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Impact of evapotranspiration on ecosystem services values in rubber (*Hevea brasiliensis* L.) plantations: insights into climate change and rubber plantation expansion in Southwestern China

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Introduction: The rapid expansion of rubber (*Hevea brasiliensis*) plantations in Southwestern China has transformed forest-dominated landscapes. However, the hydrological consequences of this land-use change have not been comprehensively quantified.

Methods: This study reconstructed the long-term actual evapotranspiration (ET_{a_reconstructed}) of rubber plantations using the "Kc-ET0" method, which integrates meteorological data and actual crop coefficients (Kc_{actual}). The coefficient of variation (CV) and the Random Forest (RF) algorithm were employed to identify the key drivers and analyze the spatiotemporal patterns of the reconstructed ET_{a_reconstructed}. Furthermore, we quantitatively evaluated the influence of ET_{a_reconstructed} on major ecosystem service values (ESVs).

Results: Our results showed that rubber plantations expanded at a rate of 12.49 × 10⁴ ha per decade between 2000 and 2022. The annual average ET_{a_reconstructed} was 952 mm, showing an increasing trend of 12 mm per decade since 1970. The ET_{a_reconstructed} exhibited stable interannual variability (CV range: 0.04–0.11) and was significantly positively correlated with maximum temperature, sunshine duration (SSD), and rubber plantation area, but negatively correlated with relative humidity. SSD (28.5%–38.4%) and rubber plantation area (11.4%–20.3%) were identified as the crucial drivers. The optimal ESVs for rubber plantations were achieved at a multi-year average SSD of 4.17 hours, where the reconstructed ET_a ranged between 2.0 and 3.0 mm/day, and carbon sequestration and oxygen release reached their peak values.

Discussion: In conclusion, the ET_a -reconstructed of rubber plantations, primarily driven by increased sunshine duration, significantly affects their ecosystem service values in Southwestern China. The identified optimal ET_a -reconstructed range provides a scientific basis for precise water management in tropical rubber plantations in the context of climate change.

KEYWORDS

crop evapotranspiration, spatiotemporal variation, climate change, land cover and use change, ecosystem services values, rubber (*Hevea brasiliensis*) plantations

1 Introduction

Crop evapotranspiration is a critical component of land-atmosphere interactions that is closely coupled with energy and water cycles (Cutting et al., 2024). Land use/cover change (LUCC) is a major driver of global environmental change that impacts global carbon cycling and biodiversity. In tropical regions, the conversion of natural forest to commercial plantations significantly alters regional hydroclimates (Wang and Zhang, 2025; Lam et al., 2022). These transformations are most pronounced in tropical areas, such as Southeast Asia, the Amazon, and Africa (Chen et al., 2024; Sarathchandra et al., 2021). LUCC influences evapotranspiration by altering the surface energy balance, making it a direct indicator of hydrological cycle disruptions. Rubber (*Hevea brasiliensis* L.) plantations, as typical human-managed ecosystems, provide ecosystem service values (ESVs) such as water conservation, carbon storage, soil retention, and climate regulation (Qi et al., 2023). Evapotranspiration, a key indicator of vegetation water consumption, governs the hydrological regulation function of rubber plantations and constrains their overall ESVs. Excessively high evapotranspiration can lead to regional water overconsumption and reduced water conservation capacity, while excessively low evapotranspiration may limit plantation productivity and impair carbon sequestration function (Li et al., 2024). Therefore, a significant trade-off exists between evapotranspiration and the ESVs of rubber plantations.

Driven by rising market prices, rubber tree cultivation has expanded into non-traditional zones at higher latitudes (22°–23°N) and altitudes (up to 1,400 m), replacing extensive natural forests and farmland (Ling et al., 2022a). As a result of this expansion, ecological service functions have declined to 21.5%–63.6% of those in primary forests (Singh et al., 2021). In Southwest China, rubber plantations now cover over 2.2 million ha, which has reduced tropical rainforest cover by approximately 50% and intensified regional aridification and water conservation losses (Thellmann et al., 2019). Rubber plantations have been called “green deserts” to highlight the severe ecological consequences of their soil erosion rates (Ziegler et al., 2009; Liu et al., 2015). The high evapotranspiration of rubber plantations profoundly disrupts regional water balances through substantial water depletion and reduced soil water storage (Tan et al., 2011;

Giambelluca et al., 2016). Rubber-dominated landscapes exhibit significantly greater water loss than other types of land cover (Lin et al., 2022; Zeng et al., 2022), which results in diminished streamflow, more frequent zero-flow days, and seasonal water shortages (Xue et al., 2024; Kumagai et al., 2015). Consequently, optimizing evapotranspiration management for climate change is critical to sustain the ecological services of rubber plantation ecosystems.

More attention has been paid to the eco-hydrological consequences of rubber plantation expansion. Giambelluca et al. (2016) reported high evapotranspiration rates in rubber plantations across Thailand and Cambodia and highlighted concerns over water consumption patterns and the potential risks to regional water security with continued expansion. The study also underscored the importance of balancing ecological considerations with the socioeconomic benefits of plantations. Comprehensive assessments of the ecosystem services inherent to rubber plantations are scarce. Kiyono et al. (2014) proposed a potential role for rubber plantations in climate change mitigation, and several investigations have addressed carbon sequestration, oxygen release, and timber utilization. Qi et al. (2023) extended this work by evaluating the integrated socioeconomic and environmental impacts of carbon, oxygen, and biodiversity services in Chinese rubber plantations. The evapotranspiration of rubber plantations has a crucial impact on the value of ecological services, but current studies are not clear.

To comprehensively assess the impacts of evapotranspiration on ESVs (e.g., carbon sequestration, oxygen release, and water conservation) in rubber plantations, a multifactorial analytical framework is essential. Our research uses quantitative and qualitative methods, including multivariate statistical methods and mechanistic modeling, to clarify the complex relationships among the influencing factors and differentiate and quantitatively assess the degree to which climatic factors and rubber plantation expansion contribute to the amount of evapotranspiration. The study has three main objectives, namely: (1) reconstructing actual evapotranspiration ($ET_{a_reconstructed}$) of rubber plantations and calculating the spatial distribution of evapotranspiration in rubber plantations by using Landsat TM/ETM/OLI data to identify rubber plantations and quantifying reference evapotranspiration (ET_0) and actual crop coefficient (K_{c_actual}) through the GIS platform;; (2)

identifying the drivers' contribution to the spatial heterogeneity of $ET_{a_reconstructed}$ in rubber plantations by using random forest (RF) models of the study area, and (3) determining the optimal interval of $ET_{a_reconstructed}$ through a coupling model of the economic and ecological values of rubber plantations. Sustainable management strategies based on $ET_{a_reconstructed}$ optimization were explored.

2 Materials and methods

2.1 Study area

Xishuangbanna and Pu'er, Yunnan Province, are located in Southwestern China (N 21°10'–24°50', E 99°09'–102°19') at an altitude of 726 m (Figure 1). The observation plot of the selected mature rubber plantation was transformed from tropical monsoon forest, and the average age of the rubber trees was 15 years old. The monsoon climate has a distinct rainy season (May–October), when precipitation exceeds 200 mm/month, and a dry season (November–April), with precipitation of less than 50 mm/month. Fog precipitation in the dry season accounted for 5% of the total annual precipitation.

Rubber trees had a plant spacing of 3 m × 6 m to facilitate rubber cutting, and the width of the reclamation area around the mountains was 1.8–2.5 m. Undergrowth vegetation consisted of a small amount of weeds and shrubs. The rubber tapping period was from April to November. In response to cold stress, rubber trees start dormancy in December, and synchronized defoliation occurs in February. Based on a comprehensive analysis of litterfall

production, leaf area index dynamics, canopy color, and sap flow, the rubber plantation's growing season is categorized into four distinct phenological periods, namely: the initial period (March–April, ~61 days), characterized by leaf expansion and flowering; the rapid growth period (May–June, ~61 days), marked by fruiting and peak water use efficiency; the mid-period (July–September, ~92 days), representing the main growth period with a dense canopy and vigorous physiological activity; and the late period (October–November, ~61 days), during which growth gradually declines in preparation for dormancy. This is followed by a dormant period (December–February, ~90 days) of concentrated leaf fall and physiological inactivity (Liu et al., 2014; Ling et al., 2021; Zhou et al., 2021). The rubber plantation evapotranspiration calculation in this study was confined to the growing season, excluding the dormant period.

The canopy tower, standing 20 m tall, was constructed at the study site for continuous micrometeorological and energy flux measurements from 2016. The latent heat flux (LE) and sensible heat flux (H) were measured using a Bowen ratio energy balance (BREB) system. The system was equipped with paired temperature and relative humidity probes (HMP155A, Vaisala, Finland) installed at different heights to determine the vertical gradients. Supporting measurements included net radiation (CNR4, Kipp & Zonen, Netherlands) and soil heat flux (HFP01SC, Hukseflux, Netherlands). Wind speed was measured with a three-dimensional ultrasonic anemometer (WindMaster Pro, Gill Instruments, UK). All signals were sampled at a frequency of 10 Hz and recorded by a dedicated data logger (CR1000, Campbell Scientific, USA). We used "Bowenby ratio closure" method for

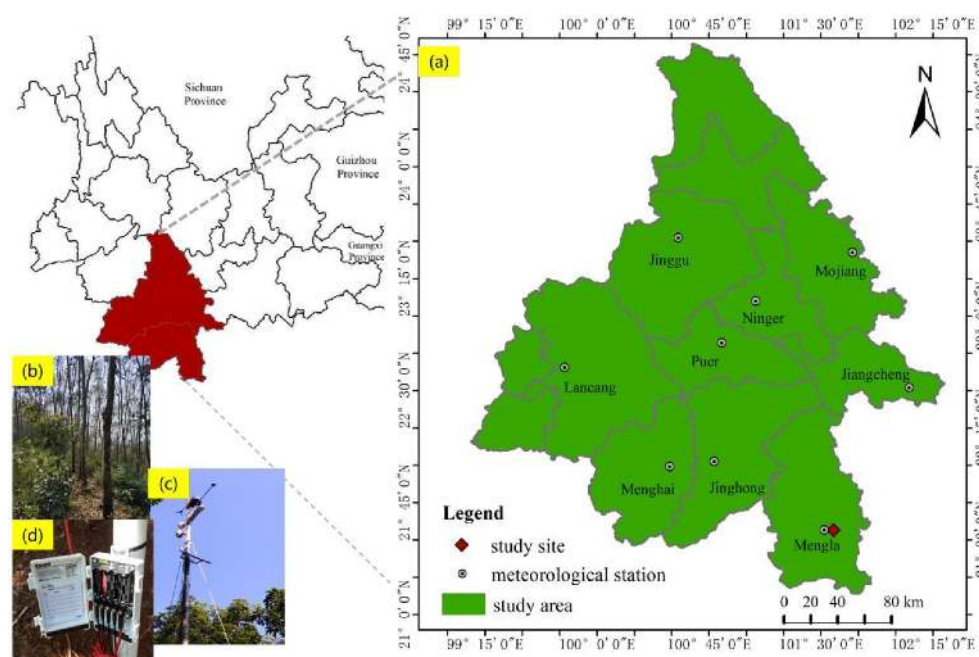


FIGURE 1

Experimental site of a rubber plantation (indicated by a solid square; 21°34'10" N, 101°35'24" E) in Xishuangbanna, Yunnan Province, Southwest China. (a) Location in Yunnan, China. (b) Observed site of rubber plantation. (c) Automatic meteorological system stations (WS-BR06, Campbell, USA). (d) Drain gauge G3 (METER, USA).

closing the canopy surface energy balance for each 30-min interval. The meteorological data and energy flux data were processed by coordinate correction, wild point rejection, data interpolation, and data quality analysis to eliminate abnormal values of rubber plantation due to uncontrollable factors (Falge et al., 2001; Baldocchi et al., 2001).

2.2 Methods and data

2.2.1 Identification and extraction of rubber plantations

A Landsat TM/ETM/OLI time-series NDVI variation spectral library of rubber plantations was constructed using land use/vegetation cover data from Xishuangbanna and Pu'er. Data was extracted from identified rubber plantations by combining the topography and rubber plantation phenology characteristics in Xishuangbanna during the typical time window (February to March) (Sari et al., 2022; Azizan et al., 2021). Remote sensing data for typical days were selected (February 25, 2000; February 22, 2010; and February 27, 2022).

Rubber plantation identification and extraction can be accomplished through an object-oriented classification method that extracts data hierarchically (Lu et al., 2019). Data from rubber plantations in Xishuangbanna and Pu'er in 2000, 2010, and 2022 were extracted at the optimal segmentation scale of 100, shape index of 0.6, and tightness index of 0.9. Data on the spatial distribution of rubber plantations were also obtained.

2.2.2 Estimation of long-term rubber plantation evapotranspiration (1970–2022)

The estimation of rubber plantation evapotranspiration followed the standardized terminology and framework for evapotranspiration assessment as recommended by DeJonge et al. (2025).

1. Calculation of the reference evapotranspiration (ET_0).

The Penman–Monteith method has been recommended as a standard model to calculate ET_0 according to the Food and Agriculture Organization of the United Nations (FAO) (Allen et al., 1998).

$$ET_0 = \frac{0.408\Delta\Sigma(R_n - G)\Sigma + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where ET_0 is the reference crop evapotranspiration, mm/day; G is the soil heat flux, MJ/m²·day; R_n is the net canopy surface radiation, MJ/m²·day; U_2 is the mean wind speed at 2 m (which is converted from the wind speed at 10 m), m/s; T is the mean air temperature, °C; e_a is the actual water vapor pressure, kPa; e_s is the saturated water vapor pressure, kPa; γ is the psychrometric constant, kPa/°C; and δ is the saturated water vapor pressure–temperature slope, kPa/°C.

2. Calculation of the actual crop coefficient ($K_{c,actual}$).

We employed the single crop coefficient approach to calculate $K_{c,actual}$ which represents the integrated effect of both plant

transpiration and soil evaporation under actual field conditions, inclusive of any water stress.

Daily actual evapotranspiration (ET_a) for the rubber plantation was directly measured using the Bowen ratio energy balance method during the 3-year period from 2016 to 2018. The corresponding daily ET_0 for the same period was obtained from a nearby meteorological station.

The daily $K_{c,actual}$ was calculated as the ratio of ET_a to ET_0 :

$$K_{c,actual} = ET_a / ET_0 \quad (2)$$

where a multi-year average $K_{c,actual}$ was derived. A mean seasonal curve was calculated for each day of the year (DOY) by averaging the $K_{c,actual}$ values from the 3 years (2016, 2017, and 2018) for that specific DOY. This daily climatological curve was then applied as a fixed seasonal pattern to represent the crop coefficient in the long-term reconstruction.

3. Reconstruction of long-term evapotranspiration (ET_a).

To reconstruct a continuous time series of rubber plantation $ET_{a_reconstructed}$ from 1970 to 2022, the following formula was applied using the long-term ET_0 data for this period:

$$ET_{a_reconstructed,i} = K_{c,actual} \times ET_{0,i} \quad (3)$$

where $ET_{a_reconstructed,i}$ is the estimated daily actual evapotranspiration for “i” year in the period 1970–2022, mm/day; $K_{c,actual}$ is the multi-year average daily crop coefficient derived from the 2016–2018 period [as described in Section 2.2.2 (2)]. $ET_{0,i}$ is the daily reference evapotranspiration for “i” year in the period 1970–2022, mm/day.

To obtain the spatial distribution of $ET_{a_reconstructed}$ across the rubber plantation in the study area, this study employed an upscaling method based on site calibration and spatial interpolation of meteorological data. Daily $K_{c,actual}$ values were calculated using Equation 2 in Section 2.2.2, based on site-measured ET_a and ET_0 derived from meteorological observations at a flux tower site representing typical rubber stands. These daily $K_{c,actual}$ values were then averaged according to phenological stages to derive representative $K_{c,actual}$ values for the standard phenological periods of rubber trees: initial period, rapid growth period, mid-period, and late period. Meteorological data, including daily T_{max} , T_{min} , RH, WD, and SSD were collected from weather stations within and around the study area (shown in Table 1). Daily ET_0 for each station was calculated uniformly using Equation 1. Subsequently, the Kriging spatial interpolation method was applied to generate continuous, spatially distributed daily ET_0 raster maps covering the entire study region.

By integrating the abovementioned two steps, the reconstructed daily ET_a for each grid cell at location (x, y) was computed using Equation 3: $ET_{a_reconstructed}(x, y) = K_{c,actual} \times ET_0(x, y)$, where $ET_0(x, y)$ represents the Kriging-interpolated reference evapotranspiration value for that grid cell on a given day, and $K_{c,actual}$ is the crop coefficient assigned according to the corresponding phenological stage of that date. The maximum rubber plantation area was determined as the current level year of rubber plantations in the study area based on the field survey and remote sensing image analysis from 2000 to 2022.

TABLE 1 Information of national meteorological stations in the study area.

Station name	Latitude (°N)	Longitude (°E)	Altitude (m)	T_{min} (°C/decade)	T_{max} (°C/decade)	WD (m/(s-decade))	SSD (/h-d-decade)	RH _{mean} (/decade)	P (mm/decade)
Menghai	100.42	21.92	1,177.5	0.273	0.323	0.113	0.098	-0.639	-20.95
Mengla	101.34	21.29	631.9	0.016	-0.037	0.112	0.084	-0.545	-0.326
Jinghong	100.47	22.00	582.2	0.313	0.321	0.091	0.109	-1.357	-8.761
Lancang	99.56	22.34	1,054.8	0.318	0.177	0.012	0.005	-0.562	-31.61
Simao	100.58	22.47	1,302.1	0.558	0.267	0.038	0.082	-0.713	-31.99
Jiangcheng	101.51	22.35	1,119.5	0.432	0.162	0.077	0.087	-0.713	-18.78
Ning'er	101.05	23.03	1,336.9	0.165	0.229	-0.006	0.208	-0.533	-27.06
Jinggu	100.70	23.50	914.7	0.309	0.187	0.082	0.159	-0.965	-17.40
Mojiang	101.67	23.42	1,316.0	0.239	0.239	0.018	-0.002	-0.401	-26.39
Mean	-	-	-	0.291	0.208	0.060	0.092	-0.714	-20.36

Then, we discuss the spatial distribution characteristics of rubber plantations $ET_{a_reconstructed,i}$ under the current level year.

To assess the overall water consumption by rubber plantations at the regional scale, this study calculated the total water consumption volume based on the spatially distributed $ET_{a_reconstructed}$. The total water consumption is calculated as the product of the $ET_{a_reconstructed}$ of each grid cell and its area. This metric represents the total volume of water resources consumed by the entire rubber plantation area over a specific period. For the whole study area, the total water consumption is obtained by aggregating the water consumption of all rubber plantation grid cells. The correlation analysis between rubber plantation area and $ET_{a_reconstructed}$ in this study essentially refers to the analysis between the rubber plantation area and the resulting total regional water consumption.

According to statistics collected from meteorological stations in the study area, the maximum temperature (T_{max}) was 27.2°C, the minimum temperature (T_{min}) was 15.8°C, the annual mean relative humidity (RH) was 79.7, the sunshine duration (SSD) was 5.70 h, the wind speed (WD) was 0.8 m/s, and the precipitation (P) was 1,472 mm. The meteorological elements of the study area (1970–2022) are presented in Table 1. P decreased by about 21 mm per decade. The most significant decrease in P was observed in the city of Jinghong. SSD increased by 0.092/(h-d-decade), and annual mean RH varied at a rate of 0.714 per decade. The minimum temperature increased at a rate of 0.219°C per decade. Pu'er was the area with the most significant increase in minimum temperature. The average temperature, SSD, and average WD showed increasing trends, while the average RH and P decreased.

2.2.3 Analysis of rubber plantation evapotranspiration spatial stability

To assess the spatial pattern of inter-annual stability of evapotranspiration in the rubber plantation, the inter-annual coefficient of variation (CV) was calculated for each grid cell (Ayehu et al., 2020).

$$CV = ET_sd / ET_a_avg \tag{4}$$

Based on multi-year annual $ET_{a_reconstructed}$ raster data, two key datasets were derived: ET_{a_avg} , representing the multi-year mean annual $ET_{a_reconstructed}$ for each grid cell, and ET_sd , representing the standard deviation of annual $ET_{a_reconstructed}$ for each grid cell, mm/year; CV values reflect the degree of variability of $ET_{a_reconstructed}$ in rubber plantations, dimensionless. CV values less than 0.1 indicate that plantations are very stable, values between 0.1 and 0.2 are unstable, values between 0.2 and 0.3 are unstable, and values larger than 0.3 are very unstable (Wang and Dickinson, 2012).

2.2.4 Contribution rate

RF models sample objects and variables to construct prediction models. The classification results of each decision tree were summarized based on the variable importance measure (VIM) in the RF algorithm. RF models were designed to assess the contributions of climate and rubber plantation area indicators to $ET_{a_reconstructed}$ performance and rank the importance of those indicators. The simulation results indicated that the method can

accurately and quickly select the indicators that have a greater impact on the evaluation results.

2.2.5 Coupled ecosystem services values: rubber plantation valuation models

1. Ecological value assessment of rubber plantations.

The primary ecological value of rubber plantation ecosystems lies in their water regulation and water purification functions. The water regulation value is calculated using the formula below:

$$U_{wr} = 10 \times C_r \times A \times \Sigma(P - ET_{a_reconstructed} - R) \quad (5)$$

U_{wr} is annual water regulation value, yuan/year; C_r is reservoir construction cost per unit storage capacity, yuan/m³, with a value of 6.11 yuan/m³ (Lu et al., 2014); A is rubber plantation area, ha; P is annual precipitation, mm/year; $ET_{a_reconstructed}$ is annual evapotranspiration, mm/year; and R is annual surface runoff, mm/year. Data was obtained from research on the Xishuangbanna Tropical Botanical Garden conducted by the Chinese Academy of Sciences (Zhang et al., 1997).

For water purification, the following formula was used:

$$U_{wp} = 10 \times K \times A \times (P - ET_{a_reconstructed} - R) \quad (6)$$

U_{wp} is the annual water purification value, yuan/year, and K is the water treatment cost, yuan/ton, in this case 2.09 yuan/ton (Lu et al., 2014). The remaining variables were defined in Equation 5.

2. Carbon sequestration and oxygen release calculation.

The photosynthetic process reflects the coupling relationship between ecosystem carbon and water cycles:

$$GPP = WUE \times Yield - scaledET_{a_reconstructed} \times C_{-c} \quad (7)$$

GPP is gross primary productivity, g-C/m²; WUE is water use efficiency, g-C/kg, which was based on data from research on the Xishuangbanna Tropical Botanical Garden carried out by the Chinese Academy of Sciences (Lin et al., 2018); and yield-scaled $ET_{a_reconstructed}$ is crop evapotranspiration, kg/m²·mm. C_{-c} is the conversion factor, representing the carbon content in the economic dry yield, with a value of 0.5 g C g⁻¹ dry yield. The WUE of rubber trees represents the grams of dry latex biomass produced per kilogram of water consumed, while the yield-scaled $ET_{a_reconstructed}$ indicates the kilograms of latex yield obtained per square meter of land per millimeter of water consumed.

The stoichiometric analysis shows that 1 kg-C = 2.2 kg organic matter, so the photosynthetic production of 1.00 kg organic matter requires 1.63 kg CO₂ fixation (containing 0.27 kg-C) and releases 1.19 kg O₂. Regional carbon/oxygen fluxes in southwestern Yunnan were calculated from vegetation net primary productivity (NPP) (Wang et al., 2019). NPP is derived by subtracting autotrophic respiration (R_a) from GPP which calculated using Equation 7 (Lin et al., 2018):

$$W_{CO_2} = NPP \times 1.2 \times 1.63 \quad (8)$$

$$W_C = W_{CO_2} \times 0.27 \quad (9)$$

$$W_0 = NPP \times 2.2 \times 1.19 \quad (10)$$

W_{CO_2} represents the amount of CO₂ fixed per unit area, g/m²; W_C denotes the corresponding carbon sequestration per unit area in wetlands, g/m²; and NPP indicates the net primary productivity of wetland vegetation per unit area per year.

Primary productivity is calculated by the conversion of atmospheric CO₂ into oxygen through photosynthesis:

$$U_{O_2} = 1.19 \times C_{O_2} \times A \times B \quad (11)$$

U_{O_2} is the annual oxygen release value of rubber plantations, yuan/year; C_{O_2} is the market price of oxygen, yuan/ton; A is forest area, ha; and B is annual forest net productivity, tons/(ha·year).

3 Results

3.1 Rubber plantation area changes in Xishuangbanna and Pu'er

The rubber plantation area was 16.86×10^4 ha in 2000, and it increased to 30.17×10^4 ha by 2022. The distribution of rubber plantations in Pu'er was less than the distribution in Xishuangbanna, and it was 1.13×10^4 , 4.43×10^4 , and 12.8×10^4 ha, respectively. The rubber plantation area increased by about 12.49×10^4 ha/decade. Xishuangbanna had an average annual growth rate of 5,789 ha/year, and the average annual growth rate increased from 2000 to 2022. The largest growth rate (10,720 ha/year) was seen from 2000 to 2010. After 2000, the planted areas of rubber plantations in Pu'er expanded rapidly, with an average annual growth rate of 76,108 ha/year. The average annual growth rate in Pu'er also increased between 2000 and 2022 (Figure 2).

Since 2000, natural rubber prices have exhibited a pattern of an initial increase followed by a decline. It peaked in 2011 with an annual average price of 34,000 yuan/ton. Coinciding with this price maximum, rubber plantation expansion reached its zenith in 2011; the planted area increased by 56.3% during the 2000–2011 period. Subsequently, rubber prices entered a prolonged downward trend and declined to an annual average of 13,500 yuan/ton in 2014, which represented a 60.2% reduction from the peak price. Concurrently, the total rubber plantation area stabilized within the range of 38.67×10^4 – 43.27×10^4 ha.

3.2 Spatiotemporal variation of rubber plantation evapotranspiration

The K_{c_actual} of rubber plantations calculated using Equation 2 (Figure 3) for the growing period ranges from 0.72 to 1.49. In the initial period, K_{c_actual} is 0.89, mid-period is 1.10, and late period is 0.91.

In the last 53 years (1970–2022), the maximum value of rubber plantation $ET_{a_reconstructed}$ was 1,098 mm (in 2020), and the minimum was 871 mm in 1990. The multi-year mean was 952 mm. Based on a linear regression, the mean increased at a rate of 12 mm/decade, but the

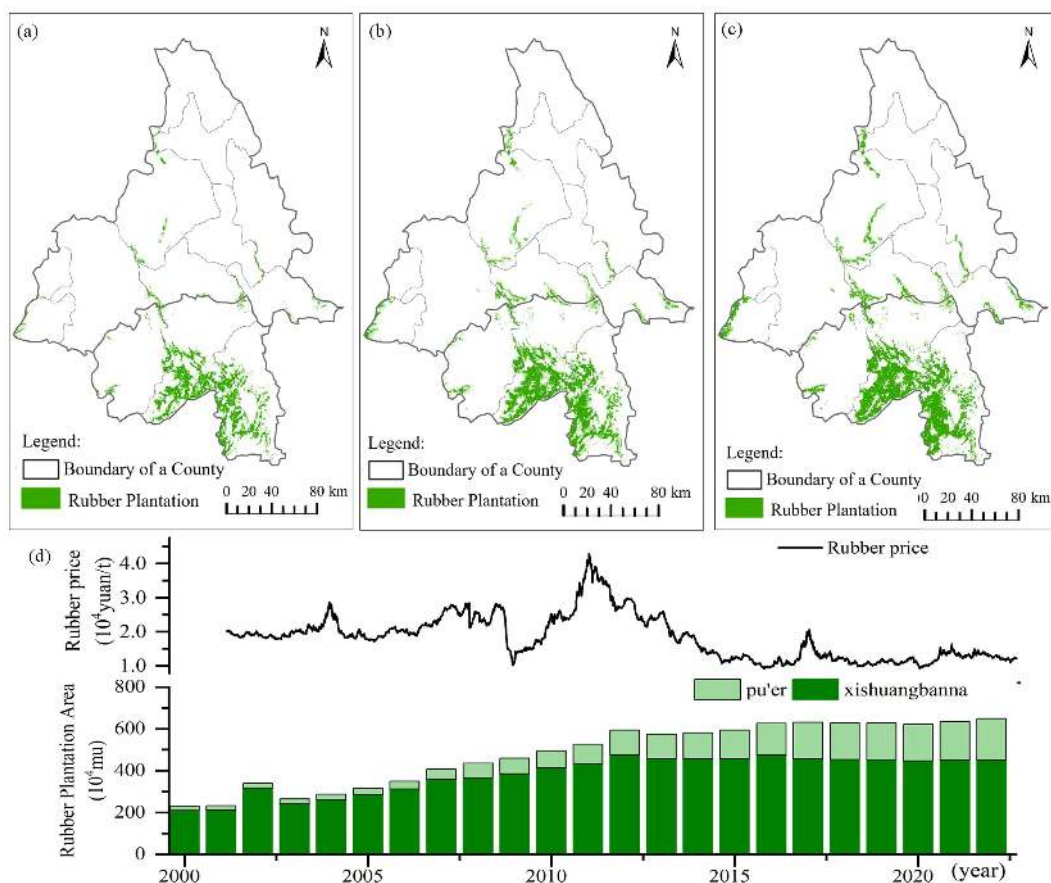


FIGURE 2

Growth trend of rubber plantation area and rubber price in Xishuangbanna and Pu'er (a) 2000; (b) 2010; (c) 2022; (d) price and rubber plantation area trend (data from Yunnan Provincial Bureau of Statistics).

increasing trend was not significant (Figure 4a). An MK test showed that the $ET_{a_reconstructed}$ from rubber plantations decreased from 1980 to 1990 and increased after 1990. The mutation point around the year of 1995 is shown in Figure 4b.

The spatial distribution of the multi-year average rubber plantation $ET_{a_reconstructed}$ in Xishuangbanna and Pu'er, obtained by using Equation 3 for the layer operation on ArcGIS 10.5, varied significantly from 1970 to 2022 (53 years) (Figure 5a). It was higher in the west and lower in the east: the central and western areas of Menghai county, Lancang county, and Jinghong county were high (annual average $ET_{a_reconstructed} > 900$ mm), while the eastern areas of Mengla county and Jiangcheng county had lower distributions that ranged from 827 to 900 mm.

The CV of rubber plantation $ET_{a_reconstructed}$, calculated using Equation 4, ranged from 0.04 to 0.11 over the 53 years, which indicates that the degree of variation in rubber plantation $ET_{a_reconstructed}$ was stable (Figure 5b) throughout the study area. The CV values were < 0.1 in the rubber plantations in Menghai county, the western areas of Xishuangbanna, Jinggu county, and Mojiang county in the north and east part of Pu'er, which indicates a very low interannual variability of $ET_{a_reconstructed}$ in the rubber

plantations in these areas. CV values of > 0.1 showed that variation was slightly higher in Lancang county, Jinghong county, Mengla county, and Jiangcheng county. The interannual variation of $ET_{a_reconstructed}$ was relatively unstable, likely due to variability in precipitation and surface moisture conditions.

3.3 Correlation analysis between evapotranspiration and driving factors

Meteorological variables (i.e., average T_{min} , T_{max} , P , SSD, WD, RH, and rubber plantation area) were selected for correlation analysis with the annual average $ET_{a_reconstructed}$ in the rubber plantations. Annual $ET_{a_reconstructed}$ in the study area was significantly positively correlated with T_{max} (correlation coefficients ranged from 0.23 to 0.8) and SSD (0.84–0.93). $ET_{a_reconstructed}$ was significantly negatively correlated with RH (correlation coefficients of -0.36 to -0.75) (Figure 6) and P (-0.03 – -0.49). More precipitation results in a lower $ET_{a_reconstructed}$ because it leads to a higher RH and a lower SSD. Greater WD resulted in an increased $ET_{a_reconstructed}$. Rubber plantation area showed a positive correlation with the regional total

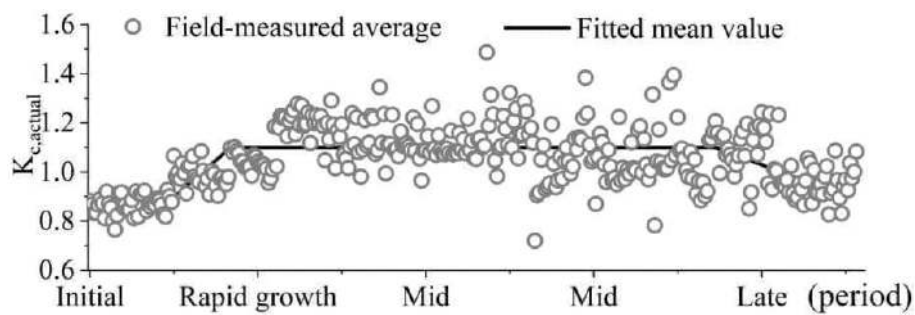


FIGURE 3
Crop coefficient ($K_{c,actual}$) of rubber plantation.

water consumption derived from these plantations (correlation coefficients ranging from 0.1 to 0.75), while a negative correlation was observed with the regionally averaged RH (-0.02 to -0.63). This indicates that the expansion of rubber plantations directly leads to an increase in the total volume of water resources consumed by this ecosystem at the watershed or regional scale, thereby exerting a significant impact on the balance of regional water resources.

3.4 Effect of meteorological factors and planted area on the spatiotemporal distribution of rubber plantation evapotranspiration

The $ET_{a_reconstructed}$ increased in the central and southeastern regions of our study area (mainly in Jinghong county and Mengla county) and decreased in the west and northeast regions (Mojiang county and Jiangcheng county). Through the RF model, we identified the driving factors of $ET_{a_reconstructed}$ variation in rubber plantations in Xishuangbanna and Pu'er.

Based on the RF, T_{min} contributed 4.15%–15.33% of the change in $ET_{a_reconstructed}$. T_{min} had a higher impact in central Xishuangbanna, Lancang county, and Pu'er county and a lower impact in the southeastern area. T_{max} contributed 12.33%–19.48% of the change in $ET_{a_reconstructed}$. The high-value areas were distributed in Mengla county (in southeastern Xishuangbanna) and Pu'er county (central Pu'er). WD contributed 2.78%–16.52% of the change in $ET_{a_reconstructed}$, and the effect was greater in Xishuangbanna than in Pu'er. RH had a contribution of 11.40%–19.21%, and it was lower in the western part of the study area and higher in Mengla county. P had a contribution of 3.95%–6.76%, which was the lowest factor that affected the change in $ET_{a_reconstructed}$. SSD and rubber plantation area were the two key drivers of the change in $ET_{a_reconstructed}$, with contributions of 28.50%–38.42% (SSD) and 11.43%–20.33% (area). SSD had a greater impact on $ET_{a_reconstructed}$ in the southeastern Mengla county and Jiangcheng county than in the other regions. Rubber plantation area had a greater impact in Jinghong county, Menghai county, Jinggu county, and Lancang county (i.e., the western region of the study area) than in the other regions (as shown in Figure 7 (a)–(g)).

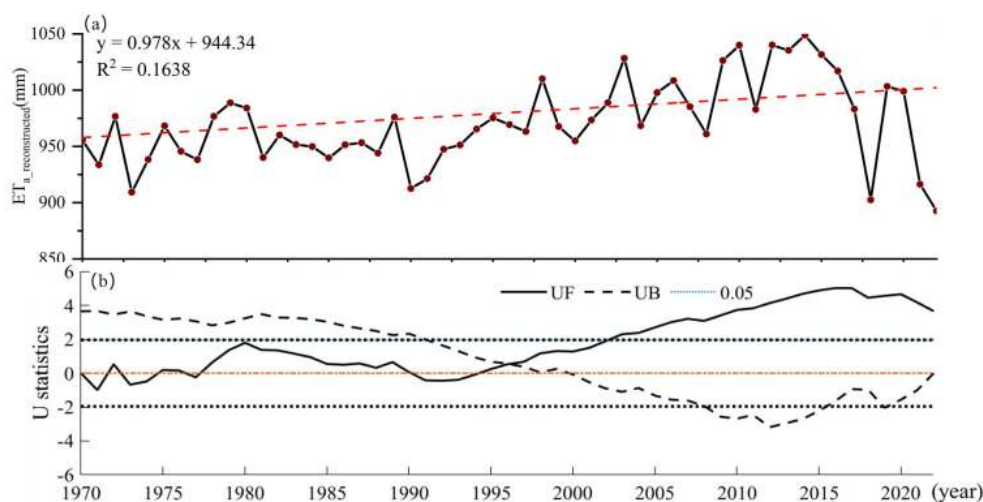
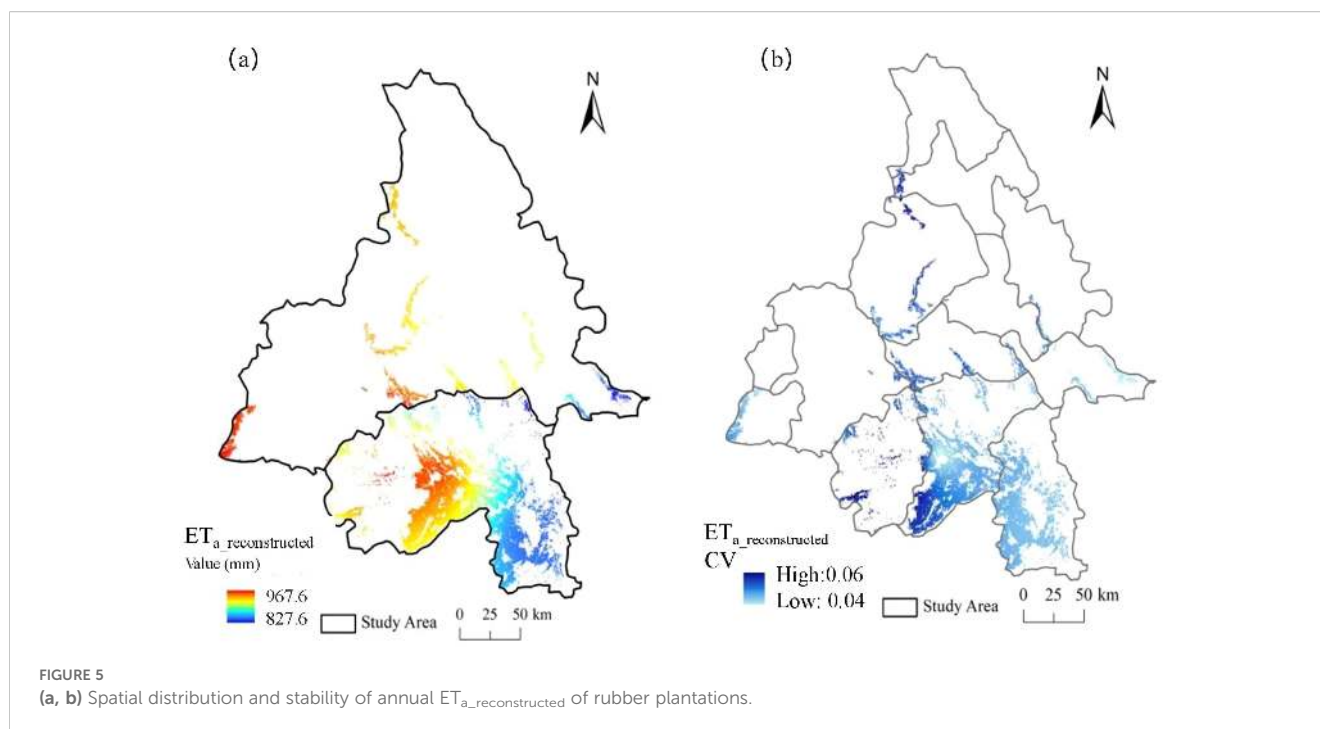


FIGURE 4
Interannual variation of $ET_{a_reconstructed}$ and M-K variation trend analysis of rubber plantations in Xishuangbanna. (a) $ET_{a_reconstructed}$ from 1970 to 2022; (b) M-K variation trend analysis from 1970 to 2022.



3.5 Influence of rubber plantation evapotranspiration on ecological and economic factors

Rubber plantation $ET_{a_reconstructed}$ directly reflects the WUE, which is closely associated with ecological service functions, such as carbon sequestration, oxygen release, and water conservation. During the period from 2020 to 2022, rubber plantation ecosystem WUE was lower in the rainy season ($2.60 \pm 1.22 \text{ g}\cdot\text{kg}^{-1}$) than in the dry season ($1.52 \pm 0.70 \text{ g}\cdot\text{kg}^{-1}$).

We employed multiple valuation approaches, including the shadow project method, market value method, and cost analysis method, to quantify the comprehensive ESVs of rubber plantations. The valuation results are presented in Table 2. (calculated by Equation 5–11)

The rubber plantation's economic value of the conservation value of water resources and carbon sequestration and oxygen release (as shown in Figure 8). Figure 9 elucidates the trade-offs and synergies between the hydrological cycle and the eco-economic service values in rubber plantation ecosystems. Figure 9a reveals a critical trade-off between the carbon sequestration and oxygen release value and the water conservation value in relation to $ET_{a_reconstructed}$. A non-linear, positive correlation was observed between $ET_{a_reconstructed}$ and carbon sequestration value, with the highest eco-economic efficiency occurring within an optimal $ET_{a_reconstructed}$ range of 2 to 3 mm mm/day. Specifically, for every 10% increase in $ET_{a_reconstructed}$ within this range, the economic value of carbon sequestration and oxygen release increased by approximately 6×10^5 yuan. However, this economic gain comes at a cost to water resources. The water conservation value exhibited a significant decline with rising $ET_{a_reconstructed}$. This negative impact was 1.4 times more pronounced during the dry season, a period

when $ET_{a_reconstructed}$ frequently exceeds precipitation, thereby exacerbating water scarcity and posing a threat to regional water security.

Figure 9b illustrates the synergistic mechanism driven by SSD. As the dominant meteorological factor controlling $ET_{a_reconstructed}$, SSD regulates photosynthetically active radiation, thereby directly enhancing GPP and, consequently, the carbon sequestration value. The analysis identifies a multi-year average SSD of 4.17 h as an optimal threshold that corresponds to the peak carbon sequestration and oxygen release value in rubber plantations. This figure demonstrates that while climatic drivers like SSD can synergistically promote both transpiration and carbon uptake, the resulting high water consumption creates a direct conflict between maximizing carbon-related economic benefits and ensuring sustainable water resource conservation.

4 Discussion

4.1 Expanded planted areas on rubber plantations

Our results demonstrated the substantial expansion of rubber plantations in Xishuangbanna and Pu'er, which increased by approximately 12.49×10^4 ha per decade from 2000 to 2022. This result represents a profound land use transformation primarily driven by market forces: the expansion trajectory closely tracked price fluctuations in the natural rubber market. The most rapid phase of expansion occurred during 2000–2011 and peaked in 2011 when rubber prices reached their maximum (34,000 yuan/ton), which corresponded to a 56.3% increase in planted area. This synchronous pattern strongly indicates that favorable market

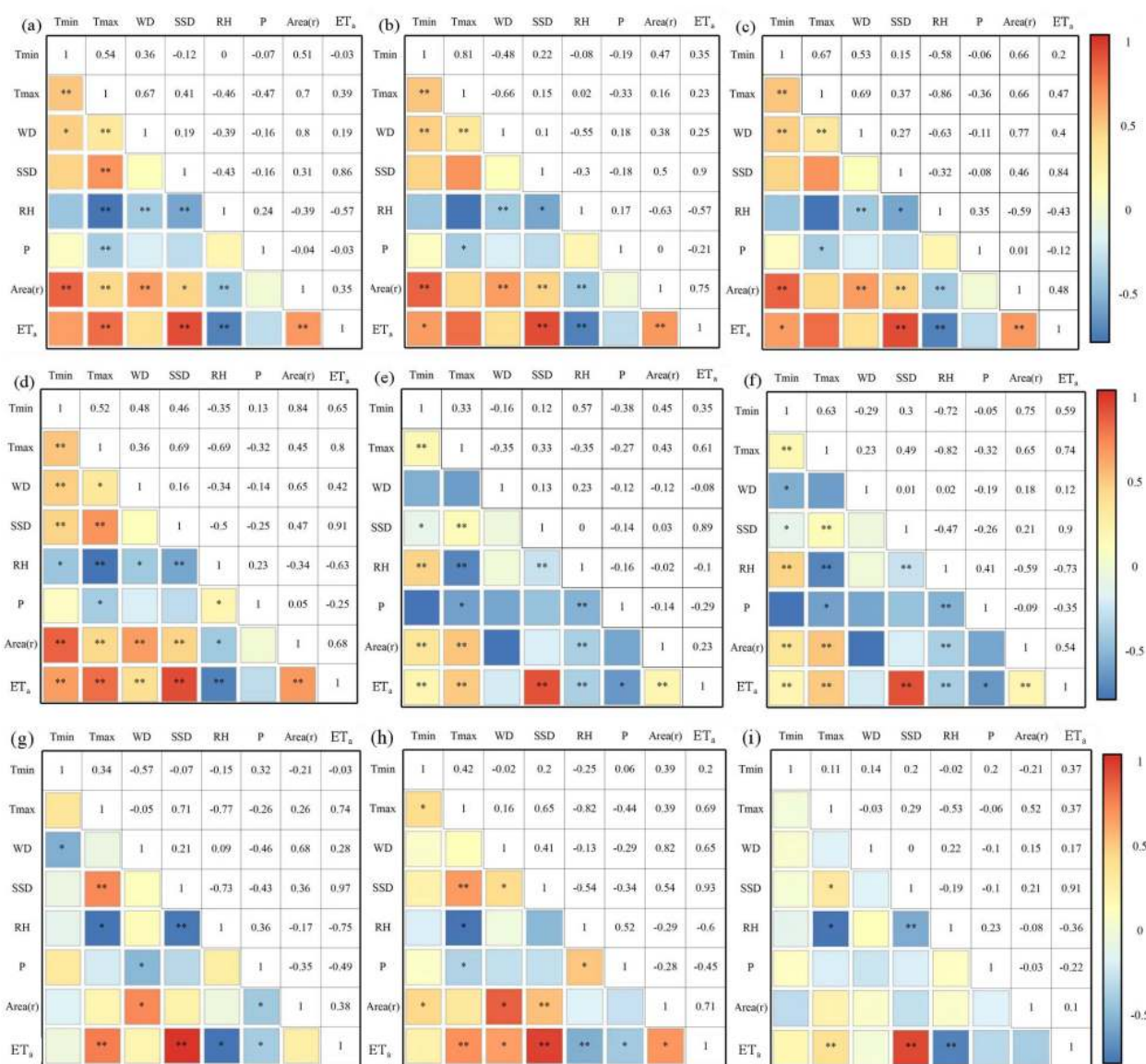


FIGURE 6

Correlation analysis of evapotranspiration driving factors in Xishuangbanna and Pu'er rubber plantations. (a) Mengla, (b) Jinghong, (c) Menghai, (d) Lancang, (e) Jiangcheng, (f) Pu'er, (g) Ning'er, (h) Jinggu, and (i) Mojiang. Area (r) is area of rubber plantations; ET_a is ET_{a_reconstructed}. *represent the P<0.05 as "statistically significant difference", ** represent the P<0.01 as "highly statistically significant difference".

conditions served as the primary catalyst for initial land conversion. The subsequent price decline to 13,500 yuan/ton by 2014, which represented a 60.2% reduction from the peak, coincided with a notable stabilization of plantation area and suggested a strategic shift from extensification to intensification management as economic incentives diminished.

This market-driven expansion had profound ecohydrological implications. The replacement of native ecosystems with rubber monocultures, which are known for their higher evapotranspiration, substantially altered regional water cycles (Lin et al., 2022; Gnanamoorthy et al., 2022). From local to regional scales, the impact of rubber plantation expansion on the hydrological cycle has increased in the humid tropics—for example, a 50% increase in rubber plantation area increased evapotranspiration by 3.3% (Celine and James, 2015).

Fog precipitation, a significant water resource, decreased because of LUCC in Xishuangbanna (Peng et al., 2020). The climate is gradually changing from humid to dry, which is accelerating the formation of climate extremes (Chen et al., 2024) and causing negative ecohydrological effects in the form of regional water resource shortages (Ziegler et al., 2009; Guardiola-Claramonte et al., 2010).

4.2 Spatiotemporal distribution of evapotranspiration

The multi-year rubber plantation ET_{a_reconstructed} in our study was 952 mm. We cross-validated the model outputs against field measurements obtained using the Bowen ratio–energy balance

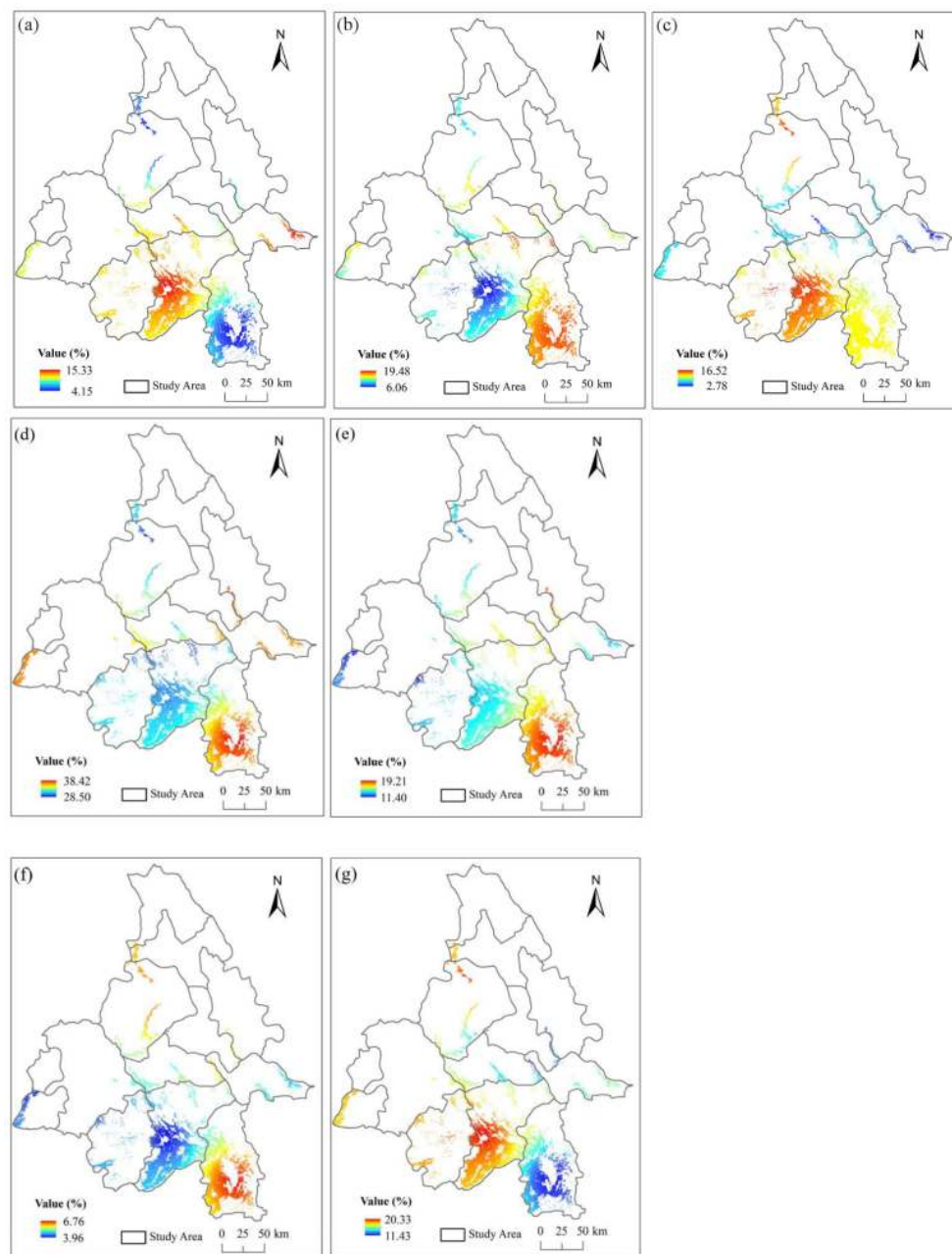


FIGURE 7

Driving factor contribution of evapotranspiration variation of rubber plantations. (a) $T_{\min}$, (b) $T_{\max}$, (c) WD, (d) SSD, (e) RH, (f) P , and (g) rubber plantation area.

method in the study area (Ling et al., 2022b). The results demonstrate a strong agreement in seasonal variation trends during the growing season, with an annual relative error of 6%. Carr (2012) found an evapotranspiration value of 1,050 mm in rubber plantations in Thailand. Tan et al. (2011) suggested that evapotranspiration on rubber plantations was 1,137 mm based on catchment water balances and 1,125 mm based on eddy covariance in Xishuangbanna. The slight underestimation in our results may be attributed to local climatic conditions, such as higher relative humidity, reduced sunshine hours, and the age structure of the

rubber trees. This observed discrepancy is considered reasonable, and it is consistent with regional characteristics (Qiao et al., 2025).

Rubber plantations exhibit higher evapotranspiration and greater water consumption than secondary forests (Igarashi et al., 2015). In Thailand, the actual water demand of newly established rubber plantations has been reported to exceed twice the water demand of conventional crops (Mangmeechai, 2020). In this study, the spatial interpolation results showed a deviation of less than 16% from the field measurements obtained at the Xishuangbanna Rubber Meteorological Center, which indicates an acceptable accuracy of the spatially distributed $ET_{a_reconstructed}$ estimates. The

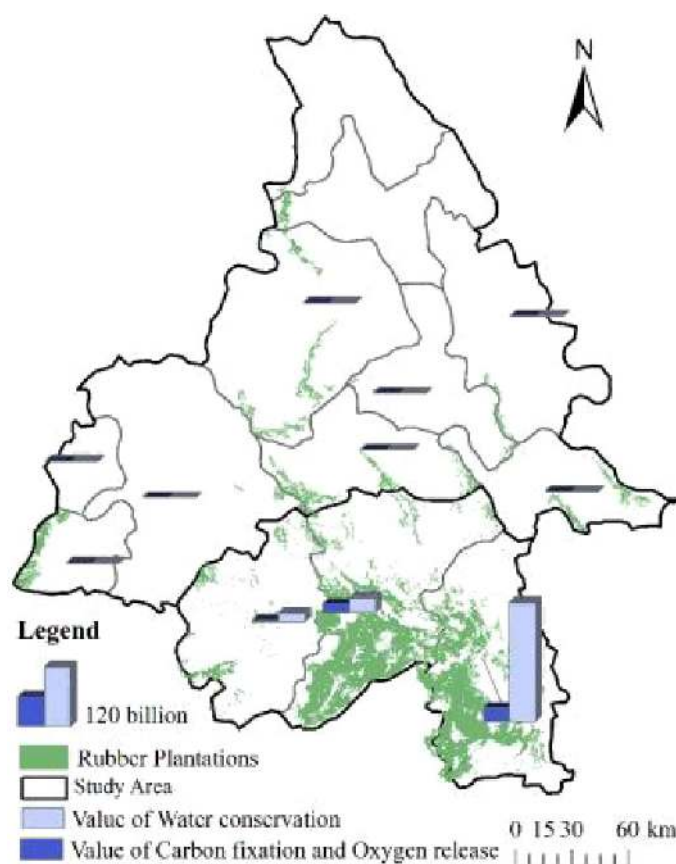


FIGURE 8

Economic value of the conservation value of water resources and carbon sequestration and oxygen release.

uneven distribution of precipitation and radiant energy in the region likely led to spatial differences in $ET_{a_reconstructed}$.

Rubber plantations exhibit higher water consumption than the prevailing crops in Southeast Asia (Chiarelli et al., 2018; Pradeep et al., 2022). Our findings from southwestern China are consistent with this pattern. They reveal significant, increasing trends in evapotranspiration from rubber plantations over the past 53 years, with a notable abrupt change that occurred around the year 1995. The rapid expansion of rubber plantations exhibited a temporal trend consistent with the region's aridification. Large-scale rubber cultivation has contributed significantly to local temperature increases and relative humidity reduction. Concurrently, southwestern China experienced an abrupt shift in potential evapotranspiration around 1995, accompanied by mutated extreme precipitation patterns and increased drought frequency (Liu and Yang, 2021; Lang et al., 2017).

4.3 Factors that influence rubber evapotranspiration

The driving factors for $ET_{a_reconstructed}$ were selected based on their fundamental roles in the surface energy balance and water vapor transfer processes that govern evapotranspiration. T_{min} and

T_{max} are proxies for the thermal energy available for evaporation, representing the water supply. SSD is a direct indicator of solar radiation, the dominant energy source for evapotranspiration. WD influences turbulent transport and affects the removal of water vapor from the surface. RH determines the vapor pressure deficit. Finally, rubber plantation area was included as a crucial land use variable to quantify anthropogenic alterations to the land surface.

The expansion of rubber plantations directly increases regional $ET_{a_reconstructed}$ by modifying the key biophysical properties of the land surface. Rubber trees allow a greater interception of solar radiation and access deeper soil moisture, which sustain elevated transpiration rates (Ling et al., 2022a). This intensified water use establishes a local climate feedback mechanism whereby increased atmospheric water vapor from transpiration lowers the near-surface RH. This finding was supported by the significant negative correlation observed between rubber plantation area and RH. The resulting drier air amplifies atmospheric evaporative demand, and the regional hydrological balance shifts as a larger proportion of precipitation is allocated to $ET_{a_reconstructed}$. Reduced streamflow and groundwater recharge intensify water scarcity during dry periods (Perron et al., 2024; Gnanamoorthy et al., 2022). This outcome is consistent with previous studies reporting substantial runoff reductions in watersheds following rubber plantation establishment.

TABLE 2 Ecosystem service values of rubber plantations in different $ET_{a_reconstructed}$.

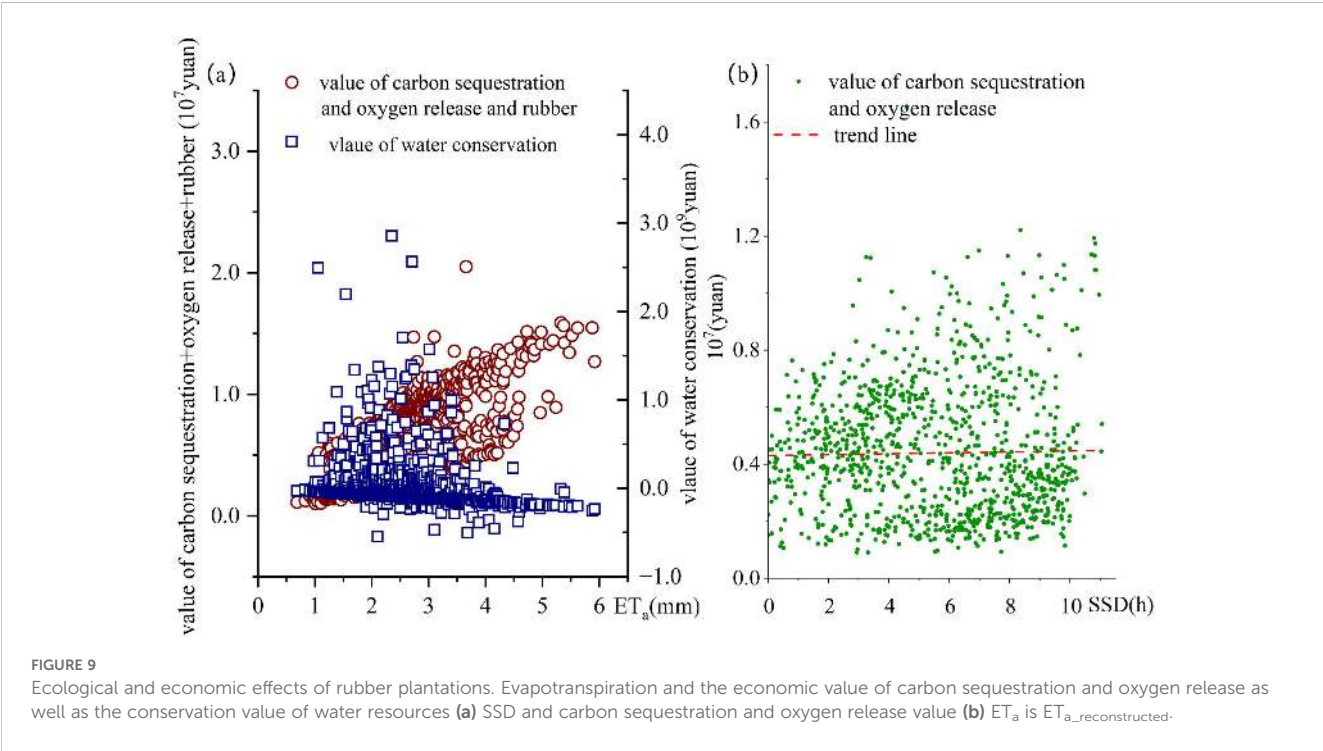
$ET_{a_reconstructed}$ (mm/day)	Carbon sequestration and oxygen release value (10^9 yuan/year)	Water conservation value (10^9 yuan/year)	Rubber value (10^9 yuan/year)
<2	0.928	20.911	0.376
2 < $ET \leq 3$	1.986	21.699	0.663
>3	2.654	-25.514	0.591

4.4 Strategies to enhance ecosystem services values through rubber plantation evapotranspiration management

The rapid expansion of rubber plantations in Southeast Asia has increased water consumption—for example, green water consumption increased by 38 km³/year (Chen et al., 2024). $ET_{a_reconstructed}$ is a critical influence on the ESVs of forest-grassland ecosystems. In semi-arid mountainous regions, potential evapotranspiration serves as a key factor that determines carbon sequestration capacity (Wang, 2024). Based on the soil-plant-atmosphere continuum theory, the photosynthetic-evapotranspiration coupling model in winter wheat validated the diurnal relationship between evapotranspiration and CO₂ flux (Wang et al., 2004). Recent research has analyzed the decoupling phenomenon between evapotranspiration and carbon sequestration under drought stress using the Shuttleworth–Wallace dual-source model and the EALCO model. The results highlighted the impact of seasonal water deficits on WUE (Bi, 2023).

The ecological functionality of rubber plantations is only 21.5%–63.6% of that of primary forests (Singh et al., 2021), which suggests that optimized evapotranspiration management can enhance their

ESVs. In high-evapotranspiration zones, such as the northwestern regions of Xishuangbanna and Pu'er, carbon sequestration and oxygen release values are elevated. Excessive WUE may induce water stress, impair physiological activity, and reduce water conservation capacity, which results in seasonal water scarcity. Conversely, low-evapotranspiration zones, such as the southeastern regions, exhibit diminished WUE, which limits photosynthesis and weakens carbon sequestration (Lin et al., 2022). Evapotranspiration critically influences rubber yield and economic returns. Excessive evapotranspiration under prolonged drought conditions reduces bark turgor pressure, which hinders latex flow and decreases tapping productivity. Insufficient evapotranspiration during the waterlogged rainy seasons may cause root hypoxia, which also suppresses latex production. SSD is positively correlated with evapotranspiration. High SSD enhances evapotranspiration but accelerates soil moisture depletion, which triggers stomatal closure and WUE reduction (Zeng et al., 2022). Thus, agroforestry intercropping with moderate shading can mitigate water stress. Rubber–*Flemingia macrophylla* intercropping systems in high-evapotranspiration areas can reduce the evapotranspiration caused by a monoculture while improving overall WUE and balancing water consumption and economic gains (Liu et al., 2019).



4.5 Limitations and future perspectives

While this study elucidates the spatiotemporal patterns of $ET_{a_reconstructed}$ in rubber plantations and its impact on ESVs, its focus on southwestern China (Xishuangbanna and Pu'er) may constrain its generalizability. This limitation arises from the significant heterogeneity in climate, topography, and management practices among Southeast Asia's principal rubber-growing regions. Extending the proposed methodology to broader geographical contexts would help verify its applicability and reveal regional differentiation patterns.

Furthermore, this study established a baseline average for K_{c_actual} of rubber plantations based on field measurements from 2016 to 2018. While using a 3-year average partially mitigates interannual variability, applying this value as a constant for reconstructing a 53-year historical series risks overlooking substantial influences from climatic decadal variability and vegetation life cycle succession. Therefore, we emphasize the representativeness limitations of this averaged value and recommend that future studies utilize such multi-year observational datasets as key benchmarks to calibrate eco-hydrological models capable of dynamically simulating crop coefficients and soil water stress coefficient, thereby enabling more reliable historical reconstruction and future prediction.

5 Conclusion

Our research investigated the impacts of climate change and rubber plantation expansion on $ET_{a_reconstructed}$ and its main implications for ESVs in Southwestern China. The spatial distribution of $ET_{a_reconstructed}$ was characterized by higher values in the western regions of the study area (968 mm) and lower values in the eastern regions (828 mm). The developed $ET_{a_reconstructed}$ model successfully facilitated the scaling of estimations from site-level observations to a regional scale. The expansion of rubber plantations was identified as a significant driver of $ET_{a_reconstructed}$ that contributed to 11.4%–20.3% increase in regional $ET_{a_reconstructed}$. This increase was primarily driven by climatic factors, of which increasing SSD and RH were the most influential. An optimal $ET_{a_reconstructed}$ range of 2 to 3 mm/day was established for rubber plantations, which achieves a balance among water consumption, carbon sequestration, and latex yield. $ET_{a_reconstructed}$ rates outside this range result in either water stress or reduced photosynthetic productivity. The optimal rubber plantation ESVs were achieved when the multi-year average SSD was 4.17 h.

In conclusion, this research provides a critical scientific basis for sustainable water resource management and climate-resilient planning in rubber-producing regions. It highlights the necessity of regulating plantation density and water use to optimize eco-economic benefits.

Data availability statement

Publicly available datasets were analyzed in this study. All spatial dataset files are available from Resource and Environment

Science and Data Center (URL: <https://www.resdc.cn/DOI/DOI.aspx?DOIID=120>).

Author contributions

ZL: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft. TX: Funding acquisition, Writing – review & editing. YS: Resources, Writing – review & editing. GH: Data curation, Methodology, Writing – review & editing. SG: Supervision, Writing – review & editing. ZZ: Investigation, Resources, Writing – review & editing. BC: Investigation, Resources, Writing – review & editing.

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Conflict of interest

Authors ZZ and BC were employed by the company Yunnan Tobacco Company.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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