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Long-term change of grassland water use efficiency on the Qinghai-Tibet Plateau

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Abstract

Understanding the characteristics of long-term changes in the water use efficiency (WUE) of grassland ecosystems is vital for WUE improvement on the Qinghai-Tibet Plateau. In this study, five vegetation types, namely alpine shrub, desert, grassland, meadow, and swamp, were evaluated. The changes in WUE over the past 16 years were calculated using the total primary productivity and latent heat flux data of the ecosystem from 2006 to 2021. In addition, meteorological data were used to further explore the relationship between WUE and environmental factors. The WUE of alpine desert, meadow, and swamp showed an increasing trend. In contrast, alpine shrub and grassland WUE showed a decreasing trend, with the WUE of shrub being significantly higher than that of grassland on the interannual scale. The WUE of all vegetation types showed seasonal maximum and minimum values in July and January, respectively, and the WUE of shrubs was significantly higher than that of the other vegetation types. The structural equation model showed that precipitation, temperature, and relative humidity were the main positive influences on the WUE of grasslands on the Qinghai-Tibet Plateau, whereas net radiation had a negative influence. Climate factors may substantially impact future changes in the WUE of various ecosystems. The results of this study provide a theoretical basis for further study of WUE changes in the grasslands of the Qinghai-Tibet Plateau.

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Keywords: Water use efficiency; Qinghai-Tibet Plateau; Meteorology; Ecosystem primary productivity

Introduction

As an important part of China's ecological security strategic pattern, the Qinghai-Tibet Plateau ecological barrier is essential to China's ecological security (Li et al., 2022). The Qinghai-Tibet Plateau, which accounts for approximately one-quarter of the total area of China, is also known as the "Third Pole" of the Earth (Qiu et al., 2008). Chinese grassland ecosystems cover a large area (Hou et al., 2021), and the Qinghai-Tibet Plateau substantially influences global climate owing to its unique climatic characteristics (Xu et al., 2014). The ecosystems in the region are unique and diverse, comprising alpine grasslands with forest, meadow, grassland, and desert zonal variation (Shi et al., 2021).

Water use efficiency (WUE) is not only a comprehensive physiological and ecological indicator of plant growth suitability (Cui et al., 2022) but is also a standard measure for studying the coupling of carbon and water cycles in terrestrial ecosystems (Dennis et al., 2001). At the ecosystem scale, grassland WUE is often expressed as the ratio of total ecosystem primary productivity to evapotranspiration (Oliveira et al., 2017). A significant increase was observed in grassland WUE from 2000 to 2015 in China, which was mainly influenced by temperature and solar radiation (Chen et al., 2021). Satellite data showed that global WUE increased at an incremental rate of 0.0025 gC kgH_2O^{-1} yr^{-1} from 2000 to 2013 (Xue et al., 2015). The multi-year average WUE in the Huaihe River basin was 1.48 gC kg H_2O^{-1} between 1981 and 2019 (Wen, 2022). The WUE in golden dewberry scrub meadows showed a significant upward trend at a rate of 0.38 g $\cdot(m^2\text{-}mm)^{-1}$ from 2003 to 2009 on the Qinghai-Tibet Plateau (Wang et al., 2021). Grassland ecosystem WUE also varies depending on the vegetation type and environmental heterogeneity. The vegetation WUE of Mauwusu sands was influenced by climate and vegetation physiology and the WUE, from highest to lowest for each vegetation type, was shrub > meadow > grassland > desert (Wang et al., 2020). The WUE of Xinjiang meadows is higher than that of deserts as the water and temperature conditions of meadows are more favorable for vegetation growth. In contrast, deserts have lower precipitation, which is unfavorable for vegetation growth (Huang et al., 2017).

The WUE of grassland ecosystems is affected by their inherent influence and the external environment. Regarding plant self-regulation, stomatal conductance affects plant gas exchange and, therefore, the WUE of grassland plants (Wu et al., 2012). Additionally, various environmental factors in the external environment, such as precipitation (Shi et al., 2020), relative humidity (Zhang et al., 2019), air temperature (Sun et al., 2020), and soil moisture (Wu et al., 2019), are the primary regulators affecting the WUE of grasslands. Changes in precipitation can directly affect grassland evapotranspiration, thereby affecting plant WUE (Fu et al., 2021). Relative humidity affects the WUE of plants, mainly through changes in vegetation evapotranspiration (Shi et al., 2020). Finally, temperature affects the WUE of grassland ecosystems, mainly by affecting the saturation water vapor pressure difference (Sun et al., 2020).

Few long-term studies on the WUE of multiple vegetation types within grassland ecosystems of the Qinghai-Tibet Plateau have been conducted. In this study, we calculated WUE changes based on total primary productivity and evapotranspiration of ecosystems from 2006 to 2021 for multiple grassland vegetation types on the Qinghai-Tibet Plateau. We aimed to: 1) clarify the long-term WUE changes of five alpine vegetation types, namely shrub, desert, grassland, meadow, and swamp, and the differences in WUE among vegetation types on the Qinghai-Tibet Plateau; and 2) identify how environmental factors regulate the WUE on the Qinghai-Tibet Plateau. In conclusion, this study aims to provide a theoretical basis for the ecological structure of the Qinghai-Tibet Plateau, the sustainable use of grasslands, and the response mechanism to meteorological factors.

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Research Methodology

2.1 Site description

The Qinghai-Tibet Plateau is located on the southwestern edge of China (27.5°–37.5° N, 75°–105° E), and has a total area of approximately 2.57 million km^2. The region is also known as the "Roof of the World," with an average altitude of over 4,000 meters above sea level. The Qinghai-Tibet Plateau experiences low temperatures throughout the year, with an average summer temperature of 7–15 °C (Zhong et al., 2010). Precipitation is low and mainly concentrated from May to September. The distribution of precipitation is uneven, decreasing from southeast to northwest, with overall annual precipitation of 400 mm. In addition, the Qinghai-Tibet Plateau experiences intense radiation and sunlight, with a radiation intensity of approximately 190–220 W/m^2.

Five vegetation types (shrub, desert, grassland, meadow, and swamp) were selected as the targets of our study, and the latitude and longitude positions of each vegetation type were extracted using ArcGIS10.8. The extracted latitude and longitude positions can be used to obtain meteorological data and thus accurately quantify the total primary productivity and latent heat flux of the ecosystem. The distribution of the selected sample sites is shown in Figure 1.

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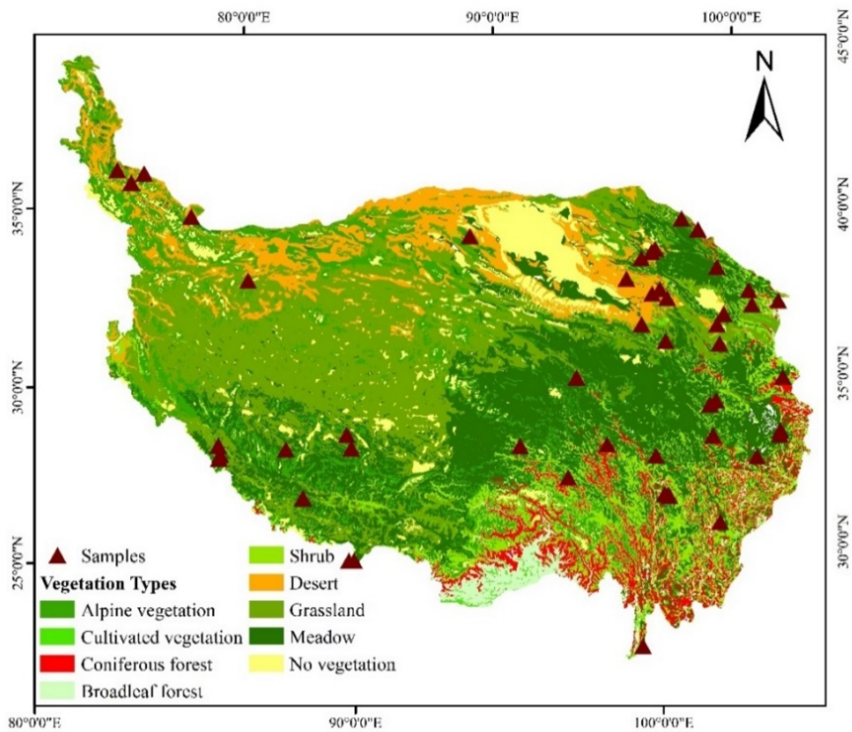

Fig. 1. Sample distribution map and main vegetation types across the Qinghai-Tibet Plateau.

2.2 Data sources and pre-processing

Data for the total ecosystem primary productivity and latent heat fluxes were obtained from the data products (MOD17A2 and MOD16A2) in the MODIS Version 6 series (https://modis.gsfc.nasa.gov/) released by the National Aeronautics and Space Administration (NASA). The timescale of the extracted data was from January 1, 2006, to December 31, 2021, the spatial resolution was 500 m $\times$ 500 m, and the temporal resolution was 8 days.

Meteorological data were obtained from the Weather and Meteorology website (https://rp5.ru/) for 243 countries worldwide. The meteorological data were integrated into the daily scale data. The meteorological data time scale was from January 1, 2006, to December 31, 2021.

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2.3 Data Analysis

Evapotranspiration was obtained by converting the latent heat flux LE ($W \cdot m^{-2}$) from vorticity observations (Tang et al., 2015). The equation is as follows.

$$ET = \frac{\text{LE}}{\lambda}$$

$$\lambda = (2500 - 2.4Ta) \times 10^5$$

where λ is the latent heat of evaporation ($J\text{-}kg^{-1}$) and Ta is the air temperature (°C).

The WUE in this study was calculated using the following equation:

$$\text{WUE} = \frac{\text{GPP}}{\text{ET}}$$

where WUE is water-use efficiency ($g\ m^{-2}mm^{-1}$), and GPP and ET are the total primary productivity ($g\ m^{-2}$) and actual evapotranspiration (mm) of the ecosystem, respectively.

2.4 Data processing and statistics

The data were organized using Excel 2016, and the relative contribution rates were calculated using the augmented regression tree (BRT) model analysis method. The BRT model is a self-learning method based on the categorical regression tree algorithm, which can improve the stability and prediction accuracy of the model by generating multiple regression trees through random selection and self-learning methods. During the operation, a certain amount of data is randomly selected several times to analyze the degree of influence of the independent variable on the dependent variable, and the remaining data are used to test the fitting results. Finally, the generated multiple regressions are averaged and output. The BRT method improves the stability and accuracy of the calculation results and yields the loadings of the independent variable on the dependent variable and the mean or constant of the other independent variables in the case of the interrelationship (Li et al., 2014).

The model was implemented in R language software (version 4.2.1) using the Dismo package, setting the learning rate to 0.001 and the tree complexity to two levels, with 50% of the data used for analysis and 50% for training each time. Ten cross-tests were performed. The structural equation model was computed using R software (version 4.2.1), implemented using the piecewiseSEM package, and plotted using Origin 2022.

Results

3.1 Characteristics of long-term changes in WUE of grassland ecosystems and other vegetation types

The WUE of deserts, meadows, and swamps has been increasing, and swamps have increased significantly over 16 years ($P<0.05$), whereas the WUE of shrubs and grasslands has been decreasing. Comparing the WUE of different grassland vegetation types, the WUE of shrubs was found to be the highest, and the WUE of the remaining four types of grassland vegetation were ranked as desert > swamp > grassland > meadow in descending order (Fig. 2). The WUE of shrubs was significantly higher than that of other grassland vegetation types ($P<0.05$), and no significant difference was observed between grasslands and swamps.

On a temporal scale, the five grassland vegetation types showed maximum ($0.86\ gC \cdot m^{-2} \cdot mm^{-1}$) and minimum ($0.71\ gC \cdot m^{-2} \cdot mm^{-1}$) values in 2006 and 2017, respectively. The environmental heterogeneity test showed that the residuals remained heterogeneous (Table 1).

Fig. 2. Long-term changes in water use efficiency (WUE) of different grassland vegetation types.

Table 1 Data heterogeneity test for different grassland vegetation types

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Vegetation Types	df	F	P
Shrub	9	312.659	<0.001
Desert	9	286.951	<0.001
Grassland	9	375.02	<0.001
Meadow	9	228.669	<0.001
Swamp	9	331.824	<0.001

3.2 Seasonal variation in WUE of different vegetation types in grassland ecosystems

Seasonally, the WUE of grasslands and other vegetation types showed an increasing trend from January to July and a decreasing trend from July to December. Overall, the maximum WUE of all vegetation types was observed in July and the minimum in January. The order from highest to lowest WUE for each vegetation type was shrub > desert > swamp > grassland > meadow. The WUE of shrubs was significantly higher than that of other vegetation types.

Fig. 3. Seasonal variation of WUE in grassland ecosystems.

3.3 Mechanisms of environmental factors regulating WUE in different grassland ecosystems

The results of the enhanced regression tree model showed that temperature, minimum temperature, and maximum temperature had the highest relative contribution to WUE in grassland ecosystems regardless of vegetation type, with mean values of 17.97%, 41.25%, and 20.93%, respectively. The two environmental factors that contributed the most to grassland were maximum temperature and net radiation, at 67.11% and 11.50%, respectively; Fig. 4).

The results of further structural equation modeling showed that precipitation, temperature, and relative humidity were the primary positive effects on the WUE of grasslands on the Qinghai-Tibet Plateau, and net radiation showed a negative effect. Precipitation, temperature, and relative humidity had direct effect coefficients of 0.065, 0.420, and 0.223, respectively, and demonstrated highly significant positive effects on shrubs. The primary regulator of WUE in the desert was temperature, with a value of 0.782. Net radiation had a significant negative effect on the WUE in grasslands, meadows, and swamps ($P<0.05$), whereas temperature and relative humidity had a highly significant positive effect ($P<0.01$). In addition, precipitation had a highly significant positive effect on WUE in swamps ($P<0.01$). The effect coefficients of net radiation, temperature, and relative humidity were 0.779, 0.128, and 0.060, respectively.

Figure 4. Relative contribution rate of environmental factors; temperature (T), maximum temperature (Tx), minimum temperature (Tn), precipitation (RRR), relative humidity (RH), and net radiation (FF), to grassland WUE.

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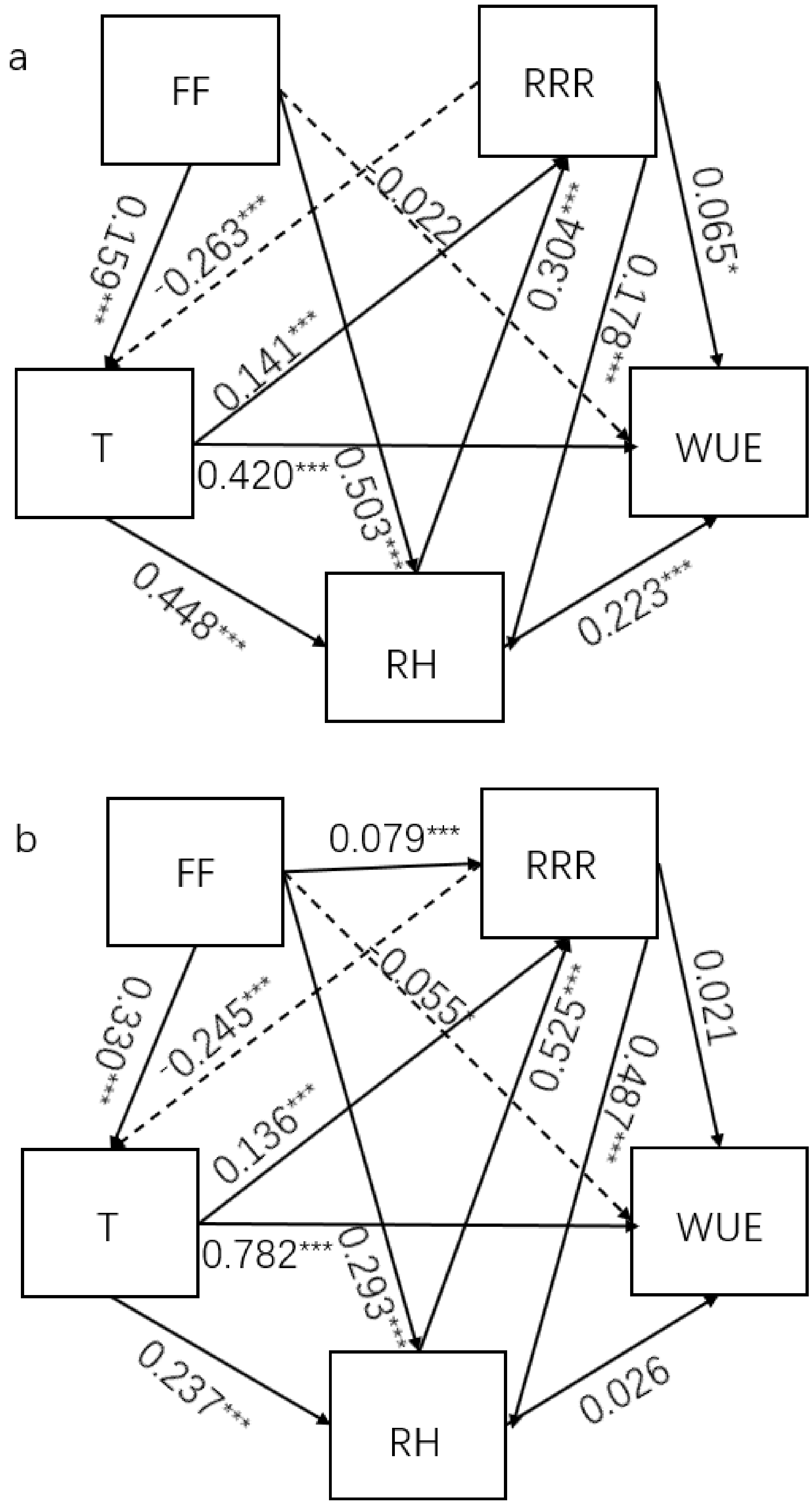

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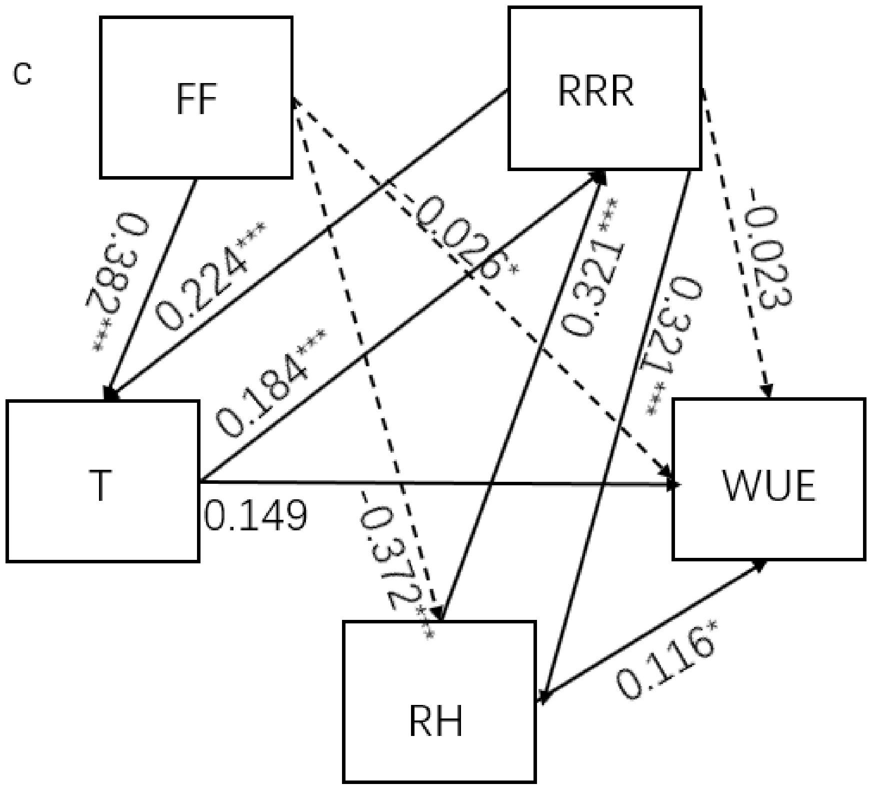

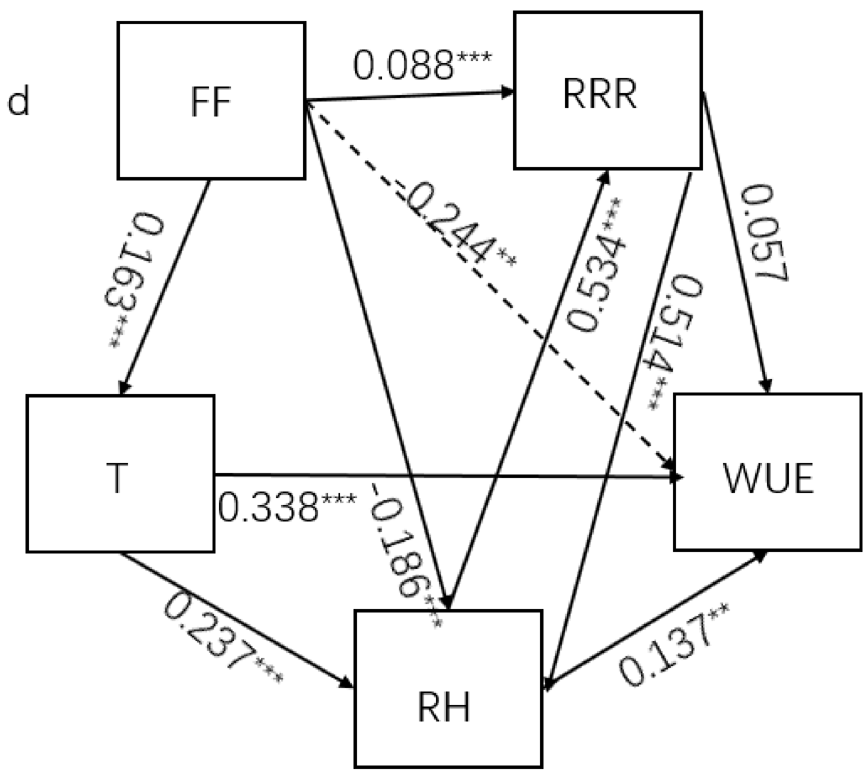

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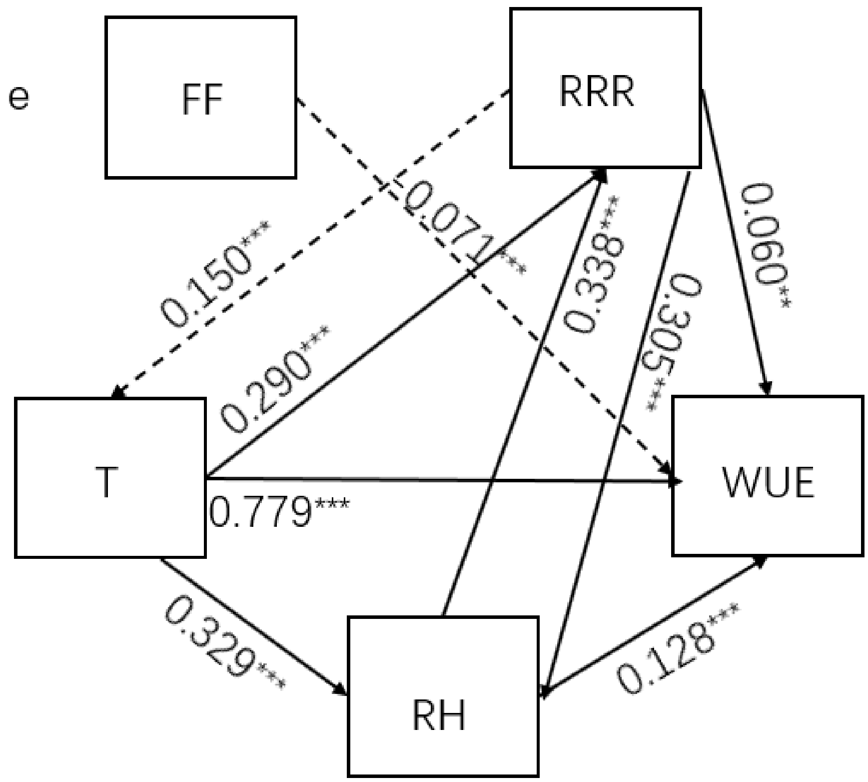

Figure 5. Structural equation diagram of the impact of environmental factors on WUE

Note: a: scrub; b: desert; c: grassland; d: meadow; and e: swamp.

Discussion

Owing to its unique geographical location, diverse ecosystems, complex climatic conditions, and differences in the photosynthetic and water-consumption functions of different vegetation types, the grassland ecosystems of the Qinghai-Tibet Plateau exhibit considerable differences in WUE (Cui et al., 2022). Our results showed that the WUE of desert, meadow, and swamp showed an increasing trend, whereas shrub and grassland decreased over 16 consecutive years on the Qinghai-Tibet Plateau. This may have resulted from the total primary productivity of grassland ecosystems being higher than evapotranspiration during this time. The evapotranspiration of shrubs and grasslands was higher than the total primary productivity of grassland ecosystems. The WUE of grasslands in the Tianshan region of Xinjiang has shown a decreasing trend for 17 consecutive years (Aizezitiyuemaier et al., 2019). The increase in temperature will increase grassland evapotranspiration and total ecosystem primary productivity to a certain degree. However, because grassland evapotranspiration is higher than total ecosystem primary productivity, WUE on the Qinghai-Tibet Plateau showed an increasing trend from 2001 to 2020, with a mean of 1.17 g $\cdot m^{-2} \cdot mm^{-1}$ (Cui et al., 2022). The annual average vegetation WUE on the Qinghai-Tibet Plateau was 0.77 $gC \cdot m^{-2} \cdot mm^{-1}$ in our study, which is relatively low. Corresponding differences in the WUE were also observed.

The WUE of grassland also varied according to vegetation type, and from highest to lowest followed the order shrub > desert > swamp > grassland > meadow. Compared to scrub meadows, deserts experience lower precipitation and poorer hydrothermal conditions, which are not conducive to the normal growth of forage grasses (Huang et al., 2017). The Heihe River Basin also exhibited higher WUE in shrubs than grassland ecosystems (Liu et al., 2020), which is consistent with our findings. Desert grasslands show higher WUE owing to higher photosynthetic rates and lower vegetation evapotranspiration in desert vegetation meadows

(Ehleringer, 1997). In contrast, meadow WUE is lower because of the low temperature and high altitude, which reduces its productivity (Shi et al., 2020).

The WUE also varies seasonally, and our results show that, regardless of the type of vegetation, the WUE of grasslands on the Qinghai-Tibet Plateau reaches its maximum in July, and minimum in January. The WUE of grasslands in Xinjiang reaches its maximum in summer because this region exhibits better water and temperature conditions in summer during similar rainy and hot periods, which is favorable for vegetation growth (Huang et al., 2017). The WUE of vegetation in Xinjiang Tianshan was highest in July (Aizezitiyuemaier et al., 2019), consistent with our findings. This may be because grassland vegetation productivity plateaus substantially and reduces vegetation evapotranspiration in the middle and late growing seasons; therefore, grassland WUE is the highest in July.

The results of this study indicate that precipitation, relative humidity, and temperature are the main factors affecting the WUE of grassland ecosystems. An increase in temperature leads to increased vegetation transpiration, which in turn leads to a decrease in WUE (Peng et al., 2021). Within a specific threshold range, precipitation is the dominant factor affecting the productivity of grassland vegetation (Cui et al., 2022). Precipitation variation is positively correlated with the WUE of grasslands in desert areas, and desert vegetation mainly depends on precipitation to complete its life cycle. The effect of relative humidity on the WUE of grasslands is primarily determined by whether the site-specific grassland WUE is dominated by total ecosystem primary productivity or evapotranspiration, and there is a positive effect of 30 min relative humidity on the WUE of Daxing grasslands (Fen et al., 2018). In contrast, relative humidity has a negative effect on the WUE of alpine meadows in northern Tibet (Shen et al., 2016).

Conclusion

The WUE of desert and meadow showed an increasing trend and that of swamp showed a significantly increasing trend, whereas the WUE of shrub and grassland showed a decreasing trend on an interannual scale. All five vegetation types showed the highest and lowest seasonal WUE in July and January, respectively.

The environmental factors, temperature, minimum temperature, and maximum temperature, had the highest relative contribution to the WUE of grassland ecosystems on the Qinghai-Tibet Plateau. For grasslands, maximum temperature and net radiation were the two environmental factors with the highest relative contribution, and the temperature change had a highly significant positive effect on the change in grassland WUE. In contrast, the change in precipitation had a highly significant negative effect on the change in swamp WUE.

Author Contributions: All authors have read and agree to the published version of the manuscript. Conceptualization, Y.D.; methodology, Y.W.; software, X.W.; validation, W.P.; formal analysis, Y.W.; investigation, Y.D.; resources, Y.W.; data curation, Y.W.; writing—original draft preparation, Y.D.; writing—review and editing, Y.D. and H.Z.; visualization, X.G.; supervision, Y.D.; project administration, X.G.; funding acquisition, Y.D.

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Conflicts of Interest: The authors declare no conflict of interest.

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`Table 1.docx` available at https://authorea.com/users/586145/articles/624405-long-term-change-of-grassland-water-use-efficiency-on-the-qinghai-tibet-plateau