

Article

Effect of Drought Types on Evapotranspiration and Canopy Conductance in a *Pinus sylvestris* var. *mongolica* Plantation in Northeast China

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Abstract

According to soil and atmospheric moisture conditions, drought can be categorized into soil drought, atmospheric drought, and compound drought. The effects of soil drought on evapotranspiration (ET) and canopy conductance (Gc) are extensively investigated in forests, but the responses of ET and Gc to atmospheric drought and compound drought still remain unclear in plantations. Environmental factors and ET were continuously measured in a *Pinus sylvestris* var. *mongolica* plantation located in the semi-arid areas of Northeast China during the growing seasons (May–September) in 2020–2024. Compared with non-drought, ET increased by 34.96% under atmospheric drought, and decreased by 23.58% and 28.86% under soil drought and combined drought, respectively. Compared with non-drought, Gc decreased by 29.27%, 15.19%, and 68.74% under atmospheric drought, soil drought, and combined drought, respectively. Different from other three water conditions, relative extractable water (REW) replaced net radiation as the most important influencing factor of ET under combined drought. And vapor pressure deficit (VPD) always had a relatively lower contribution to ET under the four water conditions. Unlike the other three water conditions, the dominant controlling factor of Gc was REW instead of VPD under combined drought. This study proved that different drought types have different effects on ET and Gc. Under warmer and drier climates, management practices such as pruning and thinning should be used to cope with the increasing water stress to ensure the sustainable development of the *Pinus sylvestris* var. *mongolica* plantations in the semi-arid areas of Northeast China.

Keywords: drought types; evapotranspiration; canopy conductance; *Pinus sylvestris* var. *mongolica* plantation

Academic Editor: Eustaquio Gil-Pelegrín

Received: 29 May 2026

Revised: 29 June 2026

Accepted: 30 June 2026

Published: 1 July 2026

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1. Introduction

The “Three-North Shelter Forest Program” covers an area of 4.07×10^6 km², which is the largest artificial forest ecological protection project in China [1]. The cumulative preserved afforestation area amounts to 3.01×10^7 ha in this program, which is of great significance for ensuring China’s ecological security [2]. This program is mainly located in arid and semi-arid areas for the purpose of windbreak, sand fixation, and soil and water conservation [3,4]. Drought events are among the most important threats to the healthy growth of plantations, and dieback and mortality have begun to emerge in some plantations as water stress increases in some areas in northern China [4]. The magnitude, frequency, duration and areal extent of drought events will all increase in the arid and semi-arid areas of China in the context of global warming [5,6]. Therefore, thoroughly investigating the relationship between the water consumption of vegetation and drought is an urgent need for the sustainable development of plantations in the water limited areas in China [7].

In terrestrial ecosystems, about 60% of precipitation is consumed by evapotranspiration (ET) [8], which is equivalent to the latent heat flux (LE) in the energy cycle; thus ET links energy exchange and hydrological processes at the ecosystem scale [9,10]. Gross primary productivity is usually coupled with ET at the ecosystem level, because both transpiration and photosynthesis take place through leaf stomata [3,11]. Canopy conductance (Gc) is an important index reflecting the weighted integration of the stomatal aperture of individual leaves; hence it is closely related to ET and gross primary productivity [3,12]. Exploring the roles of ET and Gc in the complex feedback between plantations and climate change is crucial for predicting potential changes in carbon budget, hydrological processes, and the energy cycle in the reforestation areas under future biological and physical disturbances [3,13,14]. Though lots of ecologists have studied the effects of drought on temporal variations in ET and Gc in forest ecosystems [9,11,15], few studies focus on the plantations in the arid and semi-arid areas of China.

According to soil and atmospheric moisture conditions, drought can be categorized into soil drought (linked to low soil water content), atmospheric drought (associated with high atmospheric evaporative demand), and compound drought (soil drought accompanied with atmospheric drought) [7,15,16]. Many previous studies proved that soil water deficit has a negative effect on ET and Gc in various plantations [9,11,17]. For instance, ET and Gc generally decrease when soil water content decreases in a *Pinus tabulaeformis* plantation [3]. Related to atmospheric drought, vapor pressure deficit (VPD) is the most common indicator representing atmospheric evaporative demand [15,16]. The relationship between VPD and Gc is usually a logarithmic curve, and Gc generally decreases when VPD increases [16,18,19]. There are two opposing effects of VPD on ET: one side is VPD increasing ET by improving atmospheric evaporative power, the other is VPD decreasing ET by closing leaf stomata, but the former is usually dominant according to the Shuttleworth–Wallace model [20]. Furthermore, the results of some studies showed that the synergistic effect of compound drought on water consumption is weaker than those of soil drought and atmospheric drought [7,16]. For example, the inhibitory effect of soil drought on ET is stronger than that of compound drought in a boreal larch forest [15]. However, the negative effect of compound drought on Gc is usually stronger than that of either atmospheric drought or soil drought in a Mongolian pine plantation [7,16]. Though some studies reported the effects of drought types on ET and Gc in the plantations in the semi-arid areas of China [7,16], the mechanisms of ET and Gc response to different drought types are urgently needed to be elucidated in the context of global warming.

Pinus sylvestris var. *mongolica* is naturally distributed in the northern Da Hinggan Mountains and the Hulunbeier sandy land of China [4]. Due to its physiological characteristics of cold-, drought-, and low-fertility resistance, *Pinus sylvestris* var. *mongolica* is

widely used in the “Three-North Shelter Forest Program” for windbreak and sand fixation, and has become the most important tree species for the reforestation in the semi-arid areas of Northeast China [1,4]. In this study, long-term measurements of ET and environmental factors were conducted using the eddy covariance (EC) system and environmental variable sensors during the growing seasons (May–September) in 2020–2024 in a *Pinus sylvestris* var. *mongolica* plantation in Northeast China. Our objectives were to: (1) quantify the differences in ET and Gc under different drought types, and (2) determine the effects of environmental factors on ET and Gc under different drought types.

2. Materials and Methods

2.1. Study Area

The study was conducted at the state-owned Jianping County Heishui Mechanized Forest Farm (41°58′33″ N, 119°25′32″ E, 550 m a.s.l.), Chaoyang City, Liaoning Province, Northeast China (Figure 1). The climate is a semi-arid temperate continental monsoon climate with a mean annual temperature of 5.76 °C and mean annual precipitation of 440 mm (data on 1958–2024 from Jianpingzhen weather station, 30 km from our study site). The *Pinus sylvestris* var. *mongolica* plantation is 39 years old, with a stand density of 1044 trees ha⁻¹, a mean tree height of 10.00 m, and a mean diameter at breast height of 14.26 cm. The study area is flat and uniform, and the soil texture is gray-brown with a field capacity of 28%. The understory is dominated by *Cleistogenes squarrosa*, and the coverage (10–70%) changes with soil moisture changing [21].

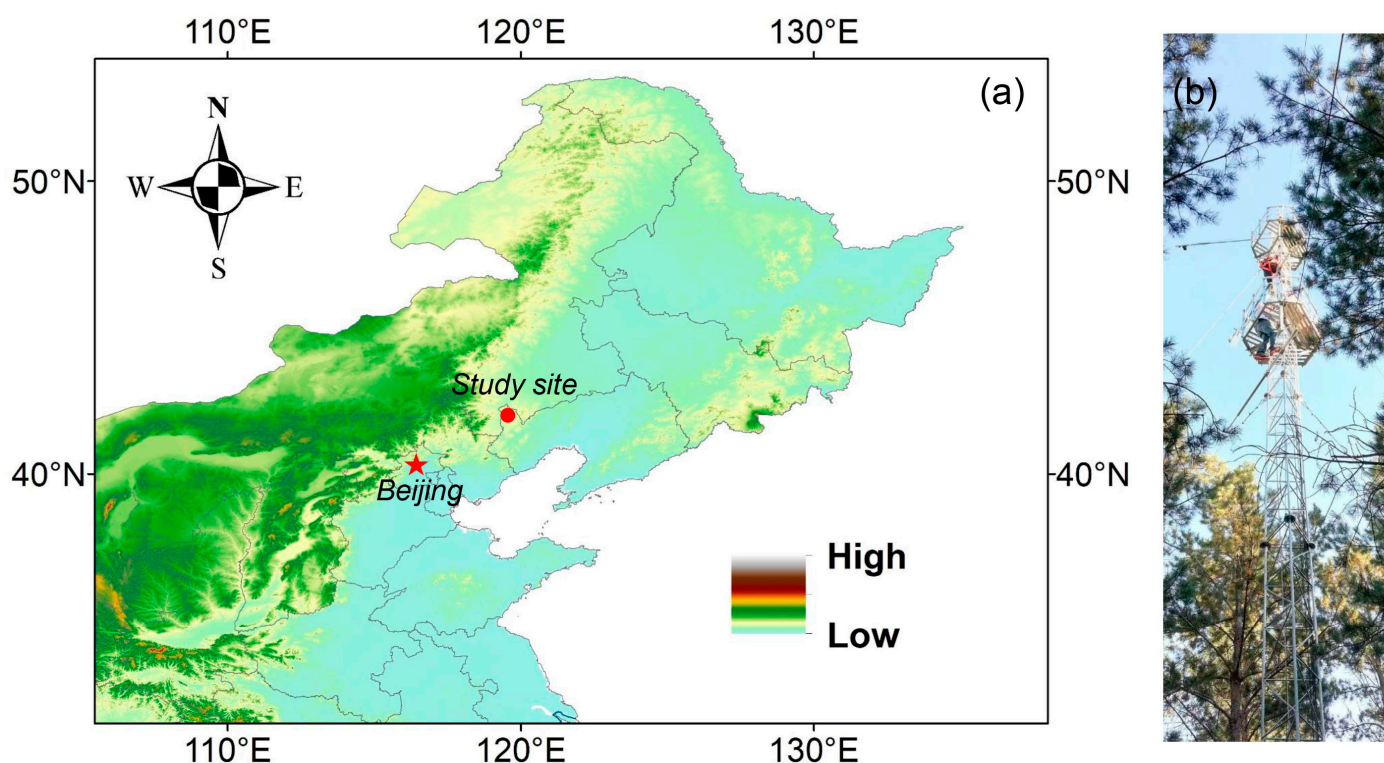


Figure 1. Location of the study site (a) and the observation tower (b).

2.2. Measurements

The EC system and environmental variable sensors were housed on an 18 m flux tower, and more details were shown in Table 1. All data used in this study were collected by a CR1000X data logger (Campbell Scientific Inc., Logan, UT, USA). The distance from

the flux tower to the nearest plantation boundary was approximately 300 m, which ensures that the measurement information originated from our plantation [21].

Table 1. Details of the eddy covariance system and environmental variable sensors in the *Pinus sylvestris* var. *mongolica* plantation.

Observations	Height/depth (m)	Model	Manufacturer
Latent heat flux (LE), fraction velocity (U^*), wind speed (U), air density (ρ_a), the specific heat of the dry air (c_p)	15 m	CSAT3B ¹ LI-7500 ¹	Campbell Scientific Inc., Logan, UT, USA Li-COR Inc., Lincoln, NE, USA
Air temperature (T_a) and relative humidity (RH)	15 m	HMP45C	Vaisala Co., Ltd., Helsinki, Finland
Net radiation (Rn)	16 m	CNR4	Kipp&Zonen B.V., Delft, Netherlands
Soil water content (SWC) ²	0.1 m ³	HydraProbe	Stevens Inc. Portland, OR, USA
Soil heat flux (G) ²	0.05 m	HFP01SC	Hukseflux B.V., Delft, Netherlands

¹ Eddy covariance system consisting of a 3D sonic anemometer (CSAT3B) and an infrared H_2O/CO_2 gas analyzer (LI-7500). ² Three repetitions. ³ According to a previous study [1].

2.3. Data Processing

The 30 min flux data were processed from the 10 Hz raw data using the EddyPro software (version 7.07, Li-COR Inc., Lincoln, NE, USA). The correction of the turbulent flux data included planar fit correction, sonic temperature correction, density fluctuation correction, and spectral correction. The calculated flux data were quality controlled by deleting the data with a quality flag of “2”. Because of quality control and instrument failure, 15% of LE data were rejected during the growing seasons in 2020–2024. The data gaps of LE were filled using the “REddyProc” R package, and energy budget components were forced to close using the Bowen ratio closure method [22].

The ET was calculated as follows [9]:

$$ET = \frac{LE}{\lambda} \quad (1)$$

where λ is the latent heat of water vaporization (2.45 kJ g⁻¹).

The Gc was calculated as follows [23]:

$$Ga = \left(\frac{U}{U_*^2} + 6.2U_*^{-2/3} \right)^{-1} \quad (2)$$

$$Gc = \frac{\gamma \cdot LE \cdot Ga}{\Delta(Rn - G) + \rho_a \cdot c_p \cdot VPD \cdot Ga - LE(\Delta + \gamma)} \quad (3)$$

where Ga is the aerodynamic conductance (m s⁻¹), U is the wind speed (m s⁻¹), and U_* is the friction velocity (m s⁻¹), γ is the psychrometric constant (kPa °C⁻¹), Δ is the slope of the water vapor pressure curve (kPa °C⁻¹), Rn is the net radiation (W m⁻²), G is the soil heat flux (W m⁻²), ρ_a is the air density, and c_p is the specific heat of the dry air.

The VPD was calculated as follows [24]:

$$VPD = 0.611 \exp\left(\frac{17.27T_a}{T_a + 237.3}\right) \times \left(1 - \frac{RH}{100}\right) \quad (4)$$

where T_a is the air temperature (°C) and RH is the air relative humidity (%).

The relative extractable water (REW) was calculated as follows [25]:

$$REW = \frac{SWC - SWC_{min}}{SWC_{max} - SWC_{min}} \quad (5)$$

where SWC is the soil water content at a depth of 10 cm (cm³ cm⁻³), and SWC_{min} and SWC_{max} are the minimum and maximum SWC in our observation period, respectively. Many previous studies proved that SWC is a valid indicator of the soil water status of this plantation, and topsoil moisture has also been used to identify drought events in various plantations [3,21,24,26].

2.4. Definition of Drought Types

According to previous studies [7,15,16], the following steps were used to define drought types. Firstly, ET was bin-averaged into 0.05 REW (Figure 2a) and 0.15 kPa VPD (Figure 2b) increments, respectively. Secondly, the inflection points of REW (0.4) and VPD (0.8 kPa) on ET were determined by the general trends of ET changing with REW and VPD. Finally, based on the inflection points, non-drought, atmospheric drought, soil drought, and combined drought were classified in the study (Figure 3). The occurrence frequency of non-drought, atmospheric drought, soil drought, and combined drought were 25.82%, 11.41%, 17.82%, and 44.95%, respectively.

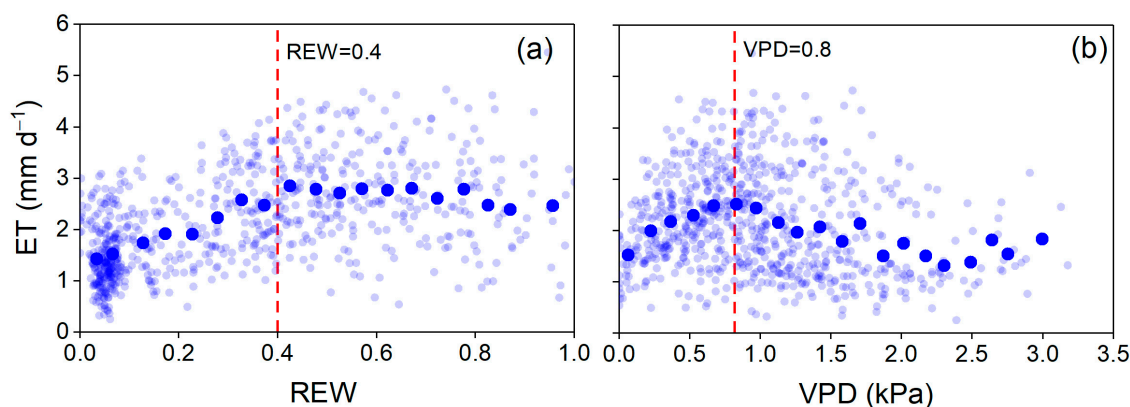


Figure 2. Identifying the turning points of (a) relative extractable water (REW) and (b) vapor pressure deficit (VPD) controlling evapotranspiration (ET) in the *Pinus sylvestris* var. *mongolica* plantation. Dark blue points are ET bin-averaged into 0.05 REW and 0.15 kPa VPD increments, respectively.

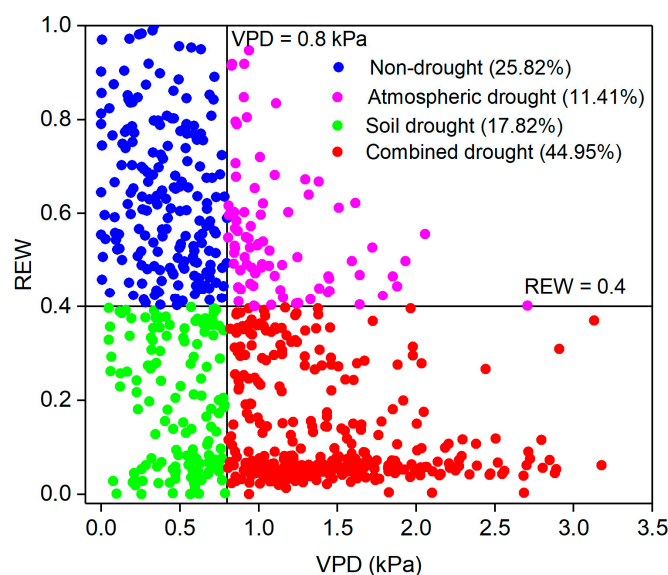


Figure 3. The occurrence frequency of non-drought, atmospheric drought, soil drought, and combined drought during the growing seasons in 2020–2024.

2.5. Statistical Analysis

Repeated measures ANOVA was used to examine differences in environmental factors, ET, and Gc under different drought types. The `calc.relimp()` function of the “relaimpo” package based on the Lindeman–Merenda–Gold (lmg) method in R software was used to assess the relative importance of each environmental factor to ET. Given that

Gc was calculated from some environmental factors (i.e., Rn, VPD, Ta, and U), the sensitivity analysis was used to evaluate the effects of environmental factors on Gc. Partial least squares regression (PLSR) combines the advantages of multiple regression analysis, canonical correlation analysis, and principal component analysis, and can effectively solve the problem of multicollinearity. The high correlation between independent variables did not exist in this study (variance inflation factor, VIF < 9). The regression coefficients of PLSR were used to quantify the sensitivity of Gc to each environmental factor. All variables were normalized before PLSR analysis, which was performed using the “pls” package in R software.

3. Results

3.1. Environmental Factors

Seasonal variations in environmental factors during the growing seasons in 2020–2024 are shown in Figure 4, and the average values of VPD, REW, Rn, Ta, and U are shown in Table 2. The VPD was usually higher in May and June (Figure 4a–e), and the average values of VPD ranged from 0.82 kPa to 1.17 kPa during the growing seasons in 2020–2024 (Table 2). Cumulative precipitation (P) during the growing season was 359.10 mm, 562.20 mm, 477.10 mm, 273.20 mm, and 468.80 mm in 2020–2024, respectively (Table 2). The seasonal pattern of REW was mainly dominated by P events (Figure 4f–j), and the maximum and minimum values of average REW during the growing season were 0.19 and 0.45 in 2023 and 2021, respectively (Table 2). Overall, the seasonal patterns of Rn and Ta were unimodal curves (Figure 4k–t), with average values of 12.32–13.11 MJ m^{−2} d^{−1} and 19.61–21.27 °C, respectively, during the growing seasons in 2020–2024 (Table 2). The U fluctuated above 1.00 m s^{−1} (Figure 4u–y), and the average values of U during the growing season ranged from 1.71 m s^{−1} to 1.91 m s^{−1} over the five years (Table 2).

Table 2. Summary of environmental factors, evapotranspiration (ET), and canopy conductance (Gc) during the growing seasons in 2020–2024. VPD, vapor pressure deficit; REW, relative extractable water; Rn, net radiation; Ta, air temperature; U, wind speed.

Variable	Year (May to September)				
	2020	2021	2022	2023	2024
VPD (kPa)	1.05	0.82	0.98	1.17	0.86
REW	0.23	0.45	0.36	0.19	0.39
P (mm)	359.10	562.20	477.10	273.20	468.80
Rn (MJ m ^{−2} d ^{−1})	12.55	12.32	13.52	12.99	13.11
Ta (°C)	20.32	19.61	20.07	21.27	20.32
U (m s ^{−1})	1.71	1.75	1.91	1.75	1.79
ET (mm)	261.21	280.02	370.68	311.45	407.26
Gc (mm s ^{−1})	3.70	4.56	4.81	4.05	6.08

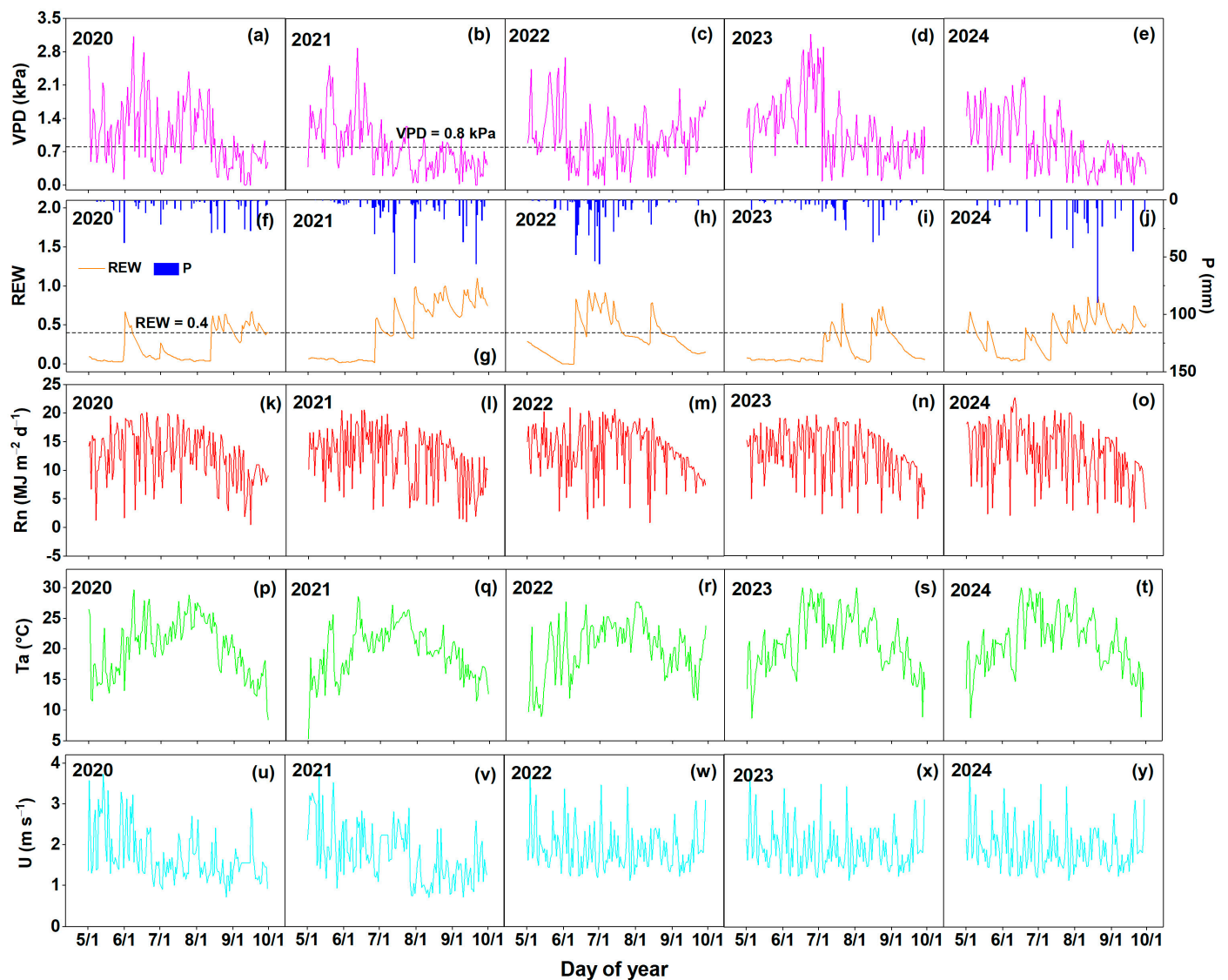


Figure 4. Seasonal variations in (a–e) VPD, (f–j) REW and precipitation (P), (k–o) net radiation (Rn), (p–t) air temperature (Ta), and (u–y) wind speed (U) during the growing seasons in 2020–2024.

In our study period, VPD values under non-drought were similar to those under soil drought, and were significantly lower than those under atmospheric drought and combined drought. The VPD was greatest under combined drought (Figure 5a). The REW was greatest and lowest under non-drought and combined drought, respectively. The REW varied significantly among the four water conditions (Figure 5b). The Rn and Ta had similar trends with VPD, but were greatest under atmospheric drought (Figure 5c,d). The U was lowest and greatest under non-drought and combined drought, respectively. The U values under non-drought and combined drought were significantly different from those under soil drought and atmospheric drought (Figure 5e).

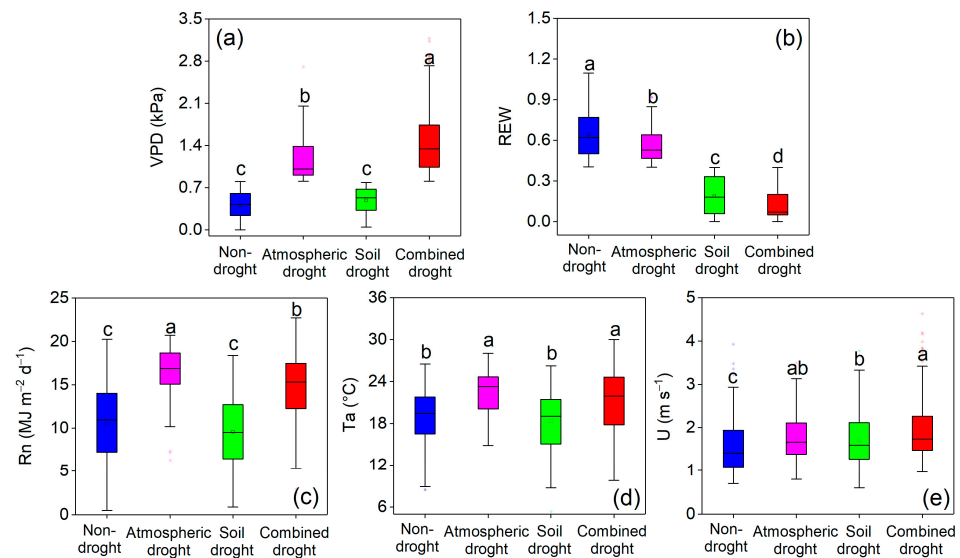


Figure 5. Differences in VPD (a), REW (b), Rn (c), Ta (d), and U (e) under non-drought, atmospheric drought, soil drought, and combined drought. Identical lowercase letters represent non-significant differences ($p > 0.05$), while the opposite indicates significant differences ($p < 0.05$).

3.2. ET and Gc

Seasonal variations in ET and Gc during the growing seasons in 2020–2024 are presented in Figure 6; cumulative ET and average Gc are shown in Table 2. The ET of our *Pinus sylvestris* var. *mongolica* plantation varied greatly (Figure 6a–e), and cumulative ET during the growing season was 261.21 mm, 280.02 mm, 370.68 mm, 311.45 mm, and 407.26 mm in 2020–2024, respectively (Table 2). The Gc was relatively high in July 2022, and in other years it was relatively high in August and September (Figure 6f–j). The average value of Gc during the growing season was 3.70 mm s⁻¹, 4.56 mm s⁻¹, 4.81 mm s⁻¹, 4.05 mm s⁻¹, and 6.08 mm s⁻¹ in 2020–2024, respectively (Table 2).

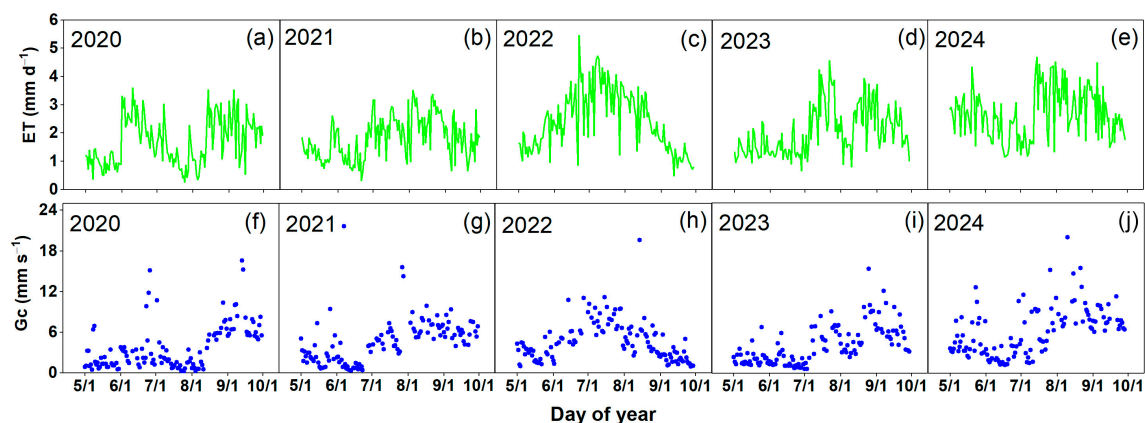


Figure 6. Seasonal variations in ET (a–e) and Gc (f–j) during the growing seasons in 2020–2024.

The mean diurnal courses of ET were similar and revealed bell-shaped curves under the four water conditions (Figure 7a). The mean diurnal courses of Gc increased sharply after sunrise, and peaked in the morning, thereafter decreasing till sunset under the four drought types (Figure 7b). Average ET was 2.46 mm d⁻¹, 3.32 mm d⁻¹, 1.88 mm d⁻¹, and 1.75 mm d⁻¹ under non-drought, atmospheric drought, soil drought, and combined drought, respectively. The ET under atmospheric drought was significantly higher than under other drought types. The ET under soil drought was not significantly different from under combined drought, but was significantly lower than under non-drought (Figure

8a). Average Gc was 8.03 mm s^{-1} , 5.68 mm s^{-1} , 6.81 mm s^{-1} , and 2.51 mm s^{-1} under non-drought, atmospheric drought, soil drought, and combined drought, respectively. The Gc varied significantly among the four water conditions (Figure 8b).

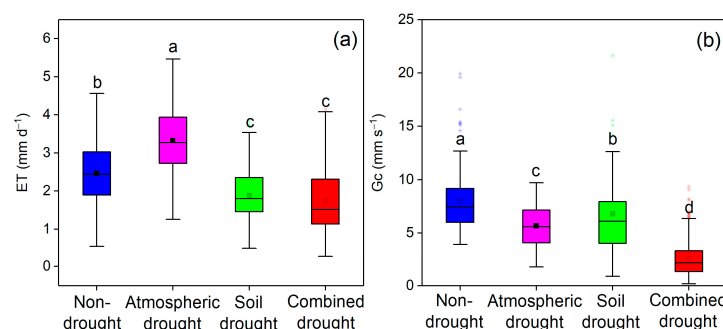


Figure 7. Mean diurnal variation in ET (a) and Gc (b) under non-drought, atmospheric drought, soil drought, and combined drought. Identical lowercase letters represent non-significant differences ($p > 0.05$), while the opposite indicates significant differences ($p < 0.05$).

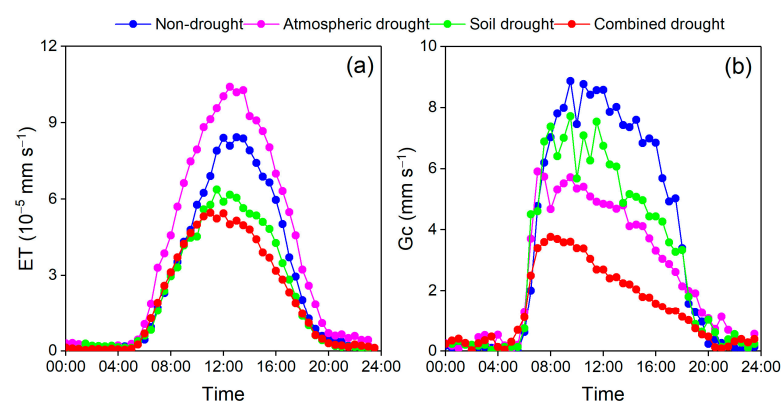


Figure 8. Differences in ET (a) and Gc (b) among non-drought, atmospheric drought, soil drought, and combined drought.

3.3. Effects of Environmental Factors on ET and Gc

The responses of ET to environmental factors were different under different drought types (Figure 9). Under the four water conditions, the effects of U and Ta on ET were relatively weak with a relative contribution of 0.13–2.41% and 2.31–10.31%, respectively (Figure 9). Under non-drought, ET was mainly controlled by Rn with a relative contribution of 41.78%, followed by VPD with a relative contribution of 12.92% (Figure 9a). Under atmospheric drought and soil drought, Rn was still the most important factor influencing ET with a relative contribution of 44.67% and 30.88%, respectively, and the following factors were VPD and REW, contributing 10.15% and 13.53% to ET, respectively (Figure 9b,c). Under combined drought, the top two factors influencing ET were REW and Rn with a relative contribution of 47.97% and 14.87%, respectively (Figure 9d).

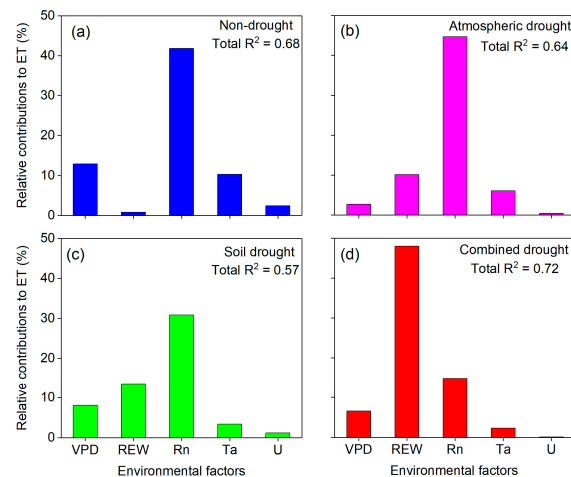


Figure 9. Relative importance of VPD, REW, Rn, Ta, and U to ET under non-drought, atmospheric drought, soil drought, and combined drought.

Under the four water conditions, Ta had no significant effect on Gc (Figure 10a–d). U only had a significant effect on Gc under non-drought (Figure 10a). For all drought types, all daily VPD had significant negative effects on Gc, and the sensitivity of Gc to VPD was higher under non-drought and atmospheric drought compared to the other two drought types (Figure 10a–d). The Rn had significant positive effects on Gc under non-drought, atmospheric drought, and combined drought with a sensitivity coefficient of 0.49, 0.21, and 0.13, respectively (Figure 10a,b,d). Under non-drought, REW had a significant negative effect on Gc, but under atmospheric drought and combined drought, it had significant positive effects (Figure 10a,b,d).

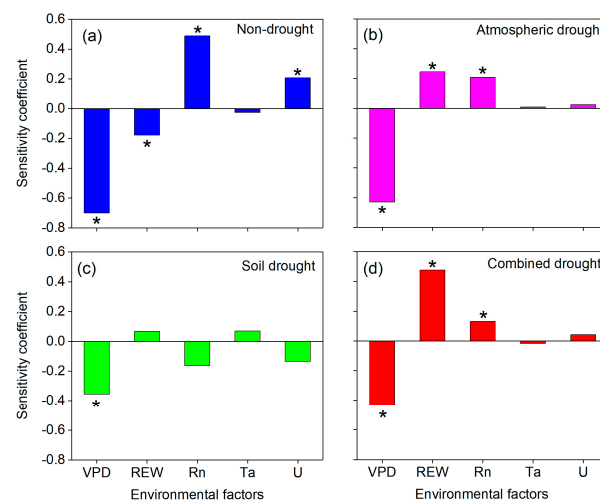


Figure 10. Sensitivity of Gc to VPD, REW, Rn, Ta, and U under non-drought, atmospheric drought, soil drought, and combined drought. Stars above or below each bar indicate statistical significance ($p < 0.05$).

4. Discussion

4.1. Variations in ET and Gc

Consistent with many previous studies [13,18,21], seasonal variations in ET were similar to those of Gc in the *Pinus sylvestris* var. *mongolica* plantation. During the five growing seasons, although VPD and Rn were relatively high in May and June (Figure 4a–e,k–o), ET and Gc were relatively low in this period (Figure 6), which was mainly due to the shortage of soil water. Conversely, ET and Gc were relatively high in the rainy season,

when VPD and Rn were relatively low in this study (Figure 4a–e,k–o). In the same study area, the effect of top soil water content on ET is much greater than that of VPD and Rn in a *Pinus tabuliformis* plantation [9]. Therefore, our results suggest that soil water supply is more important for water consumption than atmospheric evaporative demand and energy supply in plantations in semi-arid areas. Moreover, the effects of drought on ET and Gc also occur during the subsequent period following the drought [3,17]. This phenomenon is mainly due to the fact that the drought in the early growing season is unfavorable for vegetation establishment and even affects the stability of plantations [12,25,27]. The seasonal legacy effect of drought should be partly responsible for the result that ET values were still relatively lower during the periods of REW>0.4 in 2020 and 2021 compared to the other three years (Figure 6a–e).

Previous studies indicated that cumulative ET is positively correlated with cumulative P during the growing season in plantations [28–30]. However, cumulative ET did not increase when cumulative P increased during the five growing seasons in this study (Table 2). Our results suggested that the following two factors led to this result. Firstly, the plantation might use the soil water accumulated in the previous year [9,31,32], which caused cumulative P to be lower than cumulative ET during the growing season in 2023 (Table 2), and the carryover effect of soil water is very important for plantations to go through the drought period before the rainy season in semi-arid areas [33]. Secondly, the interannual legacy effect of drought on water consumption could lag by 3–4 years in forest ecosystems [34], which may be a reason for the result that cumulative ET was much lower than cumulative P during the growing seasons in 2020 and 2021 (Table 2), as annual P in 2019 (327.4 mm) was much lower than the mean annual P (440 mm) in the study area. In short, the carryover effect of soil water and the legacy effect of drought caused the complex relationship between cumulative ET and cumulative P during the growing season in this study. Average Gc generally increased with cumulative ET during the growing seasons in 2020 and 2022–2024 (Table 2). Average Gc was relatively higher with lower cumulative ET during the growing season in 2021, which was mainly due to a relatively lower average VPD compared to the other four years.

4.2. Effects of Drought Types on ET and Gc

According to the result shown in Figure 3, the frequency of drought periods in the growing season was 74.18%, indicating that the *Pinus sylvestris* var. *mongolica* plantation is usually affected by drought in the semi-arid areas of Northeast China. Low P and high free water surface evaporation cause the plantations to be vulnerable to water shortage during the growing season in semi-arid areas. It is worth noting that the mean annual P of 2020–2024 (509 mm) is higher than that of 1958–2024 (440 mm), which may result in an underestimation of drought frequency in this study. In addition, a previous study pointed out that mean annual Ta and annual P have an increasing and decreasing trend, respectively, in our study area [9]. This climate changing trend may increase the magnitude, frequency, and duration of drought, and water shortage will be more serious in the *Pinus sylvestris* var. *mongolica* plantation in the future.

Similar to previous studies [7,15,16], ET under atmosphere drought was higher than under non-drought in this study (Figure 7a). As shown in Figure 5, VPD, Rn, and Ta values under atmosphere drought were significantly higher than those under non-drought, while REW was at a relatively high level. Notably, higher atmospheric evaporative demand and energy supply combined with sufficient soil water will inevitably result in ET increasing [35]. Consistent with previous studies [9,36], ET under soil drought was lower than under non-drought in this study (Figure 7a). Under soil drought, REW was significantly lower than under non-drought, but VPD, Rn, and Ta were similar under the two

conditions. Soil water shortage has a negative effect on soil evaporation and canopy transpiration, ultimately leading to ET decreasing [20]. In this study, ET under combined drought was nearly equal to under soil drought. The reason is that compared with soil drought, the negative effect of lower REW on ET counteracted the positive effects of higher VPD, Rn, and Ta under combined drought. Overall, soil water shortage was the main reason for ET decreasing in the drought periods in the *Pinus sylvestris* var. *mongolica* plantation.

The effect of drought types on Gc was different from that of ET in this study (Figure 7), which is consistent with the results in previous studies [7,16]. The reason is that the important controlling factors of Gc were different from those of ET under different drought types. In this study, Gc under non-drought was higher than under drought stress (Figure 7b). Evidence has proven that higher VPD and/or lower REW can cause canopy stoma closing, ultimately resulting in decreased Gc [9,18]. Therefore, Gc under combined drought was lowest in our plantation, which is to be expected. Similar to the results in a *Platycladus orientalis* plantation [16], Gc under soil drought was higher than under atmosphere drought in the *Pinus sylvestris* var. *mongolica* plantation. Our results suggested the reason for this phenomenon was that the sensitivity of high VPD to Gc was stronger than that of low REW in this study (Figure 10).

4.3. Environmental Controls on ET and Gc Under Different Drought Types

In this study, the relative contributions of Ta and U to ET were relatively lower under different drought types (Figure 9). The possible reason is that Ta and U were relatively higher during the growing season, and the two environmental variables were not the limiting factors for the water consumption of the *Pinus sylvestris* var. *mongolica* plantation. Many studies have proven that the effects of solar energy supply, atmospheric evaporative demand, and soil water availability on ET are different under different atmospheric and soil water conditions [7,15]. Under non-drought, soil water availability was relatively higher, and Rn and VPD dominated water consumption in this study (Figure 9a), which is similar to the results in other studies [15,35]. Under atmospheric drought, atmospheric evaporative demand was relatively higher, and ET was mainly controlled by Rn and REW in the *Pinus sylvestris* var. *mongolica* plantation. The water consumption of two coniferous forests in the Loess Plateau is also mainly controlled by solar energy supply and soil water availability under atmospheric drought [16]. Under soil drought, REW and Rn were the dominant controlling factors in this study, and many ET models proved that when soil water availability is lower than the inflection point, it will become an important controlling factor of ET in various ecosystems [20,37]. Significantly, the relative contribution of Rn to ET was much higher than that of other environmental factors under non-drought, atmospheric drought, and soil drought (Figure 9a–c), which indicates that solar energy supply is still the most important driver of water consumption under the three water conditions in plantations in semi-arid areas. Under combined drought, REW and Rn were the main environmental factors controlling ET, but the relative contribution of REW was the highest in this study, and a similar result was found in a Mongolian pine plantation [7]. The possible explanation should be that most of the days during the compound drought period were sunny, and solar energy supply and atmospheric evaporative demand were relatively sufficient, which highlighted the controlling effect of soil water availability on ET in this study.

The effects of environmental factors on Gc were different from that of ET under different water conditions in the *Pinus sylvestris* var. *mongolica* plantation. A possible explanation is that the sensitivity of Gc to environmental factors measures the marginal effect per unit change in the environmental factors, whereas the relative importance of environmental factors to ET accounts for both the sensitivity and the observed range of variation

in environmental factors. According to many Gc models [38], U is not a key driver of Gc, but U had a significant effect on Gc under non-drought in this study (Figure 10a). The possible reason is that U was relatively lower under non-drought, which might influence the turbulent exchange over the canopy and further Gc. Under different drought types, Ta was not an important controlling factor of Gc in this study, which might be because Ta was relatively high and close to the optimal temperature of the *Pinus sylvestris* var. *mongolica*. The sensitivity of Gc to VPD was the highest under non-drought, atmospheric drought, and soil drought, and only slightly lower than REW under combined drought, which indicates that Gc was mainly controlled by VPD during the growing season in this study. Previous studies had proved that Gc decreases logarithmically with VPD increasing in various ecosystems [16,18,19]. The significant positive effect of REW on Gc was found under atmospheric drought and combined drought, which is consistent with the result in a Mongolian pine plantation [7]. However, Gc was negatively correlated with REW at the significance level of $p < 0.05$ under non-drought. The possible explanation is that higher REW was usually accompanied by lower Rn and VPD, which had significant positive and negative effects on Gc, respectively, under non-drought. In many Gc models [38], Gc increases with increasing solar radiation, which agrees with our result that Rn had a significant effect on Gc with a positive sensitivity coefficient under non-drought, atmospheric drought, and combined drought in the *Pinus sylvestris* var. *mongolica* plantation.

The effect of atmospheric drought on water consumption should receive more attention in the plantations. Under atmospheric drought, ET was the highest in this study, which resulted in rapid soil water consumption, and atmospheric drought might convert to combined drought. Soil water availability under combined drought was significantly lower than under soil drought, but ET was similar under those two water conditions. The phenomenon is more likely to cause dieback and even mortality emerge under combined drought in the *Pinus sylvestris* var. *mongolica* plantation. The frequency, magnitude, and duration of combined drought will increase under warmer and drier climates in our study area [6]. Management practices, such as pruning and thinning, can be used to ensure the health and sustainable development of the *Pinus sylvestris* var. *mongolica* plantation. In addition, the effects of drought types on carbon sequestration should be determined in the future, which is beneficial to ascertain the mechanism of the tradeoff between carbon sequestration and ET during the periods of the *Pinus sylvestris* var. *mongolica* plantation coping with drought.

4.4. Uncertainty

Uncertainty in this study mainly lay in the classification of drought types. In this study, we used the general trends of ET changing with REW and VPD to determine thresholds of REW and VPD, which were determined by piecewise linear regression in previous studies [15,16]. We believe that the inflection point of REW (0.4) can accurately identify the impact of soil drought on ET in this study, as many previous studies proved that plantations are subjected to soil water stress when REW is lower than 0.4 [3,24,26]. The inflection point of VPD was set as 0.8 kPa, which might not be extremely accurate in this study, but this does not affect the results and conclusions in this study [7]. Unlike REW, the threshold of VPD varies in the plantations with different tree species in different study areas [7,15,16]. For example, the ET of a boreal larch forest in China decreased significantly when VPD was higher than 1.00 kPa [15]. In addition to tree species specificity, the higher VPD threshold should be due to higher soil moisture in the boreal larch forest, resulting in ET reaching its maximum later with increasing atmospheric evaporative demand. In addition, artificial forest ecological protection projects in water-limited areas should pay more attention to the use of diverse tree species. Hence, water consumption

of more tree species and their response to different drought types should be studied for understanding the drought adaptation mechanism of different tree species to guide tree species selection in the semi-arid areas of Northeast China.

5. Conclusions

This study quantified the differences in ET and Gc and determined the effects of environmental factors on ET and Gc under different drought types during the growing seasons of 2020–2024 in a *Pinus sylvestris* var. *mongolica* plantation in Northeast China. Compared with non-drought, ET increased under atmospheric drought, and decreased by a similar degree under soil drought and combined drought. Compared with non-drought, Gc decreased under soil drought, atmospheric drought, and combined drought, with the degree of decrease increasing successively. Under non-drought, atmospheric drought, and combined drought, Rn was the most important controlling factor of ET. Under combined drought, the relative contribution of REW to ET was much higher than those of other environmental factors. Under non-drought, the most important controlling factor of Gc was VPD, followed by Rn. Under atmospheric drought and soil drought, the effect of VPD on Gc was much higher than those of other environmental factors. Under combined drought, the dominant controlling factor of Gc was REW, followed by VPD. In warmer and drier climates, the impact of water stress can be reduced through pruning and thinning to ensure the health and sustainable development of the *Pinus sylvestris* var. *mongolica* plantation in Northeast China.

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

Funding: This research was funded by the National Natural Science Foundation of China (32301662).

Data Availability Statement: Data will be made available on request.

Acknowledgments: Henan Xiaolangdi Forest Ecosystem National Observation and Research Station provided the environmental sensors and eddy covariance system.

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

References

1. Gao, X.; Zhou, Y.; Meng, P.; Pei, S.; Zhang, J.S. Net ecosystem exchange of *Pinus sylvestris* var. *mongolica* plantation in the western Liaoning Province, China. *Chin. J. Appl. Ecol.* **2022**, *33*, 1183–1190. <https://doi.org/10.13287/j.1001-9332.202205.001>.
2. Kang, M.; Zhang, Z.; Noormets, A.; Fang, X.; Zha, T.; Zhou, J.; Sun, G.; McNulty, S.G.; Chen, J. Energy partitioning and surface resistance of a poplar plantation in northern China. *Biogeosciences* **2015**, *12*, 4245–4259. <https://doi.org/10.5194/bg-12-4245-2015>.
3. Gao, X.; Sun, S.G.; Meng, P.; Cai, J.F.; Pei, S.Y.; Huang, H.; Zhang, J.S. Carbon fluxes and water-use efficiency in a *Pinus tabulaeformis* plantation in Northeast China and their relationship to drought. *Sci. Total Environ.* **2024**, *946*, 174258. <https://doi.org/10.1016/j.scitotenv.2024.174258>.
4. Song, L.N.; Zhu, J.J.; Li, M.C.; Zhang, J.X.; Zheng, X.; Wang, K. Canopy transpiration of *Pinus sylvestris* var. *mongolica* in a sparse wood grassland in the semiarid sandy region of Northeast China. *Agric. For. Meteorol.* **2018**, *250–251*, 192–201. <http://doi.org/10.1016/j.agrformet.2017.12.260>.
5. Chen, L.; Brun, P.; Buri, P.; Fatichi, S.; McCarthy, M.J.; Pellicciotti, F.; Stocker, B.; Karger, D.N. Global increase in the occurrence and impact of multiyear droughts. *Science* **2025**, *387*, 278–284. <https://doi.org/10.1126/science.ado4245>.
6. Gebrechorkos, S.H.; Sheffield, J.; Vicente-Serrano, S.M.; Funk, C.; Miralles, D.G.; Peng, J.; Dyer, E.; Talib, J.; Beck, H.E.; Singer, M.B. Warming accelerates global drought severity. *Nature* **2025**, *642*, 628–635. <https://doi.org/10.1038/s41586-025-09047-2>.

7. Chen, S.; Zhang, Z.; Chen, Z.; Xu, H.; Li, J. Responses of canopy transpiration and conductance to different drought levels in Mongolian pine plantations in a semiarid urban environment of China. *Agric. Forest Meteorol.* **2024**, *347*, 109897. <https://doi.org/10.1016/j.agrformet.2024.109897>.
8. Odongo, V.O.; Christiaan, V.D.T.; Becht, R.; Hoedjes, J.C.B.; Ghimire, C.P.; Su, Z.B. Energy partitioning and its controls over a heterogeneous semiarid shrubland ecosystem in the Lake Naivasha Basin, Kenya. *Ecohydrology* **2016**, *9*, 1358–1375. <http://doi.org/10.1002/eco.1732>.
9. Gao, X.; Zhang, J.S.; Cai, J.F.; Pei, S.Y.; Liu, L.Q.; Meng, P.; Huang, H. Surface energy partitioning and evapotranspiration in a *Pinus tabulaeformis* plantation in Northeast China. *Front. Plant Sci.* **2023**, *14*, 1048828. <https://doi.org/10.3389/fpls.2023.1048828>.
10. Nicholls, E.M.; Carey, S.K. Evapotranspiration and energy partitioning across a forest-shrub vegetation gradient in a subarctic, alpine catchment. *J. Hydrol.* **2021**, *602*, 126790. <https://doi.org/10.1016/j.jhydrol.2021.126790>.
11. Niu, X.D.; Chen, Z.C.; Pang, Y.; Liu, X.J.; Liu, S.R. Soil moisture shapes the environmental control mechanism on canopy conductance in a natural oak forest. *Sci. Total Environ.* **2023**, *857*, 159363. <http://doi.org/10.1016/j.scitotenv.2022.159363>.
12. Xie, J.; Zha, T.; Zhou, C.; Jia, X.; Yu, H.; Yang, B.; Chen, J.; Zhang, F.; Wang, B.; Bourque, C.P.A.; et al. Seasonal variation in ecosystem water use efficiency in an urban-forest reserve affected by periodic drought. *Agric. Forest Meteorol.* **2016**, *221*, 142–151. <https://doi.org/10.1016/j.agrformet.2016.02.013>.
13. Han, Y.N.; Jin, S.H.; Chen, W.J.; Zhan, M.S.; Yuan, Z.; Wang, X.; Bai, S.B. Biophysical controls on energy exchange and water use efficiency over a poplar plantation in Northern Hilly China. *Agric. Water Manag.* **2022**, *273*, 107920. <https://doi.org/10.1016/j.agwat.2022.107920>.
14. Li, S.G.; Eugster, W.; Asanuma, J.; Kotani, A.; Davaa, G.; Oyunbaatar, D.; Sugita, M. Energy partitioning and its biophysical controls above a grazing steppe in central Mongolia. *Agric. Forest Meteorol.* **2006**, *137*, 89–106. <https://doi.org/10.1016/j.agrformet.2006.03.010>.
15. Xu, Z.P.; Man, X.L.; Hou, Y.P.; Cai, T.J.; Duan, L.L. Interannual variations of evapotranspiration and its response to different drought types in a boreal larch forest in China. *Ecol. Indic.* **2025**, *176*, 113609. <https://doi.org/10.1016/j.ecolind.2025.113609>.
16. Chen, S.; Wei, W.; Tong, B.; Chen, L. Effects of soil moisture and vapor pressure deficit on canopy transpiration for two coniferous forests in the Loess Plateau of China. *Agric. Forest Meteorol.* **2023**, *339*, 109581. <https://doi.org/10.1016/j.agrformet.2023.109581>.
17. Li, X.H.; Zha, T.S.; Black, T.A.; Jia, X.; Jassal, R.S.; Liu, P.; Tian, Y.; Jin, C.; Yang, R.Z.; Zhang, F. et al. Stronger control of surface conductance by soil water content than vapor pressure deficit regulates evapotranspiration in an urban forest in Beijing, 2012–2022. *Agric. Forest Meteorol.* **2024**, *344*, 109815. <https://doi.org/10.1016/j.agrformet.2023.109815>.
18. Jia, X.; Zha, T.S.; Gong, J.N.; Wu, B.; Zhang, Y.Q.; Qin, S.G.; Chen, G.P.; Feng, W.; Kellomäki, S.; Peltola, H. Energy partitioning over a semi-arid shrubland in northern China. *Hydrol. Process.* **2016**, *30*, 972–985. <https://doi.org/10.1002/hyp.10685>.
19. Zhu, G.F.; Lu, L.; Su, Y.H.; Wang, X.F.; Cui, X.; Ma, J.Z.; He, J.H.; Zhang, K.; Li, C.B. Energy flux partitioning and evapotranspiration in a sub-alpine spruce forest ecosystem. *Hydrol. Process.* **2013**, *28*, 5093–5104. <https://doi.org/10.1002/hyp.9995>.
20. Gong, X.; Liu, H.; Sun, J.; Gao, Y.; Zhang, H. Comparison of Shuttleworth–Wallace model and dual crop coefficient method for estimating evapotranspiration of tomato cultivated in a solar greenhouse. *Agric. Water Manag.* **2019**, *217*, 141–153. <https://doi.org/10.1016/j.agwat.2015.06.026>.
21. Gao, X.; Cai, J.F.; Pei, S.Y.; Huang, H.; Zhang, J.S. Effects of environmental factors on evapotranspiration in a *Pinus sylvestris* var. *mongolica* plantation. *J. Forest Environ.* **2025**, *45*, 607–617. <https://doi.org/10.13324/j.cnki.jfcf.202505001>.
22. Twine, T.E.; Kustas, W.P.; Norman, J.M.; Cook, D.R.; Houser, P.R.; Meyers, T.P.; Prueger, J.H.; Starks, P.J.; Wesely, M.L. Correcting eddy-covariance flux underestimates over a grassland. *Agric. Forest Meteorol.* **2000**, *103*, 279–300. [https://doi.org/10.1016/S0168-1923\(00\)00123-4](https://doi.org/10.1016/S0168-1923(00)00123-4).
23. Liu, B.; Cui, Y.L.; Luo, Y.F.; Shi, Y.Z.; Liu, M.; Liu, F.P. Energy partitioning and evapotranspiration over a rotated paddy field in Southern China. *Agric. Forest Meteorol.* **2019**, *276–277*, 107626. <https://doi.org/10.1016/j.agrformet.2019.107626>.
24. Jin, C.; Zha, T.S.; Bourque, C.P.A.; Liu, P.; Jia, X.; Zhang, F.; Yu, H.Q.; Tian, Y.; Li, X.H.; Kang, X.Y.; et al. Multi-year trends and interannual variation in ecosystem resource use efficiencies in a young mixedwood plantation in northern China. *Agric. Forest Meteorol.* **2023**, *330*, 109318. <https://doi.org/10.1016/j.agrformet.2023.109318>.
25. Ma, J.Y.; Jia, X.; Zha, T.S.; Bourque, C.P.A.; Tian, Y.; Bai, Y.J.; Liu, P.; Yang, R.Z.; Li, C.; Li, C.Y.; et al. Ecosystem water use efficiency in a young plantation in Northern China and its relationship to drought. *Agric. Forest Meteorol.* **2019**, *275*, 1–10. <https://doi.org/10.1016/j.agrformet.2019.05.004>.

26. Liu, P.; Zha, T.S.; Zhang, F.; Jia, X.; Bourque, C.P.A.; Tian, Y.; Bai, Y.J.; Yang, R.Z.; Li, X.H.; Yu, H.Q.; et al. Environmental controls on carbon fluxes in an urban forest in the Megalopolis of Beijing, 2012–2020. *Agric. Forest Meteorol.* **2023**, *333*, 109412. <https://doi.org/10.1016/j.agrformet.2023.109412>.
27. Dong, G.; Guo, J.; Chen, J.; Sun, G.; Gao, S.; Hu, L.; Wang, Y. Effects of spring drought on carbon sequestration, evapotranspiration and water use efficiency in the Songnen Meadow Steppe in Northeast China. *Ecohydrology* **2011**, *4*, 211–224. <https://doi.org/10.1002/eco.200>.
28. Brown, S.M.; Petrone, R.M.; Chasmer, L.; Mendoza, C.; Lazerjan, M.S.; Landhaeusser, S.; Silins, U.; Leach, J.; Devito, K.J. Atmospheric and soil moisture controls on evapotranspiration from above and within a Western Boreal Plain aspen forest. *Hydrol. Process.* **2014**, *28*, 4449–4462. <https://doi.org/10.1002/hyp.9879>.
29. Wang, T.; Zhang, H.; Zhao, J.; Guo, X.; Xiong, T.; Wu, R. Shifting contribution of climatic constraints on evapotranspiration in the boreal forest. *Earth's Future* **2021**, *9*, e2021EF002104. <https://doi.org/10.1029/2021EF002104>.
30. Xiao, J.F.; Sun, G.; Chen, J.Q.; Chen, H.; Chen, S.P.; Dong, G.; Gao, S.H.; Guo, H.Q.; Guo, J.X.; Han, S.J.; et al. Carbon fluxes, evapotranspiration, and water use efficiency of terrestrial ecosystems in China. *Agric. Forest Meteorol.* **2013**, *182–183*, 76–90. <https://doi.org/10.1016/j.agrformet.2013.08.007>.
31. Sun, J.; Yu, X.; Wang, H.; Jia, G.; Zhao, Y.; Tu, Z.; Deng, W.; Jia, J.; Chen, J. Effects of forest structure on hydrological processes in China. *J. Hydrol.* **2018**, *561*, 187–199. <http://doi.org/10.1016/j.jhydrol.2018.04.003>.
32. Liu, J.; Cheng, F.; Munger, W.; Jiang, P.; Whitby, T.; Chen, S.; Ji, W.; Man, X. Precipitation extremes influence patterns and partitioning of evapotranspiration and transpiration in a deciduous boreal larch forest. *Agric. Forest Meteorol.* **2020**, *287*, 107936. <https://doi.org/10.1016/j.agrformet.2020.107936>.
33. Ma, J.; Zha, T.; Jia, X.; Tian, Y.; Bourque, C.P.A.; Liu, P.; Bai, Y.; Wu, Y.; Ren, C.; Yu, H. Energy and water vapor exchange over a young plantation in northern China. *Agric. For. Meteorol.* **2018**, *263*, 334–345. <https://doi.org/10.1016/j.agrformet.2018.09.004>.
34. Ciais, P.; Reichstein, M.; Viovy, N.; Granier, A.; Oge'e, J.; Allard, V.; Aubinet, M.; Buchmann, N.; Bernhofer, C.; Carrara, A.; et al. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature* **2005**, *437*, 529–533. <https://doi.org/10.1038/nature03972>.
35. Domec, J.C.; Meinzer, F.C.; Gartner, B.L.; Woodruff, D. Transpiration-induced axial and radial tension gradients in trunks of Douglas-fir trees. *Tree Physiol.* **2006**, *26*, 275–284. <https://doi.org/10.1093/treephys/26.3.275>.
36. Zhang, Y.Q.; Cui, Z.; Bai, Y.H.; Zhang, H.T.; Tang, Z.Y. Trees suppress growth but sustain water consumption in response to flash drought in a subtropical forest. *Agric. Forest Meteorol.* **2025**, *372*, 110727. <https://doi.org/10.1016/j.agrformet.2025.110727>.
37. Zhang, B.Z.; Kang, S.Z.; Li, F.S.; Zhang, L. Comparison of three evapotranspiration models to Bowen ratio-energy balance method for a vineyard in an arid desert region of northwest China. *Agric. Forest Meteorol.* **2008**, *148*, 1629–1640. <https://doi.org/10.1016/j.agrformet.2008.05.016>.
38. Li, S.E.; Zhang, L.; Kang, S.Z.; Tong, L.; Du, T.S.; Hao, X.M.; Zhao, P. Comparison of several surface resistance models for estimating crop evapotranspiration over the entire growing season in arid regions. *Agric. Forest Meteorol.* **2015**, *208*, 1–15. <https://doi.org/10.1016/j.agrformet.2015.04.002>.

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