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Abstract: Carbon sinks in terrestrial ecosystems can be significantly increased by afforestation, which will slow global warming. However, it is still unclear how different plantations influence the carbon sink and how they respond to environmental factors, especially in drylands. In this study, eddy correlation method (EC) was used to measure carbon and water fluxes and environmental factors of two artificial forests (*Larix principis-rupprechtii* and *Pinus tabulaeformis*) in the dryland of Northwest China, and the responses of evapotranspiration (ET), net ecosystem exchange (NEE), gross primary productivity (GPP), and ecosystem respiration (RECO) to environmental factors were also assessed. Results showed that the *L. principis-rupprechtii* forest ecosystem had higher water use efficiency (WUE), light use efficiency (LUE), GPP, and RECO than the *P. tabulaeformis* forest ecosystem. However, the proportion of net ecosystem production (NEP) to GPP in the *P. tabulaeformis* forest ecosystem (62.89%) was higher than that in the *L. principis-rupprechtii* forest ecosystem (47.49%), indicating that the *P. tabulaeformis* forest ecosystem had the higher carbon sequestration efficiency. In addition, the CO$_2$ and H$_2$O fluxes in the *L. principis-rupprechtii* forest ecosystem were more sensitive to environmental factors, compared with the *P. tabulaeformis* forest ecosystem. Further, the RECO of the *L. principis-rupprechtii* forest ecosystem was more sensitive to temperature changes, which implies that the *L. principis-rupprechtii* forest ecosystem will release more CO$_2$ than the *P. tabulaeformis* forest ecosystem with a warming climate. Therefore, the *P. tabulaeformis* forest ecosystem may have better carbon sequestration potential. These results are important for understanding the effects of climate change on the CO$_2$ and H$_2$O cycles in coniferous plantation ecosystems in drylands.

Keywords: eddy covariance; carbon and water fluxes; water use efficiency; light use efficiency; temperature sensitivity; coniferous plantation ecosystems

1. Introduction

Terrestrial ecosystems are major carbon sinks in the global carbon cycle. Arid and semiarid ecosystems cover approximately 40% of the Earth’s land surface [1,2], and play a key role in terrestrial carbon dynamics [3,4]. Forests constitute approximately one-third of the Earth’s land surface and store about 90% of terrestrial vegetation carbon [5]. The average annual carbon sequestration of forest ecosystems was about 3.5 ± 1.0 Pg C from 2008 to 2017 [6], suggesting that they are the main carbon pool in terrestrial ecosystems [7]. Moreover, forest ecosystems play an important role in global carbon and water cycles [8,9]. At present, considerable efforts have been spent on global carbon and water fluxes of tropical, temperate, and frigid forests, and fruitful research results have also been achieved [10,11].
Previous studies showed that the growth season of coniferous forests in the middle-high latitudes of the northern hemisphere was prolonged, and their carbon sequestration was significantly enhanced with the climate warming [10,12,13]. However, some experts predicted that with global warming, ecosystem respiration (RECO) would be stimulated, especially in coniferous forests of the northern hemisphere at high latitudes (mainly in permafrost), which would release more CO$_2$ and may switch from a carbon sink to a carbon source at the end of the 21st century [14,15]. However, there are few studies on the carbon and water fluxes of coniferous forest ecosystems in drylands. Therefore, clarifying the dynamic changes of carbon and water fluxes of coniferous forest ecosystems in drylands will help us better understand and predict the change trends of its carbon budget and water balance in the context of climate change.

The responses of carbon exchange and evapotranspiration (ET) to environmental factors in different forest ecosystems are different due to their physiological differences, which may lead to differences in the overall forest carbon budget and water cycle [16]. Understanding the patterns and drivers of CO$_2$ and H$_2$O fluxes in different forest ecosystems is of great significance in the context of global climate change. The ET is an important component of the hydrological cycle and energy balance [17–19]. Similar to ET, the exchange of CO$_2$ between vegetation and the atmosphere is closely related to the water cycle, which is affected by aboveground and underground biophysical processes [20,21]. Net ecosystem exchange (NEE) is the difference between CO$_2$ absorbed by the ecosystem through plant photosynthesis and the CO$_2$ released by the respiration of plants and soil microbes [20]. Gross primary productivity (GPP) refers to the total amount of carbon fixed by plants through photosynthesis [22,23]. Ecosystem respiration (RECO) can consume >50% of GPP and plays a key role in the global terrestrial net carbon balance [24,25]. The ET, NEE, GPP, and RECO variability are mainly affected by environmental factors (e.g., temperature, moisture, radiation, vapor pressure deficit (VPD), etc.) and biological factors (e.g., leaf photosynthesis capacity, plant growth rhythm, microbial activity, etc.) [24,26–28]. Therefore, understanding the responses of ET, NEE, GPP, and RECO to environments in coniferous forest ecosystems of drylands is important for assessing the water cycle dynamics and carbon sink potential of forest ecosystems under climate change [29,30].

The carbon and water cycle processes and their couplings are core to determining the carbon budget and water balance of forest ecosystems in semiarid regions [21]. Water use efficiency (WUE) is the link between the carbon and water cycle in the ecosystem, and it also reveals the interaction between carbon sequestration and water consumption in terrestrial ecosystems [31–33] because WUE is defined as the ratio of gross primary productivity (GPP) to evapotranspiration (ET) [32,34,35]. WUE can reflect water use strategy of the different species or same species in different habitats and can also be used to estimate the impact of water resources on the carbon sink/source function of terrestrial ecosystems [31,32,36]. Environmental factors that affect WUE include the vapor pressure deficit (VPD), air temperature (TA), precipitation, soil water content (SWC), solar radiation, and others [8,35]. Additionally, Zhou et al. (2014) introduced the underlying water use efficiency (uWUE = GPP × VPD$^{0.5}$/ET) and verified it with eddy-related data. Since the uWUE fully considers the nonlinear effect of VPD on the coupling of carbon and water fluxes, it can better describe the relationship between GPP and ET, which makes it widely used and greatly improves our understanding of the carbon–water coupling process [31,37–39]. In addition, the light use efficiency (LUE) of the ecosystem can reflect the response of plant carbon sequestration ability to light, which is of great significance for revealing the water–carbon coupling mechanism of plants [22,40]. The LUE value is the ratio of GPP to photosynthetically active radiation (PAR) or the absorbed fraction of PAR (APAR) [24]. Therefore, exploring the WUE and LUE of forest ecosystems and their influencing factors will help us to better understand the water–carbon coupling mechanism of forest ecosystems in drylands.

The eddy covariance (EC) system achieves the direct measurement of ecosystem carbon and water fluxes dynamics between land surface and atmosphere and is a useful
tool for accurately measuring the carbon and water fluxes of forest ecosystems [16,21]. The system includes a 3D sonic anemometer to measure three-dimensional wind speed and temperature fluctuations, and an open path infrared gas analyzer to measure carbon and water vapor densities [4,41]. It enables the detection of NEE changes at a half-hourly time resolution [42]. NEE can be divided into GPP and RECO, and WUE and LUE of ecosystem can be analyzed using GPP, ET, and meteorological factors [31,43,44]. This study was carried out in the dryland of Northwest China, and the carbon and water fluxes of two coniferous forests (Larix principis-rupprechtii and Pinus tabuliformis) were measured by the eddy correlation method [16,45]. Our objectives were to (1) compare the daily, monthly, and annual dynamics of NEE, RECO, GPP, and ET in the two forest ecosystems; (2) investigate the main environmental drivers of changes in NEE, RECO, GPP, and ET; and (3) illuminate the response of WUE, uWUE, and LUE to environmental factors and the relationship between the water and carbon in two forest ecosystems. This study will help to identify the environmental controlling mechanisms of water and carbon fluxes, WUE and LUE of two forest ecosystems in the dryland of Northwest China, and provide a reference for selecting afforestation trees in future, especially under climate warming conditions.

2. Material and Methods

2.1. Study Site Descriptions

Two artificial forests (Larix principis-rupprechtii and Pinus tabuliformis) were selected as the research objects, which were monospecific plantations, in the dryland of Northwest China. There were some sparse shrubs (Rosa ameensis, Cotoneaster multiflorus, Lonicera hispida, Cerasus tomentosa, etc.) and herbs (Carex rigescens, Aconitum sinomontanum, Fragaria orientalis, Potentilla bifurca, Medicago lupulina, etc.) under the forest, which had little impact on the carbon and water flux of the ecosystem. Further details of the study site specifics are summarized in Table S1. The study region is a temperate continental monsoon climate, with remarkable temperature differences among four seasons. According to the climate characteristics, the growing season and non-growth season are classified as the periods from May to October and from November to April, respectively [46].

Forest ages, management practices, and historical land use were all likely to affect the annual carbon and water fluxes of forest ecosystems [47,48]. Therefore, two forests selected for this study had similar ages (30–40 years), and neither the forests nor the soil were disturbed and managed by humans. More basic information of two forest stands is summarized in Table S1. The differences in carbon and water fluxes between two forest stands were attributed to tree species.

2.2. Eddy Covariance and Environmental Factors Measurements

The CO₂ and H₂O fluxes of two forest ecosystems were measured by the eddy covariance (EC) systems. The EC was composed of multiple sensors, including a three-dimensional sonic anemometer (CSAT-3, Campbell Scientific, Logan, UT, USA) with an open-path infrared H₂O and CO₂ gas analyzer (LI-7500DS, LI-COR, Lincoln, NE, USA). They combined to measure the CO₂ and H₂O molar fractions and other relevant environmental factors in the air. The sensors were installed at a height of about 2.5 m in the forest canopy to measure the three components of wind velocity vectors (u, v, and w), and the sonic temperature. The CO₂ and H₂O concentrations were collected at 10 Hz, recorded using the CR6 data logger (Campbell Scientific, Logan, UT, USA).

At the same time, the main environmental factors were also measured by the EC systems, including air temperature (TA, °C), air relative humidity (RH, %), solar radiation (Rn, W·m⁻²), four-component radiation (SWIN/SWOUT/LWIN/LWOUT, W·m⁻²), photosynthetically active radiation (PAR, µmol·m⁻²·s⁻¹), soil temperature (TS, °C), soil water content (SWC, %), atmospheric pressure (Pa, Pa), wind direction (°), and speed (m·s⁻¹). All of the above environmental factors were measured in a time step of 30 min by a data acquisition system (CR6, Campbell Scientific, Logan, UT, USA). More detailed information about the instruments and installations is described in Table S2. Vapor pressure deficit
(VPD, KPa) was calculated using the 30 min average air temperature (TA, °C) and air relative humidity (RH, %) according to the following formula [49]:

\[
\text{VPD} = 0.611 \times \exp \left( \frac{17.502 \cdot \text{TA}}{\text{TA} + 240.97} \right) \times \left( 1 - \frac{\text{RH}}{100} \right)
\]  

(1)

In this study, SWC and TS were measured at approximately 40 cm of soil layer (root zone), closely related to the vegetation growth and evapotranspiration [50]. Other meteorological data were collected at the top of the canopy.

All the fluxes data and meteorological data collected by the EC system were integrated into the SmartFlux system (LI-COR, Lincoln, NE, USA), which included an Li-7500DS, a built-in GPS module, and an embedded processor running EddyPro 7.0.6 (LI-COR, Lincoln, NE, USA). They were the software for calculating fluxes data [45,50]. The SmartFlux system was an autonomous system that collected data from the Li-7500DS and used the EddyPro program, which performed the spike detection, frequency response corrections, conversion of sonic temperature into actual temperature, coordinate rotation using planar fit method, and WPL density correction [51], and synchronization of variables from all instruments [50,52].

2.3. Calculation, Quality Control, Gap Filling, and Component Partitioning of the H\textsubscript{2}O/CO\textsubscript{2} Fluxes

The EC raw data were processed by SmartFlux system, including the eddy covariance, meteorological data, and data quality identification. Subsequently, the data quality control, gap filling, and component partitioning were further conducted with the Tovi 2.4.0 software (LI-COR, Lincoln, NE, USA) [https://www.licor.com/tovi/#pricing (accessed on 30 August 2020)] [53]. It mainly included the following steps: Firstly, it checked the quality of the eddy covariance and meteorology data. Secondly, it gap-filled meteorological data using the meteorological data from redundant or external datasets. Thirdly, it based the critical friction velocity (u*) threshold and excluded fluxes under calm wind conditions. Fourth, it determined areas of interest, computed flux location probabilities, and allocated half-hour fluxes to specific areas of interest using footprint analysis output (we adopted an extension of flux contribution at 90%). Fifth, it calculated and filled gaps of the flux variables based on the meteorological data that had been gap-filled. Finally, it discriminated GPP and RECO from NEE.

2.4. The Relationship between H\textsubscript{2}O/CO\textsubscript{2} Flux and Environmental Factors

Because the eddy covariance can provide continuous measurements of the net ecosystem exchange (NEE) and evapotranspiration (ET), gross primary productivity (GPP) and ecosystem respiration (RECO) were derived from NEE measurements according to the method provided by the Tovi 2.4.0 software. A negative NEE value was defined as the CO\textsubscript{2} fixation from the atmosphere, while a positive NEE value was defined as the CO\textsubscript{2} emission into the atmosphere [47]. The continuous NEE at 30 min intervals was calculated as follows:

\[
\text{NEE} = \text{RECO} - \text{GPP} \tag{2}
\]

In addition, the continuous NEE, GPP, RECO, and ET measurements at 30 min intervals were summed to generate the daily, monthly, and annual values of these CO\textsubscript{2} and H\textsubscript{2}O flux components.

The net ecosystem production (NEP) was the negative value of NEE [52,54].

\[
\text{NEP} = -\text{NEE} \tag{3}
\]

In order to examine the inherent differences in the response of H\textsubscript{2}O/CO\textsubscript{2} flux to environmental factors, a regression model between H\textsubscript{2}O/CO\textsubscript{2} flux (NEP, GPP, RECO, and ET) and environmental factors was established.
Firstly, the exponential regression model was used to quantify the relationship between environmental temperature and CO\textsubscript{2}/H\textsubscript{2}O flux at annual timescale [4,31]. The fitting equation was as follows:

\[ f(x) = a \times e^{bT} \]  

(4)

where \( T \) was the TA (°C) or TS (°C); \( f(x) \) represented H\textsubscript{2}O/CO\textsubscript{2} fluxes (ET, NEP, GPP, and RECO).

Then, we explored the relationship between RECO and temperature (TA (°C) and TS (°C)) in two forest ecosystems. The temperature sensitivity (\( Q_{10} \)) of ecosystem respiration (RECO) indicated that the RECO increased exponentially for every 10 °C increase in temperature, which was expressed as [31,55]

\[ Q_{10} = e^{10b} \]  

(5)

where \( b \) is the constant obtained by the Equation (3).

Furthermore, the linear regression model was used to quantify the relationship between PAR, RH, and VPD and H\textsubscript{2}O/CO\textsubscript{2} flux at an annual timescale in two different forest ecosystems [4,31]. The fitting equation was as follows:

\[ f(x) = a + bx \]  

(6)

where \( f(x) \) represented H\textsubscript{2}O/CO\textsubscript{2} flux (ET, NEP, GPP and RECO); \( x \) was PAR, RH or VPD.

2.5. Calculations of Water Use Efficiency

Water use efficiency (WUE) was defined as the carbon gain per unit of water consumed by the ecosystem. In this study, we used two formulations of WUE to explore the coupling relationship between water and carbon cycles at the two sites, which were the simple water use efficiency (WUE, g C·kg\textsuperscript{-1} H\textsubscript{2}O) and underlying water use efficiency (uWUE, g C·KPa\textsuperscript{0.5}·kg\textsuperscript{-1} H\textsubscript{2}O) [31,43,44]; the ecosystem WUE and uWUE were calculated as follows:

\[ WUE = \frac{GPP}{ET} \]  

(7)

\[ uWUE = \frac{GPP \times VPD^{0.5}}{ET} \]  

(8)

2.6. Calculations of Light Use Efficiency

Light use efficiency (LUE, g C·d·W\textsuperscript{-1}) was defined as the ratio of gross primary productivity GPP (g C·m\textsuperscript{-2}·d\textsuperscript{-1}) to PAR (µmol·m\textsuperscript{-2}·s\textsuperscript{-1}) [22,56]:

\[ LUE = \frac{GPP}{PAR} \]  

(9)

2.7. Statistical Analysis

At different timescales, we quantified the individual components of NEE, GPP, RECO, and ET of two different forest ecosystems. A multiple stepwise regression was used to identify the main environmental factors that significantly affected NEE, GPP, RECO, ET, WUE, uWUE, and LUE in two different forest ecosystems. Moreover, the relationships between NEE, GPP, RECO, and ET and the significant environmental factors were established using the linear and exponential regression models. The stepwise regression analysis was performed using SPSS 26.0 (SPSS Inc. an IBM Company, Chicago, IL, USA), and all fitting and figures were performed with Origin 2021 software (Origin Lab Inc., Northampton, MA, USA).

3. Results

3.1. Meteorology Variations of Two Forest Ecosystems

The eddy covariance sites of two forest ecosystems were constructed at different times in 2018–2019 (more detailed information in Table S2). In this study, the complete
monitoring data of two forest ecosystems in 2020 were analyzed. The variations of the daily mean air temperature (TA), daily mean soil temperature (TS), daily mean air relative humidity (RH), daily mean soil water content (SWC), daily mean vapor pressure deficit (VPD), and daily mean photosynthetic active radiation (PAR) in two forest ecosystems showed the strong seasonality, and there were obvious differences between two forest ecosystems (Figure 1). The TA and TS of two forest ecosystems reached the highest value in July and then decreased (Figure 1A,B). The maximum value of TA of the Pinus tabulaeformis forest ecosystem (26.01 °C) was the higher than that of the Larix principis-rupprechtii forest ecosystem (16.93 °C) (Figure 1A), and the TS showed a consistent pattern (20.72 °C and 11.11 °C, respectively) (Figure 1B). The RH, SWC, and VPD fluctuated greatly in the two forest ecosystems, which was mainly affected by rainfall (Figure 1C–E). The RH and SWC of the L. principis-rupprechtii forest ecosystem were higher than those of the P. tabulaeformis forest ecosystem during growing season (Figure 1C,D). However, the PAR of the P. tabulaeformis forest ecosystem was higher than that of the L. principis-rupprechtii forest ecosystem during the growing season (Figure 1F).

Figure 1. Temporal variations of the daily mean air temperature (TA) (A), daily mean soil temperature (TS) (B), daily mean air relative humidity (RH) (C), daily mean soil water content (SWC) at a depth of 40 cm (D), daily mean vapor pressure deficit (VPD) (E), and daily mean photosynthetic active radiation (PAR) (F) in two forest ecosystems.

3.2. Annual Variations of CO$_2$ and H$_2$O Fluxes

The daily variations of CO$_2$ flux (NEE, RECO, GPP) and H$_2$O flux (ET) differed remarkably in two forest ecosystems (Figure 2). The daily and cumulative NEE, RECO, GPP, and ET of the L. principis-rupprechtii forest ecosystem were higher than those of the P. tabulaeformis forest ecosystem (Figure 2A–C). The maximum daily CO$_2$ and H$_2$O fluxes in the two forest ecosystems occurred from June to August. The maximum NEE values of the L. principis-rupprechtii and P. tabulaeformis forest ecosystems were 45.20 and 32.63 g CO$_2$ m$^{-2}$ d$^{-1}$ (a
negative NEE value was defined as the CO$_2$ fixation from atmosphere, and the larger the absolute value of NEE, the greater the fixed amount of CO$_2$), and the maximum daily GPP of *L. principis-rupprechtii* and *P. tabulaeformis* were 76.03 and 40.96 g CO$_2$ m$^{-2}$ d$^{-1}$. Similarly, the maximum daily RECO in the *L. principis-rupprechtii* forest ecosystem (40.72 g CO$_2$ m$^{-2}$ d$^{-1}$) was larger than that in the *P. tabulaeformis* ecosystem (14.24 g CO$_2$ m$^{-2}$ d$^{-1}$) (Figure 2A). The *L. principis-rupprechtii* forest ecosystem had a higher annual accumulation of NEE (-3314.32 g CO$_2$ m$^{-2}$ yr$^{-1}$), RECO (3666.33 g CO$_2$ m$^{-2}$ yr$^{-1}$), and GPP (6980.65 g CO$_2$ m$^{-2}$ yr$^{-1}$) than the *P. tabulaeformis* forest ecosystem (NEE = -3128.70 g CO$_2$ m$^{-2}$ yr$^{-1}$, RECO = 1846.40 g CO$_2$ m$^{-2}$ yr$^{-1}$, GPP = 4975.10 g CO$_2$ m$^{-2}$ yr$^{-1}$, respectively) (Figure 2B). The NEP, RECO, and GPP of the *L. principis-rupprechtii* forest ecosystem were 5.90%, 98.57%, and 40.31% higher than those of the *P. tabulaeformis* forest ecosystem. In addition, the NEP of the *L. principis-rupprechtii* and *P. tabulaeformis* forest ecosystems accounted for 47.48% and 62.89% of the GPP, and the RECO of the *L. principis-rupprechtii* and *P. tabulaeformis* forest ecosystems accounted for 52.52% and 37.11% of the GPP.

**Figure 2.** Temporal variations of daily CO$_2$ fluxes (net ecosystem exchange (NEE), ecosystem respiration (RECO), gross primary production (GPP)) (A,B), cumulative CO$_2$ fluxes (NEE, RECO, GPP) (C,D), daily and cumulative H$_2$O flux (E,F) (evapotranspiration (ET)) in two forest ecosystems.

The dynamic of daily ET was similar to that of TA, showing a unimodal curve that reached the peak during growing season (Figure 2C). The maximum ET values were 5.53 mm d$^{-1}$ and 5.29 mm d$^{-1}$ in the *L. principis-rupprechtii* and *P. tabulaeformis* forest ecosystems. The difference of the annual cumulative ET between the *L. principis-rupprechtii* (456.85 mm year$^{-1}$) and the *P. tabulaeformis* forest ecosystem (468.11 mm year$^{-1}$) was not large.

### 3.3. Monthly and Half-Hourly Variations of CO$_2$ and H$_2$O Fluxes

The variations of monthly and half-hourly CO$_2$ and H$_2$O fluxes in the two forest ecosystems are shown in Figure 3. In the monthly scale, the maximum values of average NEE, GPP, and ET in the *P. tabulaeformis* forest appeared in May, which were 26.14 g CO$_2$ m$^{-2}$ d$^{-1}$, 53.09 g CO$_2$ m$^{-2}$ d$^{-1}$, and 3.39 mm d$^{-1}$, respectively (Figure 3A–D), and the average RECO in the *P. tabulaeformis* forest reached the maximum value in September, which was...
26.95 g CO₂ m⁻² d⁻¹. However, the maximum values of average NEE, RECO, GPP, and ET in *L. principis-rupprechtii* emerged in July, which were 19.42 g CO₂ m⁻² d⁻¹, 11.41 g CO₂ m⁻² d⁻¹, 26.77 g CO₂ m⁻² d⁻¹, and 2.57 mm d⁻¹, respectively (Figure 3A–D).

**Figure 3.** Monthly variations (A–D) of CO₂ and H₂O fluxes (net ecosystem exchange (NEE), ecosystem respiration (RECO), gross primary production (GPP), evapotranspiration (ET)), and hourly variations (E–H) of CO₂ and H₂O fluxes (NEE, RECO, GPP, and ET) in two forest ecosystems. The value for each point in each panel represents the mean value and standard error during the whole analysis period.

In this study, the maximum and minimum values of the half-hourly variation curves of CO₂ (NEE, RECO, and GPP) and H₂O (ET) fluxes were different every month, but their monthly change trends were similar. Thus, we selected July as a typical example to analyze the half-hourly variation of CO₂ and H₂O fluxes for two forest ecosystems. In the half-hourly scale, the CO₂ (NEE, RECO, and GPP) and H₂O (ET) fluxes of the *L. principis-rupprechtii* forest ecosystem were higher than those of the *P. tabulaeformis* forest ecosystem (Figure 3E–H). In addition, the NEE and GPP of the *P. tabulaeformis* forest ecosystem reached maximum values at about 11:00 a.m., but in the *L. principis-rupprechtii* forest ecosystem they reached maximum values at about 15:00 p.m. (Figure 3E,G). The RECO in daytime of the *L. principis-rupprechtii* forest ecosystem was significantly higher than in nighttime, but there was no significant difference of the RECO between daytime and nighttime in the *P. tabulaeformis* forest ecosystem (Figure 3F). The ET of the two forest ecosystems had different trends in the half-hourly scale. The ET of the *L. principis-rupprechtii* forest ecosystem showed an obvious double-peak curve, and the two peak values occurred at about 11:00 a.m. and 15:00 p.m. However, the ET of the *P. tabulaeformis* forest ecosystem displayed a single-peak curve, with the peak value appearing at about 14:00 p.m. (Figure 3H).

**3.4. The Relationships between Environmental Factors and CO₂/H₂O Fluxes**

The environmental factors affecting CO₂ and H₂O fluxes during growing season in two forest ecosystems were different (Table 1). The results showed that SWC did not enter the multiple stepwise regression models in both of the two forest ecosystems, which meant that SWC had no significant effect on the CO₂ and H₂O fluxes. The main impact factors of NEE, GPP, and ET are different for the two forest ecosystems. In the two forest ecosystems, NEE, GPP, and ET were influenced by PAR, while RECO was mainly affected by TA or TS and RH.
Table 1. Results for the multiple stepwise regression analysis of effects of potential meteorological drivers (TS, TA, PAR, RH, VPD, and SWC) on the CO₂ and H₂O fluxes (NEP, RECO, GPP, and ET) in two forest ecosystems.

| Forest Ecosystem Types | Multiple Stepwise Regression Equation | F-Value | p-Value | TS | TA | PAR | RH | VPD | SWC |
|------------------------|----------------------------------------|---------|---------|----|----|-----|----|-----|-----|
| Larix principis-rupprechtii | NEE = 30.567 – 0.078 PAR – 0.476 RH + 3.317 + 1.692 TA | 43.36 | 0.00 | 0.47 ** | –0.59 ** | –0.57 ** |
|                         | RECO = 3.317 + 1.692 TA + 0.081 PAR + 0.553 RH | 40.58 | 0.00 | 0.49 ** | 0.48 ** | 0.51 ** |
|                         | GPP = −38.259 + 2.074 TA + 0.017 TS + 0.005 VPD + 0.074 RH − 0.132 TA | 57.41 | 0.00 | 0.48 ** | –0.27 ** | 0.55 ** | 0.38 ** | 0.41 ** |
| Pinus tabulaeformis      | NEE = −43.615 − 0.037 PAR + 2.157 TS − 2.390 TA + 0.022 VPD + 0.431 RH | 38.28 | 0.00 | 0.27 ** | –0.35 ** | –0.46 ** | 0.34 ** | 0.40 ** |
|                         | RECO = −1.122 + 0.534 TS + 0.019 RH | 46.41 | 0.00 | 0.58 ** | 0.69 ** | 0.25 ** |
|                         | GPP = 11.053 + 0.043 PAR | 136.66 | 0.00 | 0.18 * | 0.67 ** |
|                         | ET = 0.125 + 0.043 PAR + 0.043 TA | 118.25 | 0.00 | 0.18 * | 0.67 ** |

The TS, TA, PAR, RH, VPD, and SWC columns represent the partial correlation coefficients between CO₂ and H₂O fluxes and each environmental factor. * Indicates the significant correlation at the 0.05 level. ** Indicates the significant correlation at the 0.01 level.

In order to better reveal the response of carbon (NEP, GPP, and RECO) and water fluxes (ET) to the significant environmental factors in the two forest ecosystems, the relationships between NEP, GPP, RECO, and ET and the significant environmental factors were fitted (Figure 4). The carbon and water fluxes had a linear relationship with PAR and VPD in the two forest ecosystems. The sensitivities of NEP, GPP, and ET to PAR in the L. principis-rupprechtii and P. tabulaeformis forest ecosystems were similar, and all showed a significant positive linear relationship (p < 0.05) (Figure 4A,F,I). Similarly, the sensitivities of NEP, GPP, RECO, and ET to VPD in the L. principis-rupprechtii and P. tabulaeformis forest ecosystems also showed a significant positive linear relationship (p < 0.05) (Figure 4B,D,G,J). However, the relationships between NEP, RECO, GPP, ET, and RH in the two forest ecosystems were not significant or weak (Figure 4C,E,H,K).

Figure 4. The regression relationship between the daily CO₂/H₂O fluxes (NEP (negative NEE), RECO, GPP, and ET) and daily environmental factors (photosynthetic active radiation (A,F,I), vapor pressure deficit (B,D,G,J), and air relative humidity (C,E,H,K)) in two forest ecosystems. (A–H) indicate different small panels.
In addition, the relationships between NEP, GPP, RECO, and ET and temperature (TA and TS) were established to investigate the response of CO$_2$/H$_2$O fluxes to temperature changes in two forest ecosystems (Figure 5). The NEP, GPP, and ET had significant exponential relationships with temperature (TA and TS) in two forest ecosystems, and the change rates of NEP, GPP, and ET in the L. principis-rupprechtii forest ecosystem were larger than those in the P. tabulaeformis forest ecosystem (Figure 5A,B,E–H). The temperature sensitivity (Q$_{10}$) of RECO to TA in the L. principis-rupprechtii forest ecosystem (Q$_{10}$ = 3.88) was higher than that in the P. tabulaeformis forest ecosystem (Q$_{10}$ = 2.10) (Figure 5C). A similar pattern was found for the sensitivity of RECO to TS (Q$_{10}$ = 5.61 and Q$_{10}$ = 2.99) in the L. principis-rupprechtii and P. tabulaeformis forest ecosystems (Figure 5D). Furthermore, RECO was more sensitive to TS than TA in the same forest ecosystem (Figure 5C,D).

**Figure 4.** The regression relationship between the daily CO$_2$/H$_2$O fluxes (NEP (negative NEE), RECO, GPP, and ET) and daily environmental factors (photosynthetic active radiation (A,F,I), vapor pressure deficit (B,D,G,J), and air relative humidity (C,E,H,K)) in two forest ecosystems. (A–H) indicate different small panels.

**Figure 5.** The regression relationship between the daily CO$_2$/H$_2$O fluxes (NEP (negative NEE), RECO, GPP, and ET) and daily environmental factors (air temperature (TA), soil temperature (TS)) in two forest ecosystems. (A–H) indicate different small panels.
3.5. Annual Variations of Water Use Efficiency and Light Use Efficiency in Two Forest Ecosystems

The relationships between GPP and ET, between GPP × VPD0.5 and ET, and between GPP and PAR were established to compare the water use efficiency (WUE), underlying water use efficiency (uWUE), and light use efficiency (LUE) in two forest ecosystems (Figure 6). Both GPP and GPP × VPD0.5 increased linearly with ET, and GPP also showed the same trend with PAR. The WUE and uWUE of the *L. principis-rupprechtii* forest ecosystem were 3.45 g C·kg⁻¹ H₂O and 2.70 g C·KPa⁻0.5·kg⁻¹ H₂O, higher than those of the *P. tabulaeformis* forest ecosystem (2.08 g C·kg⁻¹ H₂O and 2.42 g C·KPa⁻0.5·kg⁻¹ H₂O) (Figure 6A,B). The LUE of the *L. principis-rupprechtii* and *P. tabulaeformis* forest ecosystems was 0.10 and 0.06 g C·d·W⁻¹ (Figure 6C).

![Figure 6](image)

Figure 6. The regression relationship between GPP, GPP × VPD0.5, and ET, and between GPP and PAR in two forest ecosystems. Based on Equations (7)–(9), slopes in the figure represent the water use efficiency (WUE) (A), underlying water use efficiency (uWUE) (B), and light use efficiency (LUE) (C), respectively.

3.6. Monthly Variations of Water Use Efficiency and Light Use Efficiency

The WUE, uWUE, and LUE of two forest ecosystems during growing season were compared (Figure 7). The WUE of the *L. principis-rupprechtii* forest ecosystem fluctuated greatly among different months, and average WUE of the *L. principis-rupprechtii* forest ecosystem was higher than that of the *P. tabulaeformis* forest ecosystem (Figure 7A). Average uWUE of the *L. principis-rupprechtii* forest ecosystem was higher than that of the *P. tabulaeformis* forest ecosystem in June and September (Figure 7B). Similarly, average LUE of the *L. principis-rupprechtii* forest ecosystem had higher average LUE than *P. tabulaeformis* forest ecosystem (Figure 7C).

![Figure 7](image)

Figure 7. Monthly variations of the water use efficiency (WUE) (A), underlying water use efficiency (uWUE) (B), and light use efficiency (LUE) (C) in two forest ecosystems. The value for each point in each panel represents the mean value and standard error for each month.
3.7. Environmental Drivers of Water Use Efficiency and Light Use Efficiency

The main environmental factors that caused the differences in the WUE, uWUE, and LUE in two forest ecosystems during growing season were probed with the multiple regression analysis (Table 2). The WUE of two forest ecosystems were affected by PAR, and the effect of PAR on WUE in the L. principis-rupprechtii forest ecosystem was negative, but completely opposite in the P. tabulaeformis forest ecosystem. The main environmental factors affecting the uWUE were TS and TA in the L. principis-rupprechtii forest ecosystem, but PAR and RH in the P. tabulaeformis forest ecosystem. The LUE could be explained by TA, PAR, RH, and SWC in the L. principis-rupprechtii forest ecosystem, and by PAR in the P. tabulaeformis forest ecosystem. The PAR was the important factor in explaining the highest proportion of LUE variation in both L. principis-rupprechtii and P. tabulaeformis forest ecosystems, with partial correlation coefficients of −0.51 and −0.73. In conclusion, the PAR, TA, and RH were the crucial environmental factors affecting the WUE, uWUE, and LUE in the two forest ecosystems during the growing season. The relationships between WUE, uWUE, LUE, and PAR were significant in most of the models, which suggested that PAR played a key role in water use efficiency and light use efficiency.

Table 2. Results for the multiple stepwise regression analysis of effects of potential meteorological drivers (TS, TA, PAR, RH, VPD, and SWC) on the water use efficiency (WUE), underlying water use efficiency (uWUE), and light use efficiency (LUE) in two forest ecosystems during growing season.

| Forest Ecosystem Types | Stepwise Regression Equation | F-Value | p-Value | TS | TA | PAR | RH | VPD | SWC |
|------------------------|------------------------------|--------|--------|----|----|-----|----|-----|-----|
| **Larix principis-rupprechtii** | WUE = 3.954 − 0.024 PAR | 8.49 | 0.00 |    |    | −0.23 ** |   |    |    |
|                         | uWUE = 1.800 − 0.188 TS + 0.154 TA | 6.38 | 0.00 | −0.27 ** | 0.21 ** |    |    |    |    |
|                         | LUE = −0.094 + 0.003 RH − 0.002 PAR + 0.010 TA + 0.005 SWC | 64.59 | 0.00 |    | 0.40 ** | −0.51 ** | 0.49 ** |    | 0.30 ** |
| **Pinus tabulaeformis**  | WUE = 0.780 + 0.018 PAR | 22.70 | 0.00 |    |    | 0.37 ** |   |    |    |
|                         | uWUE = 3.030 − 0.027 RH + 0.011 PAR | 48.98 | 0.00 |    | 0.20 * | −0.34 ** |   |    |    |
|                         | LUE = 0.186 − 0.001 PAR | 165.06 | 0.00 |    |    | −0.73 ** |   |    |    |

The TS, TA, PAR, RH, VPD, and SWC columns represent the partial correlation coefficients of between the WUE, uWUE, or LUE and each meteorological climatic factor. * Indicates the significant correlation at the 0.05 level. ** Indicates the significant correlation at the 0.01 level.

4. Discussion

4.1. Effects of Two Tree Species on CO2 and H2O Budget

Photosynthesis is a physiological process closely related to gas diffusion in plant stomata that plays an important role in regulating terrestrial carbon and water fluxes [57,58]. The annual accumulation of net ecosystem exchange (NEE) and gross primary productivity (GPP) in the Larix principis-rupprechtii forest ecosystem were higher than those in the Pinus tabulaeformis forest ecosystem (Figure 2B). At the monthly scale, the carbon flux of the two forest ecosystems had the same results (Figure 3A–D), and the seasonal changes of carbon flux were consistent with plant growth dynamics. At the half-hourly scale, the carbon flux of the L. principis-rupprechtii forest ecosystem was greater than that of the P. tabulaeformis forest ecosystem, but NEE and GPP reached their peak values at different times (Figure 3E,G). Previous studies showed that L. principis-rupprechtii had higher photosynthetic capacity than P. tabulaeformis [59,60], which may result in larger GPP in the L. principis-rupprechtii forest ecosystem. Moreover, L. principis-rupprechtii is a deciduous coniferous species, and had no leaves or stomata yet to function during the non-growing season, indicating a low carbon-absorption capacity. Therefore, the differences in photosynthetic capacity and tree species between the two forest ecosystems was the fundamental reason for the differences in GPP [47]. Furthermore, the vegetation carbon uptake and canopy evapotranspiration were related to the leaf area index (LAI) [17], which was also the reason for the differences in carbon and water fluxes between the two forest ecosystems.

In addition, the ecosystem respiration (RECO) was the major pathway for plant-fixed carbon returning to the atmosphere [45,61], and forest ecosystems with larger soil organic
matter have higher RECO, because RECO is dominated by the heterotrophic respiration [45]. In this study, RECO of the L. principis-rupprechtii forest ecosystem was higher than that of the P. tabulaeformis forest ecosystem, accounting for 52.52% and 37.11% of GPP, respectively. Our previous study confirmed that L. principis-rupprechtii forest stand had higher litter carbon input, litter decomposition rate, and thicker litter layer than P. tabulaeformis forest stand [62], which could be considered as the reason for the higher soil heterotrophic respiration of the L. principis-rupprechtii forest [45]. Moreover, the low soil moisture usually inhibits the decomposition of organic matter in arid and semiarid ecosystems [45,63], which is consistent with the result that SWC of the P. tabulaeformis forest ecosystem was lower than that of the L. principis-rupprechtii forest ecosystem in this study (Figure 2).

Evapotranspiration (ET) is an important component of the water balance of forest ecosystems, which is the comprehensive result of soil evaporation, canopy-intercepted water evaporation, and plant transpiration [14,64]. On a global scale, about 60% of the precipitation on the land surface returns to the atmosphere via ET [65,66], and the transpiration is the largest water loss in the ecosystem, accounting for about 64% of ET [67,68]. In this study, the ET, annual cumulative ET, and average ET at the monthly or half-hour scales of the L. principis-rupprechtii forest ecosystem were higher than those of the P. tabulaeformis forest ecosystem (Figure 2E,F and Figure 3D,H). Noticeably, the main contribution period of annual cumulative ET was different in the two forest ecosystems (Figure 2E,F), because in the non-growth or early growth period, L. principis-rupprechtii forest had low transpiration capacity. The time to reach the peak value of ET in the two forest ecosystems was also different on one day (Figure 3H), which was caused by the difference in photosynthetic characteristics of the two trees [57,58]. Theoretically, transpiration was mainly controlled by the stomatal pores of the leaves and concurrent with photosynthesis [69], which led to the simultaneous exchange of water and carbon dioxide between the atmosphere and forest ecosystems [14]. Although the eddy covariance (EC) provides a direct measurement of ET of forest ecosystems, it cannot separate ET to measure the evaporation (E) and transpiration (T), which are controlled by different processes and have different responses to environmental factors [70]. Therefore, it is necessary to conduct separate study on them in the future.

4.2. Effects of Environmental Factors on Carbon and Water Fluxes of Two Forest Ecosystems

There are complex linear or nonlinear relationships between carbon, water fluxes, and environmental factors, including solar radiation, temperature, soil moisture, VPD, and other factors [28,47]. Understanding the effects of environmental factors on carbon and water fluxes of ecosystems is useful for analyzing the responses of carbon sink/source functions and water balance to climatic variables in different forest ecosystems [32]. In this study, although we found a similar pattern of seasonal variations of carbon and water fluxes in two forest ecosystems (Figure 2), the main environmental factors affecting water and carbon fluxes in the two forest ecosystems were different (Figures 4 and 5), and their sensitivities to the same environmental factors were different. The water and carbon fluxes in the two forest ecosystems had similar responses to the same environmental factors (e.g., TA, TS, VPD, PAR), but the sensitivities of NEP, GPP, and ET to PAR and VPD in the L. principis-rupprechtii forest ecosystem were different those in the P. tabulaeformis forest ecosystem (Figure 4). These results were largely due to the different types of underlying surfaces in different ecosystems [71]. Similarly, He et al. [54] also reported that the type and structure of the underlying surface strongly affected the carbon and water fluxes of the ecosystem and their response to environmental factors.

Temperature and moisture are two key factors regulating ecosystem productivity and evapotranspiration [28,72]. In this study, the carbon and water fluxes of two forest ecosystems had an exponential response to temperature, and the carbon and water fluxes of the L. principis-rupprechtii forest ecosystem were more sensitive to temperature than those of the P. tabulaeformis forest ecosystem. A higher temperature would promote greater GPP, but the warm temperature also caused higher RECO, which might result in
the reduced annual NEP value [47,73]. This further confirmed our results that the RECO of the L. principis-rupprechtii and P. tabulaeformis forest ecosystems accounted for 52.52% and 37.11% of GPP, respectively. Therefore, the different sensitivities of different forest ecosystems to environmental factors could result in differences in the carbon flux (NEP, GPP, RECO) and water flux (ET) of two different forest ecosystems. However, the relationships between NEP, RECO, GPP, ET, and RH were not significant or weak in both forest ecosystems (Figure 4), which indicated that the carbon and water fluxes in the two forest ecosystems were not affected by water stress.

4.3. Temperature Sensitivity of RECO in Two Forest Ecosystems

Understanding the response of ecosystem respiration (RECO) to environmental factors is critical for estimating the carbon loss from terrestrial ecosystems and their carbon sequestration potential under changing climate [24,74]. One study found that the contribution of forest floor respiration to the total ecosystem respiration ranged from 32–90% [45], and also highlighted that the budget of RECO in the forest ecosystem was mainly driven by temperature changes. This meant that RECO was greater during the daytime than during nighttime [28], which was confirmed by this study (Figure 3F). Moreover, the temperature sensitivity of RECO in the L. principis-rupprechtii forest ecosystem was higher than that in the P. tabulaeformis forest ecosystem (Figure 5C,D). In the case of increased temperature, the RECO strength of the L. principis-rupprechtii forest ecosystem may be higher than that of the P. tabulaeformis ecosystem during growing season, because of the increased respiration of the forest floor under the warming condition [45]. This meant that more soil organic matter would be decomposed by microbes, and more CO₂ would be released into the atmosphere. This portends that the L. principis-rupprechtii forest ecosystem may release more CO₂ into the atmosphere than the P. tabulaeformis forest ecosystem in drylands in the context of future global warming.

4.4. The Coupling between Carbon and Water Fluxes in Two Forest Ecosystems

Water use efficiency (WUE) reflects the coupling relationship between carbon and water cycles at time and spatial scales. The variation of WUE of the ecosystem results from the trade-off between carbon uptake and water loss in the process of plant photosynthetic [32,38]. Exploring the spatial pattern of water use efficiency and its environmental control mechanism is of great significance for evaluating the water carrying capacity of the ecosystem and estimating the ecosystem carbon budget under changing climate [32]. In this study, we assessed two formulations for water use efficiency, i.e., the original water use efficiency (WUE) [32], and the underlying water use efficiency (uWUE) [38,44]. The results of this study showed that average WUE and uWUE in the growing season of the L. principis-rupprechtii forest ecosystem were higher than those of the P. tabulaeformis forest ecosystem (Figure 6), largely determined by different tree species. In addition, both the two forest ecosystems showed higher WUE and uWUE in growing season than in non-growing season. This was attributed to the faster growth of new leaves during growing season, allowing plants to use water more efficiently, which was also the reason for the high water use efficiency in growing season.

In order to predict the GPP of ecosystems, it is necessary to understand how the water use efficiency of the ecosystem responds to changes in environmental factors [32]. Expected for different vegetation types, environmental factors also strongly affected the water use efficiency of ecosystems. In this study, the TA, TS, PAR, and RH were the main factors controlling the water use efficiency, but their effects on the water use efficiency differed in two forest ecosystems (Table 2). Although the PAR was the main environmental factor that affected the water use efficiency of two forest ecosystems, PAR had a positive influence on the WUE of the L. principis-rupprechtii forest ecosystem and had a negative effect on the WUE of the P. tabulaeformis forest ecosystem. In addition, the TA and TS were the main environmental factors affecting the uWUE in the L. principis-rupprechtii forest ecosystem, while PAR and RH were the main environmental factors affecting the uWUE
in the *P. tabulaeformis* forest ecosystem. The above results of this study will help us better understand the coupling mechanism of carbon and water fluxes, which is very meaningful for predicting the response and adaptation of different forest ecosystems to climate change.

4.5. Differences of Light Use Efficiency in Two Forest Ecosystems

Light use efficiency (LUE) is an inherent dynamic parameter, affected by plant species, physiology, phenology, and environmental factors [22,75,76]. This was one of the reasons why the LUE had different responses to environmental factors in the two forest ecosystems (Table 2). In this study, the two forest ecosystems showed higher LUE in growing season than in non-growing season (Figure 7), strongly related to the quantity of photosynthetic tissues [32,77]. During growing season, more new leaves would enhance the LUE of the forest ecosystem [78]. Moreover, the LUE of the *L. principis-rupprechtii* forest ecosystem was significantly higher than that of the *P. tabulaeformis* forest ecosystem, especially during growing season (Figure 7), which was caused by the photosynthetic capacity of the *L. principis-rupprechtii* forest being higher than that of the *P. tabulaeformis* forest [59,60].

5. Conclusions

This study systematically analyzed and compared the temporal changes and differences in the water and carbon fluxes of two coniferous forest ecosystems in drylands, and also explored the environmental driver factors controlling the variations of the carbon and water fluxes of two forest ecosystems. We found that two coniferous tree species had significant impacts on the carbon and water fluxes in the dryland of Northwest China. The *Larix principis-rupprechtii* forest had higher GPP and RECO than the *Pinus tabulaeformis* forest, the *P. tabulaeformis* forest converted more GPP to NEP compared with the *L. principis-rupprechtii* forest, and the NEP of the *L. principis-rupprechtii* and *P. tabulaeformis* forest ecosystems accounted for 48.73% and 62.89% of the GPP, respectively. Furthermore, the RECO of the *L. principis-rupprechtii* forest was more sensitive to temperature changes than the *P. tabulaeformis* forest ecosystem, which meant that it would release more CO₂ with global warming. Therefore, the carbon sequestration potential of *P. tabulaeformis* forest may be higher than that of *L. principis-rupprechtii* forest in the dryland of Northwest China, especially under future climate change. The results of this study can provide evidence for the carbon budget of the mountain forest ecosystem in drylands.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13050739/s1, Table S1: The study site basic informations of the three coniferous forest ecosystems in the semi-arid area of Northwest China; Table S2: The detailed information about the instruments and installations of the three study sites.

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