watersheds. Employing HYDRUS-1D to accurately characterize evapotranspiration dynamics with limited measured data for water balance deconstruction is therefore essential.

Given these considerations, this study applied HYDRUS-1D to estimate ETp and ETa in artificial forests within the arid mountainous western Loess Plateau. The objectives were to: (1) quantify dynamic characteristics of ETa and ETp for artificial *Platycladus orientalis* (L.) Franco forest on Nanshan Mountain in Lanzhou, Gansu Province; (2) investigate ETa-ETp relationships in arid regions; and (3) analyze environmental factor effects on ETa in the western Loess Plateau mountainous area.

2.1 Study Area

The sampling site is located at Jiaoyuting Forestry Farm (36°01 48 N, 103°55 12 E) on Nanshan Mountain in Lanzhou City, at 1755.00 m elevation (Fig. 1 [Figure 1: see original paper]). The region has a temperate semi-arid continental monsoon climate with distinct seasonal warm-cold and wet-dry variations. Annual average temperature and precipitation are 10.8°C and 322.00 mm, respectively. During the simulation period, daily average temperature was 18.7°C and cumulative precipitation reached 361.00 mm, concentrated in

July-October (Fig. 1d). The 15.5 hm^2 forest occupies a shady slope with approximately 30° gradient. Vegetation is dominated by *P. orientalis* (Fig. 1c) with an average age of 35 years. Soils are primarily gray calcareous with pH values of 7.8–8.2.

2.2 Selection of Sample Plot

Five 10.00 m × 10.00 m plots (S1-S5) were randomly established within a 100.00 m × 100.00 m block at Jiaoyuting Forestry Farm for forest stand surveys (plant height, canopy area, basal diameter) and soil water measurements. Plant height, canopy area, and basal diameter were measured for each tree in each plot, with plot averages calculated. Three sites per plot were randomly selected for soil sampling at 0.00–200.00 cm depth in 20.00 cm intervals (10 layers total), with three samples per layer. Average soil water content was calculated for each plot. Based on these measurements, plot S3, whose vegetation characteristics and soil moisture most closely matched the five-plot averages, was selected as the representative sample plot (Table 1).

2.3 Data Collection

Meteorological instruments were installed in an open area 100.00 m northeast of the forest to monitor temperature, precipitation, relative humidity, wind speed, and solar radiation from April 19 to October 31, 2023, with 30-minute data collection frequency.

A soil water monitor (EJ-200, Jianling Technology Co., Beijing, China) was installed in the representative plot to obtain high-accuracy soil moisture data. Real-time monitoring at depths of 10.00, 30.00, 50.00, 70.00, 90.00, 110.00, 130.00, 150.00, 170.00, and 190.00 cm in plot S3 occurred from April 19 to October 31, 2023, with 30-minute collection intervals.

Three sampling points were randomly selected in the representative plot for soil sample collection. To determine particle size distribution, soil samples were collected in aluminum boxes at each point, with three parallel samples per layer (matching soil water monitoring depths). Ninety samples were air-dried in the laboratory, passed through a 2.00 mm sieve, and manually cleared of roots. Soil was treated with 30.00% hydrogen peroxide and 30.00% hydrochloric acid to remove organic matter and calcium carbonate. Particle size was determined using a MS2000 Malvern Laser Particle Sizer (Mastersizer2000-APA2000, Malvern, UK), with parallel sample values averaged per layer (Table 2).

Undisturbed soil samples were collected using ring knives, with 90 total samples transported to the laboratory in an incubator. Samples were dried at 105.0°C for 24 hours and weighed. Soil bulk density was calculated as the ratio of dried soil weight to ring knife volume (Table 2).

To characterize *P. orientalis* root distribution at 0.00–200.00 cm depth, three well-grown trees in plot S3 with height, canopy area, and basal diameter near plot averages were selected as representative trees. Roots were collected with a root drill (0.08 m diameter) during the vigorous growth period (August 2023). For each tree, three sampling points were established at 120° intervals 50.00 cm from the trunk, with samples taken at 10.00 cm intervals from 0.00–200.00 cm depth (60 samples per tree, 180 total). Samples were cleaned in the laboratory, roots manually selected, oven-dried at 65.0°C for 48 hours, and weighed to obtain dry weight. Root biomass per layer was then calculated (Feng et al., 2018; Zhou and Zhao, 2020).

Leaf counts were manually conducted for each sample tree. Leaves were collected from upper and lower canopy positions in four cardinal directions (east, south, west, north), totaling eight positions per tree. Five leaves per position were collected (120 total samples). Leaf area was measured using a leaf area analyzer (Yaxin1214, LICA United Technology Limited, Beijing, China) for each direction, with single-tree average leaf area calculated. Total leaf area was derived from leaf count and average leaf area across three sample trees, with the ratio of total leaf area to plant-covered area recorded as leaf area index (Yin et al., 2015; Wang et al., 2020).

2.4 HYDRUS-1D Model

The simulation period was April 20–October 31, 2023, with a 1.0000 d time step. The upper boundary was set as an atmospheric boundary to obtain precipitation and infiltration data, while the lower boundary was free drainage. The 200.00 cm soil profile was divided into 10 layers, discretized into 200 units at 1.00 cm intervals, creating 201 nodes and 10 observation points. Initial time interval was 0.0100 d, with minimum and maximum intervals of 0.0001 and 1.0000 d, respectively.

Model parameters included soil residual water content (Qr), saturated water content (Qs), reciprocal of soil intake value (α), soil pore-size distribution parameter (σ), saturated hydraulic conductivity (Ks), and pore-connectivity parameter (l). These were obtained by inputting soil particle size and bulk density into HYDRUS-1D's artificial neural network prediction module, with subsequent adjustment using the inversion module. Final values are shown in Table 3 .

2.4.1 Parameter Sensitivity Analysis

Parameter sensitivity was analyzed theoretically through single-factor perturbation analysis. Perturbations of \$±\$10.00% step size were applied based on actual input parameters. Using simulated soil water content at 10.00 cm as output, average change rates under different parameter perturbations were calculated to assess parameter influence (Huo and Jin, 2017; de Pue et al., 2019).

2.4.2 Moisture Transport Module

Soil moisture predominantly moves vertically; thus only one-dimensional vertical transport was considered, ignoring horizontal and lateral flows. Ground surface was set as coordinate origin with positive Z-axis downward. The governing equation for one-dimensional saturated-unsaturated zone moisture transport is (Šimůnek et al., 2018):

/ t = / z[K( )(h/ z + 1)] - S(z,t)

where is soil water content (cm^3/cm^3); t is time (d); z is soil depth (cm); K( ) is unsaturated hydraulic conductivity (mm/d); h is pressure head (cm); and S(z,t) is plant root water uptake rate (cm/d).

2.4.3 Determination of Soil Hydraulic Parameters

The soil water characteristic curve was fitted using the van Genuchten model (van Genuchten, 1980):

(h) = + (-)/[1 + $|\alpha h|^n$] (h < 0) (1)

K( ) = K S [1 - (1 - S ^{1}/)]^2 (2)

S = (-)/(-) (3)

m = 1 - 1/n (4)

where is residual water content (cm^3/cm^3); is saturated water content (cm^3/cm^3); α is the reciprocal of soil intake value (/cm); n is the soil pore-size distribution parameter; l is pore-connectivity parameter; K is saturated hydraulic conductivity (cm/d); and S is effective saturation.

2.4.4 Root Water Uptake Module

Root water uptake rate S(z,t) was numerically resolved using the Feddes model based on water potential difference (Šimůnek et al., 2018):

S(z,t) = α(h) × r(z) × Tp (6)

where Tp is potential transpiration (mm); r(z) is root water uptake distribution function; and α(h) is water stress function described using an s-shaped function (Šimůnek et al., 2018):

α(h) = 1/[1 + (h/h_{50})] (7)

where h_{50} is soil water potential when potential transpiration decreases by half (cm); and p is a constant.

2.4.5 Calculation of ETp

ETp was calculated using the Penman-Monteith equation (Okkan et al., 2024):

ETp = [Δ(R - G) + C (e - e)/r]/[λ(Δ + γ(1 + r /r))] (8) where ETp is vegetation transpiration plus soil evaporation under adequate water supply (mm); λ is latent heat of vaporization (MJ/kg); R is net solar radiation (MJ/($m^2 \cdot d$)); G is soil heat flux (MJ/($m^2 \cdot d$));   is atmospheric density (kg/m^3); C is constant-pressure specific heat capacity (J/(kg · °C)); e is saturation vapor pressure (kPa); e is actual vapor pressure (kPa); γ is psychrometric constant (kPa/°C); Δ is slope of saturation vapor pressure curve (kPa/°C); r is aerodynamic resistance (s/m); and r is surface resistance (s/m).

Surface and aerodynamic resistances relate to vegetation type and growth conditions (Okkan et al., 2024):

$r = 100/LAI$ (9)

$r = [\ln((z - d)/z\ ) \times \ln((z - d)/z\ )]/(k^2 u\_z)$ (10)

where LAI is leaf area index; z and z are measurement heights for wind speed and humidity (m); u_z is wind speed at height z (m/s); d is zero-plane displacement (m); z   and z   are roughness lengths for momentum and heat (m); and k is von Kármán’ s constant.

Potential evaporation (Ep) and transpiration (Tp) were calculated according to Beer’ s law (Šimůnek et al., 2018):

$Ep = ETp \times e\hat{}(-k \times LAI)$ (11)

$Tp = ETp \times (1 - e\hat{}(-k \times LAI))$ (12)

where k is extinction coefficient for global solar radiation. Following White et al. (2000), k for *P. orientalis* is 0.51, which was adopted in this study.

2.4.6 Calculation of ETa

ETa was estimated as the sum of actual evaporation (Ea) and actual transpiration (Ta) (Šimůnek et al., 2018; Diongue et al., 2022):

$ETa = Ea + Ta$ (13)

$Ea = {}_0\ K(\ )(\ h/\ z + 1)dz$ (14)

$Ta = {}_0\ S(z,t)dz$ (15)

where L is root zone depth (cm).

2.5 Water Balance Calculation

No runoff occurred in the study area. Soil water storage change (ΔW) from the water balance equation is:

$\Delta W = P + Gr + I - Dr - ETa$ (16)

where ΔW is soil water storage variation (mm); P is precipitation (mm); Gr is upward recharge from deep soil below rhizosphere (mm); I is irrigation amount (mm) from Jiaoyuting Forestry Farm records; and Dr is deep percolation (mm).

Gr and Dr were derived from water flux iteratively fitted by HYDRUS-1D’ s water movement module. Positive flux at 200.00 cm was considered Gr; negative flux was Dr (Beyene, 2018).

2.6 Model Accuracy Evaluation

Model accuracy was evaluated by comparing simulated and observed soil water content at different depths using root mean square error (RMSE) and coefficient of determination (R^2):

$\mathrm{RMSE} = \surd[\ (x\ - y\ )^2/n]$ (17)

$R^2 = [\ (x\ - \bar{x})(y\ - \bar{y})]^2/[\ (x\ - \bar{x})^2\ (y\ - \bar{y})^2]$ (18)

where x is measured value; y is simulated value; $\bar{x}$ is measured mean; and n is sample number. Literature indicates that for farmland and wetland soil moisture simulation, $\mathrm{RMSE} < 0.0300$ and $R^2 > 0.5000$ adequately reflect soil moisture conditions and dynamics (Galleguillos et al., 2017; Er-Raki et al., 2021).

2.7 Correlation Analysis

To investigate environmental factor effects on ETa, correlation coefficient and principal component analysis (PCA) methods were employed, with Pearson correlation analysis used to obtain correlation coefficients.

3.1 Model Testing and Parameter Sensitivity Analysis

Observations and HYDRUS-1D simulations of soil water dynamics from April 20–October 31, 2023 showed significant fluctuations under external conditions at 10.00–50.00 cm depth, while 70.00–190.00 cm depth showed gentler fluctuations with substantial delay. Figure 2 [Figure 2: see original paper] compares simulated and observed soil water content. Overall soil water content ranged from 0.1266 to 0.2617 $\mathrm{cm}^3/\mathrm{cm}^3$, with simulated and observed values showing similar temporal patterns and differences of 0.0003–0.0900 $\mathrm{cm}^3/\mathrm{cm}^3$, primarily due to input data uncertainty. Errors were small and within acceptable ranges.

Model simulation accuracy was evaluated using multiple indices (Table 4). RMSE ranged from 0.0015–0.0188 (below 0.0300), while R^2 ranged from 0.5036–0.9604 (above 0.5000), confirming that simulated values were appropriate for water balance simulation in the artificial *P. orientalis* forest.

Parameter sensitivity analysis revealed significant parameter influence on simulation results (Table 5). Due to σ value range limitations, -20.00% and -30.00% perturbations were invalid ($\sigma < 1.0000$), leaving only four perturbation levels in Figure 3 [Figure 3: see original paper]. Qs showed high consistency at 20.00% and 30.00% perturbations, with overlapping simulated values. α produced identical results at -10.00% and 30.00% perturbations, also overlapping in Figure 3. Qs and σ exhibited the greatest influence, with simulation result change rates ranging from -28.58% to -19.98% for Qs and -49.92% to -57.33% for σ. Ks and l had minimal influence. Parameter influence ranking was: σ > Qs > Qr > α > Ks > l.

3.2 Water Balance Calculation

In the study area, soil water accumulation components included precipitation, irrigation, and deep layer recharge, while consumption components comprised deep percolation and ETa (Fig. 4 [Figure 4: see original paper]). Table 6 shows that soil water storage increased by 49.64 mm during the simulation period. Negative ΔW values in May, June, July, and August indicated soil water deficit due to high root water uptake during these months. Positive ΔW values in April, September, and October indicated surplus, resulting from weak evapotranspiration in April and low temperatures with persistent precipitation in September-October.

Cumulative precipitation was 361.00 mm, with total irrigation of 28.60 mm concentrated in July-August. Precipitation was primarily concentrated in July-October (78.73% of total), representing the main soil moisture source. Total deep soil recharge was 315.26 mm, peaking in September (75.54 mm) and October (93.41 mm).

Total simulated ETa was 580.27 mm, accounting for 88.56% of total soil water consumption (Table 6). Maximum ETa occurred in July (111.53 mm) and August (117.23 mm), showing an overall increase-then-decrease trend from April-October. Deep percolation (74.95 mm) was another consumption component, showing an increasing trend from April-October related to precipitation, soil physical properties, and root water uptake. Overall, total soil water accumulation was 704.86 mm and consumption was 655.22 mm, yielding a storage surplus of 49.64 mm.

3.3 Evapotranspiration Dynamics

Total cumulative ETp from April 20–October 31, 2023 was 809.67 mm (Fig. 5 [Figure 5: see original paper]), comprising Ep (95.07 mm) and Tp (714.60 mm). Total ETa was 580.27 mm, comprising Ea (68.27 mm) and Ta (512.00 mm). On monthly scales, ETp, Ep, Tp, ETa, Ea, and Ta all showed initial increase then decrease patterns. ETp, Tp, ETa, and Ta peaked in August (179.47, 167.25, 117.23, and 108.42 mm, respectively), while Ep and Ea peaked in June (20.31 and 14.62 mm). ETp, Tp, ETa, and Ta were higher in July-August than other months. With only 10 days of April data, all components were low in April; October showed the lowest values except April. On daily scales, all components exhibited considerable fluctuation (Fig. 5) but maintained the overall increase-then-decrease trend. ETp-Tp and ETa-Ta fluctuations were consistent across scales. High average Tp/ETp (0.87) and Ta/ETa (0.88) ratios indicated transpiration-dominated evapotranspiration in the *P. orientalis* artificial forest.

3.4 ETa-ETp Relationship

ETp describes atmospheric capacity to absorb surface water through evaporation and transpiration, approximating ETa under non-limiting water supply conditions. Correlation analysis yielded R^2 values of 0.9696 and 0.9635 for ETa-ETp relationships on monthly and daily scales, respectively (Fig. 6 [Figure 6: see original paper]), indicating significant positive correlations ($P<0.05$).

The ETa/ETp ratio indicates water availability and can assess drought and plant water stress severity. Ratios near 1.00 indicate sufficient water supply; lower ratios indicate greater water deficit. In this study, ETa/ETp averaged 0.72 throughout the simulation period, showing a decrease-then-increase trend (Fig. 7 [Figure 7: see original paper]). Monthly average ETa/ETp was 0.74, peaking in April (0.84) and reaching minimum in August (0.65), indicating most severe moisture deficit in August.

Daily ETa/ETp showed significant short-term fluctuations, with maxima of 0.91 and 0.95 on July 12-13, substantially higher than July’ s 0.68 average. These abrupt changes corresponded to precipitation events of 21.60 mm and 7.20 mm, indicating sufficient soil water recharge and reduced water stress. From June 14–September 5, ETa/ETp remained generally low, averaging 0.66 compared to the overall daily average of 0.75, indicating severe water stress during this period.

3.5 Environmental Factor Effects on ETa

ETa is influenced by multiple factors. This study investigated meteorological factors and 10.00 cm soil water content effects on ETa dynamics using PCA and correlation analysis. Meteorological indicators included temperature, relative humidity, precipitation, wind speed, and solar radiation.

PCA results revealed significant monthly variation in environmental factor influence on ETa during *P. orientalis* growing season (Fig. 8 [Figure 8: see original paper]). During the dormant April period, ETa showed minimal response to environmental factors. In May-June, temperature, solar radiation, and wind speed were key ETa drivers. In July, all five factors reached maximum contribution. In August, temperature, solar radiation, and wind speed contributions increased further. In September-October, relative humidity, precipitation, and soil water content became dominant factors.

On daily scales, temperature, solar radiation, and wind speed showed significant positive correlations with ETa, ranked as temperature > wind speed > solar radiation (Fig. 9 [Figure 9: see original paper]). Relative humidity and precipitation were negatively correlated. Soil water content at 10.00 cm depth was not significant ($r = -0.01$).

3.6 Environmental Factor Effects on ETa/ETp

The ETa/ETp ratio fluctuated significantly due to environmental factor dynamics, with impacts varying across time scales (Fig. 10 [Figure 10: see original paper]). On both monthly and daily scales, ETa/ETp was negatively correlated with temperature, solar radiation, and wind speed. Monthly correlation ranking was temperature > wind speed > solar radiation; daily ranking was temperature > solar radiation > wind speed. Soil water content, relative humidity, and precipitation were positively correlated, ranked as relative humidity > precipitation > soil water content. Monthly PC1 was 57.32%, PC2 35.54% (combined 92.86%); daily PC1 was 54.31%, PC2 16.32% (combined 70.63%), confirming representative and reasonable environmental factor selection.

4.1 Model Accuracy Assessment and Water Balance Analysis

Parameter determination is critical in model simulation, with significant impacts on results (Diongue et al., 2022; Zhou et al., 2022). Graham et al. (2018) investigated four soil hydraulic parameterization methods, finding that measured soil physical property data fitting provided optimal results. This study therefore used measured soil particle size and bulk density for parameter fitting and inversion. High-sensitivity parameters were σ and Qs (Fig. 3), requiring careful attention in future studies.

HYDRUS-1D estimates evapotranspiration like water balance models but without considering internal physical processes. Treating the system holistically, model applicability can be assessed by validating one component (Beyene et al., 2018). This study used observed vs. simulated soil water content for accuracy evaluation (Han et al., 2015; Zhou et al., 2021). Results showed April, September, and October as accumulation periods. April accumulation occurred because plant growth had just commenced with limited root water uptake. September-October accumulation resulted from continuous precipitation with decreasing root water uptake.

4.2 ETa Dynamics and Influencing Factors

The April-October pattern showed initial increase then decrease, with higher ETa and Ta in July-August due to elevated temperature and solar radiation, consistent with Wegehenkel and Beyrich (2014). Higher June Ea resulted from high temperatures before peak canopy coverage. Ta/ETa was 0.88 during the simulation period, higher than Wolf et al.' s (2024) 0.67-0.74 for arborvitae forests because this study focused on the vigorous growth period rather than full year. D' Acunha et al. (2024) found ETa differed significantly under different land covers, with minimal seasonal Ta variation in Amazonian tropical forests due to stable water-heat conditions year-round. In contrast, this study area' s semi-arid temperate continental climate produced obvious seasonal water-heat variations and Ta fluctuations (Li et al., 2020; Liu et al., 2022).

Environmental factor correlations showed monthly variation (Fig. 8). April' s low temperature and frozen soil state minimized environmental factor effects. May' s early growth stage saw increasing temperature, solar radiation, and wind maintaining low leaf surface humidity, intensifying photosynthesis and ETa. June-August saw rising temperature and precipitation increasing solar radiation and relative humidity, with each factor contributing substantially. September-October' s high precipitation frequency and decreasing temperature made precipitation and relative humidity dominant.

On daily scales, temperature was the key ETa factor. Guo et al. (2023) concluded energy dominates Loess Plateau evapotranspiration, with net solar radiation as the main factor and temperature having indirect effects, yielding weaker temperature correlation. This study' s use of gross radiation produced slightly different results. Liu et al. (2022) identified temperature as the primary decisive factor without considering net solar radiation, consistent with this study. Galleguillos et al. (2017) found ETa had no significant correlation with soil depth, texture, or water table. Wu et al. (2022) found soil water content affects ETa through canopy resistance, but this study found no significant correlation (Fig. 9), possibly because 10.00 cm soil water content inadequately represented root zone moisture.

4.3 ETa-ETp Correlation

Su et al. (2021) demonstrated significant ETa-ETp correlation with ETa increasing as ETp increases. This study' s simulation results showed consistent trends, with significant positive correlations on monthly and daily scales ($R^2 = 0.9696$ and 0.9635), consistent with existing research (Meza et al., 2023; Kartal, 2024). Liu (2022) developed a nonlinear function for daily-scale evapotranspiration simulation constrained by soil water, showing higher accuracy than linear and complementary relationship methods, with ETa-ETp showing unimodal annual patterns and nonlinear multi-year relationships. This study only analyzed 2023 intra-annual changes; future work should extend time scales for more accurate dynamic relationship analysis.

Li et al. (2024) studied ETa/ETp dynamics in the Heihe River Basin, finding seasonal ranking of autumn > spring > summer, with high summer temperatures and strong ETa reducing ETa/ETp. This study's spring ETa/ETp slightly exceeded autumn values, likely due to vegetation type differences (Lian et al., 2018; Zhai et al., 2019; Wang et al., 2023). The evergreen *P. orientalis* continues autumn growth under suitable conditions, unlike deciduous *Populus euphratica* with reduced autumn water availability (Li et al., 2024). Monthly and daily ETa/ETp trends were consistent, but daily fluctuations were larger with abrupt changes on May 12-13, July 12, and September 24 due to substantial precipitation. ETa/ETp fluctuations closely related to meteorological factors, with temperature as the dominant factor (Liu et al., 2019).

4.4 Artificial Forest Management Recommendations and Research Perspectives

Water balance analysis revealed varying deficit degrees from May-August. Plant water use efficiency is typically higher under sufficient water than deficit conditions (Zhang et al., 2024). Based on current irrigation practices, increased irrigation from May-August is necessary. August showed the most severe water deficit and most intense transpiration, making it the optimal main irrigation period for plant growth. The northwestern arid study area experiences strong evaporation and increasing deep percolation during high-precipitation September-October. Small-amount, high-frequency irrigation should be adopted to control soil evaporation and deep percolation. Additionally, *P. orientalis* trees in Jiaoyuting Forestry Farm exceed 30 years age with numerous dead lower branches; pruning dry lateral branches for ground cover is recommended. This mulching reduces canopy density, decreases precipitation interception loss, increases infiltration, reduces soil evaporation, and improves soil fertility, benefiting *P. orientalis* growth.

ETa and ETp are also influenced by vegetation and soil factors (Yang et al., 2014; Šípek et al., 2020; Yan et al., 2021; Dai et al., 2022; Li et al., 2022). This study only analyzed monthly and daily scale characteristics. Future research should extend time scales to comprehensively investigate ETp and ETa variation characteristics and influencing factors across temporal scales, analyze intra-annual unimodal peaks and seasonal changes, quantify contributions of meteorological indicators, leaves, and soil properties, and study ecosystem evapotranspiration dynamics. Additionally, this study considered only single-species dominant vegetation; scope should be expanded by increasing sampling points to investigate evapotranspiration dynamics and factors under different land covers, improving regional representativeness.

5 Conclusions

This study used HYDRUS-1D to quantify soil moisture dynamics and evapotranspiration characteristics of artificial forests in the western Loess Plateau. Calculations revealed overall soil water surplus during the simulation period, but soil water deficit occurred in May-August according to plant growth characteristics. ETp, Ep, Tp, ETa, Ea, and Ta showed clear seasonal variation on both monthly and daily scales. From April-October, ETp, Tp, ETa, and Ta initially increased then decreased, peaking in August; Ep and Ea also showed increase-then-decrease patterns, peaking in June. Analysis revealed transpiration-dominated evapotranspiration and significant positive ETa-ETp correlation. ETa was significantly positively correlated with temperature, solar radiation, and wind speed, negatively correlated with relative humidity and precipitation, and not significantly correlated with soil water content. Results demonstrate HYDRUS-1D’ s strong applicability for evapotranspiration analysis in arid regions. Based on findings, August is the primary irrigation period, and increasing water input from May-August through high-frequency, low-amount irrigation is essential for healthy plant growth. These results provide theoretical guidance for artificial forest water management and advance understanding of evapotranspiration processes and factor effects in arid regions. Future studies should expand land cover comparisons and extend temporal scales to provide theoretical foundations for large-scale arid region vegetation restoration and management.

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