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Soil water resources use limit in the loess plateau of China

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ABSTRACT

Soil water is a key factor limiting plant growth in water-limited regions. Without limit of soil water used by plants, soil degradation in the form of soil desiccation is easy to take place in the perennial forestland and grassland with too higher density or productivity. Soil water resources use limit (SWRUL) is the lowest control limit of soil water resources which is used by plants in those regions. It can be defined as soil water storage within the maximum infiltration depth in which all of soil layers belong to dried soil layers. In this paper, after detailed discussion of characteristics of water resources and the relationship between soil water and plant growth in the Loess Plateau, the definition, quantitative method, and practical applications of SWRUL are introduced. Henceforth, we should strengthen the study of SWRUL and have a better understanding of soil water resources. All those are of great importance for designing effective restoration project and sustainable management of soil water resources in water-limited regions in the future.

Keywords: Infiltration Depth; Dried Soil Layer; Wilting Coefficient; Soil Water Resources Use Limit; Initial Stage to Regulate the Relationship between Soil Water and Plant Growth

1. INTRODUCTION

Vegetation restoration is an effective measure to conserve soil and water and improve ecological environment. Since 1960 s, large-scale afforestation has been carried out on the Loess Plateau in order to control serious soil erosion there [1]. Tree species, selected for their capacity to extend deep roots and fast growth, have been planted at initially high planting densities in order to rapidly establish higher degrees of ground cover, biomass and yields, and thereby to quickly realize ecological, economic and social benefits during vegetation restoration. To meet evapotranspiration needs, it is advantageous that the roots of these plants can grow quickly and thus take up water from considerable soil depths. Consequently, the combination of increased water used by plants and low water recharge rates has led to widespread soil deterioration occurring on the Loess Plateau in the form of excessive soil drying under both perennial grasses and forests. Such soil deterioration can adversely affect the stability of forest ecosystems and the ecological, economical and societal benefits of forest and other plant communities. Now trees and grasses species planted in the Loess Plateau are generally suitable for the local climate[2]. Therefore, in order to regulate the relationship between plant growth and soil water, the following two issues should be solved: when we take effective measures to regulate the relationship and how much the amount of trees and grass to be cut when regulating. This paper aims to introduce the SWRUL in order to better understand and use the soil water resources in water-limited regions.

2. WATER RESOURCES OF THE LOESS PLATEAU

2.1. Characteristics of Precipitation on the Loess Plateau

The Loess Plateau, located in the central of China, largely belongs to semi-arid area and water—limited regions. Precipitation plays an important role in the terrestrial water cycle, especially in the Loess Plateau. This is because groundwater mostly lies 40 - 100 meters below the surface and the infiltration of precipitation is almost the only way to supplement soil water in the Loess Plateau [3]. Owing to a little account of the snowfall in winter, precipitation resources in this region can be represented by the rainwater resources which usually be defined as the sum of precipitation within a year in a place [4]. Annual rainfall in the Loess Plateau is limited, merely ranging from 250 mm in the northwest (9.8 inch) to 600 mm in the southeast (23.6 inch). Because of the monsoon influence, rainfall here has great seasonal variability, and about 70% of rainwater fell in the months from June to September. At the same time, the relative variance of annual rainfall is also between 20% - 30% respectively. Furthermore, spatial variability of rainwater resources in this region is strong, too. It shows a total decreasing trend from southeast to northwest, which has a direct relationship with the amount of rainfall [5].

2.2. Soil Water Resources in the Loess Plateau

Soil water resource is a kind of renewable fresh water resource with the characteristics and properties of natural resources [6]. Both rainfall and groundwater can only be absorbed and used by plants after being transformed into soil water as most of the water used by plant is obtained from the soil by plant roots system. So under rainfed conditions, soil water plays a key role in the production of agriculture and forestry. Thinking highly of the maintenance and use of soil water resources in the Loess Plateau is of great significance.

In general, soil water resources in the Loess Plateau have strong temporal and spatial variability. Multiple factors, including meteorological factors (such as rainfall, atmospheric evaporation) and soil factors (such as soil texture, land-use patterns, and soil water holding capacity) produce a combined effect on the distribution and dynamic of soil water [7]. Of which, rainfall plays a key role. Furthermore, groundwater of this region usually lies 40 - 100 m below the surface, leading to that groundwater recharge including the side stream recharge of ground- water, is difficult to occur [8]. So water cycle in this region is relatively simple, and water contents at different time and depth depend on the redistribution of rainwater resources after infiltration [9]. Limited rainfall is intercepted by the topsoil firstly, then moving down slowly under the soil water potential gradient [10]. It is the reason why the infiltration depth is shallow, and generally the depth will not exceed 3 m [11].

Furthermore, soil in the Loess Plateau mostly belongs to loam soil with a low bulk density of 1.0 - 1.3 $g.cm^{-3}$. The total porosity of this loess soil can be up to 50% and the water-holding porosity can also be up to 25% - 30%. So the loess soil in this region is often regarded as "soil reservoir" with a high water holding capacity. It is measured that topsoil in the 0 - 200 cm soil profile (78.7 inch) can hold soil water of 551.1 mm (21.7 inch) to 847.4 mm (33.4 inch) [5], which almost equals to the annual precipitation. From another perspective, those features of loess soil lead to its high evaporation in turn and soil water can only be stayed for a short time. Of course, this phenomenon has a direct relationship with abundant light and heat of this region. Taking abandoned land for an example, even in the rainy years, the evapotranspiration calculated from water balance could account for about 80% of rainwater from natural rainfall [12]. Under participation of vegetation, maintaining plant normal growth will require more water. This is the key reason why soil water content in this region is often at a low level.

3. RELATIONSHIP BETWEEN SOIL WATER AND PLANT GROWTH

3.1. Soil Water Conditions and Plant Growth

Results of studies conducted in the Loess Plateau showed that the soil water condition is a key index of plant productivity [13, 14]. Soil water is divided into available water and non-available water. Filed capacity and wilting coefficient are usually regarded as the upper and lower limit of available water. Under normal cases, soil water content in this region is always lower than the corresponding field capacity. Actual available water content in the Caragana(*Caragana korshinskii* Kom.) scrubland is less than 1/2 or 1/3 of the potential available water content [15]. Then the non-available water storage equals to the residual water storage in the soil when soil water content is smaller than the wilting coefficient, and it can be vividly called as the "dead" storage of the "soil reservoir". In the light of available water, the optimum soil water contents for different plants are different. For a certain plant, when the soil water content is within the range from wilting coefficient to the corresponding optimum soil water content, photosynthetic rate will increase to a certain extent with the increase of water content. Similarly, at the stage of soil drought, the increase of soil water content can also result in the improvement of plant's leaf water content and then accelerate the transpiration [16]. It is notable that there is a threshold for plants to react to soil water deficit. Wilting coefficient is a small range rather than a point [17], which upper limit and lower limit are called as initial wilting coefficient and permanent wilting coefficient respectively. When the soil water content is less than the initial wilting coefficient, it is difficult for plant to uptake soil water. In this case, although it won't immediately lead to the death of plant, plant's normal growth and development will be inhibited.

3.2. Soil Desiccation and Dried Soil Layer

The climate environment of "low rainfall" and "high evaporation" suggested that soil desiccation is easy to take place in most of the Loess Plateau [18]. Vegetation's participation will greatly accelerate this process. Dried soil layer has been found in farmland, artificial grassland

and forestland in semi-humid and semi-arid regions of the Loess Plateau since 1960s [19]. It results from the negative balance in soil water cycle directly. The characteristics of the local plant resources, the features of the underlying surface and the eco-climatic zones have a combined effect on the formation of the dried soil layer [8]. Among those, the decrease in rainfall and the increase in temperature would be the direct reason, and improper vegetation type and exorbitant density or productivity would accelerate its development. The appearance of dried soil layer would seriously deteriorate the soil quality, and the self-regulating capacity of soil would also be weakened [20].

Concerning the assessment standards of DSL, no consensus has been reached now. In most cases, it is often estimated according to the standards that water content is between stable water content and wilting coefficient [21]. As for the types of DSL, Li [22] divided it into temporary type and permanent type. The former refers to those dried soil layers which are located at the depth between land's surface and the maximum infiltration depth, and it can be gradually restored by thinning, plowing and other measures. But permanent type located below the depth of soil affected by rainfall infiltration is relatively stable and soil water in these soil layers cannot be restored unless experiencing high-intensity precipitation. When DSL's depth equals to the maximum depth which can be supplemented by rainfall infiltration, with the increasing forest age, strong depletion of soil water by plants will lead to serious soil degradation as the supplement amount of rainfall is limited. From this point, forestland and grassland will be further exacerbated by drought if effective human intervention and regulation measures are not carried about. Thereby it will further affect the normal growth of plant as well as vegetation's ecological benefits, even leading to the occurrence of desertification [23].

4. SOIL WATER RESOURCES USE LIMIT

4.1. Concept and Definition

In order to adapt to the dry climate coupled with low soil water content, perennials in the Loess Plateau usually have highly developed root system which are able to take root into deep soil layers quickly to uptake more soil water [24]. In the process of vegetation restoration, utilization depth of soil water by plants will increase with the age. For instance, result of study conducted in the semi-arid Loess Hilly Area showed that the utilization depth of soil water by Caragana increased from 2 cm (0.08 inch) to 200 cm (7.9 inch) during the first year after sowing [23]. The uneven distribution of plant roots in the soil profile coupled with the strong depletion of soil water by plants lead to the excessive consumption of soil water in the rhizosphere layer. Without timely and sufficient water supplement, soil water storage will reduce gradually from a higher storage at the beginning of afforestation to a very low storage at the adult Caragana scrubland because soil water content itself is limited, and dried soil layer will take place eventually. In addition, the depletion and utilization of soil water resources by plants originnally are not unlimited. Non-available water of the soil cannot be used by plants theoretically. "Dead" storage capacity accounts for a considerable volume in the "soil reservoir", especially in the Loess Plateau. So there must be an appropriate limit of soil water resources used by plants during the process of the vegetation restoration, which means soil water resources use limit (SWRUL) [25]. As precipitation is the only source of soil water supplement in this region, the maximum precipitation infiltration depth is also the maximum depth of soil water supplement. Dried soil layer and soil degradation will inevitably take place once soil water storage within the maximum infiltration depth lowered the limit. So, this concept can be defined as the soil water storage within the range from soil surface to the maximum infiltration depth in which all soil layers belong to dried soil layers. The standard of dried soil layer here is the initial wilting coefficient expressed by indicator plant, objective tree and grass species such as Caragana, Robinia pseudoacacia.

4.2. Quantitative Method

In order to determine the value of SWRUL in a certain region, it is necessary to choose the indicator plant in the local vegetation communities firstly. Here the indicator plant is usually the constructive species of natural vegetation or the purpose plant species of artificial vegetation. The maximum precipitation infiltration depth and the wilting coefficient expressed by indicator plant are two key parameters for determining the limit. The former should be determined based on measurements of infiltration depth in forestland or grassland under rainfed conditions for many years as inter-annual variability of precipitation in this region is quite strong [26]. Wilting coefficient is the lowest limit of soil water use by plants, reflecting the minimum requirement of soil water by plants. It can be got according to the direct field observations or other indoor methods.

SWRUL numerically equals to the integral of soil water storage along soil profile from soil surface to the maximum precipitation infiltration depth in which the soil water content equals to indicator plant's initial wilting coefficient. Being similar to the calculation of soil water storage, the value of SWRUL is generally got by stratified calculation method. The corresponding theoretical calculation formula is as follows:

$$L = \sum_{i=1}^{n} H_i W_i \quad (1)$$

$$H = \sum_{i=1}^{n} H_i \quad (2)$$

where, L is the SWRUL, H is the maximum precipitation infiltration, n is the number of subdivisions of dried soil layer, $H(i)$ is the depth of a certain subdivided soil profile, $W(i)$ is the initial wilting coefficient in the certain soil layer.

4.3. Significance and Application

4.3.1. The Standard of Measuring Whether the Use of Soil Water Resources by Plants is Excessive or Not

As a common physical phenomenon in the Loess Plateau, DSL increasingly threatens achievements and stability of vegetation restoration. However, under the background of climate drought and global warming, water restoration of dried soil layer is quite difficult to realize. The management of degraded land is facing with more suffering and challenges. Study results showed that in the semi-arid area of Loess Plateau, even the land use changed from alfalfa to annualcrops for 12 years, its water content also couldn't meet the needs of planting trees or perennial leguminous plants for their normal growth [27]. Therefore, the sustainable use of soil water in this region has an extremely important theoretical and practical significance. It is necessary to choose a reasonable index to evaluate local soil water conditions. SWRUL can be used as the indicator.

It is mentioned that the essence of the dried soil layers is the excessive depletion of soil water use by plants. The depth and thickness of dried soil layer are increased with the age of plants. For instance, soil water content at the soil layer of 100 cm (39.4 inch) was smaller than the wilting coefficient of Caragana scrubland in the third year after sowing. After then, soil drying becoming more and more serious with times going by, finally extending to 60 cm (23.6 inch) to 300 cm (118.1 inch) at the fifth year [28]. Hence, the use of soil water by plants began to enter the "excessive use stage" as the maximum precipitation infiltration depth was only 290 cm [23]. In fact, for deep root plants, it often doesn't need to take a long time. To sum up, according to SWRUL, we can identify whether or not plants excessively use soil water re-sources at the initial stage of vegetation restoration. This is of important value for the sustainable use of soil water resources.

4.3.2. The Theoretic Foundation to Determine Initial Stage of Regulating the Relationship between Plant Growth and Soil Water

Generally, there are disorder relationship between plant growth and soil water in forest ecosystems and grass ecosystems in the water –limited region. Regulating this relationship is an essential way to ensure healthy development of ecosystems. In water-limited regions of the Loess Plateau, the determination of the initial stage of regulating relationship between plant growth and soil water is critical. This is because if the time of regulating the relationship is earlier than the mentioned initial stage, it will result in the waste of soil water resources. Of course, if the time of regulating is later than the initial stage, it may lead to irreversible soil degradation [25].

SWRUL is the cordon of soil water use by plants and the theoretic foundation to determine initial stage of regulating the relationship between plant growth and soil water. Once the depletion of soil water by plants reached or was lowered than the limit, effective measures should be taken to regulate the plant-water relationship. These measures can be divided into the following two sorts: to increase soil water storage according to plants' requirement or to reduce evapotranspiration according to existing soil water conditions. The former is difficult to achieve in water-limited regions and the later is mainly achieved through trim or cut trees. It is reported that soil water storage in maximum precipitation infiltration depth in the soil under the 5-year-old Caragana scrubland in Shanghuang Ecoexperimental Station reached its limit, so the initial stage of regulating the plant water relationship was the fifth year [28]. Accordingly, SWRUL plays an important theoretical role in guiding the regulation of plant-water relationship at the population level.

4.4. Research Prospects

Given the importance of SWRUL in theory and practice, SWRUL in different site and vegetation types should be paid more attention. As the theory is initially proposed, many details remain to be improved, especially the following two points.

4.4.1. Determination of Maximum Precipitation Infiltration Depth

In bare lands of the Loess Plateau, the maximum precipitation infiltration depth directly depends on the initial soil water content and the amount of rainfall [29,30]. Infiltration and redistribution of precipitation will become complicated with vegetation's participation [31]. On the one hand, the distribution of plant roots lead to non-uniform consumption of soil water. Water in the soil away from the rhizosphere area will flow to the rhizosphere under soil water potential gradient [32]. On the other hand, vegetation coverage affects the characteristics of soil infiltration by canopies interception and weakening the raindrop power hitting on the surface through improving the nature of underlying surface [33]. The vegetation coverage and biomass in a plant community usually increase with time in the progress of vegetation succession. During this process there are significant improvements of soil's infiltration capacity. Biological holes such as root holes in the recovery woodland is likely to produce preferential flows, then the soil infiltration rate and maximum precipitation infiltration depth will increase to a certain extent [34]. Furthermore, waterconsuming capacity in different vegetation types as well as their influence on soil water redistribution is different. So it is necessary to determine maximum precipitation infiltration depths in different vegetation types. Then the application scale of soil water resources use limit can be expanded.

4.4.2. Vertical Variability of Wilting Coefficient in the Soil Profile

Wilting coefficient is a key element in the calculation of SWRUL. This value is usually obtained by putting the critical leaf water potential of indicator plant into soil-water characteristic curve which describing the relationship between soil water and soil suction. Taking Gardner empirical formula $\theta = a \cdot S - b$ (θ is the volumetric soil water content, S the soil suction, a, b are parame- ters) to fit the curve, wilting coefficient can be expressed as $W= a \cdot 1.5 - b$. In this formula, parameter a reflects soil's water-holding capacity, and parameter b reflects the decreasing speed of soil water content with the decrease of soil water suction [35]. Both parameter a and parameter b are mainly influenced by soil texture, or-ganic matter content and soil structure [36]. All factors mentioned change with soil depth, so it will lead to vertical variability of wilting coefficient certainly. Results of studies carried out in Shanghuang Ecoexperimental Station showed that wilting coefficient changed indeed with soil depth, the fitted values (volumetric soil water content) floated from 5.6% to 7.8%. The overall trend was that the wilting coefficient at the land surface was small and then increased to a certain level with the in-crease of soil depth. The variability of adjacent soil layers was quite strong within the depth that from soil sur-face to the maximum precipitation infiltration depth. In addition, the above analysis is based on the assumption that water suction is considered to be 1.5 MPa for temporary wilting coefficient in the Loess plateau [19]. Actually, the wilting coefficient has a relationship with soil water absorption capacity by plant, so wilting coefficients of different indicator plant types are different even in the same soil environment [37]. Under such circumstances, researches on wilting coefficient of different indicator plants should also be taken into consideration.

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