Study on Vegetation Water Requirements of Robinia pseudoacacia and its mixed plantation in Loess Gully Region

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Abstract. By calculating the vegetation water requirements (ETC) of the typical plantations of Robinia pseudoacacia and Robinia pseudoacacia-Platycladus orientalis mixed plantation in the Loess Gully Region and analysing the coupling relationship between rainfall (P) and water requirements of each plantation, thereby scientifically guides local tree planting and afforestation, and better vegetation restoration. The Penman-Monteith formula is used to calculate the reference crop evapotranspiration in the study region, and then the double crop coefficient method is used to calculate the daily ETC of Robinia pseudoacacia and its mixed plantation in different hydrological years. The result shows that from dry year to normal year, the ETC-RP-PO is less than ETC-RP by 48.8 mm and 52.2 mm respectively, and the growth season accounts for the largest proportion. The ETC-RP-PO and ETC-RP are not satisfied in most months of the growth season. Among them, the initial period and the development period of the growth season are the largest, with the largest water requirements deficits (D) reaching 58.65 mm, 51.32 mm (dry year) and 106.21 mm, 93.18 mm (normal years). The ETC of two plantation increases from dry year to normal year. And the D also increases when vegetation water requirements satisfaction (S) increases, but the increase rate is expressed ETC > S > D.

1. Introduction

Arid and semi-arid regions are the most vulnerable areas of the global ecosystem, and the Loess Plateau is a typical region among them. The contradiction between water supply and demand is the constant theme[1-2]. Since the founding of New China, the state has done a lot of work for the restoration of vegetation in this area, the most typical one is afforestation. However, many fast-growing tree species were planted in the early stage of vegetation restoration in the Loess Plateau, and most of them were single plantation species. Due to the limitation of soil moisture on the growth of plants in the Loess Plateau and the lack of strong resistance to insect pests by a single plantation species, the problems of low survival rate, low growth rate and vegetation degradation of plantation have appeared during the afforestation process[3]. Based on such problems, many scholars have studied the evapotranspiration of woodland and grassland under different land use types [4-6], but the researches are mainly based on single plantation or grassland. Compared with pure forest and pure grassland under different vegetation coverage, mixed plantation types have the advantages of complex and diverse structures, strong resistance to adversity, and sufficient land utilization. In addition, mixed plantation can significantly improve forest productivity and stability, and the survival of mixed forests is more than twice that of pure forest [7]. Moreover, mixed plantation can better improve soil conditions and restore soil quality [8].
Therefore, the Loess Plateau region uses mixed plantation instead of single plantation to improve the existing degraded vegetation community structure. So understanding the water requirements of vegetation under different vegetation covers is of great significance for regulating the water relationship, solving the contradiction between water supply and demand in the arid area of the loess, and choosing suitable site conditions. At the same time, it is possible to carry out afforestation, vegetation restoration and optimize the configuration of the shelterbelt system according to the actual situation, thereby increasing the survival rate of afforestation.

Vegetation water requirements (ETC) mainly include transpiration and soil evaporation. This thesis takes *Robinia pseudoacacia* and *Robinia pseudoacacia-Platycladus orientalis* mixed plantation as the research object and uses Penman-Monteith method to calculate the reference crop evapotranspiration in the study region. Then use the Dual Crop Coefficient method to calculate daily ETC of the Robinia pseudoacacia and Robinia pseudoacacia-Platycladus orientalis mixed plantation in dry year (2018) and normal year (2019). And analyze the coupling relationship between rainfall and water requirements in each plantation. This is of great significance to the rational restoration of vegetation in the Loess Gully Region, the improvement of plantation survival rate and the evaluation of ecological benefits.

2. Materials and methods

2.1. Experimental region overview

The experimental region is located in the Nanxiaohegou Watershed in Houguanzhai Township, Qingyang City, Gansu Province of China. The Xifeng Water and Soil Conservation Scientific Experiment Station of the Yellow River Conservancy Commission is built in the watershed. The watershed area is 36.3km², and the topography is mainly composed of highland, slope and valley, with typical loess gully area. The watershed is located in a semi-arid region. The average rainfall for many years is 533.1mm, and the rainfall is concentrated in May to September, accounting for more than 70% of the whole year, and it mostly occurs in the form of heavy rain and torrential rain. The soil types are mainly black loess soil and loess soil. There is no natural forest distribution in the watershed, and the plantations are mainly *Robinia pseudoacacia*, *Platycladus orientalis* and *Pinus tabulaeformis*. After field investigations, Robinia pseudoacacia and Robinia pseudoacacia-Platycladus orientalis, which are basically the same age and grow well, were selected as the experiment region.

2.2. Experiment design

The experiment was carried out in various plots in the Nanxiaohegou watershed during the 2018 and 2019 Vegetation growth season (April 15 to October 15), and mainly included the measurement of soil moisture, soil evaporation, vegetation parameters and the collection of meteorological data. Soil moisture was measured by TDR tube. The measuring interval was 3~5 days, the measuring depth is 200cm, the interval depth is 10cm when the depth is 0~100cm, and the interval depth is 20cm when the depth is 100~200cm. Soil evaporation was measured with a self-made mini lysimeter (depth 20cm, diameter 16cm), and the measuring interval was 3~5 days. Meteorological data (rainfall, solar radiation, temperature, humidity, wind speed at 2m, etc.) are monitored by the WatchDog 2009 series of meteorological observation systems. Vegetation canopy analysis system (WinScanopy 2006, Canada) was used for vegetation parameters for fixed-point observation and the interval is 6~7 days.

2.3. Calculation of reference crop evapotranspiration ET₀

Use Penman-Monteith formula to calculate reference crop evapotranspiration ET₀. Based on Penman's comprehensive consideration of factors that may affect evapotranspiration, such as wind speed and air saturation difference, Monteith introduced the concept of gas impedance, which provides a new idea for the study of evapotranspiration under non-uniform underlying surface conditions [9]. However, the surface (canopy) impedance and aerodynamic impedance of water vapor transmission required by the formula are not easy to obtain. So the FAO has put forward a proposal based on the aerodynamic equation and the surface impedance equation. Use FAO Penman-Monteith method for estimating
reference crop evapotranspiration (potential evapotranspiration), Specifically expressed as:

\[ ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_a + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \]  

(1)

Where \( ET_0 \) is the reference crop evapotranspiration (potential evapotranspiration) (mm/d); \( R_n \) is the net radiation reaching the crop canopy [MJ/(m•d)]; \( G \) is the soil heat flux [MJ/(m•d)]; \( \gamma \) is the psychrometer constant; \( T_a \) is the daily average temperature at 2m (℃); \( u_2 \) is the wind speed at 2m (m/s); \( e_s \) is the saturated vapor pressure (kpa); \( e_a \) is the actual vapor pressure (kpa); \( (e_s - e_a) \) is Saturated vapor pressure difference (kpa); \( \Delta \) is the slope of the vapor pressure curve (kpa/℃).

2.4. Calculation of vegetation water requirements \( ETC \)
The vegetation water requirements \( (ET_C) \) is the process of vegetation transpiration and evaporation under standard conditions (no water stress) \(^9\). In this study, the dual crop coefficient method recommended by FAO is used to calculate \( ETC \). The calculation formula is as follows:

\[ ETC = KC \cdot ET_0 \]  

(2)

\[ K_C = K_{cb} + K_e \]  

(3)

In the formula: \( ETC \) is the vegetation water requirement (mm/d), reflecting the transpiration and evaporation process of vegetation under sufficient water supply conditions; \( K_C \) is the crop coefficient; \( K_{cb} \) is the basic crop coefficient reflecting the transpiration of plants, reflect that the top soil is dry and the average soil moisture content in the root zone satisfies the ratio of \( ETC/ET_0 \) during crop transpiration; \( K_e \) is the soil surface evaporation coefficient, which reflects the impact on \( ETC \) caused by the increase of soil surface evaporation intensity in a short period of time due to surface soil moisture after irrigation or rainfall. The calculation of crop coefficient refers to the results of L.S.Pereira\(^9\) et al.

3. Results and analysis

3.1. Changes of \( ET_0 \)
First of all, according to the criteria of Judgment hydrological year, 2018 is dry year (\( P=301.5 \text{mm}, \text{rainfall anomaly percentage } P_a =-43.4\% \)), and 2019 is normal year (\( P=556.8 \text{mm}, P_a =-4.4\% \)). The \( ET_0 \) calculated according to the Penman-Monteith formula is shown in Figure 1. It shows that \( ET_0 \) is distributed between 0.52~140.06mm and 26.58~162.92mm in dry year and normal year. And in both dry year and normal year, it first increases and then decreases. The difference is that the extreme value of \( ET_0 \) in the dry year is smaller than normal year.

![Figure 1. Monthly ET_0 changes in different hydrological years](image)

3.2. Changes of \( ETC \)
According to the dual crop coefficient method, the reference crop evapotranspiration can be used to calculate the \( ETC \) under different vegetation cover. As shown in Figure 2, the rainfall is concentrated in...
April, May, June and September, and the maximum occurs in June, which is 69.6mm in dry year. And the rainfall does not increase with the arrival of summer, showing several peaks overall. The rainfall is concentrated in April to October in normal year, and its total rainfall reached 482.5mm, reaching 86.7% of the whole year rainfall. The maximum value is 126mm in August, which is the only month of the year when the rainfall basically reaches the level of water requirements.

It can be seen from Figure 2 that the $ET_C$ of Robinia pseudoacacia plantation (Abbreviated as RP in the figure) is distributed between 0.38~109.25mm in dry year. Robinia pseudoacacia-Platycladus orientalis mixed plantation (Abbreviated as RP-PO in the figure) distributed between 0.34~99.4mm. In normal year, the $ET_C$ of Robinia pseudoacacia plantation ($ET_{C\text{-RP}}$) is distributed between 10.37~140.11 mm, and the $ET_C$ of Robinia pseudoacacia-Platycladus orientalis mixed plantation ($ET_{C\text{-RP\text{-PO}}}$) is between 9.84~127.08mm. For the $ET_C$ of the two plantation, the $ET_C$ in the dry year showed a trend of first increasing and then decreasing, and the $ET_{C\text{-RP}}$ was generally larger than $ET_{C\text{-RP\text{-PO}}}$. However, in the growth season, the vegetation coverage and leaf area index are different in each month between the plantation, resulting in differences in crop coefficients, and differences in the final $ET_C$. At the initial period of the growth season (April) in dry year, the difference in $ET_C$ between the two plantation is the largest, reaches 9.8mm. In normal year, the difference is the largest in May, reaches 13.03mm. Moreover, in August of normal year, the $ET_{C\text{-RP\text{-PO}}}$ exceed the $ET_{C\text{-RP}}$ for the first time.

Figure 2. Monthly $ET_C$ and $P$ changes in different hydrological years

3.3. Analysis on satisfaction degree of water requirements of plantation

In order to evaluate the satisfaction of $P$ and $ET_C$, by drawing on the experience of the crop water requirements satisfaction index [10], the vegetation water requirements satisfaction ($S$) is established as an evaluation index. And the water requirements deficit ($D$) is used to express the quantitative relationship between $P$ and $ET_C$. Calculated as follows:

$$S = \begin{cases} 
1 & P > ET_C \\
0 & P = ET_C \\
0 & P < ET_C 
\end{cases}$$

$$D = \begin{cases} 
ET_C - P & P > ET_C \\
0 & P < ET_C 
\end{cases}$$

The degree of support of $P$ to $ET_C$ in each plantation is shown in Table 1. From dry year to normal year, the distribution of $S_{RP}$ is between 2.07%~100% and 2.77%~100%, and during the growth season (April–October) is 9.31%~100% and 24.19%~100%. The annual $S_{RP}$ is 52.27% and 65.62%, and the growth season is 60.15% and 69.97%. The distribution of $S_{RP\text{-PO}}$ is between 6.42%~100% and 3.15%~100%, and during the growth season is 10.01~100% and 26.68~100%. The annual $S_{RP\text{-PO}}$ is 57.10% and 70.19%, and the growth season is 64.72% and 74.31%. On the whole, whether it is a dry year or a normal year, the $P$ in most months does not satisfy $ET_C$, especially during the growth season. The months that satisfy $ET_C$ are all after September. During this period, the vegetation is at the end of growth and the crop coefficient is small, so the calculated $ET_C$ will also become smaller. It is easy to occur that $P$
satisfies the $ET_c$. However, the most water-needed period of vegetation should be the initial period and development period of growth. During this period, the vegetation grows rapidly and requires more water to support its physiological process and achieve normal vegetation growth.

From the perspective of $D$, it shows that $D$ is larger in the initial growth period (April) or the development period (May to June) and the performance of Robinia pseudoacacia and Robinia pseudoacacia-Platycladus orientalis mixed plantation is inconsistent. In the dry year, the $DRP$ is the largest in April at 58.65mm, and the $D$ for the whole year is 275.28mm; The $DRP$ is the largest in May at 51.32mm, and $D$ for the whole year is 226.49mm. In the normal year, both of them showed the largest $D$ in May at 106.21mm and 93.18mm. The annual $D$ is 291.75mm and 236.52mm. On the whole, from dry year to normal year, the $P$ increases, and its $ET_c$ also increases. However, when the $S$ increases, the $D$ also shows increase, but the increase rate is expressed as $ET_c > S > D$.

Table 1. Support degree of rainfall with water requirements in each plantation

| Year | Month | $P$ (mm) | $ET_c$ (mm) | $S$ (%) | $D$ (mm) |
|------|-------|----------|-------------|---------|----------|
|      |       | RP       | RP-PO       | RP-PO   | RP       | RP-PO   |
| 2018 | 1     | 1.6      | 14.83       | 12.53   | 10.79    | 12.77   | 13.23   | 10.93   |
|      | 2     | 1.3      | 22.45       | 20.24   | 5.79     | 6.42    | 21.15   | 18.94   |
|      | 3     | 24.1     | 59.12       | 52.65   | 40.76    | 45.78   | 35.02   | 28.55   |
|      | 4     | 50.6     | 109.25      | 99.44   | 46.32    | 50.88   | 58.65   | 48.84   |
|      | 5     | 29.9     | 86.64       | 81.22   | 34.51    | 36.81   | 56.74   | 51.32   |
|      | 6     | 69.6     | 93.30       | 89.11   | 74.60    | 78.11   | 23.70   | 19.51   |
|      | 7     | 21       | 52.93       | 48.02   | 39.68    | 43.73   | 31.93   | 27.02   |
|      | 8     | 4.7      | 50.51       | 46.96   | 9.31     | 10.01   | 45.81   | 42.26   |
|      | 9     | 69.3     | 30.95       | 28.74   | 100.00   | 100.00  | 0.00    | 0.00    |
|      | 10    | 17.4     | 12.84       | 12.08   | 100.00   | 100.00  | 0.00    | 0.00    |
|      | 11    | 11.1     | 0.38        | 0.34    | 100.00   | 100.00  | 0.00    | 0.00    |
|      | 12    | 0.9      | 43.58       | 36.67   | 2.07     | 2.45    | 42.68   | 35.77   |
| Total|       | 301.5    | 576.78      | 527.99  | 52.27    | 57.10   | 275.28  | 226.49  |

| Year | Month | $P$ (mm) | $ET_c$ (mm) | $S$ (%) | $D$ (mm) |
|------|-------|----------|-------------|---------|----------|
|      |       | RP       | RP-PO       | RP-PO   | RP       | RP-PO   |
| 2019 | 1     | 7.7      | 10.37       | 9.84    | 74.26    | 78.28   | 2.67    | 2.14    |
|      | 2     | 20.2     | 15.25       | 14.06   | 100.00   | 100.00  | 0.00    | 0.00    |
|      | 3     | 19.3     | 58.39       | 53.61   | 33.05    | 36.00   | 39.09   | 34.31   |
|      | 4     | 45.7     | 97.29       | 88.45   | 46.97    | 51.67   | 51.59   | 42.75   |
|      | 5     | 33.9     | 140.11      | 127.08  | 24.19    | 26.68   | 106.21  | 93.18   |
|      | 6     | 62.0     | 94.36       | 89.18   | 65.70    | 69.52   | 32.36   | 27.18   |
|      | 7     | 78.0     | 104.75      | 99.62   | 74.46    | 78.30   | 26.75   | 21.62   |
|      | 8     | 126.0    | 130.42      | 133.50  | 96.61    | 94.38   | 4.42    | 7.50    |
|      | 9     | 55.2     | 72.30       | 64.65   | 76.35    | 85.38   | 17.10   | 9.45    |
|      | 10    | 81.7     | 50.36       | 46.80   | 100.00   | 100.00  | 0.00    | 0.00    |
|      | 11    | 26.1     | 38.79       | 34.76   | 67.28    | 75.09   | 12.69   | 8.66    |
|      | 12    | 1.0      | 36.15       | 31.78   | 2.77     | 3.15    | 35.15   | 30.78   |
| Total|       | 556.8    | 848.55      | 793.32  | 65.62    | 70.19   | 291.75  | 236.52  |

### 4. Discussion

Robinia pseudoacacia, as a broad-leaved arbor plantation widely distributed in the Loess Plateau, is widely used in afforestation plans because of its drought tolerance. However, this drought-resistant tree also has a considerable requirement for water even in the seedling stage \[^{11-12}\], and the relative water content of the soil in the loess gully area is below 50% most of the time, resulting in a low survival rate of plantation and withering. This is mainly because for a single tree species, the stress resistance is unstable and the water use efficiency is not enough, so that the lack of water resources can not support the growth of the plantation \[^{13}\]. For the mixed plantation of Robinia pseudoacacia and Platycladus...
orientalis, its $ETc$ is lower than that of the pure Robinia pseudoacacia plantation. This is because Robinia pseudoacacia is a deep-rooted tree species, the root system is distributed between 0–120cm and is evenly distributed, and Platycladus orientalis is a shallow-rooted tree species, the root system is distributed between 0–90cm and mainly distributed in 0–40cm. And for the Nanxiaohegou watershed, in addition to the changes in soil moisture content that can affect the deep soil in the case of several heavy rain and torrential rain, the other more frequent light rain mainly affect the soil moisture content of 0–40cm. So it can be concluded that the moisture change is concentrated in the 0–40cm soil layer. Therefore, the mixed plantation of them can make full use of water, and its show that $ETC_{RP-PO} < ETC_{RP}$. Meanwhile, making full use of the shallow and medium layers of soil that can be affected by rainfall most of the time can also avoid soil desiccation in pure Robinia pseudoacacia plantation, which is similar to the results of Wang Li and others.

According to the $S$ in dry year and normal year, the distribution of $SRP$ in the growth season is 9.31%-100%, and $SRP_{PO}$ is 10.01%-100%. Among them, the months that do not satisfy the $ETC$ of the growth season account for the majority. Also, water shortage is the largest in April and May, and there is a general shortage in other months except for the last stage the growing season. This is because the changes in meteorological conditions and the requirements for vegetation's own growth in the initial, development, and maturity of growth period lead to greater $ETC$ during this period, and at the last stage of growth period, its $ETC$ reduced with the crop coefficient dropped sharply.

With the increase of $P$, $ETC$ increases instead. Even with the increase in $S$, the $D$ also shows increase, which is inconsistent with Yin Haixia and others results. This is because firstly there is a difference between the water requirements of crops and the plantation, and secondly, $P$ is not the only factor affecting $ETC$. It indirectly affects $ETC$ by replenishing soil moisture. The direct influence factors of $ETC$ are mainly meteorological conditions, including solar radiation, temperature and wind speed, etc.

Therefore, in dry year to normal year, although $P$ increases, $ETC$ also increase compared to dry year due to the combined influence of meteorological conditions. Meanwhile, the increase in $P$ does increase the $S$, but because the increase in $ETC$ is greater than the increase in $P$, the $D$ also increased.

5. Conclusion
This thesis uses the calculation method of crop water requirements recommended by FAO to calculate the vegetation water requirements of the typical plantation Robinia pseudoacacia pure plantation and Robinia pseudoacacia-Platycladus orientalis mixed plantation in Loess Gully Region and analyzes the coupling relationship between rainfall and it. Finally got the following conclusion:
1. The $ETC_{RP-PO}$ is 48.8mm lower than that of the $ETC_{RP}$ in dry year and 55.2mm in normal years. In growth season, $ETC_{RP-PO}$ is 30.8mm lower than $ETC_{RP}$ in dry year, and 40.3mm lower in normal year. That is, in different hydrological years, the $ETC_{RP-PO}$ is lower than $ETC_{RP}$, and the growth season accounts for the largest proportion.
2. During the growth season of Robinia pseudoacacia pure plantation and Robinia pseudoacacia-Platycladus orientalis mixed plantation, $ETC$ is not satisfied for most of the time, and the $D$ is largest in initial and development of growth period. The maximum $D$ reaches 58.65mm, 51.32mm (dry year) and 106.21mm, 93.18mm (normal year).
3. From dry year to normal year, the $P$ increases, but the $ETC$ also increases. And the $D$ also increases when $S$ increase, but the increase rate is expressed $ETC > S > D$.

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